



1. Identification of the project and report

Project title	LAUNCH - Lowering absorption process uncertainty, risks and costs by predicting and controlling amine degradation
Project ID	299662
Coordinator	Peter van Os – TNO
Project website	www.launchccus.eu
Reporting period	1 September 2019 – 28 February 2023

Participants

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The consortium





2. Short description of activities and final results

WP1: Predicting degradation

The main objectives with this WP were to develop methodologies and models to predict solvent degradation behaviour. This will enable the estimation of the extent of solvent degradation as well as give an input to the design and development of countermeasures tailored to specific solvent/flue gas combinations. This WP consists of three tasks: *Solvent degradation Database* (Task 1.1), *Predicting degradation based on process data: Big Data modelling* (Task 1.2) and *Optimized design of CO₂ capture plants: Process modelling* (Task 1.3). The main results are reported below.

Task 1.1 Solvent degradation Database

The Solvent degradation database itself has been delivered and can be used. A user guide is written that can be found on the LAUNCH website: www.launchccus.eu.

The solvent degradation database has been built and the first data has been uploaded. The database is constructed by using Dataverse – Open-source research data repository software framework (<https://dataverse.org/>). For this, a custom LAUNCH Dataverse repository was established. The database is accessible by a web portal on Azure Cloud (with SINTEF access control during the project but now made public). The solvent degradation database is a unique platform for sharing and searching for data related to the stability and degradation of amine solvents for CO₂ capture and facilitates knowledge sharing and application of real data in models and simulations of the CO₂ capture process. Data from a range of lab and pilot scale degradation tests are made available and searchable in this database, which is currently administered by SINTEF Industry. The database currently contains 45 different datasets, which are connected to published literature and experimental data from (LAUNCH) campaigns. In the database, a collection of data, metadata and additional information about setups and experiments can be found and shared

The database is located here: <https://launchdb.sintef.no>. The welcome screen is shown in Figure 1

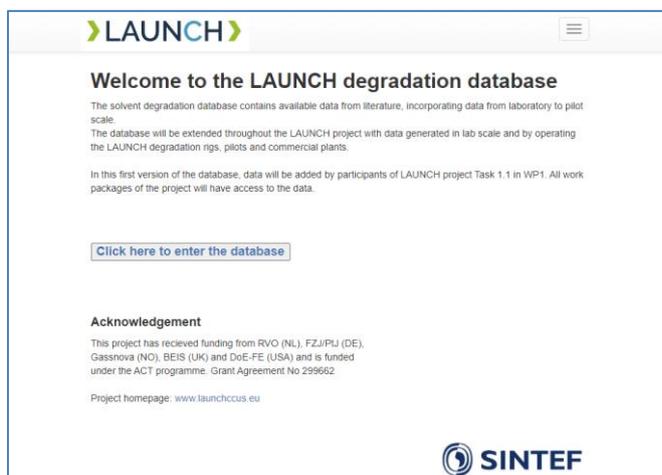


Figure 1. Welcome screen LAUNCH Solvent Degradation Database





Task 1.2 Predicting degradation based on process data: Big Data modelling

In the LAUNCH project we have explored the use of Big Data tools for improving the knowledge on solvent degradation, and particularly for identifying key degradation predictors. Prior to LAUNCH, process and solvent analysis data from the ALIGN-CCUS RWE campaign with MEA was used. However, and despite working with data from the longest ever open MEA campaign, not enough *degradation data* was available. The attempts to analyse the process data did not lead to any new insights. There is a clear need to generate larger data sets on solvent degradation. However, doing that by solvent sampling and laboratory analysis would become prohibitively expensive.

A way to get more data sets on solvent composition is by using a technique for online solvent monitoring. In LAUNCH we have worked on using a mini-ATR-FTIR (Attenuated total reflectance Fourier-transform Infrared Spectrometer) for this purpose. The final system configuration includes not only the analytical equipment itself (ATR-FTIR), but also a methodology for switching between solvent and water circulation loops. The innovative feature of the methodology developed is in the use of de-ionized water (DI) as the medium for taking backgrounds (instead of air). Equipping the system with automated pumps and valves for switching between solvent and DI water flow has the added benefit of ensuring a clean crystal, thus lowering the probability of measurement errors due to solvent accumulating on the crystal surface (amine solutions are “sticky”). TNO is filing a patent to protect the methodology developed. In an onsite test we ran into operations issues that need to be solved to make the technology more robust, but the use of the mini-ATR seems a promising route to achieve this goal and to be able to collect large data sets that will enable us to develop algorithms based on Artificial Intelligence (AI) to predict degradation. Research in this field is already ongoing.

Task 1.3 Optimized design of CO₂ capture plants: Process modelling

In this task the degradation network model (DNM) developed in ALIGN-CCUS (for MEA) was further developed, and extended to include CESAR1. The validated model can be used to optimize the design and operation of capture units to lower degradation by minimizing the solvent hold-up in plant locations that offer accelerated degradation conditions, in particular in the absorber sump.. The model is presented in report *D1.3.4 Degradation Network model*, to be made accessible through the LAUNCH website.

The DNM was calibrated using RWE’s pilot plant data and verified against the LAUNCH rigs data. The DNM model predictions were compared with the experimental results of two campaigns LAUNCH rig campaigns; one with ~37 wt% MEA and 19.8 vol% O₂, and one with ~34 wt% MEA and 7.6 vol% O₂ in the flue gas (dry basis). For more information on the campaigns, the reader is referred to the description of WP4. The DNM captures the general trend of the campaigns results, by predicting that the degradation for the higher oxygen campaign is higher than in the lower oxygen campaign, which is also seen in the experimental results. The model consistently underpredicts the degree of oxidative degradation for both campaigns, while for each campaign, the level of relative deviation (RD) remains approximately the same along the campaign. In the high oxygen campaign, the relative deviation between the predicted and measured values is -76% and, in the lower oxygen campaign, it is -30%. Hence, the model yields better results for the lower oxygen case. This reflects the fact that the model is developed and “calibrated” with degradation data from real operation of a CO₂ capture





pilot plant “low” oxygen content in the flue gas, as well as using 30 wt% MEA. Other sources of error are the high uncertainty in ammonia measurement, presence of additional oxidative and thermal degradation products as well as metals which are not accounted in the model. The model is developed with a flexible framework, and new experimental data will be generated after LAUNCH, to improve the DNM predictions. This work will be continued in the ACT4 project MeDORA, with the participation of the LAUNCH partners TNO, RWE, NTNU and SINTEF.

WP2: Controlling degradation

In WP2, strategies for controlling degradation were evaluated. Different degradation countermeasures were tested in the LAUNCH rigs. Each of these countermeasures was addressed in a separate task: 2.1 Oxygen removal; 2.2 NO₂ removal; and 2.3 Determining the role of iron and technologies for in-situ iron removal.

Task 2.1 Oxygen Removal

Within ALIGN-CCUS, TNO developed a Dissolved Oxygen Removal Apparatus (DORA), which uses a membrane contactor to remove oxygen from the rich amine. In LAUNCH, DORA was operated with MEA, MDEA/PZ and CESAR1 with DORA on and off to assess the operation. During these experiments, two membranes were used: a commercial membrane from Liqui-Cell and a dense layer membrane developed by NTNU. Unfortunately, a material incompatibility between the glue used in the dense layer membrane assembly and PZ led to the destruction of the dense layer membrane module.

During the MEA experiments, the operating conditions of the membrane such as liquid flow rate, gas flow rate and pressure (vacuum) were optimized. The most efficient operation was achieved with a combination of nitrogen as a sweep gas and vacuum on the outlet of the membrane. The use of vacuum made it possible to use significant lower amount of nitrogen in the sweeping gas. This is an important improvement of the process not only in terms of efficiency of removal but also OPEX related to the flow of nitrogen used during the operation. Another significant result was the fact that DORA was able to remove oxygen even for MEA in which degradation occurs in a fast rate. The tests with MDEA/PZ also showed the decrease in oxygen while using the DORA in the system for different CO₂ loadings. For both solvents, the oxygen content during the operation with DORA dropped to almost zero (or even zero in some cases) in less than 30 minutes. For CESAR1, it was not possible to quantify the impact of the DORA since one of the membranes was not compatible with the solvent and the other one showed a high rate of leakage when operated with CESAR1. In conclusion, DORA is potentially a technically viable solution for controlling the degradation of CO₂ capture solvents and can be applied independently or in combination with other solvent management strategies such as reclaiming. However, some further development is still needed before the technology can be commercially available. TNO, NTNU, SINTEF and RWE are starting a project called MeDORA in September 2023 (project approved in ACT4 scheme) to ensure that the DORA technology will be ready for implementation by 2026.

Task 2.2 NO₂ Removal

The oxidative degradation of amines can be connected to the presence and concentration of NO₂ in the flue gas. The relevance of NO_x as a degradation predictor has been determined in WP1.. A strategy for NO₂ removal based on thiosulfate dosing in the aqueous NaOH solution used in a





standard SO₂ pre-scrubber has been developed by UT up to pilot scale (TRL5) at NCCC. The addition of sulfite as sodium sulfite would also be necessary should the flue gas of interest not have already SO₂, as the key reactions occur between NO₂ start with sulfite. In summary, SO₂ in the flue gas reacts with hydroxides to form sulfite. Sulfite removes NO₂ and generates nitrite and sulfite radicals. Radical propagation by dissolved oxygen results in fast sulfite consumption. Thiosulfate is added as a radical scavenger to slow the sulfite consumption by competing with sulfite to react with SO₅⁻.

The removal of NO₂ from the flue gas can be achieved by addition of thiosulfate to the circulating alkaline solution of SO_x pre-scrubber/direct contact cooler. In this task, a design of a thiosulphate dosing system was done for the RWE pilot. Upstream the DCC, the RWE pilot is equipped with an “aerosol testing module”, which is a spray scrubber column. It was decided that this column was the preferred location in the RWE pilot to test the NO₂ removing technology.

The large-scale application of the removal of NO₂ from the flue gas by scrubbing with a thiosulfate solution is limited by the fact that depending on the flue gas properties (namely when moisture saturated flue gas downstream a wet limestone scrubber is used) condensate formation occurs and its drain from the pre-treatment scrubber can result in a high and ineffective consumption of thiosulfate and an additional waste stream as well as the effort for an additional column upstream the DCC. After approx. 2000 h operation with reduction of the NO₂ concentration by ≈80% in the flue gas upstream the CO₂ absorber, no clear effect on the solvent degradation and the formation rate of oxidative amine degradation products were seen. This result is confirmed by the unchanged NH₃ concentration in the CO₂-lean flue gas downstream the absorber and the comparative test with the LAUNCH rig#2. Explanations might be the negligible role of NO₂ as oxidant compared to oxygen or alternatively a too fast backformation of NO₂ from NO within the CO₂ absorber.

By measuring NO₂ content in different locations along the flue gas pathway at the RWE pilot, it was shown that some “fresh” NO₂ was formed from NO - which is available in excess in the flue gas - after the pretreatment on the way to the CO₂ absorber. This effect could also be reproduced in TNO’s lab. The processes in the CO₂ absorber (e.g. side reactions that consume NO₂, residence and lifetime of NO₂) remain unclear. This knowledge gap could be filled by additional investigations on the kinetics of conversion of NO to NO₂ in simulated flue gas (containing representative concentrations of SO₂ and H₂O) with regard to the residence time of the pre-treated flue gas (downstream NO₂-prescrubber, ducts, absorber) will be a critical element in evaluating the usefulness of NO₂ removal. A better understanding of the reactions of NO₂ in an amine-based (aged) solvent is also required.

Task 2.3 Determining the role of iron and technologies for in-situ iron removal

In this task we have designed and built a plant in which there is no contact of the solvent with metal. All components were built in plastics (most of the plant) or ceramic (packing in the stripper column). Any metal components, such as sensors were not in contact with the solvent. A picture of the constructed plant is shown in Figure 2.





The first campaign with MEA has shown that the non-metallic capture rig can operate under steady cyclic conditions where CO₂ is stripped at 0.85 barg from the solvent, similar to normal metal-based CO₂ capture processes. Liquid analysis on the metal concentration in the solvent has further shown that the iron concentration in the solvent remains constant between dosing periods of the metal, which further shows the potential of running a non-metallic CO₂ capture rig to further the understanding of solvent degradation in amine solvents.

However, in this first-of-a-kind capture rig, many problems have occurred (during the latter part of the campaign) with leakages in the stripper (connections and column itself) and the water balance of the plant. Therefore, the result, that were also presented in a paper on the GHGT-16 conference, should be mostly seen as a first indication of how such a non-metallic rig could help us further to understand solvent degradation under controlled metal concentrations and should also give indications where current difficulties are in designing a fully non-metal CO₂ capture plant. Recommendations are also given for future activities.



Figure 2. The non-metallic capture plant build by BEFORM

When it comes to metal removal technologies, these were tested at the RWE pilot. The results from the campaign with CESAR1 at the capture plant in Niederaussem show that neither the solvent colour nor the metal concentration in the solvent are appropriate measures to control solvent management technologies or to describe the performance of the solvent. Ion exchange can effectively remove





anions and cations (including metals) from the solvent, but the consequential effects on the solvent degradation rate must be carefully considered. Based on the results of the campaign with CESAR1 the removal of ligands from the solvent which form complexes with metal cations can increase the degradation rate. More investigation is needed regarding the interaction of metal cations, which have the potential to act as a catalyst for oxygen activation and solvent degradation, and degradation products with capability to form complexes to avoid the opposite of the expected effect when activating solvent management technologies.

WP3: Closing degradation knowledge gaps

The main objective of this WP was to close knowledge gaps related to degradation and its impacts. WP3 provided a fundamental understanding of the connection between degradation, corrosion, and foaming. WP3 also worked on the volatility of degradation compounds of new solvents helping to predict emissions of compounds.

Task 3.1 Connection between corrosion, foaming, and degradation

In this task, data on the corrosion- and foaming potentials of solvents and degradation components was generated using solvents degraded under highly controlled conditions in the lab, as well as solvents previously used in LAUNCH rigs or pilot plants.

UT has generated data related to corrosion of stainless and carbon steel in Aqueous Piperazine for CO₂ capture. The PhD dissertation of Ching-Ting Liu gives insight in the aspects that influence corrosion in different materials.

NTNU with support from SINTEF IND has performed experimental work to investigate corrosion tendencies in selected 2nd and 3rd generation solvents. Experiments with increasing MEA concentrations showed that the amine concentration influences the corrosion, though there is no clear correlation. At low MEA concentrations, the metal content increased with increasing amine concentration. In the midrange, though, the trend reversed. After this, the metal content decreased as the MEA concentration increased. The effect of introducing the organic solvent TEG (tri-ethylene glycol) was studied. At low concentrations of TEG, the metal concentration of the solutions with MEA increased with the increasing TEG content. Between 20 mol% and 50 mol% TEG, there was a sharp change, and for all solutions with higher TEG concentration the metal content was low. TEG also showed this effect for all other amines tested. Loaded MEA was also tested with other organic solvents. For the solvents tested with no water present, MEG (mono-ethylene glycol), DEG (di-ethylene glycol), and TEG, the same effect on the corrosion was observed. For the organic solvent, N-formylmorpholine (NFM), tested in a blend with water, the metal content was considerably higher. The results from these tests indicate that a low water content results in lower or similar corrosion tendencies compared to loaded aqueous 5M MEA solutions.

Foaming effects were studied and reported by University of Texas for PZ and by NTNU for MEA, PZ and AMP.

Task 3.2 Degradation of second and third-generation solvents





The LAUNCH deliverable D3.2.1 starts with more than 100 amines and identifies interesting solvent components from that list. The report concludes that more work is needed for non-aqueous systems or systems where part of the water is replaced with an organic solvent. Furthermore, the report encourages filling gaps by systematic investigations on how the diluents influence the chemical stability of amines. The report also identified some potential systems to be further studied in LAUNCH. The solvents proposed are from the group of imidazoles and amino alkyl-functionalized pyridines.

Based on the recommendations and discussions, **systematic thermal degradation studies** have been performed. The main findings are:

- Experiments with highly concentrated MEA solutions showed that thermal degradation of MEA was independent of the amine concentration when the absolute amount of CO₂ in the solution was constant. However, increased CO₂ loading increased degradation. The results raise the question of which CO₂-carrying species results in degradation, a topic that should be further studied.
- The results from the second experimental set indicate that adding organic solvents seems to increase the thermal degradation rates, as can be seen in Figure 3. The figure shows that TEG, MEG, MEG, N-methyl-2-pyrrolidone (NMP), tetrahydrofurfuryl alcohol (THFA) and NFM reduce amine stability. Furthermore, tertiary amines are most resistant to thermal degradation compared to primary and secondary amines in the presence of organic solvents. Even though the results are strictly speaking only valid for tested amine-diluent combinations, it does indicate that care should be taken when choosing organic diluents in water lean solvent formulations. Based on the current results, they tend to increase thermal degradation. All tested organic diluents increased the thermal degradation of MEA.

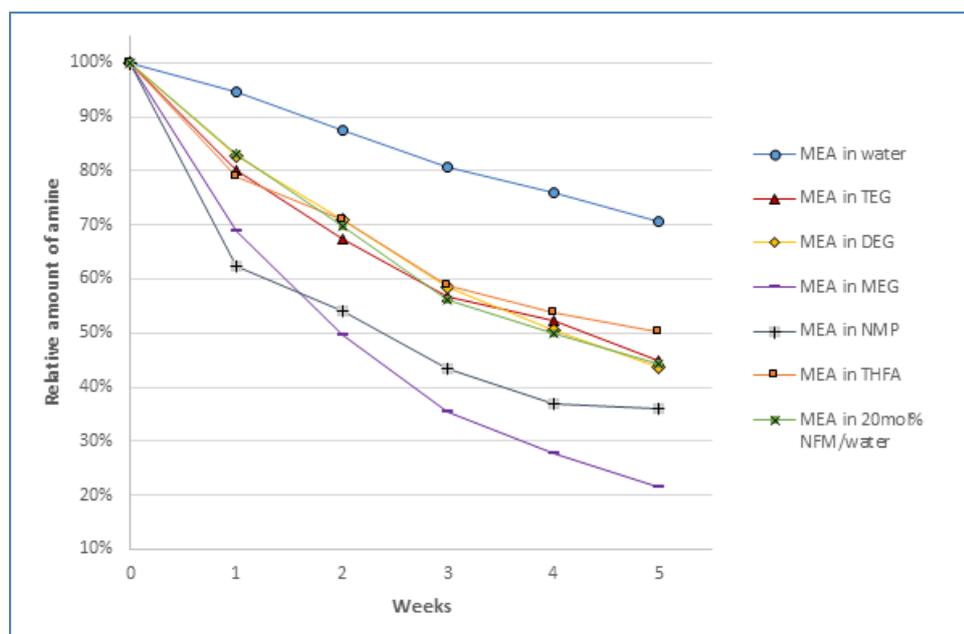


Figure 3. Thermal degradation of MEA in the presence of different organic diluents.





Task 3.3 Volatility of degradation compounds and novel solvents

Knowing the volatility of solvents and the degradation compounds is important, it allows the design of emission mitigation strategies to control the degradation impacts and is also important for thermal reclaiming. This is important for both commercial plants and demonstration plants.

Information about volatility helps, for example, the pilot facilities to evaluate operating parameters so that the plant stays below the emissions permits and to select the operating parameters for their water wash sections. It also tells what compounds should be monitored. The main objective of this work was to establish a methodology to measure the volatility of the solvent and the degradation compounds using solutions already degraded in LAUNCH rigs pilots (WP4 and WP5) and solvents tested in Task 3.2. The two methods established are both for determination of volatility of solvent mixtures, and to determine which compounds will evaporate from the blend. The simple boiling method is, as the name already indicates, quite simple. The apparatus is easy to build and does not require very advanced parts, compared to the second studied method, the ebulliometer. On the other hand, as the ebulliometer provides vapor-liquid equilibrium data, it consists of accurate pressure and temperature measurements and specially designed reactors. It also requires trained personnel to operate and is more costly and time-consuming to build than the equipment for the simple boiling method. The ebulliometer provides vapor-liquid equilibrium (VLE) data for both degraded and non-degraded solutions and concentrations relevant to water wash and the circulating solvent. This means that the data can be used to fit, for example, the VLE models used to design water wash sections. Ebulliometer can also be used to map VLE behavior of a system over a large range of conditions (amine concentrations), making it suitable for providing data needed for aerosol models also. The simple boiling method on the other hand, aims only to identify volatile degradation compounds qualitatively, and cannot produce data suitable for fitting thermodynamic models.

WP4: Development of LAUNCH solvent qualification program

The goal of WP4 was to develop the LAUNCH solvent qualification program. The qualification program was developed using the lab scale LAUNCH Rig#2 (25 kgCO₂/day) and the TERC pilot scale unit (1 tCO₂/day).

Task 4.1 Qualification of the small-scale LAUNCH rigs approach

Prior to the tests, a comparison of rig characteristics and instrumentation was done to ensure that similar trends can be expected, and comparable results collected. The operational parameters to be used were agreed between TNO and TERC.

The first tests done at TNO using approximately 35 wt% MEA as a starting concentration in LAUNCH rig#2 had a duration of 528 hours continuously. The operation of LAUNCH rig#2 at TNO was done continuously using artificial flue gas (air + CO₂) and samples of the solvent were taken every day for analysis. A Fourier-transform Infrared Spectrometer (FTIR) was connected to the outlet of the absorber to monitor the composition of the outlet gas stream.





It was found that MEA concentration demonstrated a decreasing behavior, which is an indication of solvent degradation. Indeed, formic acid and oxalic acid, which are typical oxidative degradation products, were formed and their concentration increased linearly with time. The results were used for the comparison with the operation of the TERC facility to validate LAUNCH rig#2 as a relevant testing rig for degradation tests.

The TERC pilot plant was operated for 500 hrs with synthetic flue gas comprising of CO₂ and air with 35 wt% MEA as solvent. Gas analysis was performed at different locations using FTIR while solvent analysis was performed using Mettler Toledo auto-titrator. The plant was cleaned using a comprehensive cleaning procedure due the reason that plant was moved from the old site as a result of flooding of the site, and some of the instrumentation and piping had to be replaced. The plant was passivated post cleaning with different weak concentrations of MEA before starting the test campaign with 35 wt% MEA.

Iron content, as an indication of degradation, of the solvent was measured at least once a day except weekends using colorimetric method. No other metals were monitored. Samples were collected throughout the test campaign for post analysis. Some of the samples, almost every hundred hours, were analysed by liquid chromatograph coupled a mass spectrometer (LC-MS, Liquid chromatography–mass spectrometry) at SINTEF for commonly known degradation products such as HEA, HEI, HEF, HEPO, HeGly etc.

For both LAUNCH rig#2 and the TERC pilot, the results of the analysis have indicated HEPO, HeGly and MEA-urea, were the most abundant degradation compounds, which is comparable to other laboratory rigs and some larger pilots. , Nevertheless, degradation is a complex phenomenon and there is no explanation regarding the observed differences between the small 25 kg/day TNO's LAUNCH #2 rig and the larger 1000 kg/day TERC pilot plant. It is concluded that more work needs to be done to better understand the degradation phenomenon and the factors driving it.

Task 4.2 Accelerated degradation

Different accelerated degradation techniques were tested, and the results were compared between TERC pilot plant (1000 kg CO₂/day) and the LAUNCH rig (25 kg CO₂/day). Overall, the LAUNCH rig could match the major degradation components found in the larger TERC pilot plant. Longer tests and differences in operating conditions can possibly explain the differences seen in the degradation trends, plus possibly the different metal contents as the run progresses. The main findings are discussed in this section.

Four accelerating degradation techniques were tested: increased oxygen levels in the flue gas increased solvent concentration, increased stripping temperature, and addition of NO_x, as shown in Table 1,. For the *Baseline* campaign, 7.6 vol% oxygen concentration was considered in the flue gas, since this is representative of industrial gases.

Increasing the MEA content in the solvent, the stripping temperature and the addition of NO_x were studied in combination with increased O₂ content in the gas. The acidic degradation products that were





analysed for both plants are in general in the same order of magnitude for both plants (except for acetic acid which was not detected in the LAUNCH rig#2 campaigns), with formic acid being the most dominant one. Major degradation products are HEPO, MEA-Urea and HeGly in both LAUNCH rig and TERC, which is in agreement with work performed earlier in another LAUNCH rig (SINTEF's SDR rig). HEPO is the most dominant degradation product of them, followed by MEA-Urea in almost all cases, and are used to assess the effectivity of the different strategies to accelerate degradation.

Table 1. Accelerated degradation campaigns

Campaign name	Description
Baseline	34 wt% MEA, 7.6 vol% O ₂ , 120 °C
Higher O ₂	35 wt% MEA, 19.8 vol% O ₂ , 120 °C
Higher O ₂ /MEA	37 wt% MEA, 19.8 vol% O ₂ , 120 °C
Higher O ₂ /stripping T	35 wt% MEA, 19.8 vol% O ₂ , 130 °C
Higher O ₂ /NO _x	35 wt% MEA, 19.5 vol% O ₂ , 120 °C, NO _x

A summary of results is given here:

- Increasing the oxygen content in the flue gas from 7 vol% to 18 vol% clearly accelerates degradation.
- Increasing the MEA content of the solvent does not seem to have a strong influence on the acceleration of the oxidative degradation products (acids), although it has an increasing effect on the metal accumulation seen in the studied systems.
- Increasing the stripping temperature does not seem to affect the formation of oxidative degradation products, meaning 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.
- The effectivity of adding NO_x in the flue gas as an accelerating degradation technique is shown to be dependent on the level of NO_x added and the degradation product targeted.

Although it is seen that the LAUNCH rig#2 can follow the degradation trends and the most significant degradation products as the larger TERC rig, it is noted that when comparing the trends between the two rigs, we see significant differences regarding the effects of the accelerated degradation strategies applied. Increased O₂ concentration has a general accelerating effect in both rigs. Higher stripping temperature is more influential in the LAUNCH rig, while higher MEA concentration is more influential in TERC. This could be the result of performing the campaigns in similar, yet not exactly the same parameters and conditions.





Task 4.3 Control degradation under accelerated conditions

Two degradation control technologies were investigated in isolation in LAUNCH rig#2, i.e. DORA technology and reclaiming. The tests were conducted at accelerated conditions based on the findings from the accelerated degradation protocol. More specifically, the tests were conducted at increased oxygen concentration (i.e. at 19.8 vol% O₂ in the flue gas, dry basis) since it was shown that higher oxygen concentration leads to higher formation rate of typical oxidative degradation products.

The campaigns generated useful, novel information: it was shown that, for CESAR1, the lowest increase rate of degradation products was for a mildly aged solvent without solvent management (instead of the clean solvent). This is in line with the results obtained in WP5 at the RWE pilot, and is one of the main contributions of LAUNCH: demonstrating that always keeping the solvent as clean as possible may be detrimental to the plant cost-effective operation. A longer campaign with reclaimed MEA would be beneficial for identifying if there is a point after which the degradation rate is minimized, like in CESAR1, and what the role of metals such as the atypical amounts of Cu and Zn was. Finally, developing reclaiming and cleaning procedures for solvent blends, such as CESAR1, would be beneficial for the implementation and acceleration of CO₂ capture with mixed solvents

Task 4.4 Recommendations on how to build a generic “LAUNCH rig”

The results of the complete LAUNCH project were used to discuss and determine the generic “LAUNCH rig” design with contribution from all the consortium partners. 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 kgCO₂/h. For that, it can treat 3-5 Nm³/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 **Error! Reference source not found.** 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.

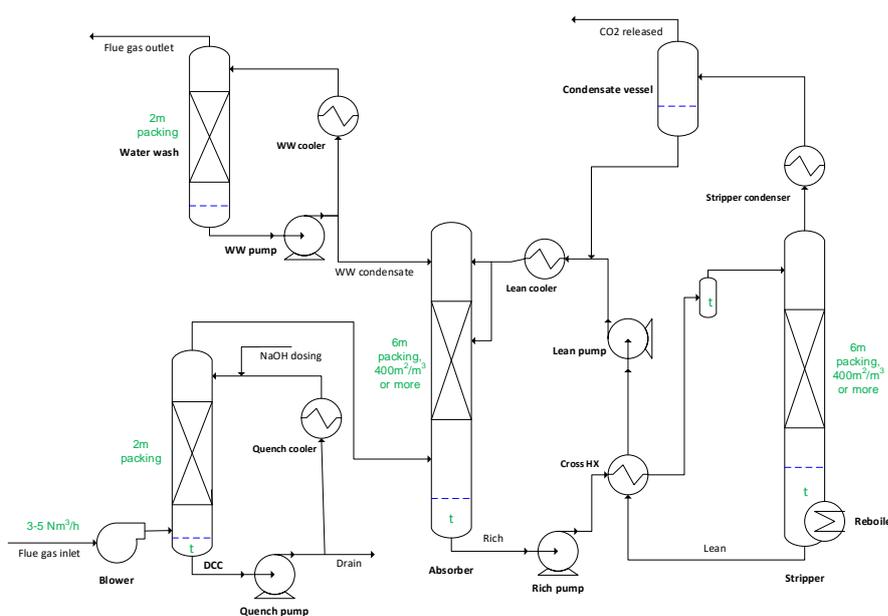


Figure 4. Simplified process flow diagram of the LAUNCH rig





WP5: Demonstration of LAUNCH solvent qualification program

LAUNCH rig#2 - which has all the elements of a large-scale plant – has been used head-to-head with the capture plants at RWE and AVR to evaluate the rigs regarding its capacity to mimic realistic full scale testing conditions as closely as possible in terms of capture rate, lean and rich loadings, residence times and temperature profiles.

After a thorough preparation, where the transport, installation and operation were described and agreed in detail, LAUNCH rig#2 was transported to Germany and commissioned at RWE.

The main findings from the head-to-head operation of the LAUNCH rig#2 with RWE's capture pilot plant are summarised in the below points:

- There is good agreement of the concentration levels and trends for formate, acetate, glycolate, propionate and oxalate (see Figure 5), as well as for the accumulation trends of inorganic compounds in the solvent (chloride, nitrate, sulfate). This applies for operating periods with and without NO₂ removal from the flue gas and increased stripper temperature- It is noted that no thermal degradation-related products were analysed in this work, due to limited analytical capabilities. Therefore, the conclusions made are based on typical oxidative degradation-related products.
- There is higher metal concentration in CESAR1 in the inventory of the LAUNCH rig #2 compared with the RWE pilot plant, especially for copper and nickel. No effect of the higher metal concentration in CESAR1 on the formation rate of degradation products is observed.
- Operating the LAUNCH rig#2 occasionally at more diluted CESAR1 concentrations does not seem to affect the degradation behaviour of the system.



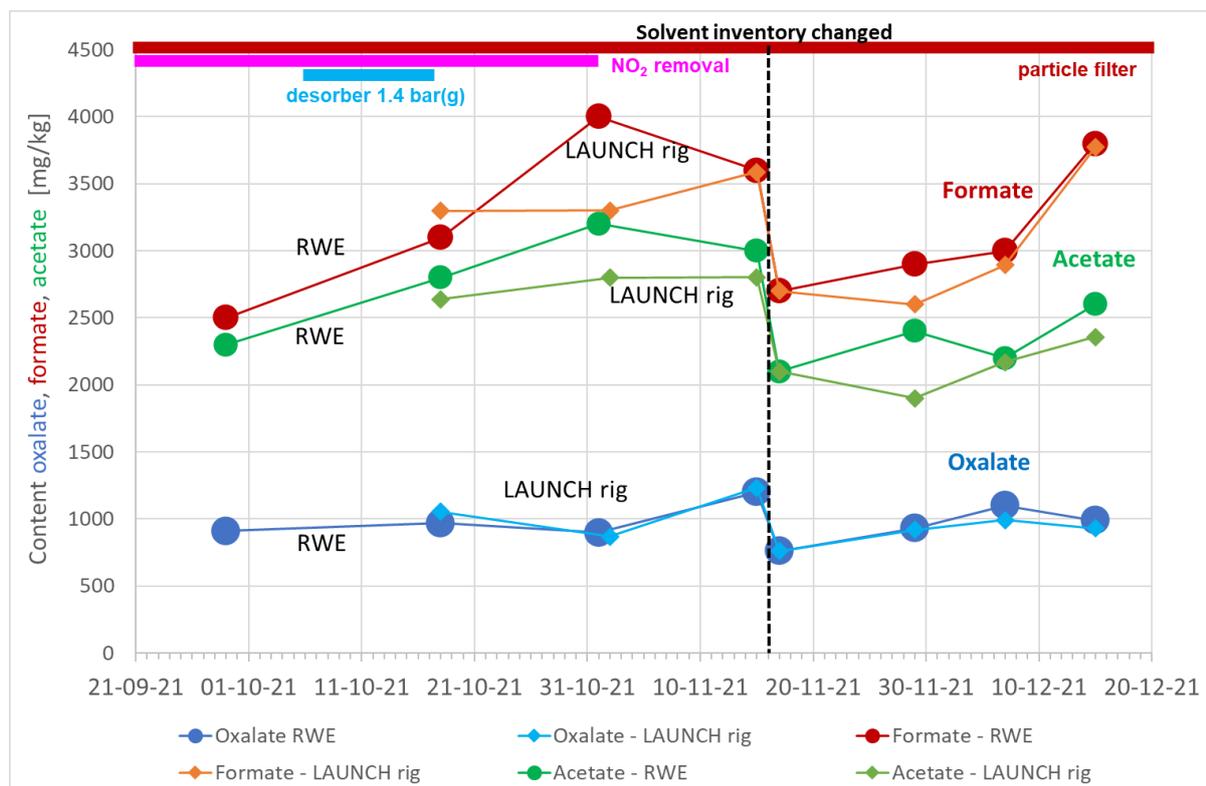


Figure 5. Development of oxalate, formate and acetate concentration during the campaign

The campaign has demonstrated that the LAUNCH rig#2 is able to provide results and trends for the degradation of CESAR1 and the accumulation of contaminants in the solvent which are representative of a significantly larger capture plant, when using the flue gas that enters the CO₂ absorber. Additionally, the tests have shown that it is a valuable tool to investigate hypothesis on the impact of contaminants in the solvent and operating parameter settings of the capture plant on the degradation rate.

Unfortunately, the campaign at AVR was delayed due to issues with the permitting process. As a consequence of this, the plant was installed at AVR in October 2022, towards the end of the season for AVR (AVR stops operating their plant during winter). The request for CO₂ for the greenhouses was quite low already which led to lowering the operational time for the capture plant. This, in combination with some operational issues and weather conditions getting worse, led to the decision to terminate the campaign after a few weeks with only 100 useful operating hours. Therefore, no useful data was obtained in the AVR campaign. Although it was sad that we missed this campaign, there was enough data available from the other campaigns to still meet the objectives of LAUNCH.

The test campaigns at Niederaussem on removal of NO₂ from flue gas by thiosulfate dosing into a pre-scrubber, removal of ionic trace elements from CESAR1 by ion-exchange, and adsorptive removal of trace elements from the solvent by active carbon progressed well and valuable results have been achieved. Since 08.04.2019 the capture plant at Niederaussem was almost continuously in operation (until November 2020 as part of ALIGN-CCUS) and the long-term testing campaign under industrial conditions provides a unique data base regarding the degradation of the CESAR1 solvent. Altogether, the CESAR1 campaign lasted for 41 months (1,240 days or 29,760 testing hours). This unique long-time





test at the CO₂ capture plant at Niederaussem was achieved without solvent inventory exchange and with almost continuous 24/7 operation. During this period, the accumulation rate of degradation products seems to follow a linear trend. No acceleration in degradation leading to a run-off situation, as generally observed for MEA, was observed.

The large-scale application of the removal of NO₂ from the flue gas by scrubbing with a thiosulfate solution is limited by the fact that depending on the flue gas properties (namely when moisture saturated flue gas downstream a wet limestone scrubber is used) condensate formation occurs and its drain from the pre-treatment scrubber can result in a high and ineffective consumption of thiosulfate and an additional waste stream as well as the effort for an additional column upstream the DCC. The test with a turbulent spray scrubber showed that structured packing is needed to provide a sufficient gas-liquid surface and, hence, NO₂ mass transfer in the pre-treatment step with the thiosulfate-based scrubbing liquid. After approx. 2000 h operation with reduction of the NO₂ concentration by ≈80% in the flue gas upstream the CO₂ absorber, no clear effect on the solvent degradation and the formation rate of oxidative amine degradation products was seen. This result is confirmed by the unchanged NH₃ concentration in the CO₂-lean flue gas downstream the absorber and the comparative test with the LAUNCH rig#2. Additionally, no effect on the concentration of nitrosamines (mononitrosopiperazine, total nitrosamine) occurred, despite the significant reduction of the NO₂ concentration in the feed gas. In contrast to this, raising the stripper temperature from 120 to 130°C allowed to degrade nitrosamines.

The impact of the removal of iron and impurities on the degradation of CESAR1 by applying solvent management technologies with different effect mechanisms (adsorptive removal, ion exchange) was also investigated..

Main results are:

- Dependent on the active carbon properties, solvent treatment by adsorptive removal of coloring agents - which are formed during the aging of the solvent - can reduce the visible absorbance of the solvent. One of the two tested active carbon qualities could also reduce the iron and chloride concentration, but this had no significant effect on the solvent degradation rate and performance of CESAR1. Therefore, the color of the solvent is an inappropriate parameter to control/activate solvent management technologies.
- One of the two tested active carbon qualities caused a significant increase of the foaming tendency of the solvent and required an increase of the dosing of antifoaming agent by a factor of 20.
- A significant part of the dissolved iron (and also zinc and chromium) forms negative charged complexes. The redox-capability, accessibility and reactivity of complexed metal ions is determined by the surrounding shell of ligands, meaning that it is uncertain whether the metals present in the solvent are in a state in which they could act as degradation catalysts.
- The concentration of iron and other metals in the solvent does not necessary correlate with the degradation rate of CESAR1.
- Anionic compounds, trace components and metal complexes can be effectively removed from the solvent by ion exchange using an anionic exchange resin (removal of >50% after treating the solvent inventory two times, >80% after treating the inventory four times), but





removal of anions alone causes a significant increase of the degradation of CESAR1 by a factor of two.

- Cations can effectively be removed from the solvent by a cationic exchange resin (70-100% after treating the solvent inventory four times), but this did not reduce the degradation rate, but reproduced the same rate compared to sole application of anionic exchange.
- In contrast to MEA, also a significant part of the uncalibrated components (contaminants which are detected in the analysis by gas chromatography, but which cannot be assigned to specific compounds) can be removed from the solvent by ion exchange.
- Removal of all contaminants from CESAR1 as fast as they are formed (according to the requirements from the UK Environment Agency) is contra-productive and would cause unnecessary waste of solvent and resources, efficiency losses as well as the unnecessary generation of wastes.

After internal discussions, deliverables 5.3.1 and 5.3.2 related to testing a ‘second generation’ solvent at the TERC plant were replaced with tests on countermeasures for solvent degradation (removal of dissolved oxygen and NO_x). Two test campaigns were conducted with NO₂ injection at 5 ppm and 15 ppm, the former being designed to mimic NO_x removal. Three test campaigns were performed with N₂ stripping to remove DO. The data available (Fe measurements) indicates that there may not be much impact of NO₂ injection rate variation from 0 to 15 ppm on solvent degradation. However, firm conclusions cannot be drawn until samples are analyzed for degradation product levels. In addition, N₂ stripping through a relatively short (3m) packed column has been shown to be an effective tool to remove DO, confirming the results obtained by the University of Austin in their pilot campaigns with PZ.

WP6: Techno-Economic Evaluation

The feasibility of nonmetallic materials of construction (MOC) for CO₂ capture plants was evaluated for a full-scale WtE system (200 kton waste/year) and compared towards metallic MOC, using MEA as a solvent. Many assumptions had to be made to perform a TEA for the non-metallic MOC case study, as there is relatively little information available for non-metallic MOC’s regarding both applicability and costs. With these assumptions in place, non-metallic materials of construction could give slightly lower CAPEX (-8%) compared to metallic counterparts. On the contrary, for the non-metallic rig built in the LAUNCH project, non-metallic MOC gave significantly higher CAPEX (+50 to +100%) than their metal counterparts. However, it needs to be noted that the non-metallic rig is a small lab set-up, and cost correlations cannot be directly extrapolated to large scale systems, as production methods are completely different. Even with this study in place, knowledge gaps remain on the exact CAPEX comparison between metallic and non-metallic MOC’s. Additionally, long term testing of a non-metallic pilot system under relevant conditions, and detailed techno-economic analyses of full-scale systems are needed to verify these assumptions, to further assess the feasibility of non-metallic materials of construction.

While the economic benefits of changing to non-metallic MOC’s seem minor, further research is needed in the form of LCA’s to assess the full chain influence of changing towards non-metallic MOC’s to further assess the potential of these materials.





Another important activity in WP6 was the development of a software tool to perform techno-economic calculations on different solvent management strategies, compared to baseline operation, in order to assess the feasibility of these different solvent management strategies. As a basis for this analysis, the results from the other work packages of the LAUNCH project on the evaluation of different solvent management strategies are used as much as possible, and assumptions are made where necessary. The solvent management strategies that are evaluated are: Bleed and feed, reclaiming (thermal and ion-exchange) and oxygen removal (DORA and N₂ sparging).

The software tool created by Altrad follows the following structure:

1. Obtaining baseline values on the kinetics of dissolved oxygen driven amine losses, based on experimental data (obtained in WP2) and fixing stoichiometric factor based on long-term testing data (obtained in WP5);
2. Calculating oxidative degradation rates in absorber packing and sump and lean/rich heat exchanger for selected case (with WP1's degradation network model);
3. Assuming thermal degradation and solvent de-activation rates;
4. Calculation of operational time before the solvent needs to be treated based on a threshold value;
5. Calculation of relevant parameters as input for sizing and costing;
6. Sizing and techno-economic analysis of different solvent management strategies.

An important assumption in the tool is that after a certain threshold is reached for solvent degradation (defined as a percentage of solvent lost through degradation), the solvent will need to be replaced (step 4). The tool is structured in such a way that during a campaign, no refills are performed, and the solvent concentration decreases until the threshold is reached. This approach might not be fully realistic towards a real system, as frequent solvent refills are expected, to maintain the desired capture rate. However, this approach does allow the comparison of simply replacing the solvent with the addition of several solvent management technologies. The model currently only considers the linear degradation regime of solvents, which are based on the long-term pilot testing results with MEA and CESAR1 at RWE Niederaussem.

While the extensive campaigns of MEA (ALIGN-CCUS) and CESAR1 (ALIGN-CCUS and LAUNCH), including tests with different solvent management technologies, have greatly informed the current models, knowledge gaps remain that influence the conclusions. While a fully functioning software tool is created, the results are dependent on the input data, for which uncertainties are currently still present. Additionally, the tool has shortcomings regarding the calculation method and the implementation of the different solvent management technologies, which can be improved in a subsequent version. Nevertheless, the tool generates initial insights on the effectiveness of several solvent management strategies, on which the carbon capture community can build their future endeavours towards researching and evaluating solvent management strategies. It also gives clear indications regarding future steps in the current models and technology developments, including the need to lower the nitrogen consumption for nitrogen sparging, evaluation of CAPEX saving strategies for thermal reclaiming (e.g., use of mobile rental units), and the relevance of degradation models for the evaluation of oxygen removal technologies.





WP0: Project Management and Dissemination

LAUNCH was a challenging technical project with a very scientific consortium that has achieved a lot of unique and valuable results in the three and a half years that LAUNCH was running. The Project Management Team faced two main issues in the very first part of the project with big consequences: the flooding of the PACT facility at the University of Sheffield and COVID-19.

A practical approach was taken to focus on the work that could continue or could be brought to the beginning of the project and deal with the delays that could not be mitigated. The consortium meetings were always very well attended with a lot of discussions that were sometimes quite intense, with everyone fully committed to getting the best results and driving the project forward. The work packages of LAUNCH were very interlinked (except maybe for WP3) resulting in extensive communication to keep the objectives and goals of the project in mind. When the project proposal was written, it seemed a good idea to have many public deliverables for each work package, but as the project evolved, it became obvious to combine deliverables to create a logical and coherent narrative that would be easier for stakeholders and interested parties to follow. The original (Table 2) and combined (Table 3) deliverable tables are presented here.

Dissemination was an extremely important part of the project. Led by the professional knowledge exchange and communications team at SCCS, based at The University of Edinburgh, Scotland, activity was developed around one simple aim: to maximise the impact of the project by making it as visible as possible. This was achieved by adopting a tailored approach depending on a combination of the output, messaging, interests of the project partners and other stakeholders and by using a range of different methods such as formal news articles, informal blogs, newsletters, videos, webinars and using the project website and social media channels. This varied approach helped to make often very technical and complex ideas and findings accessible for a range of audiences. Given the challenges presented by COVID, the coordination and management of online resources took on greater significance and importance, as opportunities for face-to-face meetings became fewer and remotely attended meetings and events became the norm.

Dissemination activity was linked – where possible – to industry and academic events, with the intention of elevating the profile of the project to wider, international audiences. One notable example is the GHGT-16 Conference which took place in Lyon, France, in October 2022, where LAUNCH was represented across several sessions (10 LAUNCH-related presentations in total), with one of the sessions being entirely comprised of outcomes and contributions from the LAUNCH project. Contributions came from across the project, demonstrating the breadth and depth of expertise and high-quality research. Academic papers resulted from NTNU in particular and the University of Texas at Austin.

Since the start of the project, the website has acted as the gateway to the important and groundbreaking work undertaken as part of LAUNCH. It will continue to do so for another 2 years beyond the official project end date (until March 2025), providing a live resource as part of the project's ongoing legacy.





LAUNCH Logo



LAUNCH Icon





Table 2. Original delivery table

Proposal	Description
D.1.1.1	Degradation database, first version
D.1.1.2	Degradation database
D.1.2.1	Guidelines for using Big Data tools for identifying key degradation predictors
D.1.3.1	Assessing the representativeness of accelerated degradation tests
D.1.3.2	Generalizing and Validating the DNM – LAUNCH rigs and pilot runs
D.1.3.3	Optimised design and operation of capture units to reduce degradation
D.1.3.4	Application: Degradation Network Model: a tool for predicting solvent degradation in industrial CO2 capture applications
D.2.1.1	Membrane selection for DORA
D.2.1.2	DORA: a novel technology for lowering solvent degradation
D.2.1.2	Design of thiosulphate dosing system for the RWE pilot
D.2.3.1	Removing metals from degraded solvents
D.2.3.2	Controlling degradation: maximum iron content and impurities removal from degraded CO2 capture solvents
D.3.1.1	Effect of PZ degradation on corrosion of carbon and stainless steel
D.3.1.2	Manuscript describing the results related to corrosion tendencies of selected 2nd and 3rd generation solvents
D.3.1.3	Foaming in PZ affected by degradation and impurities removal by adsorption
D.3.1.4	Report describing the foaming tendencies and results from the iron solubility measurements
D.3.2.1	List of the solvents to be tested
D.3.2.2	Manuscript to be submitted to an open access journal on the thermal degradation of second and third generation solvents
D.3.2.3	International conference publication describing the results of the oxidative degradation tests
D.3.3.1	Presentation in an international conference, describing the boiling method and the presenting results on volatility of degraded solvents
D.3.3.2	Manuscript to be submitted to international peer-review journal on the results of volatility of degraded solvents using the simple boiling method
D.3.3.3	A document describing the evaluation of the two methods used to measure volatility of degradation compounds
D.4.1.1	Final comparison report for LAUNCH Rig#2 and PACT
D.4.1.2	Qualification of small scale LAUNCH rigs approach
D.4.2.1	LAUNCH rig accelerated degradation tests
D.4.3.1	Comparison of results and assessment of effectiveness of countermeasures
D.4.4.1	Drawing of a generic LAUNCH rig
D.4.4.2	LAUNCH solvent qualification program summary report
D.4.4.3	Open solvents tested using the LAUNCH solvent qualification program
D.5.1.1	Results of LAUNCH rig validations in head-to-head tests at industrial locations
D.5.1.2	LAUNCH rigs: a validated tool for capturing solvent degradation behaviour
D.5.2.1	Impact of the removal of NO2 from the flue gas on degradation of PZ, CEASR 1 and SBF solvent
D.5.2.2	Impact of ion-exchange-based reclaiming on degradation of CEASR 1 and SBF solvent
D.5.2.3	Impact of the adsorption of trace elements in the solvent on the degradation of CEASR 1 and SBF solvent
D.5.2.4	Impact of the removal of NO2 from the flue gas on degradation of PZ
D.5.2.5	Demonstration of mitigation technologies for an optimizing solvent management
D.5.3.1	Demonstration of solvent qualification program for a second generation solvent: concentrated MEA
D.5.3.2	Demonstration of solvent qualification program for a second generation solvent: DEEA-MAPA blend
D.6.1.1	Feasibility of non-metallic materials of construction for CO2 capture plants
D.6.1.2	Techno-economic evaluation and guidelines for solvent management
D.6.2.1	Cost of LAUNCH's solvent qualification program





Table 3. Combined project deliverables table

Deliverables (combined)	New proposed name
D.1.1.1	Degradation database, first version
D.1.1.2	Degradation database
D.1.2.1	Guidelines for using Big Data tools for identifying key degradation predictors
D.1.3.1/D.4.2.1	Assessing the representativeness of accelerated degradation tests using the LAUNCH rigs and the DNM
D.1.3.2/D1.3.3	Generalizing and Validating the DNM – LAUNCH rigs and pilot runs
D.1.3.4	Application: Degradation Network Model: a tool for predicting solvent degradation in industrial CO2 capture applications
D.2.1.1	Membrane selection for DORA
D.2.1.2	DORA: a novel technology for lowering solvent degradation
D.2.2.1	Design of thiosulphate dosing system for the RWE pilot
D.2.3.1/D2.3.2/D.5.2.2/D.5.2.3	Controlling degradation: the impact of iron and impurities removal on the degradation of CO2 capture solvents
D.3.1.1	Effect of PZ degradation on corrosion of carbon and stainless steel
D.3.1.2	Memo describing the results related to corrosion tendencies of selected 2nd and 3rd generation solvents
D.3.1.3	Foaming in PZ affected by degradation and impurities removal by adsorption
D.3.1.4	Report describing the foaming tendencies and results from the iron solubility measurements
D.3.2.1	List of the solvents to be tested
D.3.2.2	Manuscript to be submitted to an open access journal on the thermal degradation of second and third generation solvents
D.3.2.3	International conference publication describing the results of the oxidative degradation tests
D.3.3.1	Memo describing the boiling method and the presenting results on volatility of degraded solvents
D.3.3.2	Manuscript to be submitted to international peer-review journal on the results of volatility of degraded solvents using the simple boiling method
D.3.3.3	A document describing the evaluation of the two methods used to measure volatility of degradation compounds
D.4.1.1	Final comparison report for LAUNCH Rig#2 and PACT
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 capturing solvent degradation behaviour, including solvent testig
D.4.3.1/D.5.2.5	Demonstration and assessment of mitigation technologies effectiveness on solvent degradation
D.4.4.2	LAUNCH solvent qualification program summary report
D.5.1.1	Results of LAUNCH rig validations in head-to-head tests at industrial locations
D.5.2.1	Impact of the removal of NO2 from the flue gas on degradation of PZ, CEASR 1 and SBF solvent
D.5.2.4	Impact of the removal of NO2 from the flue gas on degradation of PZ
D.5.3.1/D5.3.2	Demonstration of solvent qualification program for a second generation solvent: concentrated MEA
D6.1.1a	Construction and operation of a non-metallic pilot CO2 capture rig and the influence of iron
D6.1.1b	Feasibility of non-metallic materials of construction for CO2 capture plants
D.6.1.2	Techno-economic evaluation and guidelines for solvent management





3. Project impact

Table 4 and Table 5 give an overview of the key expected results (KER), as defined in the project proposal, per work package in LAUNCH. The table also discuss the outcomes of each KER.

Table 4. LAUNCH main technical milestones and expected results related to understanding degradation

WP	Key expected result	Impact	Outcome
Understanding degradation: WPs 1 and 3			
WP1	Final version of the degradation database publicly available The Degradation database will be a publicly available research data management tool with a web interface for data storage, -search and -retrieval tailored for data analytics tasks.	Stakeholders will have access to a searchable tool compiling knowledge on degradation for various solvents. This will support decision making and accelerate implementation of CCUS	Realized.
WP1	Degradation network model tool publicly available The degradation network model will be a publicly available application to predict degradation potential of multiple solvents by giving plant design and flue gas data as input.	Stakeholders will have access to an application to identify mitigation strategies to lower degradation-associated solvent loss. This will reduce implementation risks for existing and new projects.	The Degradation Network model is available.
WP3	2 nd and 3 rd generation solvents to be used in the LAUNCH rigs and pilot runs tested for: <ul style="list-style-type: none"> • Corrosion potential • Thermal degradation • Oxidative degradation 	These activities will close knowledge gaps related to novel solvents degradation, and de-risk solvent testing within LAUNCH	Realized.

Table 5. LAUNCH main technical milestones and expected results related to controlling degradation

WP	Key expected result	Impact	Status
Controlling degradation: WPs 2, 4 and 5			
WP2	DORA validated for 2 nd and 3 rd generation solvents using LAUNCH rig#2 DORA is a technology for removing dissolved oxygen from solvents .	This technology is intended at controlling degradation at a low level. The oxidative degradation rate is expected to be lowered by at least 90% . This will bring DORA to a TRL level where technology providers can step in in follow up projects to further commercialize DORA.	The removal of oxygen from solvents using DORA has been achieved. To validate the impact on degradation, more data is needed. The oxygen sensor used to optimize and measure the effectiveness of the DORA system had a material compatibility issue with third generation non-aqueous





			solvents. Therefore, the tests could not be performed.
WP2	LAUNCH rig#3 commissioned LAUNCH rig#3 will be a complete absorber-desorber unit made completely out of non-metallic materials	LAUNCH rig#3 will allow us to decouple the mechanisms of degradation and corrosion and determine threshold limits for metal content in amines and give possible options for small to mid-scale commercial plants. Can give very interesting results for commercialization and further research.	This first of a kind plant is built and tested. The plant runs stable but needs an update since we experienced leakages. Many unique learnings from this activity.
WP2	Removing iron from degraded solvents using LAUNCH rigs #3 and #4	This technology is intended at controlling degradation at a low level. The oxidative degradation rate is expected to be greatly lowered. This will de-risk implementation and lower costs for capture.	The patent on IRIS has been submitted. Further testing is recommended. On the other hand, understanding from WP5 long-term tests suggests that metal removal from CESAR-1 may increase the degradation rate. This new understanding poses questions regarding the usefulness of metal removal for this solvent.
WP4	LAUNCH rigs qualified against the PACT pilot	Showing that the LAUNCH rigs produce representative results regarding solvent degradation will enable the development of the LAUNCH solvent qualification protocol. Important step in the project.	Realized. The results were not as good as expected. This may be due to the fact that we could not use the same settings, due to design limitations of the rigs.
WP4	Documentation on how to build and operate a generic “LAUNCH rig” released	Stakeholders will have access to drawings of a generic LAUNCH rig, and guidelines for operation, i.e., the LAUNCH solvent qualification protocol . Important result for solvent developers to bring down qualification costs.	Realized.
WP5	LAUNCH rig validations with CESAR 1, MEA and SBF solvent completed in head-to-head test at RWE and AVR	Demonstrating that the LAUNCH rigs produce representative results regarding solvent degradation in an industrial environment, using real flue gas and degraded solvent , will give the stakeholders confidence to use the LAUNCH protocol	Realized. Very good result since the degradation profile of the LAUNCH rig and the RWE plant was very similar. Key project result!
WP5	Demonstration of degradation control techniques: NO _x removal, DORA, adsorption of	The techniques will be demonstrated in an industrial environment, at TRL5 (DORA) and TRL8 (all others).	Realized.





	impurities and ion-exchange for 2 nd generation solvents at RWE		
WP5	Demonstration of the LAUNCH solvent qualification program at PACT	Demonstrated the LAUNCH solvent qualification program for 2 nd generation solvents will give the stakeholders confidence that the program produces good results.	Realized.

When we look at the tables above and the achieved results from the project, we can conclude that LAUNCH contributed significantly on accelerating the implementation of carbon capture by working on the knowledge gaps in solvent degradation. In Post Combustion Capture, solvent management and controlling solvent degradation are key issues.

It takes too long to mention all highlights of the project, but let us try to put a short list:

- There is a database for the community to share large experimental data sets.
- We have proven that a small-scale rig can mimic the degradation profile of a larger plant, which is an enormous advantage in de-risking implementation of carbon capture (especially cost wise).
- We have run the longest CESAR1 campaign with the same solvent ever in the world, generating unique and very valuable data and knowledge about solvent management and degradation mitigation measures. To our knowledge, this is also the longest campaign ever reported using an open solvent. The data generated can greatly support the implementation of CO₂ capture in multiple industries.
- After ALIGN, there was reluctance from the project partners in proposing CESAR1 as the new benchmark, mainly due to uncertainties regarding the solvent lifetime. In LAUNCH, we have closed this knowledge gap, and have published data that support the establishment of CESAR1 as the new benchmark for post-combustion capture, replacing MEA.
- We know a lot more about corrosion, foaming, volatility, the impact of metals on solvents.
- We have built and operated the first of a kind non-metal plant in the world.
- We have developed and patented solvent degradation mitigation measures (IRIS and DORA)
- We have published a design of a LAUNCH rig that can be used for de-risking carbon capture implementation.
- We have developed the Solvent Qualification Protocol.

By de-risking the implementation of carbon capture there are more opportunities for companies to get (more) into the CCUS business. The number of companies successfully entering the market of new or improved capture solvents is increasing rapidly. Some of the mitigation technologies investigated in LAUNCH need more testing, but will in the end enter the market, creating opportunities for companies for delivering solutions to bring down the costs of ownership for CO₂ capture plants. Examples are the commercialization of DORA, the realization of solvent reclaiming technologies and advanced control systems to automate plants with mitigation technologies based on on-line solvent quality monitoring.

New market opportunities will develop: there will be more requests for testing in the field using LAUNCH rigs. The Network Degradation Model can be further developed and used to predict





degradation patterns, leading to more advanced plant designs where the engineering industry can play an important role. Artificial Intelligence (AI) will be part of model development and advanced degradation monitoring and control strategies. The basis for this was established in LAUNCH.

Better control of degradation leads to less emissions and less waste streams, which will make the environmental footprint of capture plants smaller, hopefully also leading to increased public acceptance.

Gender equality in LAUNCH

Accelerating the commercialization of CCUS is not gender sensitive. Nevertheless, the project, the consortium and the participants' organizations are committed to the promotion of equal opportunities between men and women. In LAUNCH, the leadership of the R&D work packages and the scientists and technical staff of persons working on the project is very balanced between men and women.





Implementation

The SET Plan Implementation actions describe ten targets of which a number of them will benefit from the results in LAUNCH:

- Target 1: At least one commercial scale, whole chain CCS project operating in the power sector;
- Target 2: At least one commercial scale CCS project linked to an industrial CO₂ source, having completed a FEED study;
- Target 6: At least 3 pilots on promising new capture technologies, and at least one to test the potential of sustainable Bio CCS at TRL 6-7 study.

Making carbon capture more affordable (by appropriate solvent management) and less costly (by the Solvent Qualification Protocol and less waste disposal), the LAUNCH results will accelerate the realisation of the SET targets. Implementation is already ongoing. If we look at the Waste-to-Energy sector in the Netherlands, a commercial plant is being operated already for a few years (AVR, operational results monitored and published as part of LAUNCH), new commercial plants are being built (Aker at Twence) and a number of companies have received permits and put out tenders for more plants to be built. CCUS implementation has increased a lot. Also in the UK, Norway and Germany a lot of initiatives are being developed. The carbon capture plants in the Northern Lights project will benefit from the knowledge gained in LAUNCH.

Lowering the costs of advancing new solvents to the market using the Solvent Qualification Protocol will create opportunities for existing and new companies involved in solvent development.

The LAUNCH results will also contribute to the Mission Innovation goal on carbon dioxide removal “enable carbon dioxide removal (CDR) technologies to achieve a net reduction of 100 million metric tons of CO₂ per year globally by 2030”, for instance via the application of post-combustion capture in BECCS.

Industrial participation – Results taken up by industry

In LAUNCH we have 4 industrial partners:

- RWE Power AG: a power company in Germany
- Altrad Babcock (formerly named Doosan Babcock): a technology supplier in the United Kingdom
- AVR: a waste to energy company in the Netherlands
- BEFORM (formerly named BIOBE): a supplier of products in thermoplastic and thermosetting materials in Norway

The industrial partners contributed a lot to achieving the results of the project. Current results are already taken up by many industries, like for instance the Waste to Energy sector. We see an increase in consultancy questions from the industry on how to decarbonize their business. This increase is partly due to the fact that implementing CO₂ capture is seen as less risky than before. Projects like LAUNCH, ALIGN-CCUS, NEWEST, NCCS, SCOPE and the H2020 project REALISE help to make carbon capture more attractive. Also, initiatives like the full-scale plant at AVR, LONGSHIP and the recent initiatives in the Netherlands (2 billion Euros) and USA (\$99 Million) help to boost the implementation. Next to that, we also see an increasing interest in CCS at the shipping industry, that has also committed to reduce emissions. The TNO LAUNCH rig#2 is being hired for on-site campaigns





and there are requests for more. Industrial parties are also very interested in the DORA technology and have approached TNO about possibilities for cooperation/licencing.

Some of the technologies investigated in LAUNCH like oxygen removal with DORA, In Situ iron removal with IRIS, nitrogen sparging, NO_x removal etc. are also part of new (ACT) initiatives. The development of DORA will continue in the MeDORA project in 2023, in which also the technology providers have a bigger role, showing more trust from that side of the value chain. The valuable results on the degradation behaviour of CESAR1 gained in LAUNCH will be used to analyse the long-time degradation behaviour of the solvent while operating a capture plant at highest CO₂ capture rates in the project DRIVE (CETP).

4. Collaboration and coordination within the Consortium

The management structure of LAUNCH is shown in Figure 6 .

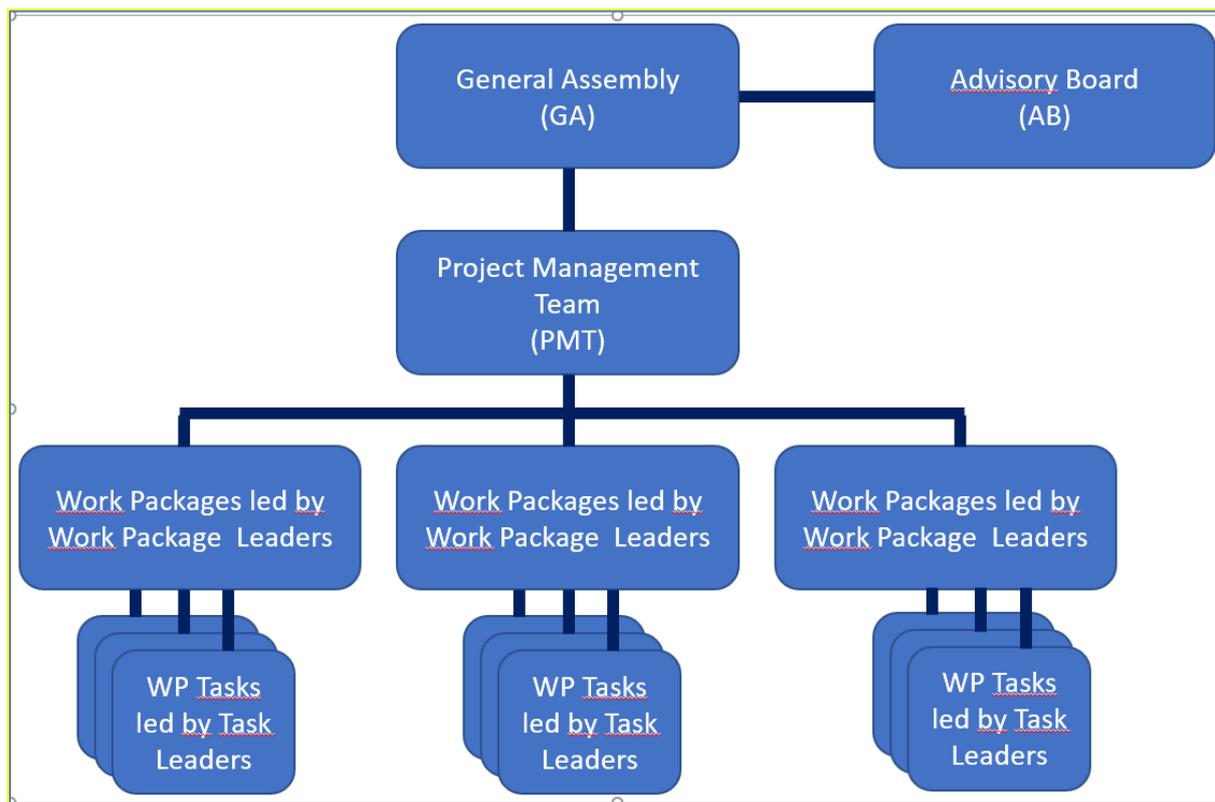


Figure 6. Management structure in LAUNCH

The project had a flying start because the people in the consortium knew each other well (some already for many years) from the network or previous projects like ALIGN-CCUS, HPERCAP, OCTAVIUS, CESAR (in which the CESAR1 solvent was developed). A strong and experienced Project Management Team (PMT) is needed to deliver a successful project. When setting up the project, we were able to put this team together from the leading organisations in the field. The PMT was constituted of the following people / organisations.





PMT members LAUNCH

Function	Person(s) in charge	Organisation
Coordinator	Peter van Os	TNO (NL)
Technical coordination	Juliana Monteiro	TNO (NL)
Dissemination coordination	Richard Lo Bianco Richard Lindsay Stevenson	SCCS (UK)
WP1 leader	Andreas Grimstvedt	SINTEF IND (NO)
WP2 leader	Roberta Veronezi Figueiredo	TNO (NL)
WP3 leader	Hanna Knuutila	NTNU (NO)
WP4 leader	Jon Gibbins	Uni. Of Sheffield (UK)
WP5 leader	Peter Moser	RWE (DE)
WP6 leader	Jonathan Slater	Altrad Babcock (UK)
USA representative	George Scot Goff	LANL (USA)

Due to organisational reasons, the tasks of WP2 leader Juliana were taken over by Roberta. Juliana had still a strong involvement as technical specialist for the coordinator for the whole project.

General Assembly

The General Assembly (GA) was the ultimate decision body of the project. Every partner had one vote in the general assembly. All decisions of the GA have been unanimous.

Advisory Board (AB).

An Industrial Advisory Group was established for LAUNCH.

PMT members LAUNCH

Carbon Clean Solutions	United Kingdom
ION Engineering	USA
UK-China (Guangdong) CCUS Centre	China
Mitsubishi Heavy Industries	Japan
Shell	The Netherlands
International CCS Knowledge Centre	Canada
Total	France
Twence	The Netherlands
BASF	Germany
Technology Centre Mongstad (joined later)	Norway

The IAG were invited and participated in the various webinars that were organised for LAUNCH. We also had a separate meeting with the Advisory Board where the work package leaders presented the results of LAUNCH. All members of the board mentioned the importance of the work performed but there were not many questions, probably due to the fact that they were in the same meeting with a lot of their competitors. In this meeting the Solvent Degradation Interest Group was proposed. There was interest from all participants to join a group that yearly shared (public) research results.





Cooperation within ERA-NET ACT

There was a lot of knowledge exchange with the ALIGN-CCUS project, that has been finalized at the end of November 2020. Due to the focussed and technical scope of the LAUNCH project, there has not been much knowledge exchange with the other ACT2 projects. This was also hindered by the fact that we are not able to meet in person in a more informal environment for a long time due to COVID. The LAUNCH project really appreciated the presence of the funders in the consortium meetings we had (Li Hua and Harry Scheurs from RVO attended all of them). Their feedback was welcomed and appreciated, as well as the support from the ACT organisation. Also, the mid-term review meeting was very useful and the feedback from the reviewers was appreciated and improved the project.

European Trans-national collaboration on CCUS

The impacts of CO₂ emissions are not limited by countries' borders and it is evident that international collaboration is essential to meet the goals as specified for LAUNCH. In LAUNCH we developed solutions for one of the main remaining issues regarding solvent based Post Combustion CO₂ capture: degradation of the used solvent. Tackling the issue requires fundamental knowledge, operation experience and creativity to think and to develop solutions. To cover this broad field of expertise, international cooperation is essential on a worldwide level. In ACT2 and ACT3 projects this was possible. Although the contractual side of the cooperation was very difficult in LAUNCH and took a long time, the value of working with top partners in the field from across the world has proven to be a great value for LAUNCH.

We can conclude that the cooperation with the University of Texas was a great success. The excellent discussions were of great value and inspiring and participation in the regular meetings was very good, despite the time difference between the USA and Europe.

5. Dissemination activities

One of the most important tasks at the start of the project was to develop the branding, to give the project its own distinctive identity that would help to establish LAUNCH as an important and pioneering project in the field of CCS. The dissemination team at SCCS developed a modern and intuitive website, along with corresponding document templates, giving the project a clear, professional and very recognisable look, as can be seen in the screenshot in Figure 7.



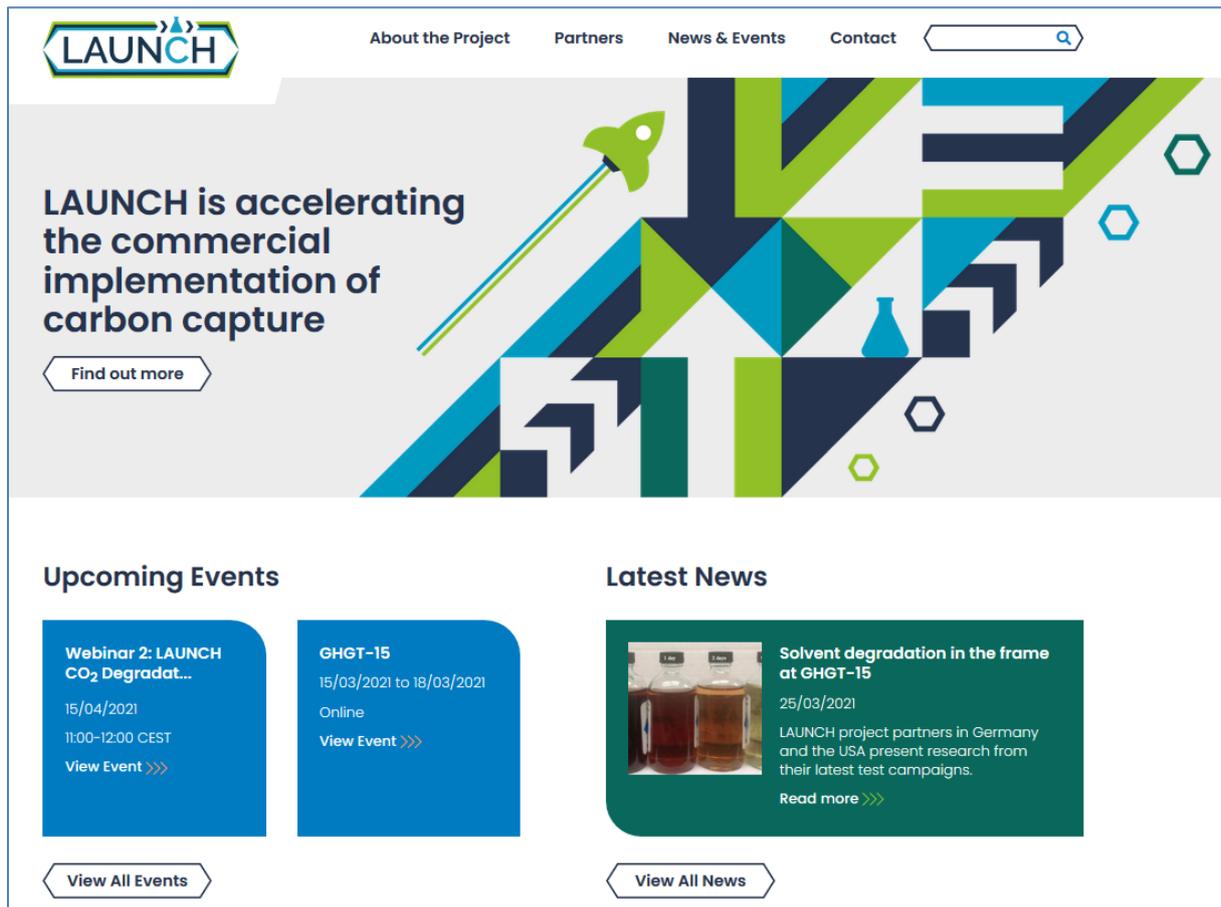


Figure 7. Screenshot LAUNCH website

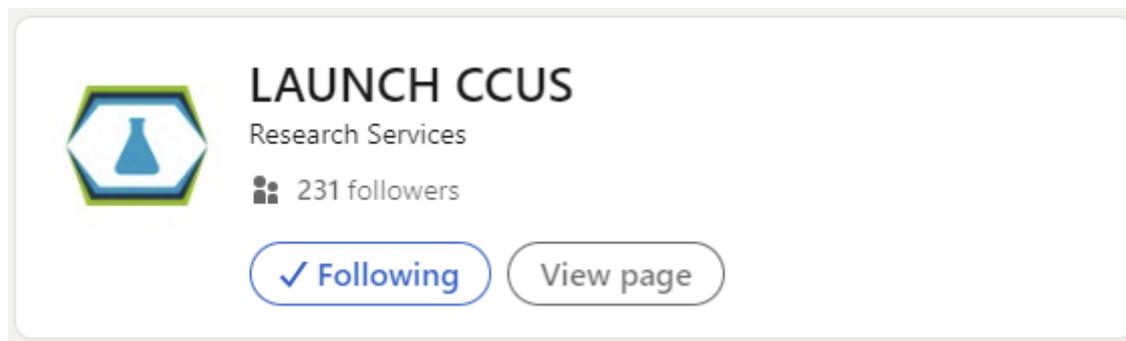
The LAUNCH website was an important tool as it facilitated communications and interaction between project partners as well as with external stakeholders and audiences. Social media channels – Twitter and LinkedIn – were also developed, to maximise the reach of the project to the wider CCS community and world. Both Twitter and LinkedIn accounts had many followers.





A picture of the current twitter account.

The number of Twitter followers went up from 233 (halfway the project) to 394 at the end.



A picture of the current LinkedIn account.

On LinkedIn we went from 79 followers halfway to 231 at the end of the project.

Table 6 lists all dissemination activities to date.





Table 6. LAUNCH dissemination activities since project start

What	Where	When	Who	Description
O	ACT Knowledge Workshop 2019	November 2019	TNO	Pitch presentation of LAUNCH by Peter van Os
O	CATO Day The Netherlands	November 2019	TNO	Pitch presentation of LAUNCH by Jasper Ros (TNO)
N	Newsletter through website	December 2019	SCCS, TNO	News about the LAUNCH Kick Off
O	5 th University of Texas conference on Carbon Capture and Storage	January 2020	RWE	Results of the effect of active carbon and particle filter on solvent degradation, color and trace element content.
N	Newsletter	February 2020	SCCS, Biobe	Partner profile: Moulding the future of carbon capture
B	Blog on Website	March 2020	SCCS	Blog: The science behind LAUNCH's focus on capture solvents
N	News on Website	March 2020	SCCS	LAUNCH-CCUS Covid-19 statement
Web	LAUNCH Webinar 1	May 2020	Coordinator and WP leaders	Project presentation including first results.
B-V	During LAUNCH meeting	July 2020	SCCS, TNO	Video: TNO's 'Ceiling of Impact' and the launch of LAUNCH
O	ACT Knowledge Workshop 2020	November 2020	TNO	Online presentation of LAUNCH and first results
A	GHGT15	March 2021	RWE	NO ₂ removal for PCCC
A	GHGT15	March 2021	RWE	Demonstrating solvent management technologies for an aqueous AMP/PZ solvent
A	GHGT15	March 2021	University of Texas	Effects of Carbon Treating on Piperazine Oxidation in pilot plant testing of PZASTM
A	GHGT15	March 2021	TNO, SINTEF, NTNU, RWE, Sheffield, Altrad	LAUNCH, an ACT-project to develop a solvent qualification program accelerating the development of breakthrough technologies for CO ₂ capture
O	GHGT15	March 2021	RWE	NO ₂ removal for PCCC



What	Where	When	Who	Description
OP	GHGT15	March 2021	RWE	Demonstrating solvent management technologies for an aqueous AMP/PZ solvent
O	GHGT15	March 2021	University of Texas	Effects of Carbon Treating on Piperazine Oxidation in pilot plant testing of PZASTM
N	Newsletter	March 2021	SCCS	Solvent degradation in the frame at GHGT-15
O	RCCS Capture-Storage Theme Meeting, Heriot-Watt University	March 2021	RWE	Development of Post-Combustion Capture
Web	LAUNCH Webinar 2	April 2021	Coordinator and WP1 partners	All you need to know about our CO2 degradation database and how you can use it.
A	TCCS-11	June 2021	TNO, Delft University	Techno-Economic Performance of DORA with MEA and CESAR1.
A	PCCC-6	October 2021	NTNU	Oxidative degradation tests
A	PCCC-6	October 2021	TNO, SINTEF	LAUNCH accelerated degradation campaigns
A	PCCC-6	October 2021	RWE, TNO	Degradation management for AMP/PZ-based solvents at the capture plant at Niederaussem - NO ₂ removal, ion exchange, LAUNCH rig
A	PCCC-6	October 2021	University of Texas	Piperazine Oxidation by Ferrous-Ferric Shuttle Mechanism
A	PCCC-6	October 2021	University of Texas	[Inhibitor A] as an Amine Oxidation Inhibitor in CO ₂ Capture
A	PCCC-6	October 2021	SINTEF	Current state of understanding of degradation of amines used for post-combustion CO ₂ capture
Web	LAUNCH webinar	April 2021	TNO, SINTEF, NTNU	LAUNCH CO ₂ Degradation Database – collecting datasets for solvent R&D
Blog	Website	April 2021	TNO	Combating oxidative degradation with membranes by Tanya Srivastava
PR	Website article.	June 2021	All	Giving industry a head start in choosing capture solvents



What	Where	When	Who	Description
P	UTCCS 2022	January 2022	TNO	Impact of DORA on CESAR1 operation in combination with the LAUNCH rig at Niederaussem
P	UTCCS 2022	January 2022	RWE - TNO	34 months continuous testing of the CESAR1 solvent at Niederaussem
P	UTCCS 2022	January 2022	TNO	Effect of CO ₂ loading on oxygen depletion in monoethanolamine
P	UTCCS 2022	January 2022	Uni of Texas	Pilot campaign to test oxidation mitigation strategies
P	UTCCS 2022	January 2022	Uni of Texas	Corrosion in PZAS™
P	UTCCS 2022	January 2022	Uni of Texas	Effect of carbon treating on PZ oxidation
P	UTCCS 2022	January 2022	Uni of Texas	PZ oxidation at stripper conditions with dissolved Fe
P	UTCCS 2022	January 2022	Uni of Texas	Piperazine oxidation by NO
O	ACT Knowledge Workshop	June 2022	TNO	Presentation on progress by Peter van Os
OPa	GHGT16	November 2022	Uni of Sheffield, TNO, SINTEF	Comparison of TERC and TNO's LR2 CO ₂ capture rigs for normal and accelerated degradation
OPa	GHGT16	November 2022	NTNU, SINTEF	AN experimental assessment on the impact of amine concentration in the oxidative degradation of amines
OPa	GHGT16	November 2022	Uni of Texas	Purification of degraded aqueous piperazine by ion exchange and carbon treating
OPa	GHGT16	November 2022	TNO	Construction and operation of a non-metallic pilot CO ₂ capture rig
OPa	GHGT16	November 2022	Uni of Texas	Role of carbon treating piperazine oxidation
OPa	GHGT16	November 2022	Uni of Texas	Pilot testing of Mitigation methods for Piperazine oxidation
OPa	GHGT16	November 2022	TNO	DORA demonstration at TRL7 at HVC in the Netherlands
OPa	GHGT16	November 2022	Uni of Texas	Review, column design and TEA of nitrogen sparging to reduce amine oxidation



What	Where	When	Who	Description
OPa	GHGT16	November 2022	Uni of Texas	Stainless and carbon steel corrosion in aqueous piperazine at absorber and water wash conditions
OPa	GHGT16	November 2022	RWE	Conclusion of 3 years of continuous capture plant operation without exchange of the CESAR1 solvent at Niederaussem – Insights into solvent degradation management.
OPa	GHGT16	November 2022	TNO	Predicting Oxidative degradation for CESAR1 using a degradation network model.
PoPa	GHGT16	November 2022	NTNU, SINTEF	Design and operation of water-wash sections to minimize MEA emissions.
V	Through RWE website	November 2022	RWE	LAUNCH rig video: https://www.rwe.com/en/research-and-development/rwe-innovation-centre/co2-utilisation-and-integrated-energy/carbon-capture/launch
WS	Public part of final event	February 2023	TNO - All	The 2 nd day of the LAUNCH final event was public. There were 60 participants (43 online, 32 from outside LAUNCH)
Podcast	Podcast	March 2023	TNO	Interview Peter van Os, Solving for Solvents: How International Partnerships are Enhancing the Solvents Needed for CCS - Episode 7 Global CCS Institute Podcast - Capture, Store, Repeat - Global CCS Institute
P	TCCS12	June 2023	Uni of Texas	Dissolved Oxygen Consumption in Amine Scrubbing
Pa	Industrial & Engineering Chemistry Research, 2023, 62, 1, 610–626	2023	NTNU, SINTEF	Chemical Stability and Characterization of Degradation Products of Blends of 1-(2-Hydroxyethyl)pyrrolidine and 3-Amino-1-propanol



What	Where	When	Who	Description
Pa	Industrial & Engineering Chemistry Research, 2022, 61, 43, 16179–16192	2022	NTNU, SINTEF	Impact of Solvent on the Thermal Stability of Amines.
Pa	International Journal of Greenhouse Gas Control, Volume 106, March 2021, 103246	2021	NTNU, SINTEF	A review of degradation and emissions in post-combustion CO2 capture pilot plants

O = Oral Presentation, Web = Webinar, WS = WorkShop, V = Video, A = Abstract, B = Blog, I = Interview, Po = Poster, Pa = Paper, Pat= Patent application, N = Newsletter, OPa = Oral presentation and paper, PoPa = Poster and Paper, PR = Press Release



Annex 6: Final financial report

ACT Final Financial Report

Project Name: LAUNCH
 Project Number: 299662
 Actual costs per country / per
 organisation

Country	Act Funding	Other public funds	Private funding, R&D institution	Private funding, industry	In-Kind, R&D institution	In-kind industry	Other funds	Total after three years per org
The Netherlands	€ 983.459	€ -	€ -	€ -	€ 309.959	€ -	€ -	€ 1.293.418
TNO	€ 978.419				€ 304.919			€ 1.283.338
AVR	€ 5.040				€ 5.040			€ 10.080
Norway	€ 1.104.160	€ -	€ -	€ -	€ 548.531	€ -	€ -	€ 1.652.691
NTNU	€ 323.488				€ 345.862			€ 669.350
SINTEF AS*	€ 551.830				€ 37.678			€ 589.508
BEFORM	€ 228.842				€ 164.991			€ 393.833
Germany	€ 694.416	€ -	€ -	€ -	€ -	€ 1.230.946	€ -	€ 1.925.362
RWE Power	€ 694.416					€ 1.230.946		€ 1.925.362
United Kingdom	€ 1.313.569	€ -	€ -	€ 142.944	€ 267.218	€ -	€ -	€ 1.723.731
University of Sheffield	€ 1.024.343				€ 258.376			€ 1.282.719
Altran Babcock**	€ 142.944			€ 142.944				€ 285.888
University of Edinburgh / SCCS***	€ 146.281				€ 8.842			€ 155.124
United States of America	€ 850.000	€ -	€ -	€ -	€ -	€ -	€ -	€ 850.000
Los Alamos National Laboratory	€ 850.000							€ 850.000
Total per funding	€ 4.945.604	€ -	€ -	€ 142.944	€ 1.125.708	€ 1.230.946	€ -	€ 7.445.202



Project no. 691712:
ACT – Accelerating CCS Technologies
Monitoring guidelines, Final report ACT2

LAUNCH, Project no 299662





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