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Technical Conference Paper

10 years of EZ cutter experience, a proven contribution to salt cavern development

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SMRI Spring 2025 Technical Conference
27-29 April 2025
Wilhelmshaven, Germany

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Abstract

Cutting pipes remains a challenge of major concern for storage cavern operators and salt producers. Changing the position of leaching strings when developing salt caverns or re-accessing underground caverns with bent casing, often requires heavy and delicate operations that are both time-consuming and costly.
The first solution mining dedicated casing cutter enables clean and perfectly controlled cuts without explosives, chemicals or other expensive workover alternatives. By simplifying transportation, logistics and safety issues, it can be deployed on any standard wireline unit. The only significant requirement is conductive fluid in the well, such as brine or sea water.
This versatile and lightweight logging tool, capable of cutting both inner and outer casings, has proven highly effective in many configurations over the past decade.
Smartly combined with the other tools of the "Flodim Cavity suite", cavern intervention programs can be made faster, lighter and cheaper.
The "EZ cutter" has been successfully operated since 2014 in 14 countries worldwide, cutting more than 400 casings in many distinctive configurations.
As the demand for massive underground storage is expected to grow fast and as brine & potash extraction remains on an upward trend, the electrochemical cutting technology should become a game changer with unique advantages to optimize any leaching intervention program.
This paper presents the operational feedback of 10 years of casing cuts, including case studies and innovations that have enhanced the tool's capabilities to better serve the underground cavern industry. It also highlights the ongoing development prospects, introducing the future XS Cutter and XL Cutter that will increase the intervention capabilities and reduce effective cutting times.

Key words: salt caverns, casing cut, cavern development, sonar, well casing, well logging

In this milestone year of 2025, marking the 60th anniversary of SMRI, the 45th anniversary of our partner SONIC SURVEYS, and FLODIM's 30th anniversary, we are thrilled to also celebrate the 10th anniversary of EZ Cutter : a pure solution mining dedicated instrument based on an electrochemical principle to cut pipes, especially those hanging in brine caverns.

Over the past 10 years, more than 400 casing cuts were made with the EZ Cutter instruments in more than 14 countries quite often when nobody else could succeed, thanks to the unique specific characteristics of the method that is presented in this paper.

Before the patent and the initial prototype in 2015, several historical clients of Flodim were complaining of not being able to identify adapted solutions to cut pipes when leaching caverns with frequent bent or collapsed pipes, despite a significant range of available services from the Oil & Gas industry.

Combined with other dedicated cavern instruments (the "cavity suite" of Flodim), it is possible and even proven to optimize development cost, time and HSE concern of caverns under leaching with only little Work-Over assistance or a crane (Crabeil et al. 2020). Additional understanding and knowledge could be developed since then with results now available.

The next steps to come soon of the unique downhole electrochemical method are now first the incorporation of the latest evolutions within EZ Cutter in a 'Challenging the limits' spirit. The XS Cutter instruments is currently under development for small sizes and deviated completions, like those of the potash solution mined industry. The cutter is also under declination in a XL version of the instrument to significantly divide cutting times when casing diameter is 7" or more.

1. The innovative EZ cutter

a. Back on history

Electrochemical methods to cut pipes in salt caverns were attempted from the 1930s up to the late 1970s by the old ICI "Imperial Chemical Industries" in UK. An electrode was run into the casing on insulated cable down to the cutting depth and a potential difference was applied. The 'cut' which proceeded by galvanic erosion of the casing took many weeks. The cut was not always in the targeted area, not radial, even sometimes in a vertical direction.

More recently, in the nineties, a large size Oil & Gas Service Company did consider electrochemical cutting, but the option was discarded because the Faraday law when applied to well logging was:
- too much time consuming as only limited power could be transported through a logging cable to a downhole instrument,
- too big to fit in an acceptable pressure envelope as the Silicon Carbide 'SIC' technology to imagine power electronic components only became accessible 10 or 15 years later.

Flodim took over the idea and our initial move consisted of applying Faraday's laws to a brine immersed casing with the main idea of declining the Cavern Sonar rotation system to electrodes to dig out metal and obtain a 360° cut.
But soon, we realized things were not as easy as expected with many independent problems that really made the whole system complex.

EZ cutter was imagined, developed and patented 10 years ago to offer a new casing cutting technology specifically adapted to Solution Mining requirements such as pipe recovery and changing leaching strings intervention.

As a reminder, the following main requirements were identified to offer a new cutting technology adapted to the specific needs of Salt cavern Solution Mining:

1. Quality: clean and sharp cut allowing safe subsequent wireline below the cut.
2. Safety: no dangerous products to store, transport and handle.
3. Lightweight operation : wireline unit, light tool, easy to handle.
4. Thin, same size as a 2-7/8" sonar instrument and relatively short tool, easy to run in classical leaching completions
5. Versatility: able to cut pipes within a wide range of diameters

6. Robust and adaptable to cut at different depths in consecutive runs.
7. Fast: if cut is slow compared to other conventional methods, overall intervention timesaving is real.
8. Profitable: overall cost-saving for salt cavern operators
9. Reliable: the tool must prove a success rate which is at least equivalent to the other technologies.

Its principle is based on the downhole application of the electrochemical Faraday laws focused on a groove that is deepened until the rotating electrodes get through the steel made-up pipe, making a clean and perfectly controlled cut.

With no use of explosives or chemicals, there is no transportation, safety nor logistic issues. The only requirement is to have conductive fluid which is generally the case when dealing with Solution Mining as brine is a highly conductive fluid.

EZ Cutter can then be deployed on our own or on third party's production logging units, thanks to the many improvements that were implemented over time (mono-conductor line, extension to deep cavern conditions, incorporation of a DSCL, maintainability and consumables management) and which are still ongoing towards higher targets.

b. Basic principles of the electrochemical cut

Electrochemical machining

Electrochemical machining (ECM) consists in connecting the conductive workpiece at the positive voltage (anode) of a direct current generator and the tool for machining at the negative voltage (cathode). Both workpiece and tool are immersed in a conductive solution called electrolyte.
In our application, the workpiece is the casing to cut, the tool for machining is called electrode(s) and the electrolyte is brine, the cavern fluid.
At the anode, the electrochemical reaction is initiated and maintained all along the cutting process. During the reaction, metal goes from solid state to solution and forms hydroxides that may reduce the conductivity but with brine mixing, electrolyte renewal is naturally ensured.

The amount of material that can be removed is directly proportional to the power given to the system, which is the current delivered to the electrodes multiplied by time.

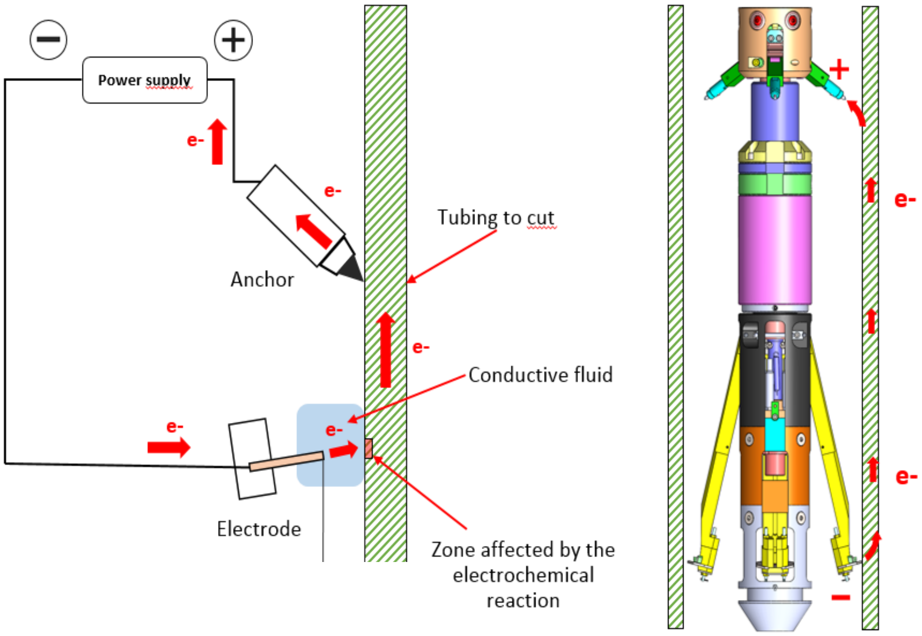


Figure 1. Basic principle of the electrochemical cutter

Electrochemical theory

Under strong current applied to the electrodes, the two main reactions take place:

- At the anode, $Fe \rightarrow Fe^{2+} + 2e^-$
- At the cathode, $2 H_2O + 2e^- \rightarrow H_2 + 2 OH^-$

As a more global result, $Fe^{2+} + 2 OH^- \rightarrow Fe (OH)_2$, which presents black particles that settle down quite fast if not agitated.

So, if reaction is properly controlled with distance anode–cathode adjusted, electrode(s) shape optimized and rotation ensured, metal is dig out all along a circular groove with a limited width in order to have all of the work to deepen the groove until it gets through, and the pipe drops.

Faraday laws of Electrolysis say that the mass of a substance altered during electrolysis is directly proportional to the quantity of electricity transferred, as summarized:

$$m = \left(\frac{Q}{F}\right)\left(\frac{M}{z}\right)$$

- *m is the mass of the substance liberated at an electrode in grams*
- *Q is the total electric charge passed through the substance (then, Q = I*t)*
- *F = 96485 C mol^{-1} is the Faraday constant*
- *M is the molar mass of the substance*
- *z is the valence number of ions of the substance (electrons transferred).*

From the above, time prediction is a direct function of casing diameter and casing thickness.

Description

Obtaining a continuous removal of material requires several specific considerations for the electrochemical reaction that occurs in an irreversible mode:

- Current density must be high enough to create proper electrochemical conditions,
- Renewal of the electrolyte must be ensured,
- Pre-cleaning of the area has to be made before the cut starts,
- Electrodes need special shape and protectors to optimize duration,

Developing a new logging instrument requires strict specifications to match the market expectations:

- Small diameter in order to enter standard 3” or 4” pressure equipment,
- Appropriate transfer of energy from surface to downhole tool,
- Capability to anchor in any type of casing ranging from 4-1/2” to 11-3/4” or more,
- Capability to organize a local electrochemical circuit,
- Presence of an appropriate sensor (DSCL) to correlate depth.
- Anticipated weak points to face downhole issues.

So, the initial EZ Cutter system is made of:

- a surface unit that powers the downhole instrument and ensures communication through a standard mono-conductor cased hole logging cable,
- a downhole instrument that incorporates
  . a DSCL (Dual string Collar locator) to correlate depth to the cemented casing shoe,
  . an electronic module in order to supply the electrodes with appropriate current characteristics,
  . a motorized mechanical module with anchoring and rotary devices,
  . a customized cutting head adapted to the casing to cut,
  . appropriate in-line / outer centralizers.

c. Conventional methods when cutting leaching strings

Different cutting methods may apply depending on the ‘Solution Mining’ request to be considered. In the table below are presented the available cutting techniques from Oil & Gas current services.

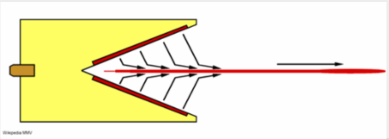
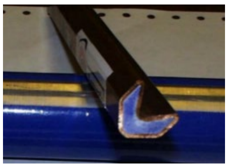
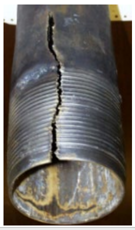
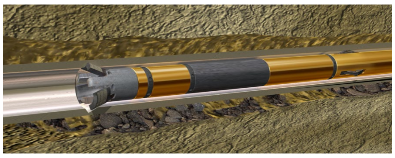
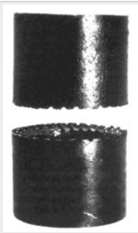
- When the requirement is to cut the inner casing for remedial work or for depth adjustment.

- When the requirement is to change the leaching strings configuration (both inner and outer casings).

Cutting the inner leaching string

The cavern operator may require cutting an internal casing/tubing for a number of operational or productive reasons, which may range from bent or collapsed inner casing remedial works to a new leaching position, possibly after a sonar survey is completed.

The following table shows the main advantages and drawbacks of all the existing and well-known techniques out of a wide range of oil & gas capabilities, before the electrochemical cutter (EZ Cutter) comes out (presented in chapter 2)

Type of method	Advantages	Drawbacks
Segmented cutter A shaped charge is to explode 	Fast. Reliable. 	No clean cut. No safe logging possible. Outer casing may be damaged. Cutter OD may require pipe scrapping. Explosives. Acceptation required.
Split shot cutter 	Fast. Slim tool. Produces a vertical cut to break at collar level. 	No clean cut. No safe logging possible. Outer casing may be damaged. Dangerous explosives. Acceptation required. 
Mechanical cutter from WO rig 	Reliable. Clean cut. Safe logging possible.	Mobilization time. Duration of intervention. Expensive.
Rotating knives / Electromechanical cutter 	Clean cut. Safe logging possible. Reliable. 	Not available for big sizes. Expensive wireline instrument. Little availability. High voltage & current logging cable. Compression is a problem for knives.
Chemical cutter 	Clean cut. Safe logging possible. 	Incomplete cuts happen often. Pipe in extension if possible. Dangerous product. Acceptation required
Radial cutting torch 	Clean cut. Safe running of logging tool. The RCT utilizes a proprietary mixture of powdered metals. The resultant molten plasma is then ejected through the nozzle section.	Not available for sizes over 9-5/8”. Expensive. Acceptation required.

Cutting both the inner and the outer leaching strings

The development of salt caverns is generally made of successive leaching phases to obtain the best possible characteristics of volume and shape for storage caverns, and of brine concentration for salt producing cavities, with respect to the authorized extension conditions.

A cavern changing phase program aims at repositioning the casing shoes of each leaching string and at adjusting the blanket level to its new depth before starting again water injection and brine production.

Most of the current methods present instruments with an OD close to the ID of the pipe to cut. They are not suitable for outer casing shoe adjustment, and they require full inner casing retrieval at first.

So, no conventional method provides a simple and realistic answer to the need of cutting both inner and outer casings.

2. EZ cutter as a masterpiece of the "Cavity suite"

a. Casing cuts with EZ cutter

Unique Characteristics

- EZ cutter is a logging tool and works on standard cased-hole or production logging cable, up to 5000m of 7/32", up to 7000m of ¼" mono-conductor). No need for special high voltage cable.
- Unique cut quality, clean, thin and precise making subsequent measurements and surveys possible. All other conventional methods are developed to sever pipes through hard ways.

Figure 2. EZ cutter lower part

Figure 3. 11-3/4" cut with EZ cutter

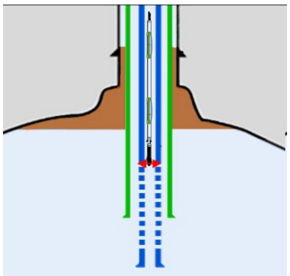


Figure 4. Inner pipe cut

- Cuts the inner casing without altering the outer one

A device is implemented to avoid the risk of the electrodes being stuck in the open part of the groove at the end of the process.

The penetration of the electrochemical reaction is then limited to the remaining metal of the inner pipe to cut, keeping the outer one away from active machining.

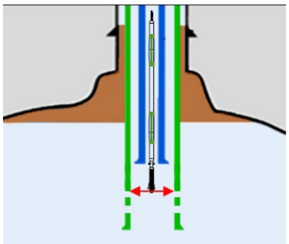


Figure 5. Outer pipe cut

- Can be lowered inside the inner casing to cut the outer one

When lowered inside the inner casing previously cut or pulled above the determined depth, EZ Cutter can cut the outer casing. This applies to most completion's configurations.

- EZ cutter accommodates deformed or ovoid pipes up to 10%. It is not that much but conventional cutting methods are not able to match deformed pipes.

- It is able to cut pipes in compression which may happen when the bottom part of the pipe is stuck in the sump. Such a configuration is -of course- more difficult than a pipe in extension. At the exact time of the cut, some of the electrodes might be stuck but adapted weak points allow the release.

<u>Well intervention, scope of capabilities</u>

- Requires conductive fluid like brine or sea water which isn't generally an issue under solution mining. Heterogeneous salt like sylvinite has been tested and validated. The method could also apply to cased hole well intervention when previously killed with brine.

- Small size instrument able to enter standard 4" WPCE
If cavern pressure is to be maintained under leaching, storage operation or any solution mining / geotechnical requirement, EZ Cutter can be placed in a 4" WPCE before RIH and cut casings up to 13-3/8", according to FLODIM experience.

- Large range of cutting capability from 4-1/2" to 11-3/4", soon extended from 2-7/8" to 20" thanks to XS & XL cutters.

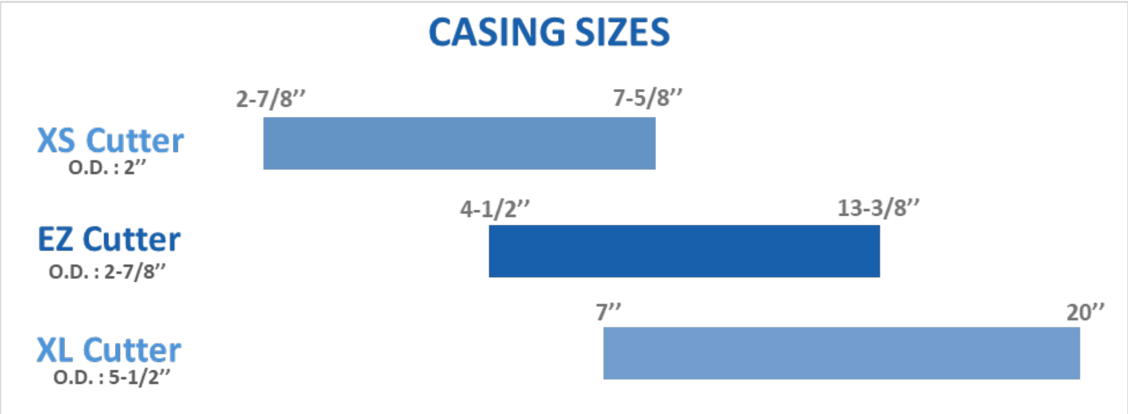


Figure 6. Casing sizes cut with XS, EZ and XL cutters

- Casing thickness is not an issue, so far, the maximum thickness Flodim had the opportunity to cut is 14.78mm on a 11-3/4" 71lbs/ft type of casing. Coated pipes won't work as the electrochemical process cannot be established with the coating. Hard scaling like gypsum or non-removable chemicals may also be a limit.

<u>Cost & Time reduction when changing leaching phase, logistics is improved</u>

- Significant time reduction: if no heavy W.O. is to be planned if the heavy outer pipe is to be cut by EZ Cutter at the next leaching position and is not to be pulled out to control both the cavern upper part and the cavern neck. Only a light Work-Over unit or just a crane for a limited time duration is necessary to run the inner string down to the desired next leaching position.

- Significant time reduction within a new changing leaching phase program:
Considering the optimized scenario presented in part 2.c.ii., a few days (3 to 5) might be necessary instead of three weeks for the following operations : first inner pipe cut, full sonar survey with sections through two casings, second inner pipe cut, outer pipe cut, eventually partial complementary sonar of upper cavern, before running the few stands of casing and adjusting the blanket level.

- No heavy dismantling of the wellhead and of its environment:
Running the Explorer, the EZ Cutter operations and the Sonar survey(s) only require taking off the cap on top the wellhead. During these operations, the cavern can be slowly depressurized until the W.O. rig or the crane (with substructure and hydraulic wrenches) is ready. Dismantling will then only concern the upper part of the wellhead.

- Improved logistics when mobilizing external services (W.O., Logging, Pumping …)
  All deciding Companies in our part of the world know that logistics may be tough when a W.O. rig with its personnel, pumping services (decompressing cavern and removing blanket) and a sonar unit have to be planned in advance. This is to be put in balance with the right combination of well logging and cavern survey instruments that can be available in the same logging unit.

- Improved logistics when combining Cavern Services with a light W.O. rig or a crane.
  On top of improved global logistics, the "Cavity Suite" is made of several appropriate instruments that work one after the other to cover the required steps of changing leaching phases programs. Only a light W.O. rig would be necessary on top for a very limited amount of time.

Additional benefits for leaching programs

- No down time for brine saturation.
  Brine saturation may require significant time before the Solution Mining engineers declare the cavern is ready for changing leaching phase intervention. Cavern pressure bleed-off also takes time as there are decompression rules to apply for stability reasons.

- No down time for blanket removal and blanket setting.
  Diesel oil or nitrogen removal is to be done before retrieving the inner pipe and moving the outer pipe in conventional programs. Blanket setting is also to be run after the pipes are in place for the next leaching stage. These operations require attention and logistics. Which are avoided when using EZ-Cutter.

- Cavern neck integrity is preserved if no blanket is removed.
  Non saturated brine is a potential issue for the cavity neck which is a cavern security element as it may increase its lateral extension. The cavern neck remains forever the most dangerous part when accessing a cavern, especially when salt is not homogenous. It would then be wise, whenever it is possible, to never remove the blanket.

- Cemented casing integrity: POOH a bent or a damaged outer casing is a risk for the cemented casing which is to be kept in the best condition to allow packer setting if the cavern is to be used for gaseous fluid storage. In any case, the outer casing should not be cut with explosives.

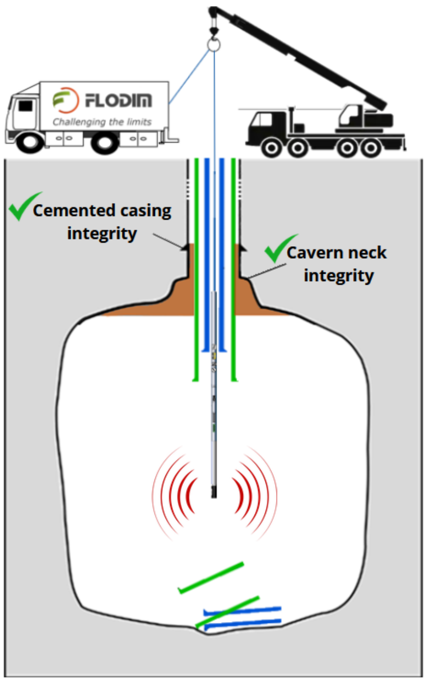


Figure 7. Standard cavern after inner & outer pipe cuts

- Subsequent sonar survey is run straight after the first inner casing cut to gather enough information on the cavern development and decide where to place the leaching strings for the next cavern development phase. A rush report is handed over straight to help solution mined engineers to decide the cut(s).

  A complementary partial sonar survey can be run after the outer casing cut to improve the 3D points network with better velocity data.

<u>Quality and H.S.E.</u>

- No dangerous products like explosives (segmented cutter, split shot cutter) or chemicals (chemical cutter, radial cutting torch). Only the liberation of a few grams of Hydrogen are released by EZ Cutter while cutting, which are rapidly absorbed on their way to the surface.

- Massive reduction of diesel oil consumption and of CO_2 emission:
  A medium size logging unit may have a diesel oil consumption level of only 25 liters per day and a crane which is most of the time still above the wellhead requires little energy. As a comparison, a Work-Over rig while in operation is in the range of 20 times more.

- No heavy operations and multiple mobilizations:
  When running W.O. rig, safety is always at stake. Well control responsibilities on a rig involve a coordinated effort by multiple personnel including those of the final client, each tasked with critical roles during well control operations. Cutting pipes with EZ cutter limits multiple and risky operations.

- Acceptance of mining authorities:
  EZ Cutter is a standard logging instrument which does not contain any dangerous product. It is not subject to detention, transport, storage and intervention authorizations.

b. The smart combination of tools to save cost & time

According to FLODIM 30 years of Well Logging & Cavern Survey experience in Storage Cavern Development and in Salt Production Mining, measurement Services while leaching underground caverns mainly consist in the right combination of the following e-line instruments that make the “cavity suite”:

- Explorer for cavern access, depth correlation, well deviation, with cased hole sensors,
- Sonar surveys for cavern dimensioning and tridimensional mapping,
- Electrochemical cutter to cut the standard pipes of the Solution Mining industry,
- PNT tools for blanket control and interface measurements, no expected radioactive exposure,
- BHS for downhole sampling, in connection with higher product quality requirements.

Figure 8. The Flodim “Cavity suite” of instruments

Latest improvements related to time & cost of changing leaching phases intervention:

- Improved sonar acquisition rate in relation with our North American experience that points out the importance of supplying minimized intervention times while respecting the rules of art.
- Better acoustics when sonar surveying through two casings, thanks to adapted transducers, to identified new integrated circuits and to additional electronic noise reduction.
- Integration of our experience in the 'Through two strings' pipe combinations data sheet that presents best propagation results depending upon size and grade of each pipe.
- Acceptance of downgraded results for the upper cavern sonar survey, but with enough data to decide on the next leaching string position.
- Possibility to run the sonar instrument after the outer casing cut in case of unclear or insufficient data in the upper part of the cavern, in order to provide a full report up to the best standard.

c. Typical operations with EZ cutter

Over the last 10 years, EZ cutter was mainly used for changing leaching phase of a cavern by only repositioning the inner string (74%) or repositioning both inner and outer strings by consecutive cuts (6%). Ultimately, 20% of EZ cutter interventions occurs in order to recover simple access to a cavern after a bent or collapsed pipe.

Among all the interventions in caverns under leaching, 44% of the EZ cuts were anticipated and performed to reposition the inner string according to the leaching program. 46% of the cuts and repositioning were decided because of a bent pipe and 10% after the pipe being trapped in the sump of the cavern.

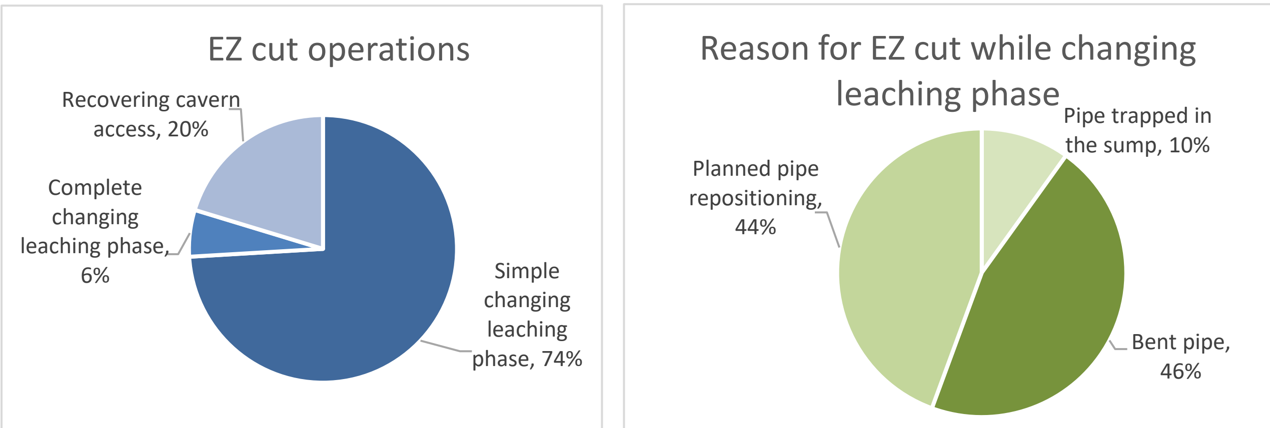


Figure 9. Typical operations with EZ cutter from 2014 to early 2025

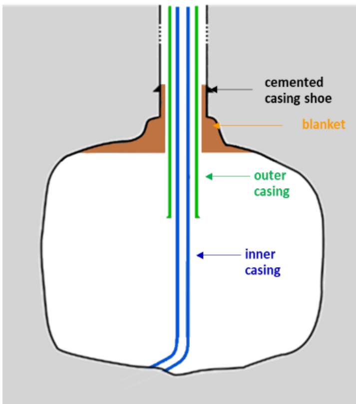
i. Bent pipe or inner casing trapped in the sump while leaching

The first frequent application of the EZ cutter during the past 10 years is a remedial intervention for a bent pipe trapped in the sump, with the objective to recover access to the cavern within a reasonable time and if possible, without cavern decompression which is a long and sometimes dangerous process.

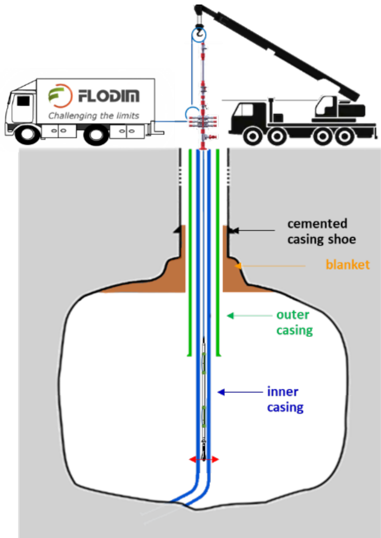
After fast and reactive mobilization of the logging unit and WPCE rig-up, the stuck pipe is cut with EZ cutter within a single day, and the sonar survey is performed straight after to enable the cavern operator to resume the leaching program with no or only little downtime.

In small or medium-sized caverns, a double cut of the inner string is sometimes required to ensure that the piece of pipe left in the sump won't stand vertically and be a nuisance for future cavern intervention.

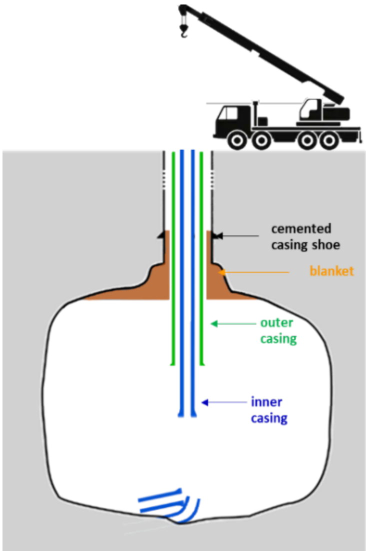
Both EZ-Cutter and Sonar instrument are lowered from a 4" lubricator assembly even if the pipe to cut is 7" or more. During the intervention, the cavern pressure is maintained.



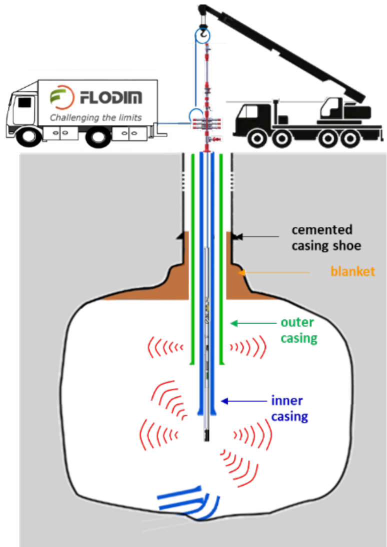
1. Inner pipe trapped in the sump



2. Fast mobilization of logging unit with WPCE
to cut the stuck pipe right above the bent part



3. A second cut might be run to ensure
clearance in the cavern



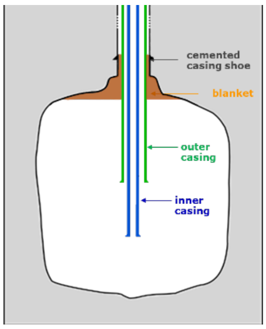
4. Sonar survey is performed immediately with
the same wireline unit under WPCE

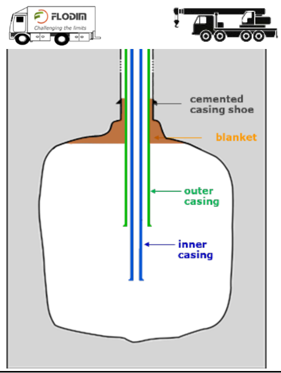
ii. Optimizing the changing leaching phase in a salt cavern development

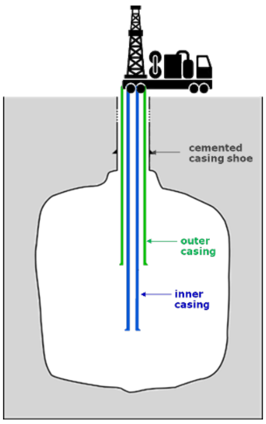
The second EZ cutter application of interest within the “Cavity Suite” is when changing the leaching positions of inner and outer strings during a standard salt cavern development. In this configuration, EZ cutter proved its efficiency a number of times as inner and outer successive casing cuts can be performed together with the necessary sonar survey(s) and blanket control.

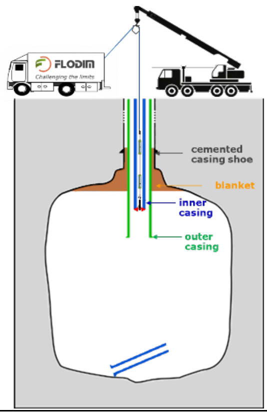
The following example is based on the highly standard case of a cavern developed between 1000m (3000 ft) and 1500m (5000 ft) in several phases with a nitrogen blanket, making it necessary to use heavy casing below the wellhead in order to stand high pressure difference between the annular spaces, one in brine, one in nitrogen.

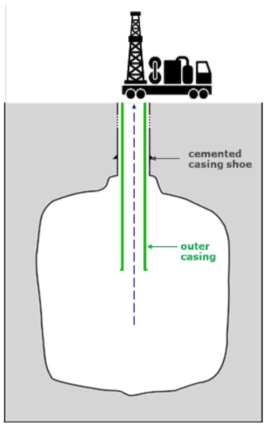
When only low-grade inner pipe adjustment is to be made in a well-known cavern environment, a standard crane with an equipped substructure is able to manage the repositioning of a very limited few stands of inner casing at the required position.
If this solution is not available, a light and inexpensive work-over rig would -of course- do the job.

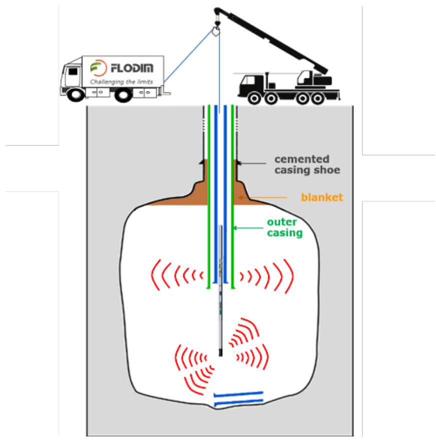
<table>
<tr><th>⌛</th><th>CONVENTIONAL W.O. RIG INTERVENTION</th><th>“CAVITY SUITE” INTERVENTION</th><th>⌛</th></tr>
<tr><td>5 DAYS</td><td>
➢ Leaching is stopped for brine saturation
➢ Saturation time necessary for cavern neck integrity
➢ Cavern pressure balance and pressure bleed-off
➢ Removing the Nitrogen blanket
➢ Heavy duty rig Mobilization


</td><td>
➢ Changing leaching phase can be decided any time
➢ Fast mobilization of a crane and of a logging unit
➢ Fast mobilization of cavern instruments
➢ Cavern is not yet depressurized


</td><td>0 hour</td></tr>
<tr><td>2.5 DAYS</td><td>
➢ Surface lines are bled off and dismantled
➢ Heavy duty Work-Over rig installation
➢ Safety and coordination meetings


</td><td>
➢ Explorer run to confirm access
➢ EZ cutter cuts inner pipe above outer casing shoe
➢ Pressure equipment is available. Slow decompression of the cavern


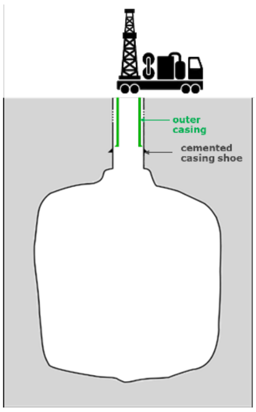
</td><td>8 hours</td></tr>
<tr><td>2 DAYS</td><td>
➢ Wellhead upper part is dismantled
➢ Inner pipe is unanchored
➢ Inner pipe is fully removed


</td><td>
➢ Sonar survey in open cavern through horizontal and tilted sections
➢ Sonar survey through one or two pipes


</td><td>8 hours</td></tr>
</table>

<table>
<tr>
<td>2 DAYS</td>
<td>

- Wellhead central part is dismantled
- Outer casing is pulled up above the cemented casing shoe



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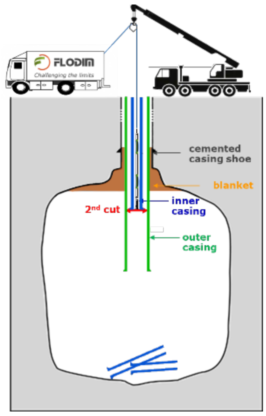
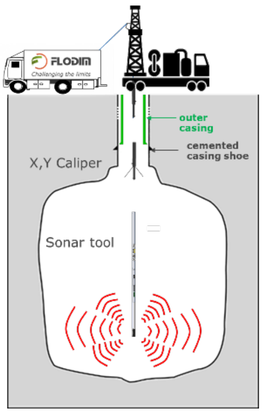
<td>

- After rush sonar processing, the leaching engineer in charge decides upon the next leaching strings positions.
- The inner casing is cut 20 ft (6 meter) above the next outer casing position.



</td>
<td>6 hours</td>
</tr>
<tr>
<td>1.5 DAY</td>
<td>

- Full sonar survey is run in an open cavern
- Cavern neck with XY caliper log or with sonar instrument successive sections



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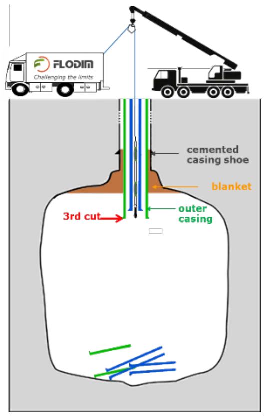
- Outer casing is cut at next leaching phase position
- Optional 2nd sonar survey for a higher definition of the upper part



</td>
<td>10 hours</td>
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<tr>
<td>2 DAYS</td>
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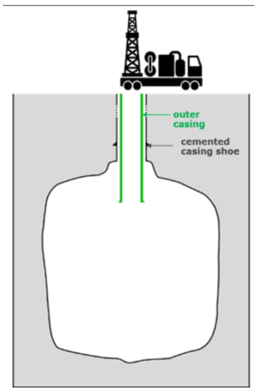
- The leaching engineer in charge decides the next position of the outer casing shoe
- Outer pipe is run at new position and anchored
- Wellhead central part is rebuilt



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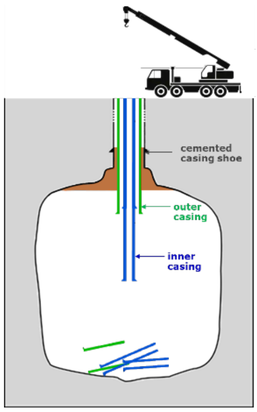
- Dismantling upper part of the wellhead
- Setting up the substructure with torque capability
- RIH stands of inner casing to the desired position



</td>
<td>8 hours</td>
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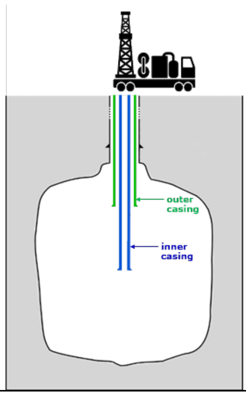
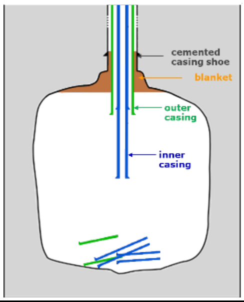
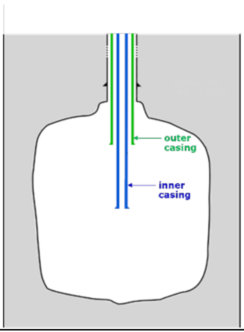
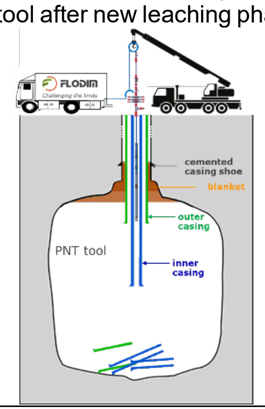
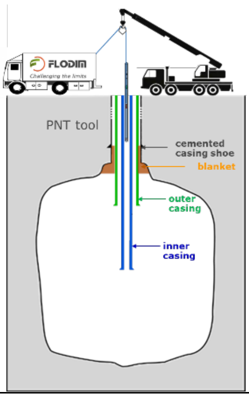
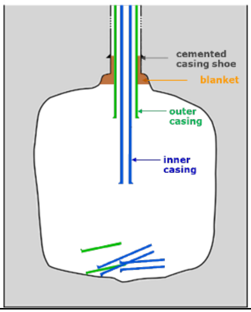
2 DAYS	➢ The leaching engineer decides the next position of the inner casing shoe. ➢ Inner pipe is run at new position ➢ Wellhead upper part is rebuilt 	➢ Re-building wellhead top part and surface lines ➢ Substructure rig down, crane departure. ➢ **New leaching phase starts** 	4 hours
2 DAYS	➢ Heavy duty Workover rig down and departure 	➢ Nitrogen blanket interface is adjusted under WPCE with PNT tool after new leaching phase is engaged. 	0 hour
2 DAYS	➢ Surface lines are rebuilt and tested ➢ Nitrogen blanket is pumped in the outer annulus ➢ Nitrogen blanket interface is set at the right depth ➢ **New leaching phase is ready to start** 	➢ **New leaching phase proceeds** 	
	➢ 21 DAYS ➢ HEAVY MOBILIZATION COSTS ➢ HEAVY OIL CONSUMPTION	➢ 5 DAYS ➢ COST REDUCED ➢ CO_2 EMISSIONS REDUCED	

Overall cavern immobilization can be as little as 4 to 5 days with the 'Cavity Suite' method instead of three weeks with the conventional method. When mobilization of the 'cavity suite' of instruments is not fast because of long distance or customs authorizations, logistics may be improved through the combination of several cavern interventions within the same campaign.

A significant amount of time and money can then be saved.

3. A proven contribution to optimize cavern intervention programs

a. Casing cuts over the last 10 years

The flexibility and lightness of the EZ cutter makes it easy to deploy on any wireline unit. Around 400 cuts have already been performed in 14 countries in many distinctive pipe and well configurations.

Diameter	Weight	Thickness	Number of cuts
4"	9.5 lbs/ft	5.74 mm	2
4-1/2"	9.5 lbs/ft	5.205 mm	1
	10.5 lbs/ft	5.69 mm	2
	11.6 lbs/ft	6.35 mm	5
5"	11.6 lbs/ft	5.59 mm	1
	15 lbs/ft	7.52 mm	3
	18 lbs/ft	9.195 mm	1
5-1/2"	15.5 lbs/ft	6.985 mm	65
	17 lbs/ft	7.72 mm	3
	20 lbs/ft	9.17 mm	4
6-5/8"	20 lbs/ft	7.318 mm	2
	24 lbs/ft	8.943 mm	9
7"	17 lbs/ft	5.865 mm	6
	20 lbs/ft	6.91 mm	17
	23 bs/ft	8.05 mm	89
	26 lbs/ft	9.195 mm	65
	29 lbs/ft	10.365 mm	13
	35 lbs/ft	12.65 mm	10
7-5/8"	26.4 lbs/ft	8.331 mm	5
8-5/8"	32 lbs/ft	8.941 mm	9
	36 lbs/ft	10.16 mm	13
	40 lbs/ft	11.43 mm	4
9-5/8"	32.3 lbs/ft	7.923 mm	3
	36 lbs/ft	8.943 mm	3
	40 lbs/ft	10.033 mm	8
	43.5 lbs/ft	11.048 mm	2
	47 lbs/ft	11.988 mm	1
10-3/4"	40.5 lbs/ft	8.89 mm	7
	45.5 lbs/ft	10.16 mm	16
11-3/4"	47 lbs/ft	9.525 mm	7
	54 lbs/ft	11.049 mm	1
	60 lbs/ft	12.421 mm	1
	71 lbs/ft	14.783 mm	5
13-3/8"	68 lbs/ft	12.192 mm	1

Figure 10. Repartition of cuts per casing type from 2014 to early 2025

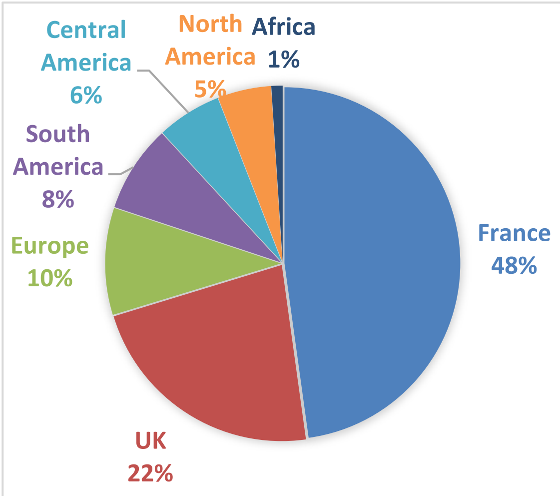


Figure 11. Worldwide repartition of casing cuts 2014 – early 2025

Most of the popular casing grades used in solution mining (K55, J55, L80, N80), and even highly re-sisted pipes (C90, P110) have already been successfully cut in the past 10 years, whatever the casing sizes. The grade can highly influence the effective cutting time as low resistance grades (H40, J55, K55) are easier to cut than medium resistance ones (N80, L80) or even higher resistance casings (C90, P110).

The cutting head has been designed and constantly optimized to fit increasing thickness of the pipes and improve cutting times.

Preliminary informations about the pipe size, grade, chemical composition and weight are of utmost importance when planning the job. Based on these elements, the cutting head is carefully prepared and adapted to best fit the pipe specifications.

Well characteristics are also collected upstream and especially the type of fluid behind the casing to cut in order to avoid any unexpected blanket invasion in the tubing once the first perforation of the groove appears.

b. Success rates

Casing cuts operations are carefully registered and classified in Flodim database under the 3 defined states "success, assisted or fail".

"Successful" cut refers to casing cuts when the pipe is falling during the operation right after the cut operation is completed. Pipe cutting and fall are closely monitored in real time by an experienced field engineer onsite.

"Assisted" cut refers to operations when the cut seems to be completed 100% or close but the pipe doesn't fall right away. External assistance is then required such as: fluid movement with the cavern back to leaching, small pipe lifting with the crane or just time. For example, a large part of assisted cuts are cemented casings that will only fall after a few weeks of leaching.

"Fail" cut refers to the failure of an attempted cut where the pipe doesn't fall after significant hours of cut nor after external assistance defined above. The monitoring of the cut usually reveals that the groove has deepened with time, often with perforation of the pipe on a significant but not homogenous part of the 360° pipe section.

Over the last 10 years and after about 400 casing cut operations, the raw success rate can be registered at 70% and climbs to 81% when assisted cuts are considered a successful operation for the cavern operator in the end.

Among the registered "failed" cuts, 49% of them have been immediately followed by a successful cut on the 2nd attempt performed the same day or the next following day.

Indeed, for most of the pipes in compression or extension, a 1st attempt of cut at a lower depth helps to release the tension on the pipe and induces a 2nd upper cut that will be successful.
This methodology of a 2-steps cutting job was largely described and anticipated as "torque strains" cuts. (Crabeil, Ballus et al. 2015)

In our database, those 1st step attempts of cuts are still registered as "fails" but considering this information and the fact that the overall cutting operation is actually a success thanks to this 1st attempt, the global success rate of the EZ cutter operations reaches 89%.

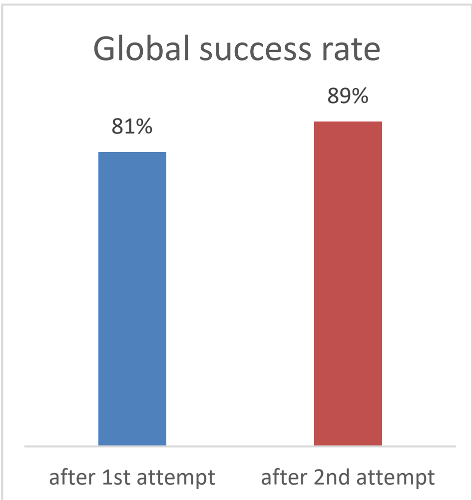


Figure 12. Success rate after 1 or 2 attempts

The success rate by casing size on first attempt of cut is over 80% or more when mixing various sizes, grades and clients, except for 8-5/8” ratio. This size of casing 8-5/8” was encountered at two client’s sites where the wells are pretty old, pipes are highly encrusted and very few information could be collected upstream on the pipes conditions in order to prepare the cutting operation in the best conditions. A second attempt on a few of those wells proved efficient and the 8-5/8” global success rate then climbs to 70%.

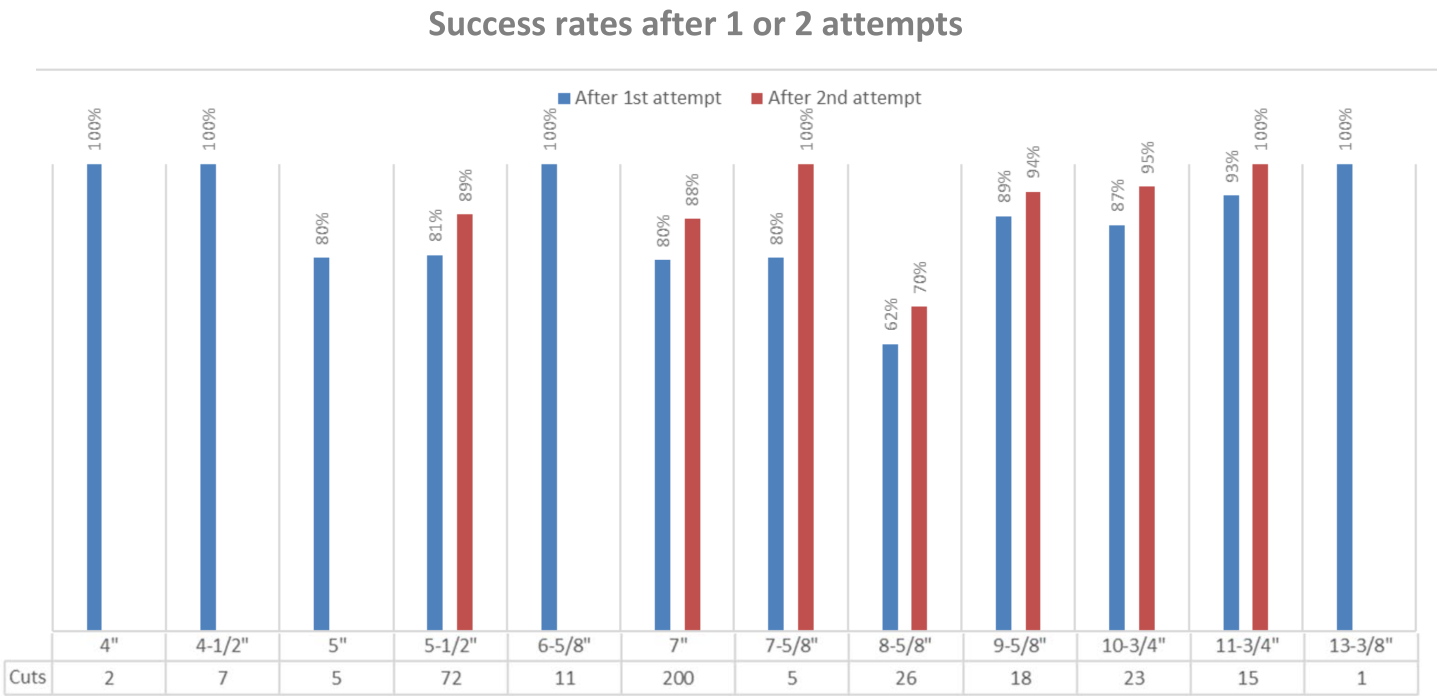


Figure 13. Success rates per casing size after 1 or 2 attempts

Reasons for real failure have been carefully analyzed and led to the continuous innovations of the tool described in the next part.

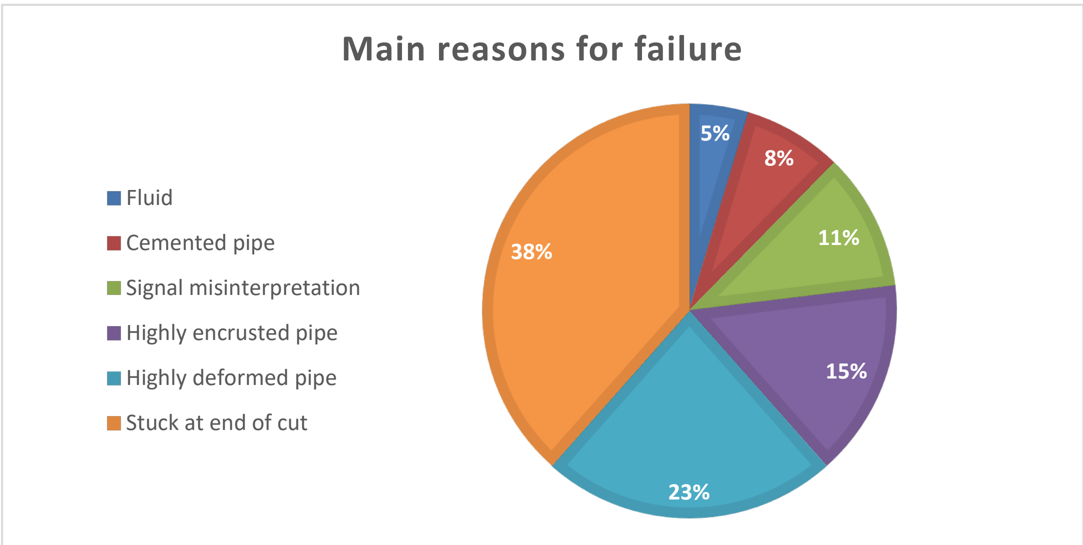


Figure 14. Repartition of the main reasons for failure of an EZ cut

Among the registered failed cuts, main identified reasons come from the pipe’s conditions: pipes in compression, highly deformed pipes (23%) or highly encrusted casings (15%) that couldn’t be managed by the quick initial operation to remove rust and scale deposits. Most of the time, the cut process is interrupted by the tool rotation getting stuck in the cut groove due to a movement of the tubing cut part around the end of the process. Those fails very often result in a partial cut, where more than 80% of the cut is completed.

In 50% of the cases of failure, a second attempt a few centimeters above is a success as the compression of the pipe has been released by the partial 1st cutting attempt.

For ovoid shapes issues, we consider that EZ cutter can accommodate a 10% margin of ovalization (defined as out of round ratio in Crabeil, Ballus et al. 2015). For pipes with stronger ovalization, a second attempt of cut is usually performed and successful right above where the casing is in better condition.

After these over-time analysis, it is mandatory to have an initial explorer run to choose the best possible depth to cut in order to anticipate abnormal casing configurations (inclination, ovalization…) and thus increase the success rate.

c. Effective cutting time

The operating time is an important concern when comparing different techniques of cutting pipes. The effective cutting time of the different methods should be compared taking into account the totality of the operating time, from the moment the cut is requested (or the cavern put in standby) to the end of the operation and the cavern is back to operation. This total immobilization time of the cavern can be days, sometimes weeks or months.

The EZ cutter being lowered as a standard logging instrument; mobilization time is fast, preparation of the well is none as the EZ cutter can work under pressure, so there is no additional downtime such as workover rig installation, dismantling the upper part of the wellhead, completely removing the blanket or stopping brine production. When the cut is over, cavern is immediately available for sonar surveys by the same logging unit and no extra cost or mobilization charge are required.

The effective cutting time, from 2 to 18 hours today, must be put in balance with the total immobilization time of the cavern mentioned above from the time the need for a pipe cut is established.

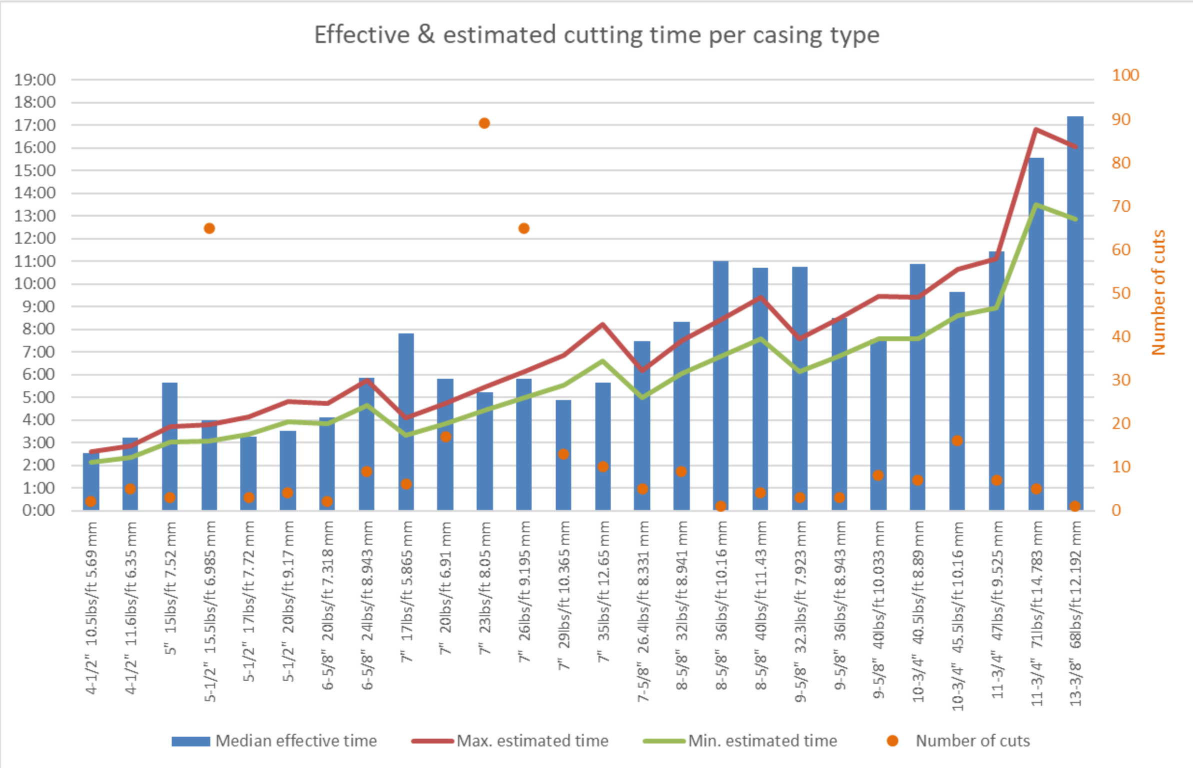


Figure 15. Effective & estimated cutting time per casing type

An estimated range of cutting time is calculated prior to the cut thanks to the multiple parameters provided by the cavern operator especially the size, thickness of the casings, the type of fluid in the well, the cavity state (producing or not). The overall timing of a cutting operation can then be anticipated and monitored in real-time.

Effective cutting time is a direct function of the thickness of the casing. From our experience during the past 10 years, a 7" casing cut for example can vary from 3 hours to 12 hours as the thickness for this casing diameter varies from 5.87 mm to 12.65 mm.

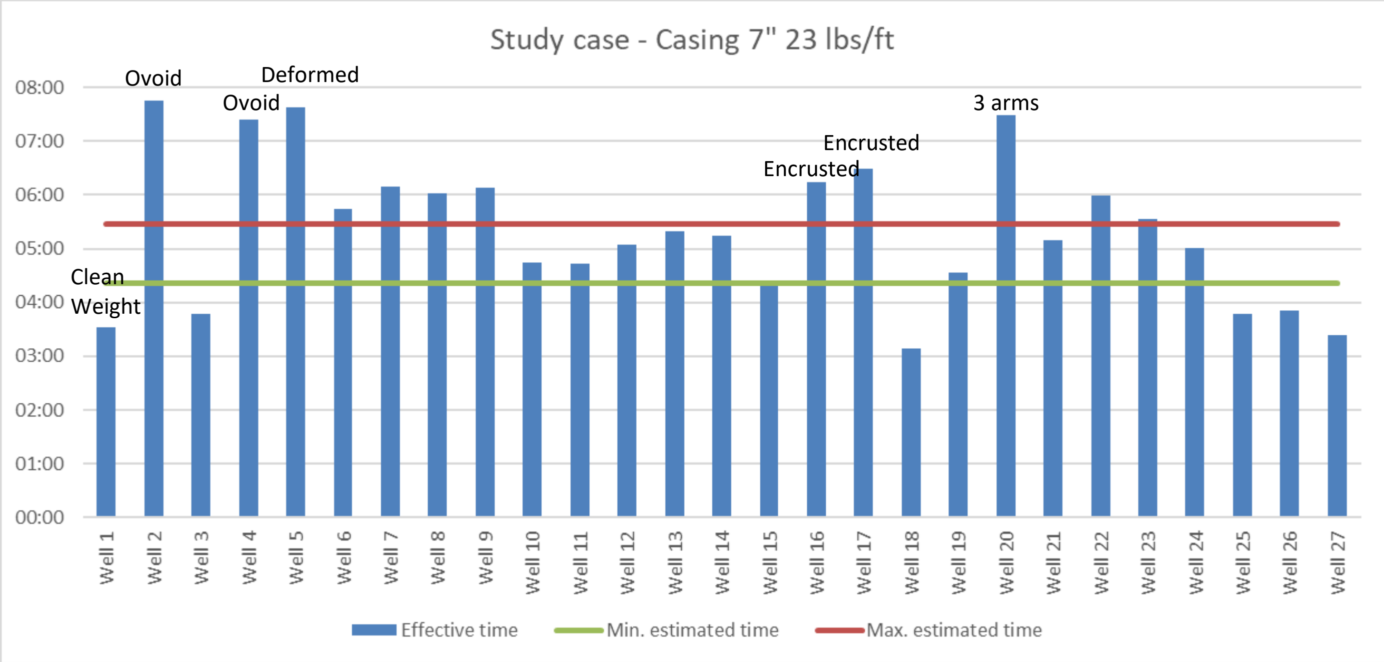


Figure 16. Study case – Casing 7" 23lbs/ft

For a same size and thickness casing type, 7" 23lbs/ft above for example, the last 27 cuts of this type reveal that 60% of the cuts are within or below the estimated time range, 26% are less than an hour overtime. 4 cuts with more overtime can be explained either by highly encrusted pipes or deformed / ovoid shapes that still could be overcome with time.

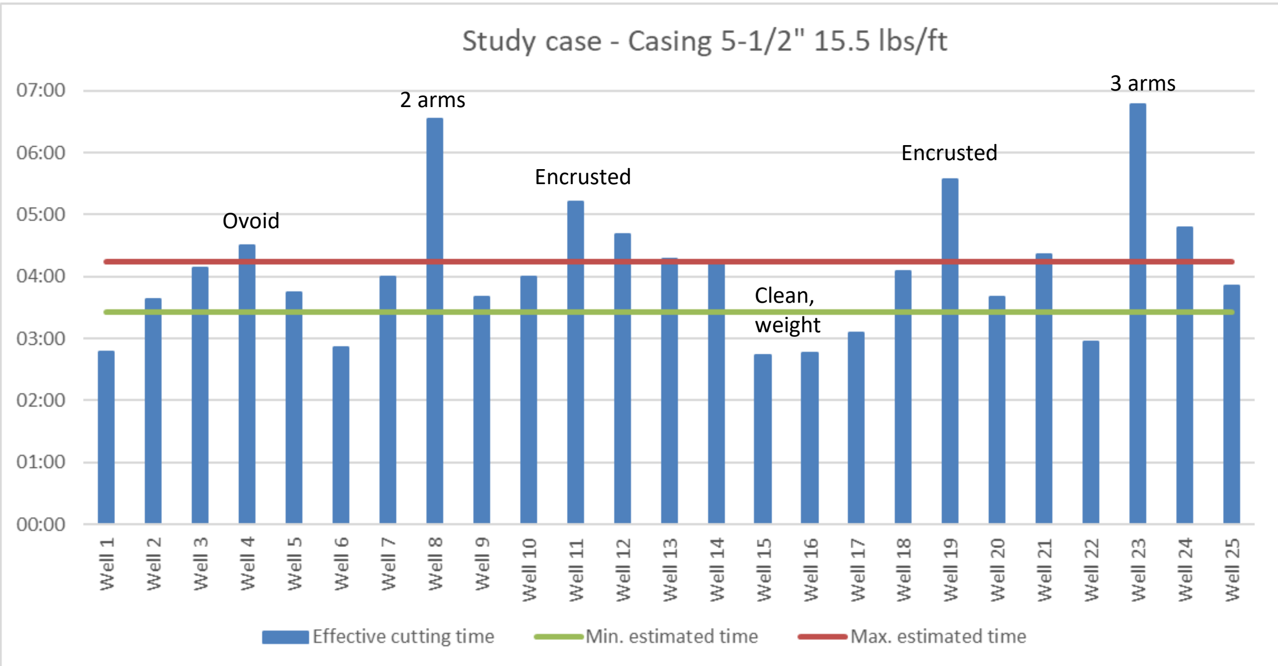


Figure 17. Study case – Casing 5-1/2" 15.5 lbs/ft

On the above study case of the last 25 cuts of 5-1/2" 15.5 lbs/ft, 68% of the pipes were cut within the estimated range of time or below. Only 4 cuts suffer excessive overtime due to ovoid shapes, highly encrusted pipes or EZ cutter functioning on reduced number of arms probably due to deformed pipes.

On the two study cases above, effective cutting time can also be considerably reduced compared to the estimated range when pipe is in compression or extension.

Figure 18. EZ cut of a 6-5/8" encrusted tubing

Figure 19. Clean EZ cut of a 13-3/8"

4. Continuous innovations serving the underground cavern industry

a. Improvements of the EZ cutter for better & faster services

From the 1st version of the EZ cutter tool to the actual EZ cutter G3, the instrument has undergone numerous modifications in order to provide the best adapted cutting tool for salt caverns.

- Experience acquired during the first casing cuts helped to optimize the electric circuit of the tool and made us place sacrificial anodes on strategic points to protect the instrument from leakage current even if minimized.
  Now, with the right combination of shape, distances and connections quality, more than 99% of the current supplied to the electrodes is dedicated to the cut and we have no more noticeable corrosion attacks on the EZ Cutter body of the tool.

- A pressure compensating system has been added to the tool to perform deeper cuts. The tool is now able to perform cuts under maximum conditions of 550 bars (8000 psi) and 100°C (200°F).

- The system was improved to bring enough power to the electrodes on a standard 7/32" cased hole logging cable first to 1500m, then 2000m, and now more than 5000 meters.

  Over the last 10 years, 37 successful cuts have been performed at a depth over 1000m (3280ft), 13 of them being deeper than 1500m (5000ft) with record of a 8-5/8" pipe cut at the exact depth of 1985.2m (6513 ft)

- Preparation of the cutting arms and heads was carefully improved in order to precisely adapt the tool to the pipe to cut. A significant modification was applied for faster and easier maintenance to perform consecutive cuts in the same well, or in different wells from the same wireline unit.

Figure 20. Different sizes of EZ casing cuts

- A special stackable compartment integrating DSCL, inclinometer and accelerometer was developed to better monitor the cut and to know the exact time the cut is complete. Dual String Collar Locator ensures a precise depth correlation and confirms the cut through an upward log straight after.

- A local scraping system was implemented to get rid of corrosion or deposits inside the casing before starting the cut, through hard protection around the electrodes that manage all cases but gypsum.

- After advanced analysis of the first casing cuts, an optimized combination of distances, rotation speed and adjusted current characteristics made the cut progress controllable.

Figure 21. Scrapped corrosion inside a tubing, before the cut

- From our 10 years of experience, just like for the electromechanical cuts, the last 5% to 20% of the cut is always risky as it often means a 'Pac-Man' effect when the cut is not complete and when the knives or electrodes might be stuck at the edge while rotating. In salt caverns, this mainly comes from stress on the bent pipe, from non-constant thickness repartition over 360° and from deformed / ovoid shape.

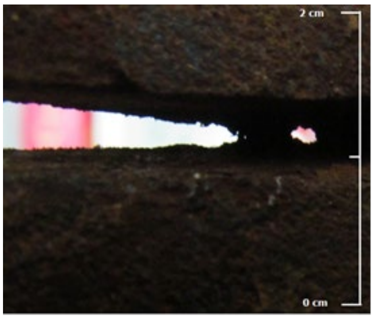


Figure 22. Groove

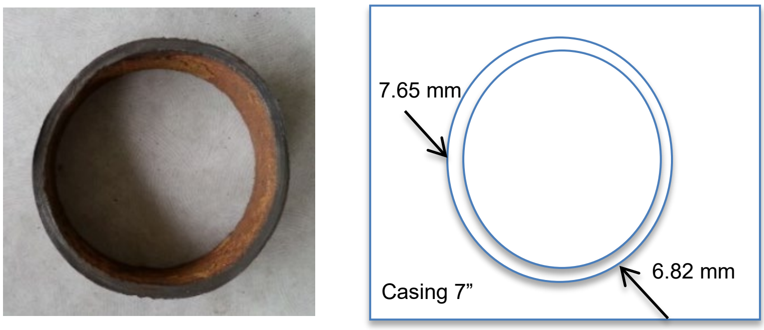


Figure 23. Deformed casing

Fortunately, we could bring answers to this inconvenient problem, thanks to new strong rotating capabilities and to additional devices avoiding pinching and jamming.

b. Expanding the capacity of intervention with XS & XL cutters

XS Cutter and XL Cutter projects were launched to cover the full range of casings to cut at a time EZ Cutter could only work from 4-1/2" to 10-3/4" and when some of our accessible markets were out of EZ Cutter capabilities.

- 2" O.D. XS Cutter was designed to cut pipes ranging from 2-7/8" to 7-5/8" in vertical and deviated wells. XS Cutter can be run from a 3" WPCE.

- 5-1/2" O.D. XL Cutter was designed to cut pipes ranging from 7" to 20" in vertical wells with additional arms mounted electrodes. XL Cutter can be run from a 6" WPCE.

Figure 24. XL cutter cutting head

Figure 25. XS cutter cutting head

In both cases, the major idea was to significantly reduce the effective cutting time as the comparison to other cutting methods, when the rig time is not of high concern, is not in favor of the electrochemical cut.

Even if the Faraday law cannot be pushed, the optimization of the XS and XL Cutters -according to our initial tests- should lead to the following results:

- When pipes are of small size, let's say a 3-1/2" 7.7 lbs/ft or 9.3 lbs/ft casing, the expected time to cut is divided by 2.5 to 3, in the range of 1 hour and 40 minutes.

- When pipes are of big size, let's say a 13-3/8" 72 lbs/ft casing, the expected time to cut is divided by three because of 12 electrodes instead of 4, in the range of 4 hours but in a less competitive market.

The cutting times should then become acceptable regarding maintenance or remedial single cavern interventions (*).
Additional improved features for both instruments will concern the centralizing and anchoring capabilities, the rotation speed to manage abnormal shapes and the groove progress real time information.

(*) single intervention is different from a 'changing leaching phase' or a 'production program' intervention when the characteristics of the electrochemical cut are already of major interest.

Conclusion

The downhole electrochemical Casing Cut is now a mature technology in use for long enough that many of its initial inadequacy and inherent problems have been removed, leaving room for higher success rate and for the next generation of XS Cutter and XL Cutter.

Running downhole casing cuts in brine caverns is often more difficult than in wells because of the stress induced by stuck, bent or damaged pipes which may cause deformed or ovoid shapes and later hard to solve pack-man effects.

Still, in a wide range of configurations, the EZ Cutter instrument has shown unique efficiency, running into special issues that could not otherwise be solved.

Thanks to its small size O.D, EZ Cutter could develop the very special features presented in this technical paper with considerable interest when combining with the other instruments of the 'cavity suite'.

It then becomes possible to significantly improve the logistics of the 'Changing Leaching Phase' campaigns when repositioning Casing shoes is necessary together with surveying the cavern and readjusting the blanket level. At the same time, drastically reducing intervention time, intervention cost, CO_2 emission and securing both the cavity neck and the cemented casing integrities.

It also becomes possible to cut damaged pipes while keeping the cavern under pressure and avoiding the sometimes-dangerous transitory geotechnical effects of cavern decompression.

Finally, the analyses and understanding of the numerous cases encountered have enabled better preparation of intervention and maintenance from a thorough approach of the pipes characteristics and environment, keeping the trend of even higher success rates in the Flodim "challenging the limits" spirit.

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