

ACT LAUNCH Project No 299662



The LAUNCH project is funded through the ACT programme (Accelerating CCS Technologies, Horizon2020 Project No 294766). Financial contributions are made from: Netherlands Enterprise Agency (RVO), Netherlands; Bundesministerium für Wirtschaft und Energie (BMWi), Germany; Gassnova SF (GN), Norway; Department for Business, Energy & Industrial Strategy (BEIS) together with extra funding from NERC and EPSRC research councils, United Kingdom; US-Department of Energy (US-DOE), USA.
All funders are gratefully acknowledged.



Lowering Absorption process UNcertainty, risks and Costs by predicting and controlling amine degradation

**Deliverable Nr.
D.4.1.2/D.4.4.1/D.5.1.2/D4.4.3/D6.2.1**

Qualification, drawing and validation of the LAUNCH rigs as a tool for measuring solvent degradation

Dissemination level	Public	
Written By	Juliana Monteiro, Roberta Figueiredo, Eirini Skylogianni (TNO), Hanna Knuutila (NTNU), Gary Rochelle (UT)	Date: 19.05.2023
Checked by WP4 Leader	Jon Gibbins (U Sheffield)	Date: 25.05.2023
Approved by the coordinator	Peter van Os (TNO)	Date: 26.05.2023
Issue date	26.05.2023	

Executive summary

In this report, we have discussed the LAUNCH rig, a fully automated CO₂ capture plant designed to de-risk scaling-up of solvent technologies by representing the solvent degradation behaviour of full-scale plants. This plant is designed with a small capacity of 1 kg/h of captured CO₂, or 0.025 tonne per day. This small rig system, proposed before LAUNCH and further validated within the project, can be used to quantify the formation of degradation products over time. The drawing of a generic LAUNCH rig is given in the Figure below, and different design aspects are discussed. The rig is mobile, has a small footprint (6 m²) and can be easily connected at different industrial sites. This opens up the possibility to qualify solvents using different flue gases. The cost of the LAUNCH rig is estimated at 500 k€.

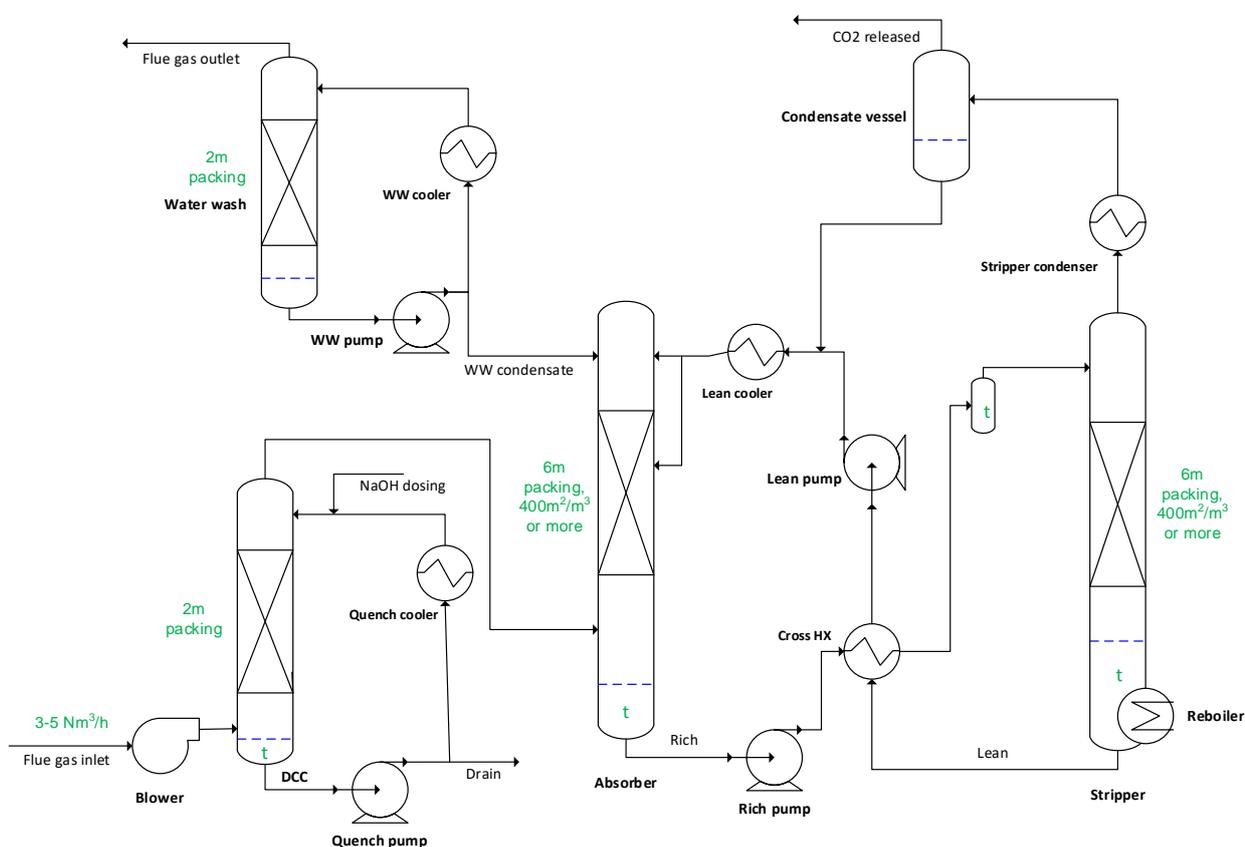


Figure. Simplified process flow diagram of the LAUNCH rig

In this report, we also have proposed a solvent qualification protocol (SQP), which is summarized in the following Table. The recommendations of the SQP are based on the LAUNCH partners' experience in running similar campaigns prior to and within the project. The LAUNCH SQP consists of 2 campaigns, and can be executed within 3-8 months. Estimated marginal costs for a 6 months' program are 104 k€ (50k€ CAPEX,

54k€ operational), which is in line with LAUNCH's target of 100 k€, but very dependent on the assumed costs for analytical techniques development – the item with largest uncertainty in this cost estimate. The cost breakdown is given in the Figure below. For comparison, the average cost of a technology qualification run at TCM is estimated at € 6 million.

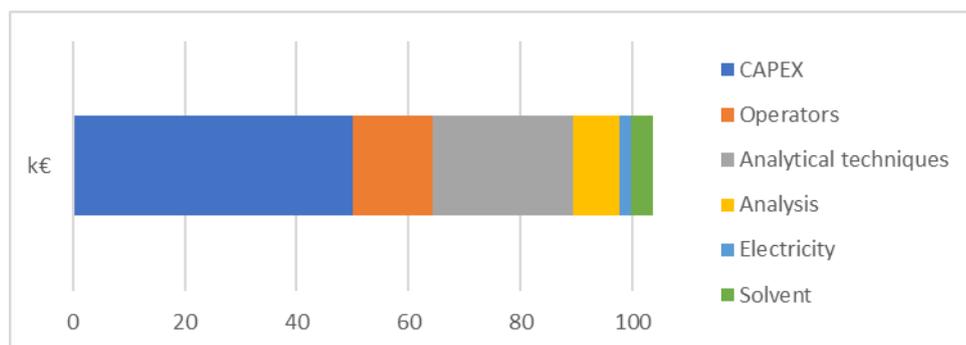


Figure. Marginal costs of running the proposed SQP

Table: LAUNCH Solvent Qualification Protocol

SQP campaign	Flue gas	Termination criteria	Solvent sampling	Expected duration
Degradation characterization	Artificial or real. In case of artificial, add NO _x to realistic level. In both cases, use increased O ₂ content (close to 20%).	Liquid degradation products account for 5% of the initial solvent N content	Weekly quantification of products. Comprehensive analysis so that mass balance is closed.	500-1000 hours
Benchmarking	Ideally real flue gas. In case of artificial, add NO _x to realistic level.	Maximum acceptable solvent loss rate reached (kg/ton _{CO2}), based on business case	Weekly quantification of main degradation products	2-6 months

The LAUNCH SQP is the first attempt that we are aware of suggesting a methodology for solvent qualification. This could be very helpful in accelerating the implementation of CCS. This protocol needs to be validated by running multiple campaigns with different solvents and evaluating the results against long-term campaigns. The SQP work performed in LAUNCH used MEA, and a next step could be to apply the developed protocol to CESAR1 and PZ.

CO₂ capture technology providers would greatly benefit from a proven SQP, and this would also facilitate investment decisions by end-users, and permit processes from environmental authorities.



Table of Contents

1	INTRODUCTION	6
1.1	COMMERCIAL SOLVENTS.....	6
1.2	THE DRIVE TO DEVELOP BETTER SOLVENTS	7
1.3	THE DRIVE TO LOWER THE COSTS OF SOLVENT DEVELOPMENT.....	8
1.4	ARE THE CURRENTLY AVAILABLE SOLVENTS GOOD ENOUGH?.....	9
2	THE LAUNCH RIG	10
2.1	VALIDATION OF LAUNCH RIGS.....	10
2.2	DESIGN OF THE LAUNCH RIG.....	12
2.3	DRAWING OF A GENERIC LAUNCH RIG	14
2.4	COSTS OF THE LAUNCH RIG	15
2.5	ADDITIONAL CONSIDERATIONS ON THE LAUNCH RIG DESIGN AND USE	16
3	THE LAUNCH SOLVENT QUALIFICATION PROTOCOL	18
3.1	THE LAUNCH ACCELERATED DEGRADATION TESTS.....	18
3.2	THE SQP PROTOCOL	19
3.3	MARGINAL COSTS OF RUNNING THE SQP	21
4	CONCLUSIONS AND NEXT STEPS.....	23
5	REFERENCES	25

1 Introduction

One of the main objectives of LAUNCH was to develop a Solvent Qualification Protocol (SQP). This protocol is presented and discussed in the current report. But before that, we introduce the topic by briefly discussing the need for the development of novel solvents. LAUNCH focuses on solvent degradation, and likewise our protocol aims at qualifying a solvent *regarding its degradation behaviour* overtime.

As long as solvents are based on amines, degradation is to be expected. For most solvents, oxidative degradation is the primary concern. In LAUNCH, we have shown that not only the solvent's initial composition but actually the solvent matrix – i.e., including all minor components that are accumulated in the solvent due to degradation, corrosion and co-absorption flue gas impurities – will influence the degradation rate [1]. Moreover, the degradation rate is influenced by process factors such as the temperature profile and residence time of the solvent at different unit operations along the plant. Therefore, the combination of the solvent formulation, the capture process design and the flue gas composition is relevant.

1.1 Commercial solvents

Amine-based post-combustion CO₂ capture is a mature technology, demonstrated at full scale, and currently entering the implementation phase in various industries. The first-generation amine solvent, 30 wt% aqueous solution of monoethanolamine (MEA), is currently used commercially at the AVR capture plant at their waste-to-energy site in Duiven, The Netherlands. As a partner in LAUNCH, AVR has provided the project with plant operational data and solvent samples. Analysis of the data reveals an average reboiler duty of 3.36 MJ/kg CO₂, which is slightly lower than the performance tests at the Test Centre Mongstad (TCM) and in line with a recent modelling studies [2]. As an open solvent, aqueous MEA-based CO₂ capture plants are offered commercially by a number of EPC (engineering, procurement and construction) companies. Also, Fluor offers a solvent solution based on aqueous MEA, with additives (Econamine FG PlusSM) [3].

AVR uses bleed and feed as a solvent management strategy. This, along with controlled stable operation (as opposed to parametric testing campaigns), has allowed the company to operate the plant with relatively low MEA losses, as compared with some pilot campaigns, see Figure 1. In this Figure, the AVR data for the operational years of 2020 and 2021 is represented by a range, between 0.5 and 2.0 kg_{MEA}/ton_{CO₂}. By contrast, relatively short-term pilot campaigns (up to 2000 hours) have reported MEA losses between 1.5 and 3.0 kg_{MEA}/ton_{CO₂}, while the RWE campaign performed during the ALIGN-CCUS project at the Niederaussem pilot showed lower degradation rate, increasing from 0.3 kg_{MEA}/ton_{CO₂} in the beginning of operations to 0.6 kg_{MEA}/ton_{CO₂}, after more than 8000 hours.

One of the main challenges for operating MEA commercially is its degradation. In pilot tests performed without solvent management strategies, the MEA degradation rate eventually reaches an exponential regime (e.g. [4], [5]), with MEA losses rising uncontrollably. As a consequence, the solvent loses absorption capacity and the energy demand increases. If this point is reached, a complete inventory change is necessary, potentially accompanied by plant cleaning and treatment to re-build the stainless steel passivation layer [5]. The campaign at RWE has shown that leaving a relatively small fraction of the degraded MEA inventory inside the plant (5-10%), which could remain inside heat exchangers, piping and sumps, for instance) when refilling with fresh solvent would immediately trigger the exponential degradation behaviour [4].

Even though MEA is a relatively low cost solvent, solvent management strategies may prove cost-effective as they can lower the plant downtime required to perform an inventory swap and plant cleaning (estimated at 2-3 days). Regardless of costs, solvent management would lower the operations environmental impact.

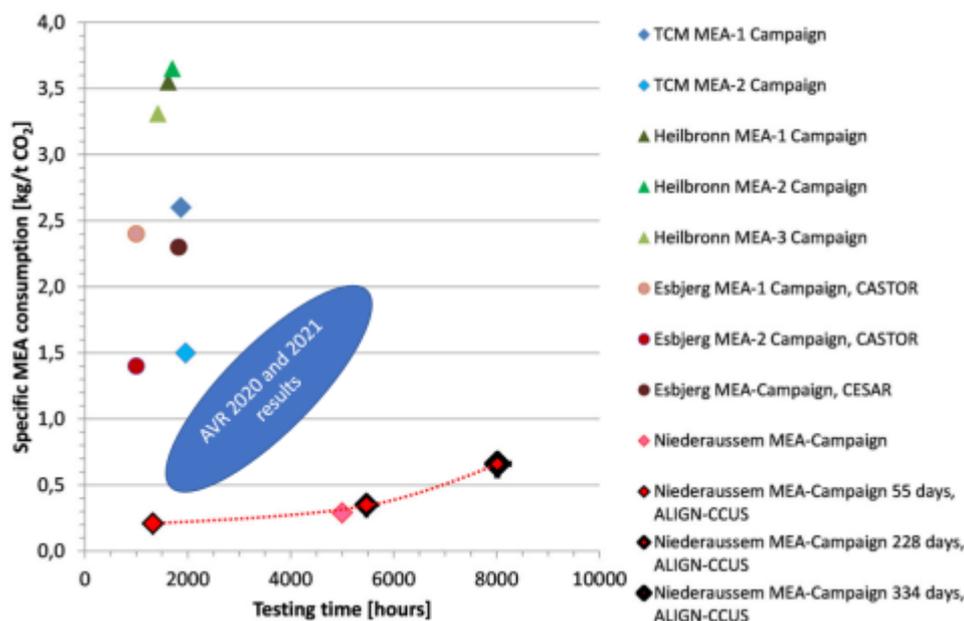


Figure 1. Specific MEA consumption at AVR and in various pilot campaigns. Figure adapted from Moser et al. [4]

The relatively high energy demand and degradation rate of MEA have led to the development of second-generation amine solvents. These include aqueous piperazine (PZ), blends of methyldiethanolamine (MDEA) and PZ, CESAR1 (aqueous blend of 3M 2-amino-2-methyl-1-propanol (AMP) and 1.5M PZ) and several commercial amine formulations, usually consisting of blends of amines. CESAR1 has been proposed as the new benchmark for post-combustion capture, as it has about 20% lower energy demand than MEA [6]. The lower energy demand has been confirmed at TCM [7] and RWE [8]. Within LAUNCH, RWE has conducted the longest-ever CESAR1 campaign. The plant was operated with the solvent for over 4 years without inventory changes [1], [8], [9]. This campaign clearly shows a lower degradation rate of CESAR1 compared to MEA.

1.2 The drive to develop better solvents

The second-generation open solvents all rely on the use of PZ. While these solvents offer advantages over MEA, particularly regarding higher chemical stability and lower energy demand, PZ use requires additional safety measures. It is a chemical of concern from an HSE perspective, as it is “suspected of damaging fertility” and “suspected of damaging the unborn child” [10], [11]. Moreover, being a secondary amine, PZ leads to the formation of nitrosamines when reacting with NO₂ (present in flue gases). Some of these degradation products are carcinogenic, and their accumulation in the solvent leads to a hazard. Therefore, while first- and second-generation solvents are relatively mature and commercially available, there is still room for improvement. Novel solvent formulations could potentially overcome some of the shortcomings of the current best available solvents.

Historically, the work on the development of novel solvents has focused on lowering the energy demand, which is the main cost driver of capture. For evaluating the energy demand, data on vapor-liquid equilibrium (VLE) are normally generated. Thermodynamic models are then fitted to these data, and used to estimate the

cyclic capacity and energy consumption of the novel solvents at given operational conditions. To support techno-economic evaluations, data on the kinetics of reaction between CO₂ and the solvent are generated, and used to size the absorber column (the most costly item in a capture plant). Along with physical data such as density, viscosity and heat capacities, this usually completes the minimum data set used to propose a new solvent formulation. Corrosion tests are normally also conducted before testing a novel solvent at pilot scale.

A recent review paper assessed the properties of 132 amine solvents proposed in literature for CO₂ capture [12]. Despite the large number of solvent alternatives proposed and tested at lab scale (TRL0-4), no breakthrough in energy demand was achieved. In fact, there is little room to improve in this aspect: while existing amine-based designs for point-source capture already gives thermodynamic efficiencies of about 50% [13], industrially applied separation processes have typical efficiency ranges from 5-40% [14].

Beyond energy numbers, degradation rates, volatility and HSE aspects are all critical parameters that drive the desire to develop novel solvents. One example of commercial solvent improvement following this trend is given by Mitsubishi Heavy Industry (MHI). In 2016, MHI successfully delivered the largest CO₂ capture plant built to date (with a capacity of 4776 tpd) for the Petra Nova Project. The solvent used was MHI's KS-1™. Recently, the company launched its new generation solvent, KS-21™, with reduced volatility and thermal and oxidative degradation rates, and comparable energy consumption [15].

MHI's R&D activities on novel solvent piloting started back in 1991, with its first CO₂ capture pilot plant being constructed at Kansai Electric Power Co., Inc.'s Nanko natural gas fired power plant. To this day, MHI continues to use this 2 metric tonnes per day (tpd) pilot plant to test new solvents [16].

1.3 The drive to lower the costs of solvent development

Sustaining R&D efforts and operating a pilot plant for over 20 years, as MHI is doing, is costly. While some of the bigger players in the CO₂ capture market are (part of) large companies (e.g., MHI, Shell, Aker), others are start-ups with presumably less financial capacity to carry on costly piloting campaigns.

According to TCM's website, since its operational start-up in 2012, Aker Solutions (Norway), Alstom SA (France), Cansolv Technologies Inc (Canada), Carbon Clean Solutions (UK/India), ION Engineering (USA), Fluor Corporation (USA) and Mitsubishi Heavy Industries Engineering (MHIENG) are among those that have tested their technologies at TCM. "The private companies which come to TCM, usually receive funding support from governmental entities in their home countries. For instance, The U.S. Department of Energy (DOE) has awarded approx. USD 40 million to six American companies to come to TCM for advanced carbon capture technology testing" [17]. This means that the average cost of a technology qualification run at TCM is at least USD 6.7million, or € 6.6 million, assuming the funding was sufficient to cover all costs. These campaigns typically focus on several aspects of the solvent. like energy requirements, operatively, solvent and degradation component emissions, emission control and solvent degradation.

One of the most effective ways of lowering the costs of CO₂ capture is to ensure there will be competition in the market. To this end, one of the LAUNCH targets was to develop a Solvent Qualification Protocol (SQP) that could allow for *lowering the time and costs for solvent qualification*.

The TCM pilot plant has capacity to capture up to 3480 kg/h of CO₂ [18]. In LAUNCH, we proposed reducing the costs by qualifying solvents at a much smaller scale. The proposed LAUNCH rig has capacity to capture up to 1 kg/h of CO₂. It should be emphasized that the LAUNCH SQP focuses solely on *solvent degradation, typically requiring long pilot campaigns*. Due to the reduced plant scale, wall effects and heat losses make the estimation of the specific reboiler duty very difficult (while the losses can be estimated, these are of the same order of magnitude as the duty, which introduces high inaccuracy in the obtained value).



1.4 Are the currently available solvents good enough?

A solvent qualification protocol is useful in speeding up the development of novel solvents, and in closing degradation-related knowledge gaps on the currently available first and second-generation solvents. This is arguably where most of the value of the SQP is, as the adoption of CCS needs to be greatly accelerated. In a few decades from now, hundreds to thousands of amine-based CO₂ capture plants are expected to be operational. It is likely that limited amount of solvents (5-10) will dominate the market. These could be either proprietary or open formulations. It could be argued that, instead of looking for the “holy grail” of solvents, we should focus on the development and demonstration of degradation mitigation methods, making sure that the first and second-generation solvents already developed can safely and timely answer to that market demand.

2 The LAUNCH rig

In LAUNCH, we have performed and evaluated data from 4 solvent development rigs, herein called LAUNCH rigs, or LR for short. All rigs are small-scale CO₂ capture plants, capable of operating in cyclic (absorption-desorption) mode in a continuous way.

LR1 was designed and built by SINTEF. Prior to LAUNCH, the LR1 was operated with, amongst other solvents, MEA. The MEA data was transferred to LAUNCH and assessed during the project. LR2 is a mobile capture plant designed and built by TNO prior to LAUNCH. Within LAUNCH, it was used in multiple campaigns in WPs 4 (MEA) and 5 (CESAR1), with an accumulated running time of over 4500 hours in the project. LR3 was designed and built within LAUNCH. The plant is entirely made of non-metallic materials and had the purpose of allowing us to decouple the phenomena of corrosion and degradation. Finally, LR4, the largest of LRs, is the TERC plant in the UK Carbon Capture and Storage Research Community (UKCCSRC), with capture capacity of 1000 kg CO₂/day.

By evaluating the design of the different LRs, and upon analysing the results of the LAUNCH campaigns, the LAUNCH partners have proposed the design of a LAUNCH rig – a unit designed to qualify solvents regarding their degradation behaviour, serving as the main element of the LAUNCH SQP. The design of the LAUNCH rig is discussed in item 2.2. Before that, we present evidence that a LAUNCH rig, despite its much smaller scale as compared to traditional pilots, is effective in mimicking the behaviour of a larger scale plant.

2.1 Validation of LAUNCH rigs

Prior to LAUNCH, four MEA campaigns in different conditions were performed at SINTEF's LR1. A comparison of LR1 and pilot results show that the same degradation profile trends are achieved [19], [20].

Within LAUNCH, a head-to-head validation campaign was performed by operating the LR2 and RWE pilots in parallel for 3 months. The mobile LR2 was installed at the RWE Niederaussem premises, next to the existing capture plant. A slip stream (ca. 4 Nm³/h) of the RWE flue gas downstream of the direct contact cooler was directed to LR2. About 20 litres of CESAR1 solvent was taken from the RWE pilot and filled to the LR2. The LR2 operation was set so that the rich loading, as well as the temperature profile in the absorber were matched. The operational parameters used in both plants along with the campaign results are described in more detail in D5.1.1 (publicly available).

Despite the difference in scale between the two plants (RWE: 300 kg/h; LR2: 1 kg/h), the results show that the concentration of the degradation products formate, acetate, glycolate, propionate and oxalate in both plants followed the same trend throughout the campaign. The results, given in Figure 2 and Figure 3, indicate that the LR2 can be used to study the degradation behaviour of CESAR1.

With the combined results from LR1 and LR2 and generalizing from the MEA and CESAR1 results, the approach of evaluating the degradation behaviour of solvents in small scale CO₂ capture plants is validated. This is a key result of LAUNCH, as it is an enabling factor in achieving the intended reduction of the costs associated with solvent qualification.

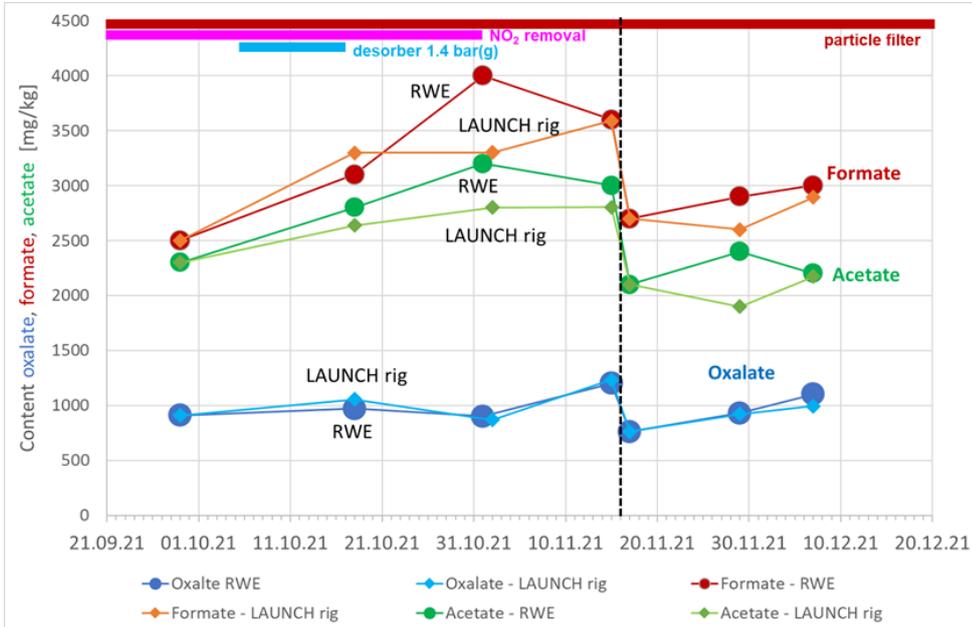


Figure 2. Evolution of concentration of formate, acetate and oxalate during the head-to-head campaign between LR2 and the RWE pilot

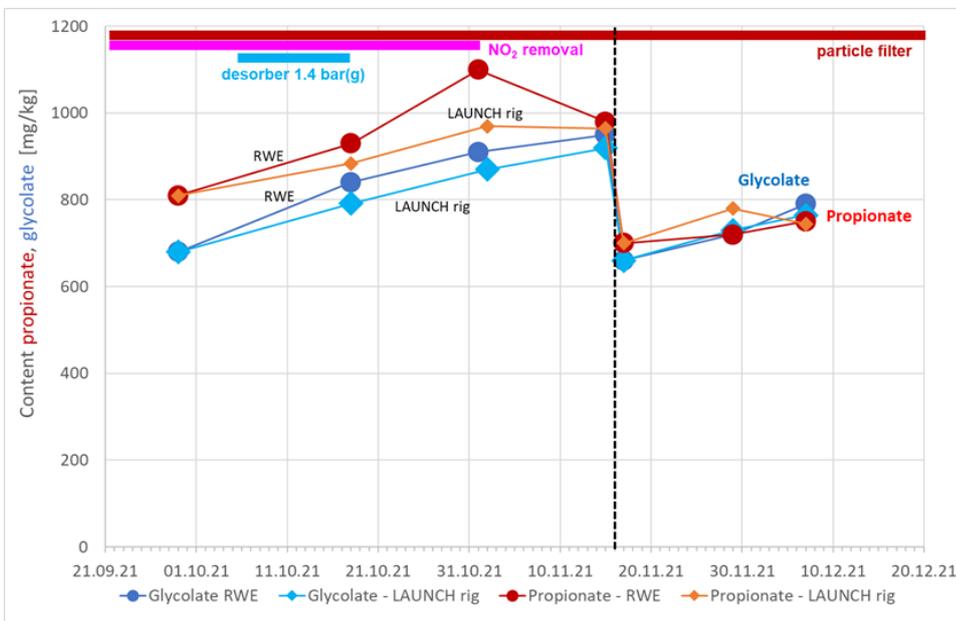


Figure 3. Evolution of concentration of glycolate and propionate during the head-to-head campaign between LR2 and the RWE pilot

2.2 Design of the LAUNCH Rig

The LAUNCH Rig's design follows a number of decisions regarding the objectives and functionalities of the rig. These decisions were taken based on discussions amongst the partners in LAUNCH, throughout the project. Next, the discussions behind each of the aspects considered are summarized.

2.2.1 Scale and mobility

As mentioned, LR2 (TNO's miniplant) is a mobile plant with capacity of 1 kgCO₂/h (or 0.025 ton per day, tpd). For comparison, Aker's mobile test unit (MTU) has a capacity of 1 tpd, and AECOM has designed a mobile system of 5-9 tpd [21]. This is in the same scale as the RWE plant and one order of magnitude larger than LR4.

Designing a plant as a mobile system allows testing at multiple locations, thus exposing solvents to different flue gases. As demonstrated in LAUNCH, this is important as impurities may influence the degradation behaviour of solvents. At the same time, it was demonstrated that the scale of LR2 is sufficient to test this. Larger scale plants would be needed to demonstrate energy requirement, which is a function of the CO₂ content in the gas. However, it does not seem necessary for a plant with this objective to be designed as a mobile system, as the CO₂ content in flue gases can be easily manipulated by e.g., diluting with nitrogen or air to reduce the concentration, or mixing with produced CO₂ to increase it.

Therefore, it would make sense to have larger scale stationary pilot plants (such as TCM, RWE, NCCC) used to validate the energy demand of solvents in relatively short-term campaigns; and small scale mobile plants that could be operated at multiple sites to study solvent degradation behaviour in long-term campaigns. The advantages of having small systems being:

- mobility of the rig;
- decreased costs of construction, transportation and operation;
- facilitated installation in the host plant – both regarding footprint, and connection to flue gas line.

A flue gas flowrate of 5 Nm³/h can be drawn from sample ports in the gas line, which avoids the need for tie-ins.

While the ability to perform on-site work with multiple flue gases is an advantage, initial investigations on solvent degradation behaviour are preferably performed in a controlled environment. Using synthetic flue gas allows to control the presence of different impurities in the gas and avoids host-process related fluctuations that may complicate the interpretation of the results. Lab campaigns will generate degraded solvent samples that are needed for the analytical work of identifying and quantifying degradation compounds. This work is preferably done prior to testing solvents on-site, for health and safety reasons.

2.2.2 Sizing of components

The sizing of the components of the LAUNCH rig will depend on the intended use. The rig should be designed with the capability to run with different (drop-in) solvents. This means that the design should consider variations in kinetics (absorber height), cyclic capacity (pump flowrates), energy demand (reboiler duty), etc. To be representative of a full-scale system, the LAUNCH rig must operate at representative conditions. This starts by being capable of reaching rich and lean loadings representative of full-scale plants using reasonable liquid-to-gas-ratios. This means achieving representative capture rates of 95% and above. The plant should

also offer the possibility to vary the residence time of the solvent at different equipment parts, such as the absorber sump, and the rich solvent line before and after the cross heatexchanger.

To achieve representative loadings, the absorber height needs to be sufficient. Flexibility in absorber height can be achieved by working with two absorber columns in series or by having the possibility to change the liquid inlet point along the column. Using a high area density packing (e.g., 400 m²/m³) will help achieve the desire rich loading with limited packing height. One initial size indication could be a total of 6m of packing height, in 2 sections of 3m.

A water wash should be included to maintain the system water balance and control volatile solvent losses. This controls the solvent composition over time, which is an important parameter in degradation studies. A column with 2m of packing could be used for this purpose.

Also to keep the water balance, upstream of the absorber a quench/direct contact cooler is required to saturate the gas at the desired operating temperature (normally around 40°C). This can also be achieved by a column with 2m packing height. When operating on-site with SO_x-containing flue gases, NaOH should be added to the quench water circulation loop to control the SO_x inlet to the absorber below 1 mg/Nm³. Also, in the case of operations on-site, a particle filter downstream of the quench may be necessary to avoid uncontrolled aerosol-based emissions, which could quickly alter the solvent composition.

Piping length and residence times are more tuneable in a LAUNCH rig than in a full scale plant. If desired, additional vessels can be included in the piping sections, to increase the residence time and thus represent longer lines (representing a case an absorber would be placed away from the stripper due to footprint constraints, for instance). The operational levels can be used to control the residence times in the absorber and stripper sumps.

2.2.3 Degradation mitigation technologies

Within LAUNCH, a number of degradation mitigation technologies were studied. For oxygen removal from the rich solvent, N₂ sparging and DORA were investigated. Both technologies can be placed in line, and are simple to scale down, thus they can be included in the design. The same goes for active carbon beds.

The impact of each one of these technologies on the degradation of different solvents, at varying operational conditions, can then be investigated.

Reclaiming technologies are not to be included since operating these units continuously at such a small scale can be very challenging. If these are specified as a requirement for the solvent in question, then batch operation seems more likely to be applied at the proposed scale.

2.2.4 Materials of construction

The material should be stainless steel following standard choices for full-scale plant components, also providing easy manufacturing and maintenance (which is not necessarily the case when plastic materials are chosen). The materials of construction should be commercially relevant.

2.2.5 Instrumentation

The plant should be fully instrumented so that it can be automated. The control system should allow stable, 24/7 operations. Additional instrumentation compared to normal design of full-scale commercial plants would include more temperature sensors along the absorber column, so that the temperature profile is well captured by the data.

An online tool should be available for gas analysis, for tracking the major (CO_2 , O_2 , water) and minor components (NO_x , amines, NH_3) at the absorber inlet and outlet. This could be an FTIR equipped with a ZrO_2 cell for oxygen measurements.

On the liquid side, valves should be available for taking samples of the lean and rich solvent, as a minimum. Online analyzers are also available for measuring oxygen in the solvent. It would be of interest to have one of these sensors connected to the rich solvent line.

2.3 Drawing of a generic LAUNCH rig

In summary, the LAUNCH rig is a complete full cycle (absorption + desorption) system, capable of continuous 24/7 operation. It has capacity for producing approximately 1 $\text{kg}_{\text{CO}_2}/\text{h}$. For that, it can treat 3-5 Nm^3/h of gas (synthetic gas mixtures, real flue gases), with up to 25 kg/h of solvent circulation.

A simplified process flow diagram is given in Figure 4. Some of the main characteristics are annotated in green. A green "t" in any unit means that the residence time should be carefully considered, and flexible when possible.

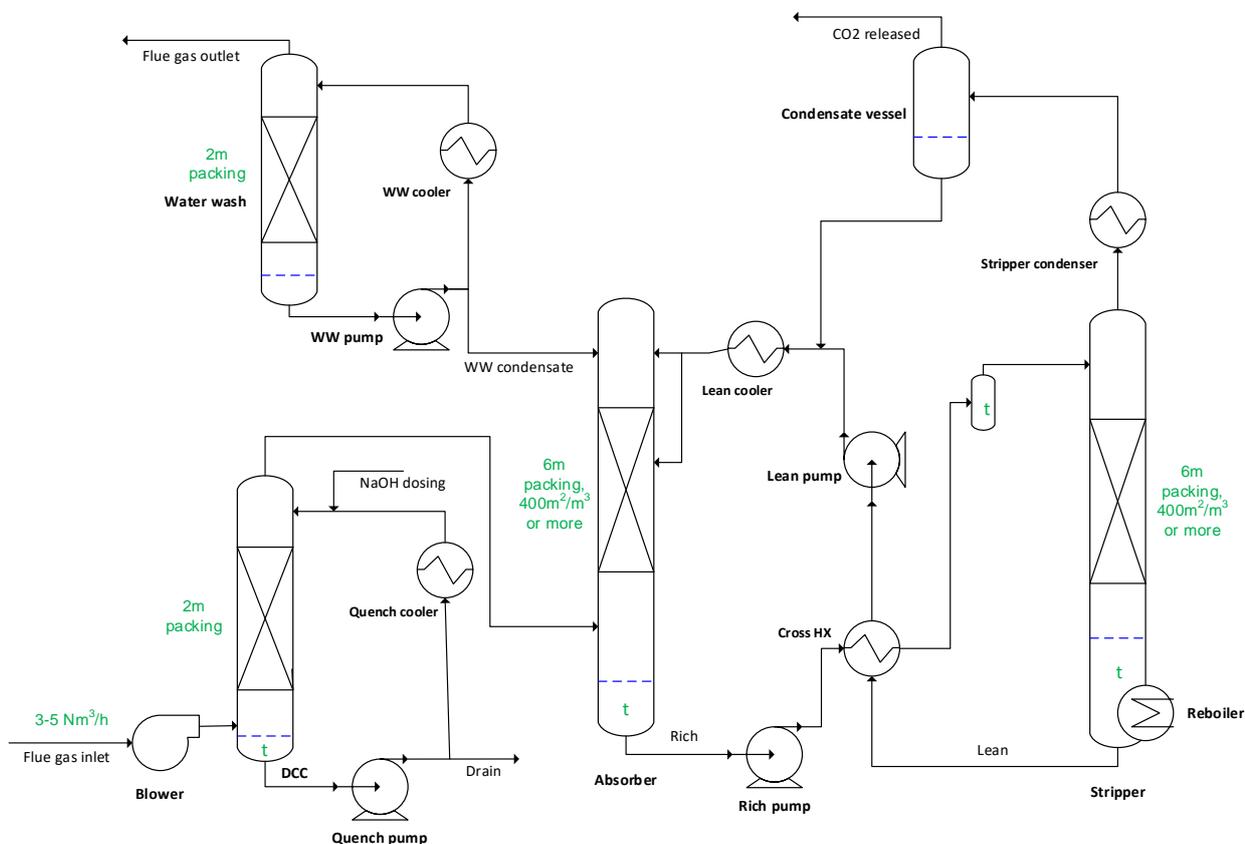


Figure 4. Simplified process flow diagram of the LAUNCH rig

2.4 Costs of the LAUNCH rig

The cost of the LAUNCH rig is estimated at 500 k€, based on partner's experiences on engineering and building similar plants. This includes all necessary instrumentation and automation, as well as online analytical equipment (FTIR, oxygen sensor). A study by AECOM, commissioned by the UK's Department for Business, Energy & Industrial Strategy (BEIS) has looked into different possibilities for the design of a mobile demonstration CO₂ capture plant [21]. In that report, three different sizes of demo units were investigated (9, 20 and 100 tonnes of CO₂ captured per day, tpd). These units are seen as long-term de-risking facilities, design to conduct extended test campaigns on real-world flue gas with duration in the order of 10.000 hours in order to de-risk projects.

AECOM has advised for choosing the smaller scale unit, due to the following benefits:

- "Lower capital cost (reduced government or company funding required)
- Quicker deployment, owing to easier integration within existing sites (lower power and cooling demand)
- Smaller footprint required
- Mobile, allowing units to be reused on multiple sites once test campaigns are complete
- Lower operating costs"

In the current report, we argue that benefits are potentialized when working at even smaller scale – and we show evidence that LAUNCH rig scale is sufficient to draw conclusions regarding solvent degradation behaviour. It should be mentioned that the scale limiting factor of the BEIS demo unit is the minimum column diameter of approximately 0.4m, which is the threshold size for valid scaling of packing performance. By decoupling the assessment of packing and energy performance from that of the solvent degradation performance, the LAUNCH approach allows for long-term operations for solvent qualification at much lower costs.

A comparison between the different scales of the BEIS demo unit and the LAUNCH rig is given in Table 1. It should be noted that the BEIS demo units also include liquefaction and a thermal reclaimer. Assuming that these would represent 40% of the investment, then cost of a LAUNCH rig approximately 5 times lower than the small scale BEIS demo unit.

Table 1 – LAUNCH rig cost as compared to that of other mobile plants of larger size

Unit	CO ₂ captured (tpd)	Cost (k€)	Footprint (m ²)	Source
LAUNCH rig	0.025	500	6	LAUNCH project
BEIS demo unit, small	9	4.000	N/A	[21]
BEIS demo unit, intermediate	20	7.000	N/A	[21]
BEIS demo unit, large	100	20.000	3.000-5.000	[21]

2.5 Additional considerations on the LAUNCH rig design and use

As discussed earlier, the LAUNCH rig is primarily designed for degradation studies of solvent blends both at research laboratories and industrial sites. This means that the LAUNCH rig will not be suitable for testing other aspects related to solvent qualification and piloting. One of these is the energy requirement of solvent regeneration, as discussed earlier.

Similarly, even though the pilot has a water wash section, solvent and degradation compound emissions can only be qualitatively measured. This is because the water wash section design's main objective is to help control the water balance. In an industrial plant, the water wash section would additionally be designed to minimize the solvent and degradation compound emissions by typically adding two water wash sections and sometimes even an acid wash section. This limitation could be at least partly addressed by adding a second water wash section with temperature control and the possibility of using impingers to take gas samples from the gas leaving the water wash sections. However, the rig's generic design is suitable for the identification of volatile compounds if liquid samples from the water wash section and gas samples (after the water wash) using impinger trains are withdrawn.

Another aspect that should be considered is the presence of particles that could lead to high solvent component emissions through aerosol formation. Presence of aerosols can increase solvent emissions and loss significantly. This will make it harder to evaluate the solvent degradation and ensure long-term stable conditions without having to add large amounts of makeup solvent. Therefore, when working with flue gases that might contain aerosols, a technology to mitigate those emissions is desirable.



To qualify solvents for CO₂ capture, one must possess a thorough understanding of the expected degradation compounds and the ability to analyze them. By using knowledge of chemistry, the solvent's structure, and the degradation mechanisms of known solvents, certain predictions can be made regarding the mechanisms and compounds that may be formed in other amines [22]. However, understanding the degradation of new solvents will always require research to propose likely degradation compounds and develop analytical methods to identify and quantify them.

3 The LAUNCH Solvent Qualification Protocol

The SQP makes use of the LAUNCH rig and is performed when the technology is at TRL4 or higher. This means that all data necessary for bringing the solvent to TRL4 are available (VLEs, physical properties, kinetics, etc.), and the optimized process operation conditions are known (lean and rich loadings, reboiler temperature and pressure, etc.).

Some of the campaigns in the SQP will make use of accelerated degradation. Next, we explain what this means and which techniques were tested within LAUNCH.

3.1 The LAUNCH accelerated degradation tests

Within LAUNCH, we have conducted a number of campaigns in LR2 and LR4 in order to support the design of a solvent qualification protocol (SQP). More specifically, the objective was to evaluate whether test protocols for accelerating degradation could be devised which would allow for faster, but still representative testing of solvent degradation behaviour. The driver behind this is to lower the costs and time of solvent qualification. It is important to mention that all tests were performed with MEA. Generalization of the findings is attempted, but further testing with other solvents should be performed to validate and consolidate the recommendations made in the SQP.

Three accelerated degradation techniques were studied in LR2: increased oxygen levels in the flue gas, increased stripping temperature, and addition of NO_x to the flue gas. We intended to test a fourth technique, increased solvent concentration. However, due to water balance issues in operating the LR2, the MEA composition was increased from 35 wt% (baseline) to only 37 wt%, and not to 40 wt% as initially intended. This concentration increase wasn't sufficient to observe significant differences between the campaigns.

We have observed that increased oxygen content (19.8 vol% as compared to 7.6 vol% in the baseline) increases the solvent degradation rate, while leading to a representative mix of degradation products when compared to the baseline campaigns. This is therefore considered an efficient and representative method for accelerating degradation.

The subsequent acceleration test combined Increased oxygen content with higher stripping temperature (130°C instead of 120°C). Increasing the stripping temperature does not seem to affect the formation of oxidative degradation products, such as formic and oxalic acid, while it led to the highest concentrations of HEPO and MEA-Urea and metal accumulation in the system, compared to the rest of the campaigns. Therefore, it changes the distribution between the different degradation pathways in a way that may not be representative of industrial operations. How this effect would impact the rate of the different pathways in the degradation network reactions of different solvents is unknown. Moreover, there is a question related to how to choose the increased temperature value when comparing solvents which are designed to operate at different temperature levels already (eg., MEA at 120°C and PZ at 150°C). Therefore, while increasing the temperature accelerates degradation, the representativeness of this method is questionable.

Finally, increased oxygen content was combined with higher NO_x content. The effect of adding NO_x into the flue gas on the degradation rate is shown to be dependent on the level of NO_x added. Tests in the LR2 were performed at a relatively high NO_x content of 169 ppmv. A sharp increase in the formation formic acid was observed, while the HEPO, MEA-Urea and metals concentration remained at similar levels. This shows that plants with high NO_x levels can suffer from a higher solvent degradation rate, as NO₂ acts as an oxidizing agent. In contrast, tests in LR4 were conducted with 15 ppmv NO_x. No clear effect was observed when comparing formic acid, HEPO and MEA-Urea products. This is in-line with the results observed at the RWE pilot campaign, which indicate that the effect of small variations of NO₂ content in the flue gas had no

measurable effect on the degradation of CESAR1 [9]. These findings are contrary to the results obtained at the TCM pilot during the CESAR1 ALIGN-CCUS campaign, which show acceleration of degradation upon increase of the NO₂ content in the gas [23]. Pilot plant testing with piperazine has also demonstrated a strong effect of NO₂ alone at only 1 ppm on amine oxidation [24]. Given the currently available evidence, increased NO_x content is not indicated as a degradation acceleration methodology at this stage, as the level of NO_x to use (which NO:NO₂ ratio, and how to control that) remains unclear. Nevertheless, these results stress the importance of using industrially relevant NO_x content (for each use case considered), or better yet, testing with real flue gases.

The addition of NO/NO₂ mixtures to artificial flue gases should be done with care. If highly concentrated streams of NO_x are used, the local concentration at the point of injection may cause oxidation of NO to NO₂, due to the presence of oxygen. This would lead to experiments inadvertently being performed at a higher NO₂ content than originally planned. To avoid this, gas mixtures of low NO_x concentration (order of magnitude 1000 ppm) in nitrogen are preferred.

3.2 The SQP protocol

For discussing a SQP, it is important to understand that there are no established hard criteria that qualify/disqualify a solvent immediately. The results of the SQP are to be used in a more holistic evaluation of the proposed capture technology. When it comes to factors that can be evaluated in the LAUNCH rig, solvent loss over time, corrosivity (or accumulation of metals over time), and environmental impact all play a role in solvent qualification. Other key factors include total investment costs, operational costs (and in particular those energy-related) and amine supply (can the components be easily procured, are they specialties).

3.2.1 Degradation characterisation campaigns

Degradation characterisation campaigns target performing a characterization and quantification of degradation products. These campaigns must be performed for health, safety and environmental (HSE) concerns. For these campaigns, working with increased oxygen content to accelerate degradation and include relevant NO_x content in the artificial flue gas (or work with real flue gas) is suggested. Weekly solvent samples should be taken and analysed comprehensively. The ambition should be to close the nitrogen balance, indicating that all degradation products are known and accounted for. In practice, a margin could be acceptable when the technology is still at TRL 5-7. For TRL8-9, closing the N mass balance is important.

The duration of the campaign is not to be defined in hours. Instead, it should run until a threshold value for solvent loss is achieved. We suggest that once 5% of the nitrogen is accounted for in the liquid degradation products, then the campaign can be terminated. An expected duration of such a campaign is between 500-1000 hours.

Besides being necessary from an HSE perspective, these characterisation campaigns are critical in evaluating solvent management strategies. The nature of the degradation products being formed will define how best to separate them from the solvent during long-term operations. For instance: ionic products can be separated by ion exchange or electrodialysis; and molecular products of higher boiling points than the solvent constituents can be separated by thermal reclaiming.

Within LAUNCH, we have used a lab scale evaporator to perform thermal reclaiming of MEA. In this operation, the entire inventory of the LR2 (ca. 25 litres of degraded solvent) was treated. Then, another campaign was executed with the reclaimed solvent – the results are available in D4.3.1. Such tests can also be performed with different reclaiming technologies, to allow for a simple, low-cost evaluation of reclaiming performance

(energy demand, amount of solvent recovered) as well as generating realistic reclaimer waste streams that can also be characterized. In this way, in translating the results obtained in the LAUNCH rig to a full scale plant, the best available solvent management technologies can be considered.

3.2.2 Degradation benchmarking campaigns

Solvent degradation performance is easier to be evaluated on a comparison basis, and benchmarking against open solvents for which a large body of data is available is a sensible approach. Therefore, a “benchmarking campaign” executed in the LAUNCH rig can be useful to compare the performance of a novel solvent against the chosen benchmark – MEA or CESAR1, for example.

Both the benchmark and candidate solvent campaigns should be performed under the optimal operational conditions envisioned for each solvent. For instance, MEA plants normally operate between lean and rich loadings of 0.23 and 0.5 mol/mol, whereas CESAR1 will operate between 0.1 and 0.67 mol/mol. As a result of the higher CESAR1 capacity, the L/G is lower. These differences need to be taken into account when designing the campaign. When the LAUNCH rig is at the same state (e.g., corrosion-wise) at the start of the two campaigns, comparison criteria can be proposed. For instance, the solvent loss in terms of kg/tonCO₂ captured can be calculated based on the rate of accumulation of the main degradation products.

Benchmarking could be conducted with either artificial flue gas or on-site, with real flue gas. The advantage of working on-site is that a more realistic representation is obtained, as the impact of flue gas impurities and possible host-process dynamics will be reflected in the measured degradation. On the other hand, this requires that the host process operates similarly throughout the two different campaigns with the different solvents. For instance, a fuel (quality) change, or maintenance in the gas treatment line in between the campaigns could influence the conclusions.

Benchmarking campaigns should provide the inputs for considering solvent degradation in the techno-economic assessment. This includes defining the reclaiming frequency and solvent losses over time. These factors are hard to evaluate when using accelerated degradation techniques, as there are not reliable models to translate accelerated degradation data back to “normal degradation rate” operations.

The solvent loss should be monitored throughout the campaign and compared against that of the benchmark. Based on the LAUNCH findings, we believe that these campaigns should have a minimum duration of 2 months (1400 h). The campaign termination criteria should be set in terms of the maximum accepted solvent loss, in terms of kg/tonCO₂. It should be noticed that this is a flexible criterion. As MEA is a relatively cheap solvent, losses up to 1 kg/tonCO₂ or higher could be acceptable. However, for more expensive formulations such as CESAR1, the acceptable loss may be set lower, at 0.5 kg/tonCO₂. In this way, the benchmarking campaign represents the first operational cycle of a solvent, from start-up of the plant with fresh solvent to the moment at which reclaiming should be started. This assumes that reclaiming operations would be discontinuous in the full-scale operations.

For the benchmark tests, we recommend weekly solvent samples are taken. A complete mass balance is not required (as opposed to degradation characterisation tests), but monitoring the concentration of the solvent amine components, accumulation of metals and some key degradation products previously identified should suffice. This greatly lowers the laboratory-related operational costs.

In order to obtain meaningful results, it is essential to: control the water balance (crucial to use a water wash, advisable to use a tracer such as lithium), to correct the liquid analysis results for CO₂ and water content, and keep track of the addition of fresh solvent or any other changes in the plant. Also, the analytical uncertainty must be reported.

3.3 Marginal costs of running the SQP

The SQP considered for this cost evaluation consists of a degradation characterization campaign lasting 1000h, followed by a benchmark campaign lasting 4 months. Therefore, the total SQP would last for ca. 6 months. The marginal costs of running the SQP are estimated at 103.7 k€, and are discussed next. The cost distribution is given in Figure 5.

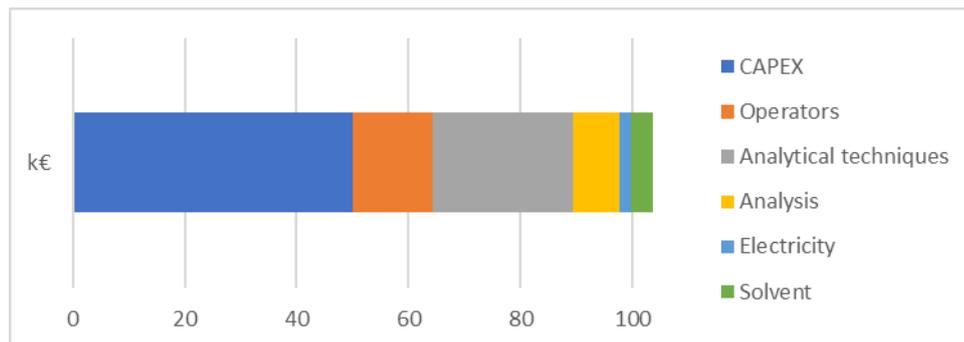


Figure 5. Marginal costs of running the proposed SQP

3.3.1 CAPEX

The investment of a LAUNCH rig is estimated at 500 k€, as discussed. The expected life-time of a LAUNCH rig is at least 10 years. If it would have 100% availability, 20 campaigns would be possible. Considering this is a research facility, 50% availability seems reasonable, leading to 10 campaigns over the LAUNCH rig lifetime, or a CAPEX of 50 k€ per campaign.

3.3.2 Operators

The rig requires two operators for 2 working days to start a campaign (solvent preparation, filling the plant, achieving the desired operational parameters, closing a CO₂ mass balance). Then, as the system is fully automated, one operator can control the plant throughout the campaign by working for 1h per day. This includes verifying the levels in the different vessels of the plant and in the cooling water system, adding solvent or water make-up when required, checking the process parameters for any deviations and taking samples once per week. For terminating the campaign, again 2 operators are needed for 2 working days (draining the plant, and thoroughly cleaning it with water).

The operators' costs are estimated at 88 k€/year. With a working year consisting of 1770 hours, this gives a cost of ca. 50 €/h. One SQP campaign would cost approximately € 14400 in operator hours (€ 5250 characterization + € 9150 benchmarking).

3.3.3 Utilities

The rig only required electricity. The reboiler is either electrical or connected to an electrical oil bath. The coolers are connected to an electrical water-cooling system. The total electrical duty is estimated at 5 kW, and the electricity cost is estimated at 100 €/MWh. Running the SQP campaigns would cost approximately €1940 (€ 500 characterization + € 1440 benchmarking).

3.3.4 Solvent inventory

The solvent inventory cost is dependent on the solvent formulation. If a solvent component can be bought at about 10 €/kg, and the solvent formulation is 40 wt% in water, then the cost of an inventory (25 kg) is estimated at €100. However, for novel solvents bought at low volumes, the price of the chemicals can be much higher. Considering a high cost of 200 €/kg, an inventory costs € 2000. For running the SQP, two inventories are needed, one per campaign. Hence, the solvent cost is conservatively estimated at € 4000.

3.3.5 Laboratory costs

Lab technician costs are also estimated at 88 k€/year. We consider that 2 working days are necessary to process each sample from the characterization campaign, leading to approximately € 4770. The benchmarking campaign requires less analysis, hence we estimate 4 hours per sample, leading to € 3580.

Costs of developing analytical techniques for identifying the main degradation products is roughly estimated at 25 k€. This is the most uncertain cost element of the SQP.

4 Conclusions and next steps

In this report, we have discussed the LAUNCH rig, a fully automated CO₂ capture plant designed to de-risk scaling-up of solvent technologies by representing the solvent degradation behaviour of full-scale plants. This plant is designed with a small capacity of 1 kg/h of captured CO₂, or 0.025 tonne per day (tpd). This small rig system, proposed before LAUNCH and further validated within the project, can be used to quantify the formation of degradation products over time. The drawing of a generic LAUNCH rig is given, and different design aspects are discussed. The rig is mobile, has a small footprint (6 m²) and can be easily connected at different industrial sites. This opens up the possibility of qualifying solvents using different flue gases. The cost of the LAUNCH rig is estimated at 500 k€.

Larger pilot units are still required for qualifying solvents regarding process performance (e.g., reboiler energy demand) at varying operational conditions. However, decoupling the two aspects – process and degradation performance – allows for small LAUNCH rigs to be used in long-term degradation campaigns (months), while larger pilots can be used in short-term process performance campaigns (weeks). It should be emphasized that good thermodynamic models exist for simulating solvent process performance, and once these are validated (for every new solvent) with large pilot data, they can be used to accurately predict the process performance at varying conditions, including the CO₂ content in the inlet gas. Therefore, these large pilots do not need to be mobile. A number of large-scale pilots are already available, including the Technology Centre Mongstad (TCM) and SINTEF's Tiller facility, UKCCSR's TERC, the RWE Niederaussem pilot, and the National Carbon Capture Center (NCCC). Therefore, there seems to be sufficient infrastructure to evaluate process performance.

In this report, we also have proposed a solvent qualification protocol (SQP), which is summarized in Table 2. The recommendations in the SQP are based on the LAUNCH partners experience in running similar campaigns prior to and within the project. The LAUNCH SQP consists of 2 campaigns and can be executed within 3-8 months. Estimated operational costs for a 6 months program are 104 k€, which is in line with LAUNCH's target of 100 k€, but very dependent on the assumed costs for analytical techniques development – the item with largest uncertainty in this cost estimate.

Table 2. LAUNCH Solvent Qualification Protocol

SQP campaign	Flue gas	Termination criteria	Solvent sampling	Expected duration
Degradation characterization	Artificial or real. In case of artificial, add NO _x to realistic level. In both cases, use increased O ₂ content (close to 20%).	Liquid degradation products account for 5% of the initial solvent N content	Weekly quantification of products. Comprehensive analysis so that mass balance is closed.	500-1000 hours
Benchmarking	Ideally real flue gas. In case of artificial, add NO _x to realistic level.	Maximum acceptable solvent loss rate reached (kg/tonCO ₂), based on business case	Weekly quantification of main degradation products	2-6 months

The LAUNCH SQP is the first attempt that we are aware of on suggesting a methodology for solvent qualification. This could be very helpful in accelerating the implementation of CCS. This protocol needs to be



validated by running multiple campaigns with different solvents and evaluating the results against long-term campaigns. The SQP work performed in LAUNCH used MEA, and a next step could be to apply the developed protocol to CESAR1 and PZ, solvents for which there is extensive degradation data available. After testing those solvents, other open formulations such as MDEA/PZ blends, potassium taurate and potassium alanate could also be qualified. The more data is generated, the higher the confidence in the proposed methodology will be.

CO₂ capture technology providers would greatly benefit from a proven SQP, and this would also facilitate investment decisions by end-users, and permit processes from environmental authorities.

5 References

- [1] P. Moser *et al.*, “Demonstrating solvent management technologies for an aqueous AMP/PZ solvent,” *SSRN Electron. J.*, 2021, doi: 10.2139/ssrn.3812211.
- [2] J. Ros *et al.*, “Results of the 2020 and 2021 campaigns of the commercial carbon capture plant at AVR Duiven,” *SSRN Electron. J.*, 2022, doi: 10.2139/ssrn.4282665.
- [3] T. Do, D. Narendra, F. Paul, and M. Azzi, “Process Modelling for Amine-based Post-Combustion Capture Plant,” 2012. [Online]. Available: <https://www.globalccsinstitute.com/archive/hub/publications/169153/process-modelling-amine-based-post-combustion-capture-plant.pdf>.
- [4] P. Moser *et al.*, “Results of the 18-month test with MEA at the post-combustion capture pilot plant at Niederaussem – new impetus to solvent management, emissions and dynamic behaviour,” *Int. J. Greenh. Gas Control*, vol. 95, p. 102945, 2020, doi: <https://doi.org/10.1016/j.ijggc.2019.102945>.
- [5] A. K. Morken *et al.*, “CO₂ capture with monoethanolamine: Solvent management and environmental impacts during long term operation at the Technology Centre Mongstad (TCM),” *Int. J. Greenh. Gas Control*, vol. 82, pp. 175–183, 2019, doi: <https://doi.org/10.1016/j.ijggc.2018.12.018>.
- [6] P. H. M. Feron, A. Cousins, K. Jiang, R. Zhai, and M. Garcia, “An update of the benchmark post-combustion CO₂-capture technology,” *Fuel*, vol. 273, p. 117776, 2020, doi: <https://doi.org/10.1016/j.fuel.2020.117776>.
- [7] C. Benquet, A. B. N. Knarvik, E. Gjernes, O. A. Hvidsten, E. Romslo Kleppe, and S. Akhter, “First Process Results and Operational Experience with CESAR1 Solvent at TCM with High Capture Rates (ALIGN-CCUS Project),” *SSRN Electron. J.*, no. October, pp. 13–15, 2021, doi: 10.2139/ssrn.3814712.
- [8] P. Moser *et al.*, “ALIGN-CCUS: Results of the 18-month test with aqueous AMP/PZ solvent at the pilot plant at Niederaussem – solvent management, emissions and dynamic behavior,” *Int. J. Greenh. Gas Control*, vol. 109, 2021, doi: 10.1016/j.ijggc.2021.103381.
- [9] P. Moser, G. Wiechers, S. Schmidt, R. Veronezi Figueiredo, E. Skylogianni, and J. Garcia Moretz-Sohn Monteiro, “Conclusions from 3 Years of Continuous Capture Plant Operation Without Exchange of the Amp/Pz-Based Solvent at Niederaussem – Insights into Solvent Degradation Management,” *SSRN Electron. J.*, 2022, doi: 10.2139/ssrn.4274015.
- [10] Sigma-Aldrich, “Piperazine safety data sheet (SDS) version 7.4,” 2023. <https://www.sigmaaldrich.com/NL/en/sds/sial/p45907> (accessed May 10, 2023).
- [11] ECHA, “European Chemicals Agency - Substance Infocard, piperazine.” <https://echa.europa.eu/substance-information/-/substanceinfo/100.003.463> (accessed May 10, 2023).
- [12] I. M. Bernhardsen and H. K. Knuutila, “A review of potential amine solvents for CO₂ absorption process: Absorption capacity, cyclic capacity and pK_a,” *Int. J. Greenh. Gas Control*, vol. 61, pp. 27–48, 2017, doi: <https://doi.org/10.1016/j.ijggc.2017.03.021>.
- [13] Rochelle G.T., “Amine scrubbing for CO₂ capture,” *Science (80-.)*, vol. 325, pp. 1652–1655, 2009,

doi: 10.2139/ssrn.2379600.

- [14] J. Wilcox, P. C. Psarras, and S. Liguori, "Assessment of reasonable opportunities for direct air capture," *Environ. Res. Lett.*, vol. 12, no. 6, p. 065001, May 2017, doi: 10.1088/1748-9326/aa6de5.
- [15] K. OBrien *et al.*, "Full-scale FEED Study for Retrofitting the Prairie State Generating Station with an 816 MWe Capture Plant using Mitsubishi Heavy Industries Engineering Post-Combustion CO₂ Capture Technology," *SSRN Electron. J.*, 2021, doi: 10.2139/ssrn.3815206.
- [16] T. Hirata, M. Inui, D. Shimada, S. Kishimoto, T. Tsujiuchi, and S. Kawasaki, "MHI's Commercial Experiences with CO₂ Capture and Recent R&D Activities," *Mitsubishi Heavy Industries Technical Review Vol. 55 No. 1*, pp. 32–37, 2018.
- [17] TCM, "We test technologies." https://tcmda.com/technology-testing/#private_companies_testing_at_tcm (accessed Feb. 14, 2023).
- [18] E. Gjernes *et al.*, "Documenting Modes of Operation with Cost Saving Potential at the Technology Centre Mongstad," *SSRN Electron. J.*, no. October, 2020, doi: 10.2139/ssrn.3366235.
- [19] S. J. Vevelstad *et al.*, "Comparison of different Solvents from the Solvent Degradation Rig with Real Samples," *Energy Procedia*, vol. 114, pp. 2061–2077, 2017, doi: <https://doi.org/10.1016/j.egypro.2017.03.1341>.
- [20] A. Einbu *et al.*, "A new test rig for studies of degradation of CO₂ absorption solvents at process conditions; comparison of test rig results and pilot plant data for degradation of MEA," *Energy Procedia*, vol. 37, pp. 717–726, 2013, doi: <https://doi.org/10.1016/j.egypro.2013.05.160>.
- [21] AECOM, "Next Generation Carbon Capture Technology. Case Study: Mobile Demonstration Plant Work Package 4," 2022. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1079537/aecom-next-gen-carbon-capture-technology-mobile-derisking-plant-annex-2.pdf.
- [22] S. J. Vevelstad, V. Buvik, H. K. Knuutila, A. Grimstvedt, and E. F. da Silva, "Important Aspects Regarding the Chemical Stability of Aqueous Amine Solvents for CO₂ Capture," *Ind. Eng. Chem. Res.*, vol. 61, no. 43, pp. 15737–15753, Nov. 2022, doi: 10.1021/acs.iecr.2c02344.
- [23] matthew Campbell, S. Akhter, A. Knarvik, Z. Muhammad, and A. Wakaa, "CESAR1 Solvent Degradation and Thermal Reclaiming Results from TCM Testing," *SSRN Electron. J.*, 2022, doi: 10.2139/ssrn.4286150.
- [24] F. Closmann, Y. Wu, C.-I. Chen, A. Plantz, and G. Rochelle, "Pilot Testing of Mitigation Methods for Piperazine Oxidation," *SSRN Electron. J.*, 2022, doi: 10.2139/ssrn.4283222.