



CATO-2 Deliverable WP1.2A4-D01

Progress report and location for pilot plant SEWGS

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1 Executive summary

Sorption Enhanced Water Gas Shift (SEWGS) is a pressure swing adsorption process based on reversible CO₂ adsorption on solid materials at elevated temperatures between 350 and 550 °C. Accordingly, cooling and partially condensing the fuel gas and subsequent reheating upstream of the gas turbine are avoided. The reactor vessels are loaded with sorbent pellets. As CO₂ is removed from the synthesis gas by adsorption, CO is simultaneously converted to CO₂ by the water-gas shift reaction, which ultimately ensures low CO₂ emissions and high carbon capture ratios. The sorbent is periodically regenerated by purging with steam at low pressure.

In order to develop novel cycles and design the reactors, a dynamic model of a SEWGS reactor, including the chemical reactions and adsorption and desorption processes, has been developed. The model contained mass and energy balances, kinetics of commercial shift catalysts, and a CO₂ adsorption isotherm for a reference promoted hydrotalcite. The model has been validated with experimental results from a test rig consisting of 6 adsorption columns each 6 m tall. CO₂ breakthrough curves as well as desorption curves could be predicted. The model allows to simulate the performance of a SEWGS unit by simulating the dynamic composition of the feed and product streams during cyclic operation. Using the model, simulations of SEWGS pressure-swing cycles can reveal design knowledge for power generation (NGCC and IGCC) and for non-power applications.

Promising non-power applications include carbon abatement from blast furnace top gas in the steel sector and gasifiers in refineries. Conceptual designs for these applications are planned for next year.

The current Technology Readiness Level (TRL) of SEWGS is assessed as Level 5. This implies that in a couple of years the technology could be scaled up to a pilot unit and be demonstrated on this scale with a real feed gas. The demonstration of the technology in this pilot unit is a key step towards successful commercialisation. A first step in the pilot plant planning process is the selection of the best application for SEWGS, such as NGCC, IGCC, or blast furnace application. The best application will benefit most from the characteristics of SEWGS in comparison to competing technologies, such as chemical or physical absorption. Also, the best application will have a large market potential. The choice of the best application will be an important criterion for the following step: the selection of the location of a host site. Important considerations for the choice of a location include: commitment and value for the owner of the host site, availability of sufficient land area and utilities such as steam, safety, operational and legal issues. A list of potential host sites in the Netherlands include hydrogen production plants, a coal-gasifier, an oil-residue gasifier, and a blast furnace. A decision for a specific location will be made in the second year of the CATO-2 project.

Location for pilot plant SEWGS

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(this section shows the historical versions, with a short description of the updates)

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Acknowledgement

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2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the “legal” basis to the work performed)

	Title	Doc nr	Version date
AD-01	Beschikking (Subsidieverlening CATO-2 programma verplichtingnummer 1-6843)	ET/ED/9078040	2009.07.09
AD-02	Consortium Agreement	CATO-2-CA	2009.09.07
AD-03	Program Plan	CATO2-WP0.A-D.03	2009.09.29

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	Doc nr	Issue/version	date
HAI van Dijk et al.	Testing of hydrotalcite based sorbents for CO ₂ and H ₂ S capture for use in sorption enhanced water gas shift.	Proc. GHGT-10, Amsterdam		2010.
A Wright et al.	Reduction in the Cost of Pre-combustion CO ₂ Capture through Advancements in SEWGS	Proc. GHGT-9, Washington		2009.
HThJ Reijers et al.	Modelling study of the Sorption Enhanced Reaction Process for CO ₂ Capture.	Ind Eng Chem Res		2009: 48 (15) 6966-74

2.3 Abbreviations

(this refers to abbreviations used in this document)

ATR	Auto-thermal reforming
IGCC	Integrated gasification combined cycle
LDF	Linear driving force
NGCC	Natural gas combined cycle
PDU	Process development unit
SEWGS	Sorption enhanced water gas shift
TRL	Technology readiness level
WGS	Water gas shift

3 Progress Report

Reporting period	From start (2009.04.15) – till 2010.08.31
Actual Program Plan version	CATO2-WP0.A-D03-v2009.09.17 (Program-Plan-CATO-2a)
Work Package	WP1.2A4
Work Package Leader	E. van Selow
SP-Coordinator	D. Jansen
Participants	ECN, Shell, Corus
Approved by EB on	25-09-2009

3.1 Introduction

The main objectives of the capture technology development in CATO-2 are:

- Increasing efficiency and reducing costs of first generation capture technology that can be implemented in large scale facilities by 2015.
- Continuing research and developing a strong reduction in capture cost and efficiency penalty with novel types of second generation capture technologies to be implemented at a later stage.

The Sorption Enhanced Water Gas Shift (SEWGS) process under development is a second generation technology which has shown the potential to reduce the capture efficiency penalty with at least 25% and reduce capture costs with also at least 25% (Wright et al, 2008).

In CATO-1, CAPTECH and the EU IP CACHET and FP7 project CAESAR, ECN and partners delivered proof-of-concept of two innovative and potentially high-efficiency pre-combustion capture technologies. One is the SEWGS process. SEWGS combines the water-gas-shift step with the CO₂ separation step, which leads to considerable efficiency improvements of the CO₂ capture process. A description of the technology is given in <http://caesar.ecn.nl>.

ECN is one of the leading institutes on high temperature sorbents for CO₂ capture. For the SEWGS development ECN has two unique process development units. Both units were co-financed by the EU and the CCP-2 consortium (seven oil companies). These test facilities have been used in the CATO-2 project. Besides, the knowledge developed in the above mentioned projects has been used in this CATO-2 project.

As shown in Figure 1, the SEWGS development contains various tasks. The main focus in the first project year was on modelling, requiring experimental data as input. By model simulations, reactor and cycle designs can be optimised, which can then be experimentally verified. The core of the technology development is the sorbent, which will be emphasised in the second year. Sorbent improvements will lead to changes in modelling, reactor and cycle design and new experiments. The application and system integration issues set the requirements for the SEWGS process and have implications on all tasks.

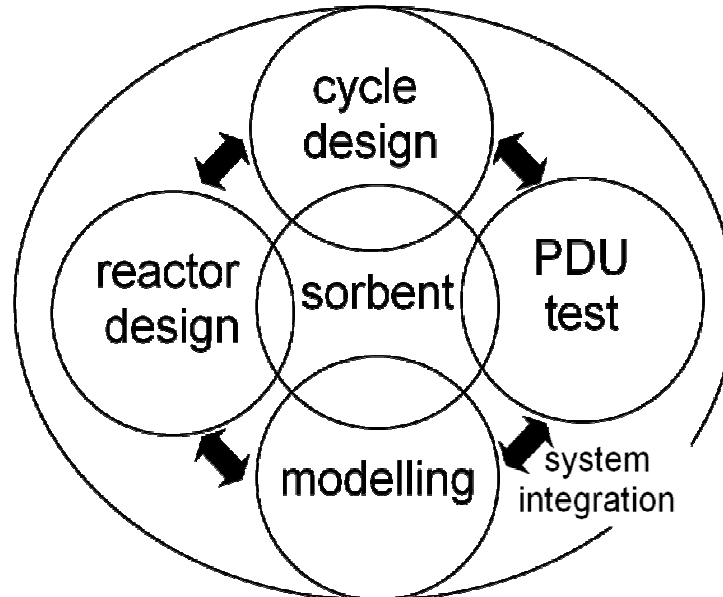


Figure 1 The various tasks and interrelationships of the SEWGS development in the CATO-2 project

The SEWGS technology is nearly ready for moving to the stage of the building of a first pilot unit, and in CATO-2 a suitable location will be found. Possible locations are ATR-based hydrogen production facilities, an oil residue gasification unit of a refinery, a coal gasifier, and a blast furnace.

3.2 Reactor modeling and cycle design

In order to develop novel cycles and design the reactors, a dynamic model of a SEWGS reactor, including the chemical reactions and adsorption and desorption processes has been developed. The model is written in MATLAB™ and contains mass and energy balances, kinetics of commercial sweet shift catalysts, and a CO₂ adsorption isotherm for a reference promoted hydrotalcite. The model allows to simulate the performance of a SEWGS unit by simulating the dynamic composition of the feed and product streams during cyclic operation. Both the cocurrent CO₂ rinse cycle and the countercurrent steam rinse cycle can be simulated. The model has been validated using results of adsorption and desorption experiments from the SEWGS multi-column test rig.

The model assumptions are (Reijers et al, 2009):

- 1-dimensional: only axial profiles are modelled, radial profiles are assumed to be flat
- Instantaneous mass and heat transfer between gas and solid phases (pseudo-homogeneous)
- Fixed bed reactor
- Plug flow (see Figure 2)
- Ideal gases
- Monodisperse, spherically-shaped, homogeneously mixed sorbent and catalyst particles
- Only water-gas shift reaction
- Only CO₂ is adsorbed
- Linear driving force (LDF) model for CO₂ adsorption (Figure 3)
- Diffusion limitation of the catalyst is taken into account by using an effectiveness factor

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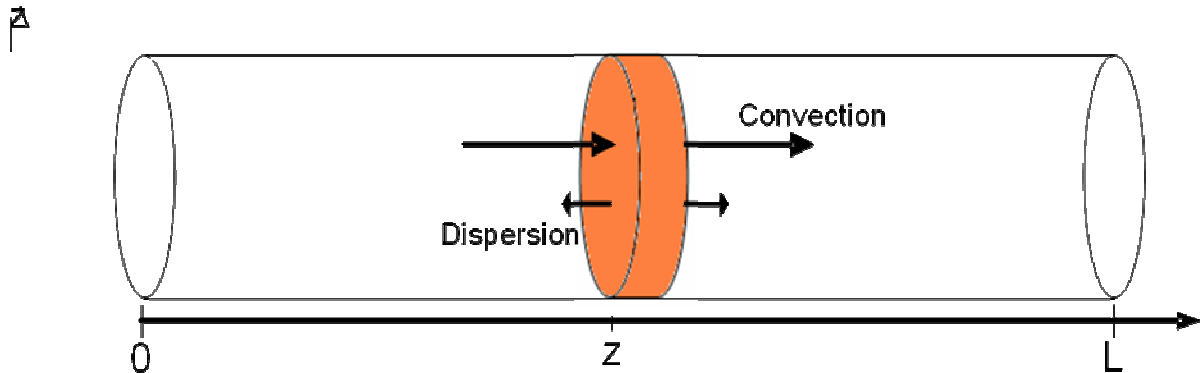


Figure 2 The one dimensional, axially dispersed plug flow model of a SEWGS reactor

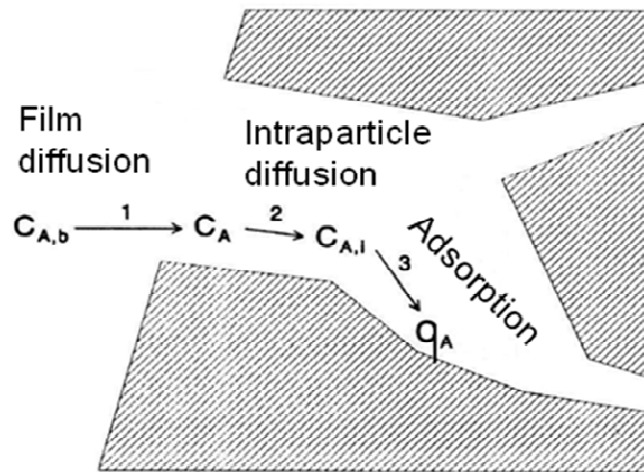


Figure 3 The kinetics of adsorption are determined by various mass transfer processes, which are lumped into one linear driving force model

Parameters or relations derived from literature are:

- Specific heats of the solid and gas phases
- Thermal conductivity of the solid and gas phases
- Viscosity of the gas
- Molecular diffusion coefficient in voids
- Molecular diffusion coefficient in particle
- Axial dispersion coefficient
- LDF model for CO₂ adsorption
- Thermal conductivity of the bed
- Wall-to-bed heat transfer coefficient

The following computer code changes have improved the performance of the simulations:

- Several relations for the WGS equilibrium constant were compared. Although the differences in the equilibrium constants were small, they resulted in significantly different conversion rates. These results are not well understood, and further research is needed to explain these results.

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- When simulating a breakthrough experiment, a double exotherm was obtained. It was discovered that this was caused by a discontinuity in the value for the heat transfer coefficient (gas-to-wall) since two different correlations were used for the reacting zone and for the non-reacting zone. This has been adjusted.
- It is impossible to simulate true step changes because these will introduce infinite gradients. Therefore instantaneous changes are smoothed to a very fast transient by introducing a smoothing time. The smoothing time determines how a step change in feed composition is transformed in a fast but continuous change in feed composition. The smoothing time should be chosen small enough so that the smoothing time does not have an effect on the simulation results, but large enough to prevent numerical issues such as non-convergence. The effects of the smoothing time chosen on the simulation results was investigated. Smoothing time was observed to be slow enough to guarantee convergence but fast enough not to influence simulation results: the final mass transfer zone during adsorption was independent of limited changes in the smoothing time.
- The effects of the number of grid points on the simulation results was investigated, indicating a suitable number of grid points chosen.
- A SEWGS reactor is operated in cocurrent and countercurrent modes. However, the equations are always solved in the direction of the gas flow. The results are thus obtained in a non-consistent way, requiring additional post-processing steps. Modifications have been made so that $z = 0$ now always corresponds with the bottom of the reactor. As a consequence, the simulation results are always consistent and results do not need to be inverted for the steps with countercurrent gas flow.

The model includes a steady-state approximation for the momentum balance, which is only valid for the feed and regeneration steps where the pressures at the reactor inlet and outlet do not change. However, during pressurization and blowdown the dynamic pressure effects are much more pronounced. This turned out to be the cause of a number of major problems encountered, including long simulation times, lack of robustness, that is, non-convergence if small adjustments in simulation parameters were made, and small but significant errors in the mass balance. The partial differential equations and boundary conditions formed an overspecified problem when two reactors are coupled, for instance during pressure equalisation steps. This means that the final pressures need to be provided in order to be able to run the simulation, whilst they should actually be calculated since they should be such that the mass balance is correct (but for the calculation one needs the simulation first). This is an issue that can be found in other modelling papers but it has not been solved so far, other than sticking to the steady-state approximation. Work is now progressing with a proper inclusion of the continuity equation and a redefinition of the boundary conditions, in order to obtain rapidly converging solutions and appropriately reconcile the mass balance.

The bed temperature profiles during the feed were simulated (1) in absence of water-gas shift reaction (2) in absence of sorption (3) in presence of water-gas shift reaction and sorption. The results could be qualitatively explained.

Breakthrough profiles during adsorption, such as shown in Figure 4, are very well known in adsorption literature. These profiles have been simulated with the model. It can be seen that adsorption takes place in a very restricted zone, called the mass transfer zone (MTZ), which moves from the feed end towards the product end of the reactor. In the reactor area upstream the MTZ the sorbent is saturated with CO₂ and the feed gas passes without change in composition. In the reactor area downstream the MTZ, the decarbonised product gas streams towards the reactor outlet without reacting with the sorbent. The steepness of the MTZ is determined by the kinetics of adsorption.

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Furthermore, the sorbent loading profiles during regeneration, using countercurrent steam for stripping, could be simulated, see Figure 5. At $t=t_0$, the reactor is loaded with CO_2 , adsorption has stopped whilst the reactor end was still in the mass transfer zone. Hence, the CO_2 loading falls towards the end of the bed. The pressure is lowered, resulting in a partial desorption (not shown in the graph). By providing steam as stripping gas from the right hand side, the equilibrium loading is reduced, CO_2 desorbs and the steam pushes the CO_2 present in the gas phase out of the reactor. In contrast to adsorption, where interaction takes place in a small mass transfer zone, the desorption takes place in the whole reactor. This phenomenon is well-known from adsorption theory for sorbents with a favourable adsorption isotherm. After a certain time period of stripping t , the CO_2 loading has substantially decreased. However, after another time period of stripping t , keeping the steam flow rate constant, only a small additional amount of CO_2 is stripped. It can be seen that after another time period of stripping, an even smaller amount of CO_2 is stripped.

Thus, it is confirmed that regeneration efficiency decreases over time since the amount of steam required for regeneration per amount of CO_2 recovered increases as the loading decreases over time. This phenomenon is shown in Figure 6. In the beginning of the regeneration, for each mmole of stripping gas provided, more than one mmole of CO_2 is recovered. However, efficiency rapidly drops. When the bearing coefficient is 1, exactly 1 mmole of CO_2 is recovered for each additional mmole of H_2O . At the point where the curve crosses the dashed line, a total amount of CO_2 was recovered exactly equal to the total amount of stripping gas provided. At time step t , the amount of steam provided during the regeneration clearly exceeds the amount of CO_2 recovered. This ratio becomes larger as regeneration further proceeds. The regeneration efficiency drop can be primarily attributed to the shape of the adsorption isotherm, which is favourable for adsorption but, as a consequence, unfavourable for desorption. Depending on operating conditions, the efficiency of regeneration may be hampered by mass transfer limitations as well. The importance of these results is that a full regeneration is not economical since it would require excessive amounts of steam. Instead, a partial regeneration with a limited amount of steam would be more economical. However, reducing steam consumption would decrease the cyclic capacity of the sorbent. The most economical way of operation would therefore be determined by a balance between cyclic capacity and steam consumption.

As steam consumption is one of the key criteria determining the efficiency of the SEWGS process, the sorbent shall not be completely regenerated before the process switches to a new adsorption step. Hence, the cyclic capacity of the sorbent is smaller than its total capacity. Figure 7 shows the thermodynamic and kinetic limitations that determine the cyclic capacity of the sorbent. The thermodynamic limitations are determined by the shape of the adsorption isotherm. It can be concluded that the CO_2 adsorption isotherm and desorption rates are the dominant factors governing the SEWGS performance.

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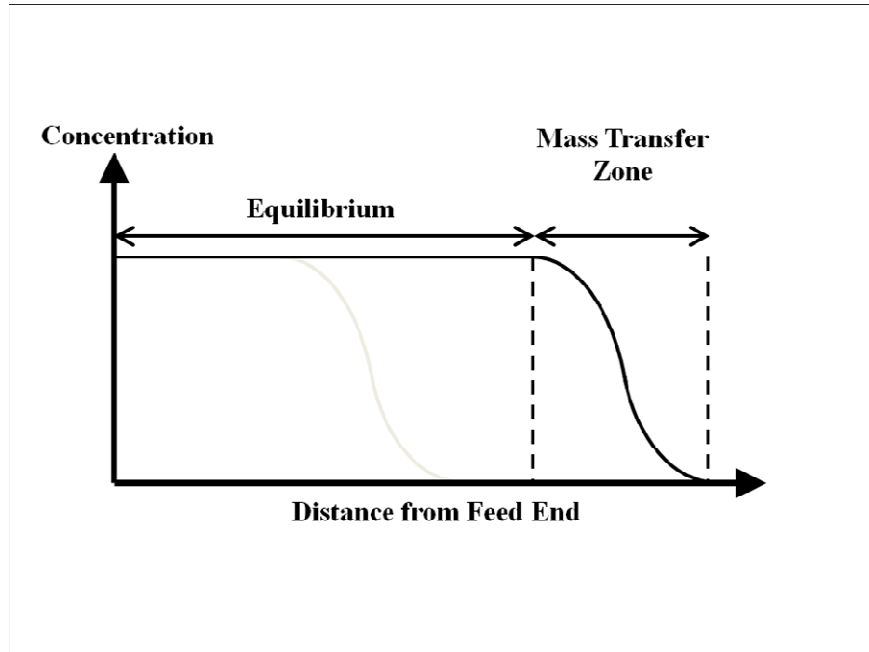


Figure 4 The progress of the CO₂ concentration profiles in a reactor during adsorption

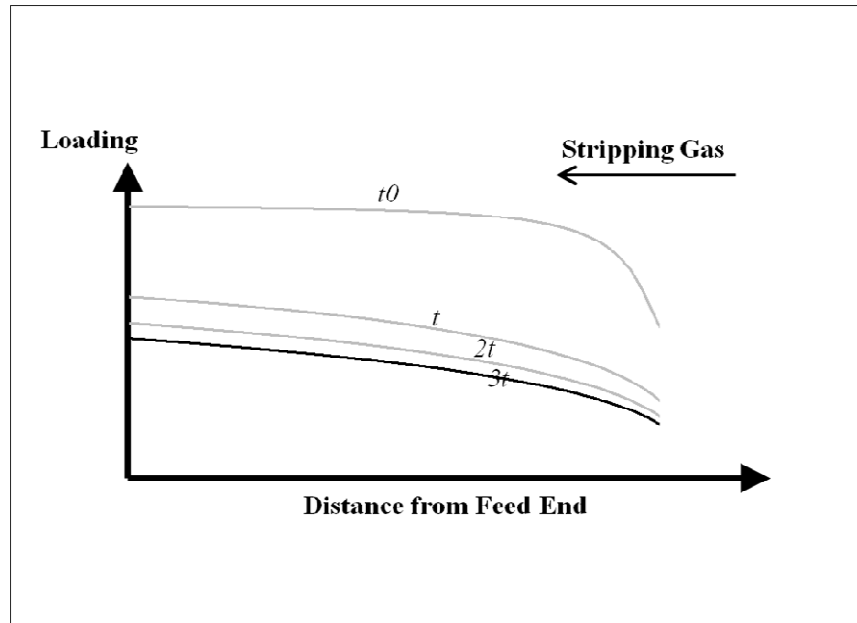


Figure 5 The progress of the CO₂ concentration profiles in a reactor during regeneration

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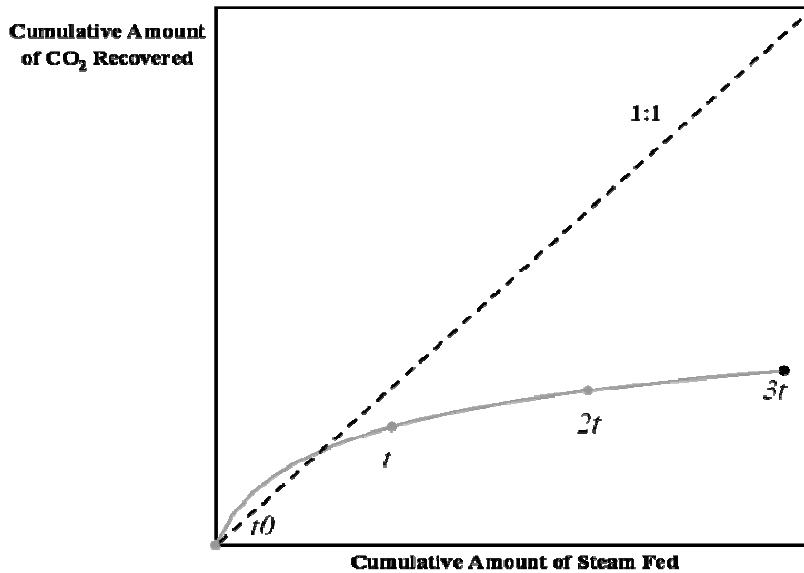


Figure 6 The amount of CO₂ recovered during regeneration as a function of the cumulative amount of steam fed used for stripping.
 Dashed line: equal amounts of steam provided and CO₂ recovered.

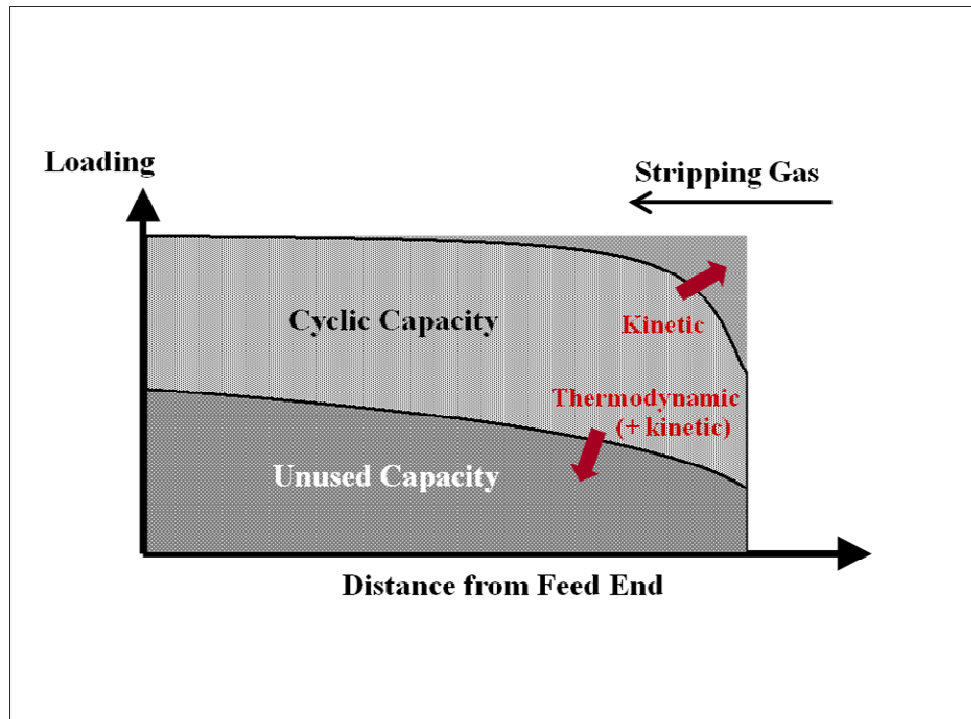


Figure 7 The difference between total capacity and cyclic capacity.

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For the model validation, simulation results were compared with experimental results from the multi-column SEWGS process development unit. In this test rig, various pipes interconnect all reactors. For the gas volumes in these pipes, gas composition and pressures fluctuate during operation, which may have an influence on the compositions and flow rates of the two product flows. This effect was simulated with the model, indicating that the volume of the interreactor pipes used for equalisation have only a minor effect on the SEWGS performance.

In a second validation step, breakthrough test data from the process development unit were used to estimate an adsorption isotherm at 400 °C and the mass transfer coefficient. Figure 8 shows the normalised dry CO₂ concentration of the product gas over time when a mixture of CO₂, N₂ and steam is fed to a SEWGS reactor, for varying CO₂ partial pressures. The isotherm was incorporated in the model to simulate the breakthrough tests accurately. In order to obtain the best match of the breakthrough curves, the theoretical mass transfer coefficient had to be slightly adjusted.

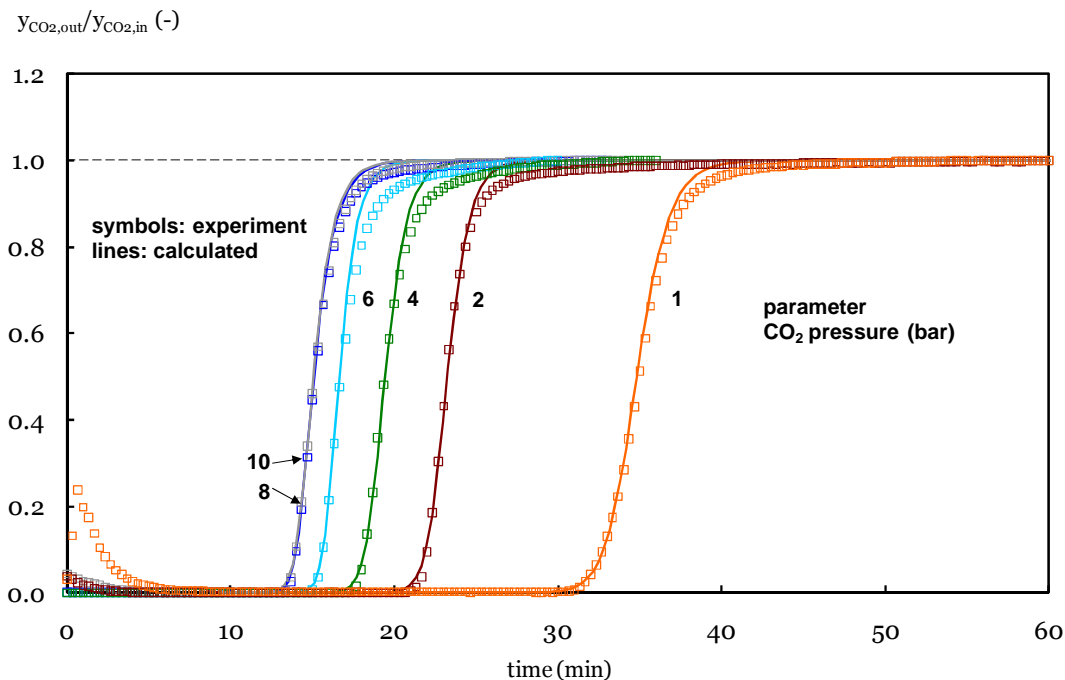


Figure 8 The model can accurately predict measured breakthrough curves under a range of CO₂ partial pressures (1 – 10 bar)

The desorption could be reasonably well simulated if the mass transfer coefficient was adjusted from the theoretical value, as shown in Figure 9.

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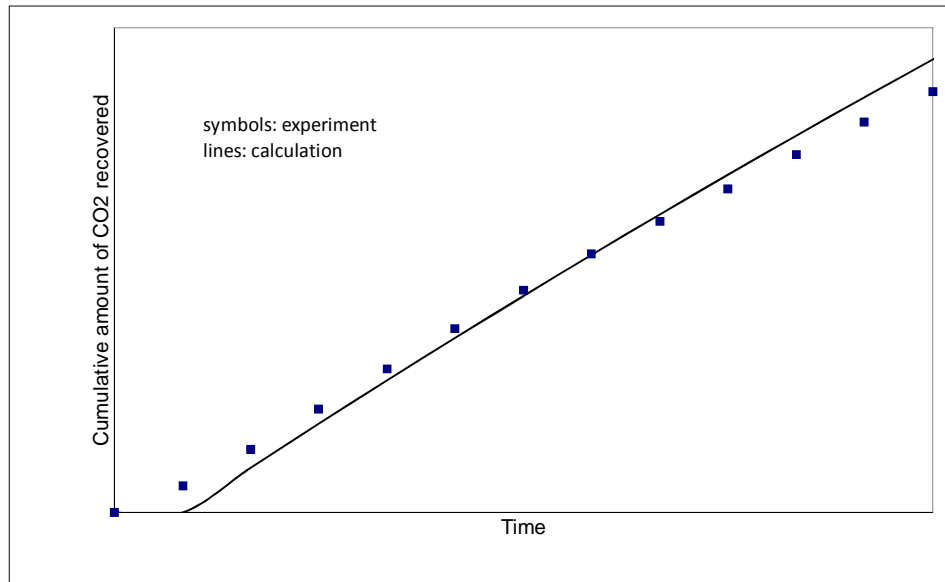


Figure 9 The amount of CO₂ recovered during regeneration as a function of time: measurements and simulation

In the coming years in this work package of the CATO-2 project, the model will allow determining the favorable temperature and pressure range for the SEWGS process and optimisation of the cycle. Moreover, novel cycles will be designed, primarily focussing on reduction of the quantity of rinse gas needed. The merits of novel reactor configurations will be investigated. Also, the cycle parameters will be optimised. The difference of optimisation for natural gas and coal-based syngas will be investigated. Optimisation of the cycle will be accomplished with respect to lowest costs of CO₂ capture, which can be determined by establishing a simplified capital cost model of a SEWGS unit and operational costs data.

3.3 PDU testing

ECN operates two SEWGS test rigs on the scale of about 25 kW_{th}. One test rig contains just one reactor vessel of 2 m tall, and is primarily used for characterisation of sorbents under realistic conditions, yielding estimations of working capacity and other key performance indicators such as steam consumption and cyclic stability. In this single-column unit, the effect of H₂S on sorbent performance can be investigated as well. The other test rig contains six reactor vessels of 6 m tall, and is primarily used for characterisation of the whole SEWGS process including the application of novel cycles and the effects of varying process conditions.

In the reporting period, some maintenance and repair activities of the SEWGS multi-column test rig have been completed. Leaking safety valves and steam shut-off valves have been replaced. The CO flow sensor was sent for repair to the supplier. Leaking check valves have been replaced.

Some short experiments have been performed in this test rig, providing data for validation of the SEWGS model.

Gas volumes of various sections in the test rig were determined experimentally, in order to be able to take this into account in the model and predict their effects on process performance, such

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as product stream purities. Also the sorbent porosity was experimentally determined with the same objective, which is important for instance because the mass transfer coefficient is dependent on porosity.

Breakthrough experiments under varying feed flow rates have been conducted to observe any external mass transfer limitations. In these experiments, the multi-column test unit loaded with an admixture of K-MG70 sorbent material and a high-temperature water-gas shift catalyst was used. For the largest feed flow rates, breakthrough capacities were slightly lower but additional testing is required to determine whether the difference is significant. The difference may also be attributed to the formation of $MgCO_3$ which will form more extensively for longer adsorption times, that is for lower feed flow rates. Hence, slightly longer breakthrough times could be expected for lower feed gas flow rates. It is expected that the absence of mass transfer limitations (film diffusion, see Figure 3) is confirmed when these experiments are repeated with a sorbent that does not form $MgCO_3$.

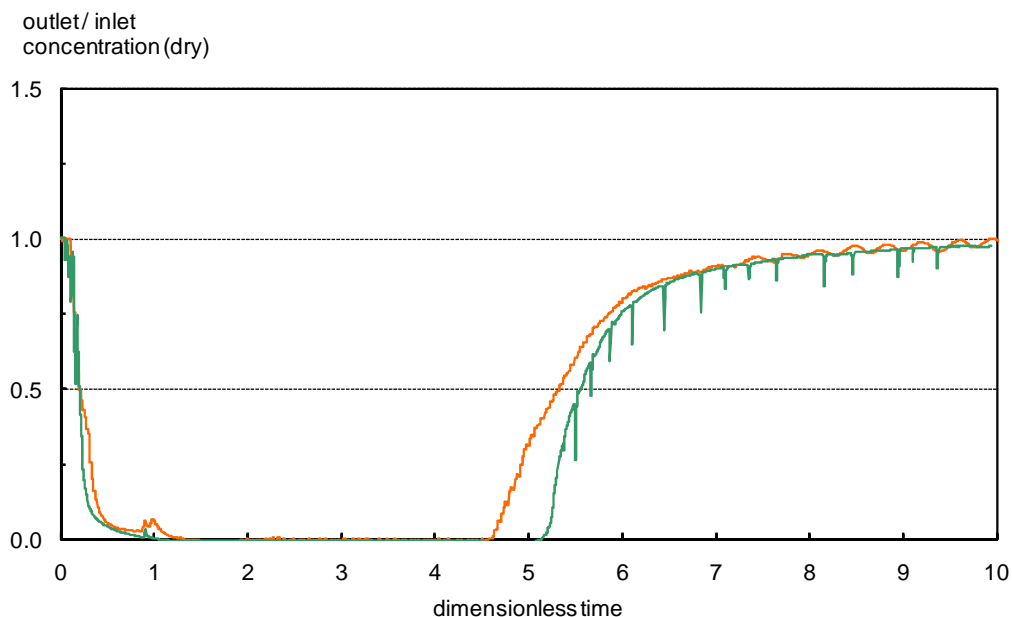


Figure 10 Breakthrough of CO_2 at 30 bar adsorption. Time is normalised with respect to residence time. Feed flow rates: (green) 17 slpm (orange) 32 slpm. Gas composition is fixed.

Dedicated desorption experiments showed the effect of purge flow rate of the efficiency of sorbent regeneration. The quality of these experiments was not optimal due to a mass flow sensor that did not always yield a correct flow reading. However, the data could be used for a preliminary determination of the mass transfer resistance during desorption. The desorption experiments will be repeated with improved metering equipment in place (see later in the text).

The thermodynamic and kinetic model contain lumped parameters, which may depend on operating conditions. In order to determine the effect of operating conditions on these parameters, a design of experiments was made. The design contains roughly 30 experiments, each of which is a breakthrough test followed by a desorption test.

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In order to obtain reliable experimental data, the following modifications in the multi-column test rig were engineered and constructed:

- Extension with an improved gas pre-sampling system to allow sampling from the reactor top, bottom, and in the reactor bed. With these measurements it will be possible to accurately determine of the kinetics of adsorption.
- Provision of Ar as a tracer gas in the feed gas, and configuration of the MS to measure Ar. This modification will provide a check on the dead times in the test rig and in the sample line.
- Extension of the product lines with dry test meters, which can measure the product flows much more accurately than flow sensors. These dry test meters do not need corrections for changes in the gas composition. With these meters, more accurate desorption curves can be established. Furthermore, they will support the mass balance reconciliation during cyclic tests.

In the next years of this work package of the CATO-2 project, and as part of the process development in Task 3, an optimized cycle will be demonstrated in the SEWGS multi-column test rig. Operation of the optimised cycle will be demonstrated for several thousand of cycles.

3.4 Process integration

In order to assess the merits of adopting the SEWGS technology in various applications, such as power production from natural gas and coal, thermodynamic flow sheeting studies have led to establishment of conceptual designs for these applications. The sorption enhanced reaction technology can also be used to produce decarbonized hydrogen for refinery applications, viz. gasification of oil residues. Corus is interested in the application of the SEWGS process to de-carbonize blast furnace gasses. Therefore, the feasibility of non-power plant applications i.e. refinery and blast furnaces was also investigated.

In the first year of the project, a sanity check on the application of SEWGS in a blast furnace was executed. The top gas from a blast furnace at Corus is partly used for power generation in a gas turbine, which is specifically designed for handling fuel gas with a low calorific value. The top gas contains large amounts of CO, CO₂ and N₂. It is first dedusted and then compressed before being sent to the gas turbine. The SEWGS unit would best be placed between the compressor and the gas turbine. A water gas shift reactor section just upstream the SEWGS unit could convert the bulk of the CO in the gas with steam to CO₂ and H₂. The concentrations of CO₂ and CO in the blast furnace gas are comparable to those in an IGCC application. Sulphur levels are so low that a conventional high temperature water gas shift can be applied. Addition of the shift reaction is required to obtain high carbon capture ratios, since CO would otherwise not be captured. Yet, a shift section requires substantial amounts of steam and may heavily penalise the efficiency. Hence, cost studies should indicate whether addition of a shift section increases or decreases the costs of CO₂ abatement. The value of SEWGS capturing CO₂ from blast furnace gas is that the hydrogen is produced at elevated temperatures, so that it can be directly fed to a gas turbine. Besides lowering greenhouse gas emissions, an additional benefit of carbon removal is the increase in calorific value of the fuel gas, which will substantially increase the efficiency of power generation.

In the following year, the optimal integration of a SEWGS unit in a blast furnace application will be studied and the favorable operating temperature and pressure will be determined. Cost studies will reveal advantages and challenges of the SEWGS technology and establish further R&D issues.

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By comparison of the costs of CO₂ abatement, the costs per avoided ton of CO₂, the most favorable application will be selected. However, this selection is not a straightforward comparison of CO₂ mitigation costs across sectors, since the options of carbon removal in the industries are rather limited compared to the available options in the power sector.

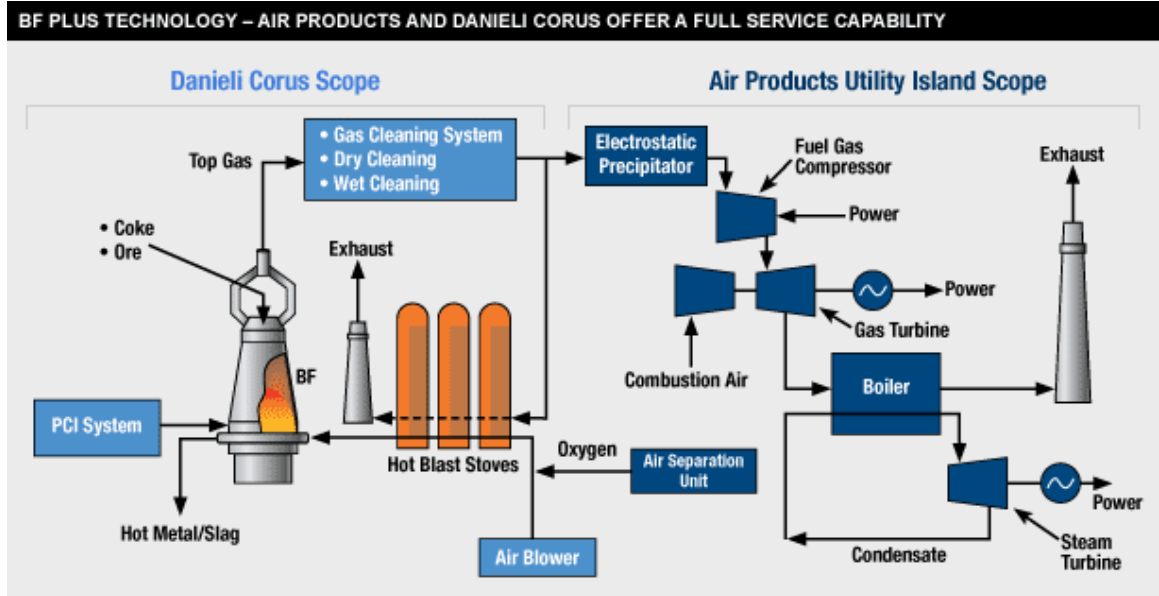


Figure 11 The blast furnace top gas is used as a fuel for power generation in a gas turbine (Picture from Air Products)

Possible applications for SEWGS are NGCC, coal gasification, oil gasification, and blast furnace gas. Criteria have been determined to determine in which of these the SEWGS technology will provide the highest value. This is predominantly determined by the cost of carbon capture, and by the size of the targeted market.

3.5 Dissemination

The following presentations were given in the first year of the project:

- E.R. van Selow. Pre-combustion Capture by Adsorption. 2nd Dutch Capture Technology Symposium, Utrecht, 14 December 2009.
- R.Th.J. Reijers. Simulation Results of the Pre-Combustion SEWGS Process. CATO-2 day, Utrecht, 4 June 2010.

The following abstract was accepted by the GHGT-10 conference for a poster presentation.

- H.Th.J. Reijers, E.R. van Selow, P.C. Cobden, J. Boon and R.W. van den Brink. Development of a Model for SEWGS: Validation and Process Cycle Optimization. 10th Conf. Greenhouse Gas Technologies, 19 – 23 September, 2010, Amsterdam.

More results from this work package will be disseminated through conference proceedings, peer-reviewed papers and patents in the coming years.

4 Location for a pilot plant

The demonstration of the technology in a pilot unit is a key step towards successful commercialisation. Currently, the SEWGS process has been demonstrated on a 25 kWth scale in the laboratory, with six reactors that can be operated with various pressure swing process cycles. Feed gases are always technical gases. Given a sorbent and an optimised process cycle, the performance of the SEWGS process is predominantly determined by the length of the reactors. Since the length of the reactors in the process development unit is close to the length of the reactors in an industrial unit, the performance in the lab is expected to closely match the performance in the field. The next step of designing a pilot plant would thus involve scaling-up the technology, as well as demonstrating the effects of impurities in industrial syngas on the SEWGS performance. It is aimed at making this step in the next couple of years.

An important decision to be made is the selection of the location of a host site. As a first step in the pilot plant planning process, the technology readiness should be accurately determined. All issues that can be solved in the laboratory shall be solved before building a pilot unit, since it will be much more expensive and time consuming to solve these issues once a pilot unit has been built. As a second step, the selection of the best application for SEWGS, such as NGCC, IGCC, or blast furnace application, should be made. The best application will benefit most from the characteristics of SEWGS in comparison to competing technologies, such as chemical or physical absorption. Also, the best application will have a large market potential. The choice of the best application will be an important criterion for the selection of a host site. A decision for a specific location will be made in the second year of the CATO-2 project.

The Technology Readiness Level (TRL) is an indicator used by many of major companies and by government agencies such as the NASA to assess the maturity of a technology before it is applied in a system. The primary purpose of using Technology Readiness Levels is to help management in decision making with regards to the development of technology. As such it is a tool for risk management and to make decisions concerning transition of technology. The nine TRLs are shown in Figure 12. A key element in the development of technologies is to make sure that all issues that *can* be solved at a certain TRL, *will* be solved at that level before moving to the next level. If a technology is classified erroneously in a too high TRL, then the development project risks being jeopardized by delays or cost over-runs.

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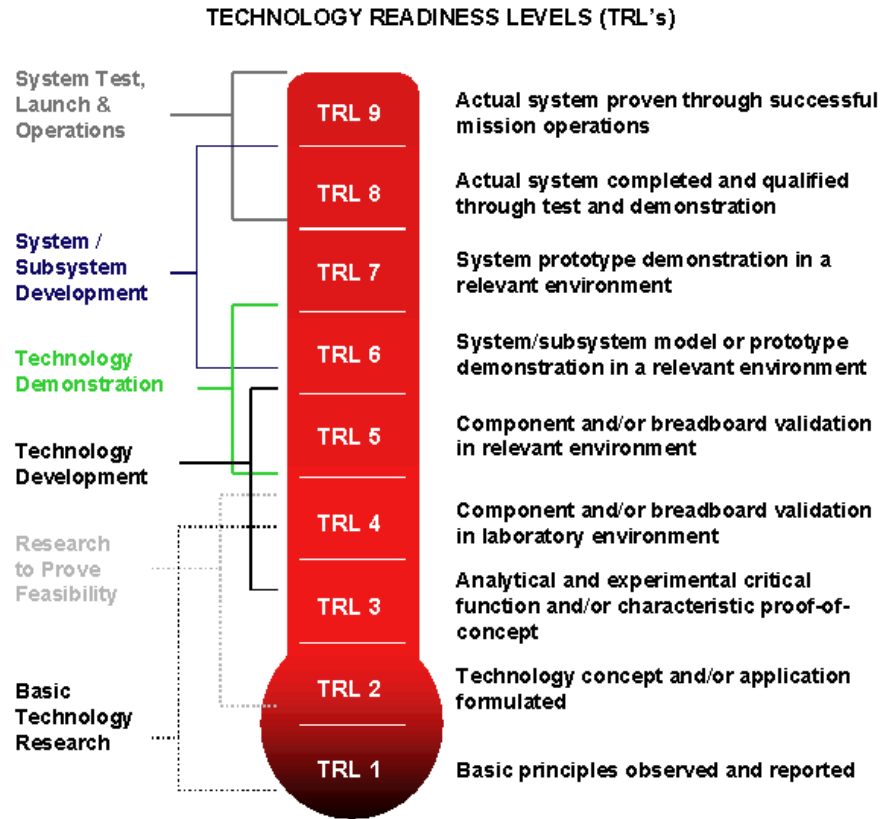


Figure 12 The nine Technology Readiness Levels

The maturity of the SEWGS technology was assessed by this method, shown in Figure 12. Based on the demonstration of the full cyclic process for thousands of cycles in the multi-column test rig, the Technology Readiness Level of SEWGS applied in a NGCC application was assessed at TRL 5, adopting the definitions used by NASA:

Component and/or breadboard validation in relevant environment. At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment.

When all issues at the TRL 5 have been solved, the next step of development would be the scaling up to a pilot plant and subsequent demonstration in a realistic environment, in TRL 6:

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system - which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding - would be tested in a relevant environment.

For the SEWGS development this would translate to designing, constructing and operating of a pilot unit with a full configuration of all components in a true industrial environment. The scale-up would be somewhere in between the laboratory system, roughly 10 kW_e, and a full size commercial unit, roughly 100 MW_e. The size of the pilot unit would preferably chosen such that a

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reliable scale-up can be made when going from the pilot unit to a full size commercial unit. It has to be born in mind, though, that the size will be limited by financial constraints and host site integration issues.

For the other applications of SEWGS, as mentioned in Chapter 3, the TRLs are lower than 5, primarily due to the effects of sulphur in the syngas on the SEWGS process. The SEWGS development for these applications should first be brought to TRL 5 before they can be considered as candidates for a pilot plant. Promising results (Van Dijk et al, 2010) indicate that the SEWGS technology for these applications may reach TRL5 on the short term.

A major objective of building a SEWGS pilot unit would be to demonstrate the value and the maturity of the SEWGS technology in an industrial environment. Issues to be addressed in this development level include: reliability of the high-temperature switching valves, vessel design, cycle performance such as carbon capture ratios, product purities, steam consumption, and importantly, long term stability of the sorbent.

An inventory of potentially suitable locations was made. The inventory includes:

- A hydrogen production facility
- A coal gasifier
- An oil residue gasifier
- A blast furnace

The pilot plant would operate on a small slip stream of syngas. A selection of a location should be based on the following criteria:

- Commitment of the host site management
- Sufficient plot area
- Availability of utilities and steam
- Assessment of the conceptual designs (most favourable applications)

Based on the current technology status, a hydrogen production facility would be the preferred location. Such facility could supply a sulphur-free syngas stream with a composition resembling a syngas from an oxygen-blown ATR. If nitrogen could be supplied the syngas composition could resemble the syngas from an air-blown ATR.

Choice of the location is needed to be able to define the user requirements, such as carbon capture ratio, feed gas composition including contaminants, and sizing. Next, a Basis of Design document will be drafted. Based on this document and on the results from Tasks 2, 3, 4, and 5 in this Work Package, a Basic Design Package of a pilot unit will be made in year 4. This design will include heat and material balances, process flow diagrams, piping and instrumentation diagrams, a Hazop study, a cost estimate and so on. The SEWGS pilot unit is then ready for detail engineering and construction by a subcontractor. Reliability issues will be identified and addressed.