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RESEARCH ARTICLE

Integrated System for Digital Monitoring of CO_2 Storage and Information of the Social Partners

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ABSTRACT

The author and a team are involved in an international project that aims to create a configurable system for monitoring CO2 deposits. The overall objective of the DigiMon project is to materially accelerate the implementation of Carbon Capture System by developing and demonstrating an a 'ffordable, smart, flexible and societally embedded Digital Monitoring early-warning system, for monitoring any CO_2 storage reservoir and subsurface barrier system. The aims is to develop and combine distributed fibre-optic sensing technology, seismic point sensors and gravimetry with proven Ethernet-based digital communication and near real-time, web-based smart data processing software with the information of the social partners in the potential risk area. This paper will present the system concept and component blocks.

Keywords: Carbon Capture System (CCS); CO2 storage; Digital Monitoring; SCADA System; Social Partners

Introduction

The aim of the DigiMon project is to develop and combine distributed fiber optic detection technology, seismic point and gravimetry sensors with digital communications and intelligent real-time data processing software, based on web technology to build a coherent and flexible SCADA system. The system will be flexible and interchangeable in terms of the environment (offshore or onshore) and the new components provided by technological development.

The key component of any Carbon Capture System (CCS) is measurement, monitoring and verification (MMV), which demonstrates that projects are planned, safe and executed in a useful, cost-effective way for society, ensuring safety and security. The system will have a special emphasis on the environment of communication and dissemination of knowledge with the public and decision makers (internal and external to the operating site).

The project involves the development and integration of modules and system components, available at different levels of technological training (TRL). The project will develop the system components to a uniform, consistent, high TRL before integrating the components into the early warning system.

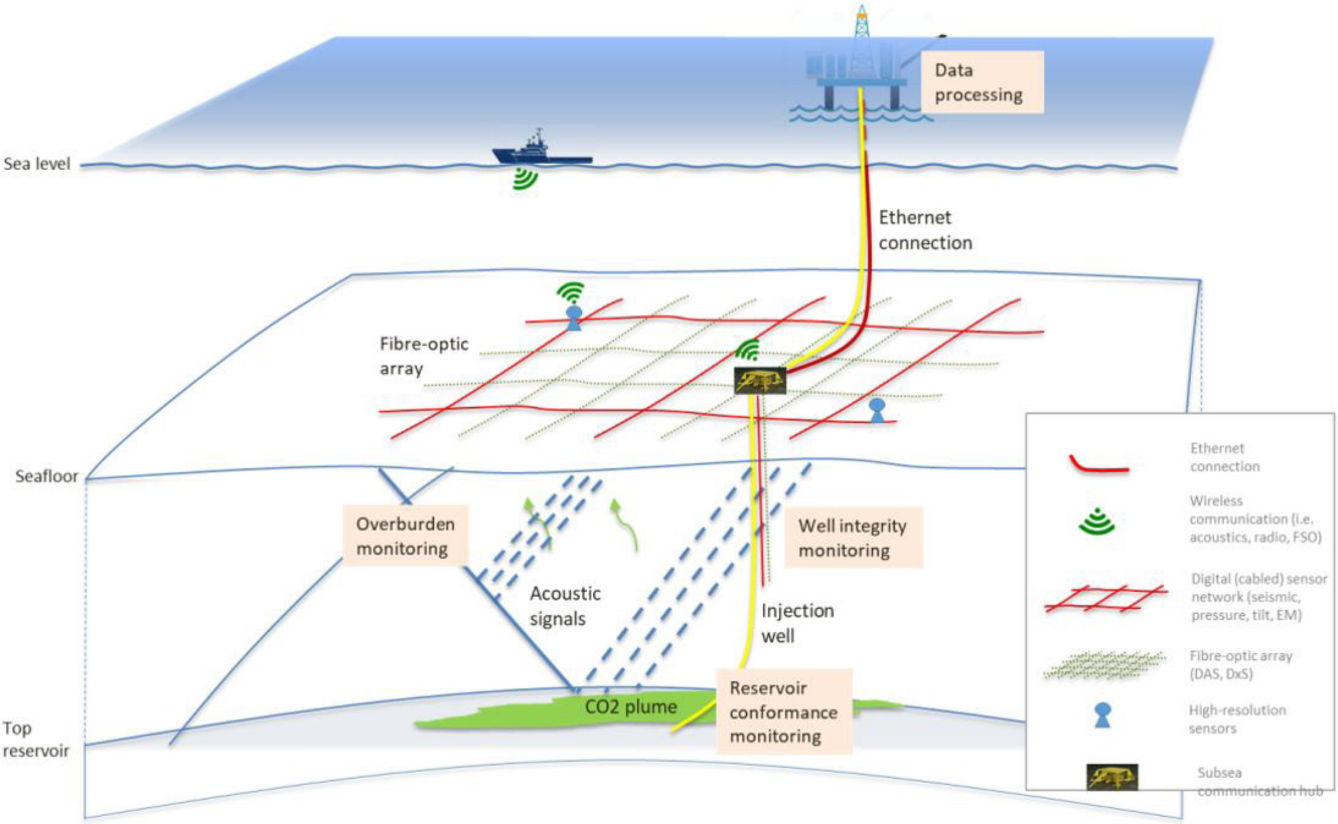

Figure 1: Digital Monitoring system of CO2 storage

One of the most critical R&D challenges lies at the heart of this project - integrating a broad range of technologies for MMV at CO_2 storage sites (i.e. distributed fibre-optic sensing technology (DxS), seismic point sensors and gravimetry). Combined with Ethernet-based digital communication and near real-time, web-based smart data processing software, the project presents a novel, cost-efficient early-warning solution for monitoring CO_2 storage reservoirs and subsurface barrier systems. In addition, it uniquely considers the possibilities of monitoring technologies for CCS from the point of view of societal acceptability, trust and benefit. Such a system is desired by, but not yet available to, the CCS industry and other industries exploiting subsurface resources.

This paper will explore the system concept and the block components of the system that will assure the necessaries functions.

From a technological point of view, the CCS chain consists of three parts; capture of carbon dioxide, transport of carbon dioxide and safe storage of carbon dioxide emissions, underground, in depleted oil and gas fields or in deep salt formations.

First, capture technologies allow the separation of carbon dioxide from gases produced in electricity generation and industrial processes through one of three methods: pre-combustion capture, post-combustion capture and oxygen with fuel. The carbon dioxide is then transported by pipeline or by ship for safe storage. Millions of tonnes of carbon dioxide are already transported annually for commercial purposes, by tanks, ships and pipelines.

Carbon dioxide is then stored in storage spaces, made up of carefully selected geological rocks, which are usually located a few kilometres below the earth's surface.

The commercial development of CCS involves the widespread adoption of these CCS methodologies and techniques, combined with robust monitoring techniques and government regulations. CCS is one of a number of technologies needed to combat climate change, including renewable energy, nuclear energy and energy efficiency.

Technical and scientific solution

CO_2 storage in geological reservoirs is a key component of most strategies to reduce greenhouse gases in the atmosphere. CO_2 is captured at emitters, such as power plants, and is injected through deep drilling holes in subsurface storage tanks (carbon capture and storage - CCS).

A number of measurement, monitoring and verification (MMV) strategies can be used to ensure that CO_2 remains in place. As a regulatory requirement, MMV plans must demonstrate Compliance (that models are aligned with monitoring data), verify Content (be able to ensure that there are no leaks), and provide Contingency plans (taking corrective action in in case of a leak) for CO_2 storage projects.

The overall goal is to demonstrate the commercial availability of a digital monitoring system that is suitable for cost-effective and socially accepted CO_2 storage MMV.

The system will focus on:

- Monitoring the movement of feathers in the tank using mainly remote passive geophysical measurements of saturation and pressure changes (compliance monitoring).
- Monitoring the integrity of the well, mainly by detecting downward pressure, temperature and rock tension (monitoring of retention and contingency).
- Overload monitoring, including monitoring of CO_2 migration from the upper area and early detection of anomalies (retention and emergency monitoring).

A monitoring system oriented towards human safety

Public support is vital for the development and development of CO_2 storage projects. Lack of public support weakens political support, reduces deployment and accessibility, and may require alternative technological configurations and risk management practices (Watson, Kern, & Markusson, 2014) [3].

The lack of political support has already hindered the deployment of CCS in some countries (Raven, Kern, Verhees and Smith, 2016) [2,4, 5].

In many cases, it is not a lack of knowledge, but a lack of trust in systemic issues, so stakeholders simply do not believe what they are told.

One of DigiMon's goals is to find out if and how these CCS monitoring systems can help alleviate local communities' concerns about any impact.

However, the support of these communities for the project is based primarily on the equitable distribution of costs and benefits, the correct decision-making process and the building of trust in developers and governing authorities ([10,6] Huijts, Molin and Steg, 2012; Wüstenhagen et al. al., 2007; Van Engelenburg & Puts, 2015) [7,8,9] and also to clarify what are the possible benefits for a community.

Previous research programs on mining have found that the participation of all relevant stakeholders and the consideration of their perceptions, interests, questions and concerns about a project or technology are key factors for the integration of new energy technologies in society and promote procedural justice, trust and confidence, in project developers and government authorities and public support for the project (Duijn & Puts, 2013) [1].

Societal embeddedness of a CCS monitoring system is characterized by 4 dimensions, which are the impact on environment, stakeholder involvement, policies and regulations, and market and financial resources. In terms of monitoring aspects, they are translated as follows:

- monitoring system contribution towards reducing or preventing CCS environmental impact
- monitoring system contribution towards engaging organizations or individuals involved or affected by CCS
- monitoring system contribution towards developing and complying with CCS policies and regulations
- monitoring system contribution towards mobilizing market and financial resources for CCS projects
- to create an informatic SCADA system that integrate all the facilities

In order to effectively contribute to trust-building among stakeholders, a CCS monitoring system should be low cost, efficient and easy to maintain over a long time, measure and predict leakages and plume movement, transparent, allowing real-time access to monitoring data, provide continuously reliable access to experts for questions on the data, externally supervised by unbiased institutions and connected to a safety concept that states what happens when the data divert from normality.

Solution aimed at preventing the impact of CCS on the environment

Technological developments are all directly related to the environmental dimension of the societal embeddedness, by providing cost efficient methods to monitor and reduce the impact to the environment of CO_2 geological storage.

The instrument response and site response determination, as well as the development of processing techniques for micro seismic data of a Distributed Acoustic Sensing (DAS) system allows recordings to be converted to velocity in a similar way to the conventional methods used for geophones. This permits a DAS fibre-optic system to map the subsurface seismic velocity field in a geological storage site. The evolution of seismic velocity field over time can provides an image of CO_2 plume location and expansion, as well as an early warning of potential CO_2 migration in the water table or potential leakages at the sea floor or ground surface.

Cross well seismic velocity tomography provides direct calibration to depth of seismic surveys, making possible CO_2 plume mapping and its evolution at depths greater than 400 m, where seismic velocity calculations accuracy from surface recordings alone drops below the level required to identify velocity changes related to CO_2 movement.

The development of data acquisition techniques and processing software for a time lapse microgravity survey provide another accurate and cost efficient method for subsurface CO_2 plume mapping and evolution, by defining the subsurface density distribution. Coupling with a distributed strain sensing (DSS) fibre-optic system will provide a cost efficient mapping of seafloor or ground surface deformation and the necessary calibration to the density data.

System structure

The objectives are:

- Integration of the constituent subsystems of the DigiMon system in a coherent and unitary informatics system aiming to ensure the functions proposed by the project.
- Elaboration of the structure of an IT system for increasing the safety in operation in units subject to technological risk.
- Define a communication system between the sensors / equipments situated in the technological field and the control room
- Define the sub-systems and the functions they assure.
- Elaboration of the structure of an IT system to communicate with social partners;
- Homogenization of information between the social partners interested in the system

We proposed a modular, configurable, distributed and open system for monitoring and control of the technological process, monitoring the utilities and informing the decision and information factors (inside and outside the technological unit), in a format specific to the attributions and the workplace.

The subsystems we want to integrate in the unitary and coherent system are:

- DAS subsystem
- Seismic tomography
- DCS for CO_2 leakage monitoring
- 4D gravity and seafloor subsidence data acquisition system
- Modelling framework at CCS sites
- Technology Platform Monitoring
- Risk analysis, simulation and management
- Informing social partners

The structure of the functional blocks of the informatics system is shown in the figure below.

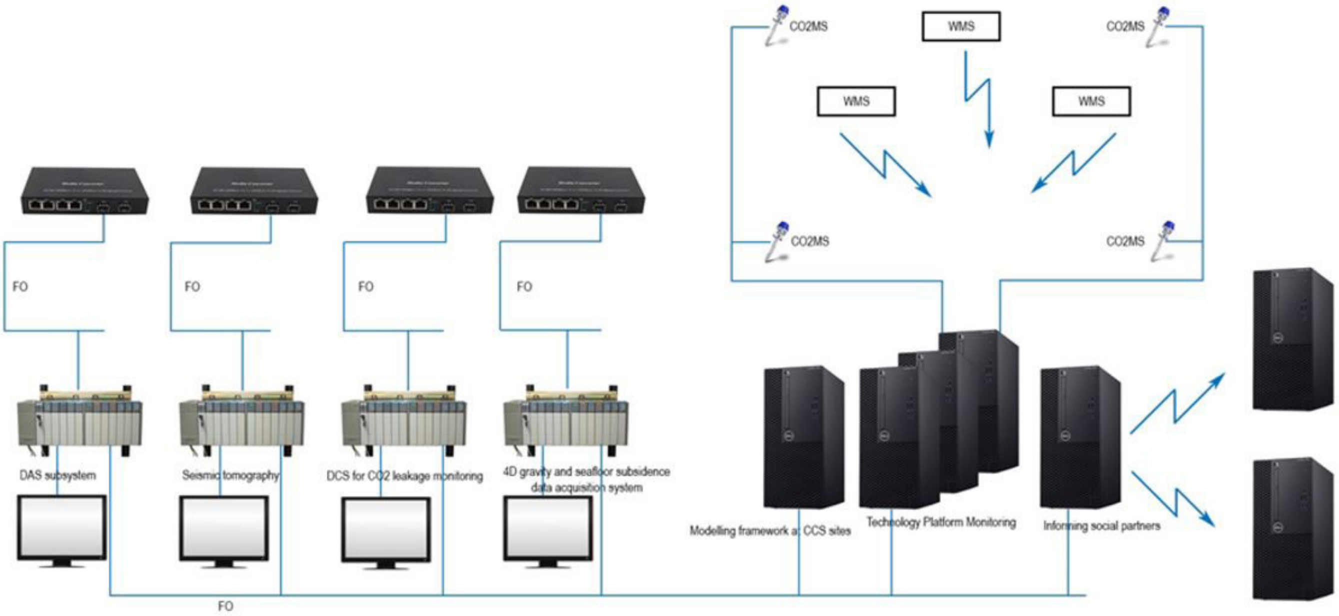

Figure 2: Block diagram of the informatics system

Security and chemical alarm system

A hierarchical system was conceived, openly distributed with the possibility of development in stages, with the possibility of further integration of other subsystems.

The subsystems that are the object of the present documentation, being security systems, must be implemented the concrete ways of safety supply. he need to achieve a distributed, reliable, redundant system that allows easy calibration and maintenance of the monitored sensors and equipment in the system was taken into account.

The implemented schemes take into account the need for fast transmission of information to the decision makers of the Technological Platform subject to the technological risk in the impact region.

The described system lays the foundations for the realization of the INTRANET of the technological platform through its components of monitoring / analysis of the factors that determine the chemical alarm plan and informing social partners / decision makers.

Based on the analysis of the technological process, of the operative management and its operation, of the conditions and impositions regarding the safety in operation, an integrated IT system solution of type Decision Support System / Management Support System - SCADA was proposed and implemented which leads to an increased safety in operation of the technological process.

We proposed a modular, configurable, open system for monitoring and control of the technological process, monitoring the utilities and informing the decision and information factors (inside and outside the technological unit), in a format specific to the attributions and the workplace.

From a constructive point of view, the system, the software packages ensure:

- Risk assessment through the System I and II module
- Risk management through the module Monitoring system of the technological process related to risk areas,
- Analysis and management of risk situations through the Data Communication Modules, information, analysis, Decision Factors.
- Data security; Firewall. WAN communications.

By implementing the system and the software packages, the increase of the safety in operation in units subject to the technological risk is ensured. The application program package also includes the compatibility with the other subsystems, data communications in the LAN network and in the WAN network.

By decision factors we mean the internal compartments of the unit as well as units outside the Technological Platform / the social partners: the Inspectorate of Environmental Protection and the Inspectorate of Civil Protection and other information units.

System functions provided:

- Taking over the characteristic data from the Technological Platform
- Monitoring and control
- Simulation and virtualization
- Determining the possible chemical outbreak, monitoring accidents, determining the causes and potential effects
- Informing decision makers including the social partners in the potential risk area.

The factors that contribute to the fulfillment of the chemical alarm plan are:

- The local dispatcher who determines and remedies the cause of the chemical outbreak;
- The chemical alarm dispatcher who applies the chemical alarm plan in case of an accident affecting a larger area inside or outside the plant;

- The Civil Protection Inspectorate involved in case the accident spreads and affects areas outside the plant;
- The Environmental Protection Inspectorate as a control body, ascertaining;

In order to control the technological process, the industrial management, in safe conditions in operation on the Technological Platform, it is necessary to interconnect the SCADA type subsystems in a unique system of acquisition, processing, monitoring and data transmissions to form the basis for the Intranet of the Technological Platform.

Through this concept, the unitary view of the concepts of technological risk, industrial safety, prevention of accidents by real-time monitoring of the technological process is achieved.

The role of the system is to prevent risk situations through the security component and to support the human factor in order to make optimal decisions within the chemical alarm plan by providing adequate information in a format specific to the duties and the workplace.

The system that is the object of this documentation takes into account these aspects, its forecast and information component realizing:

- determining the place where the outbreak occurred;
- determining the amount of leaked gas;
- determination and presentation of meteorological parameters;
- determining the shape of the cloud and its evolution;
- presentation of the evolution on the map of the region;
- real-time information of decision makers inside and outside the plant;

By coupling the sensor system, the origin of the leak can be determined precisely.
By correlation, the gas escape cone from the technological platform can be determined, as well as the evolution of the gas cloud.

The proposed systems are based on the concept of distributed and open system, and can be adapted and extended in successive stages and interfaced with applications so as to cover the requirements of a security and emergency response system, operating in conditions of technological risk.

The systems provide information to the departments that contribute both to the operative management of the technological process and to the follow-up and decision-making regarding the impact of a chemical event on the area inside or in the vicinity of the Technological Platform.

Within the chemical alarm plan, depending on the location of the chemical outbreak and the amount of gas escaped, a certain scenario is chosen.

In the final stage, the system could provide, as an operator guide, the information necessary to choose the intervention scenario, each scenario leading to the choice of the appropriate action plan.

CO2 dispersion, impact zone forecast, simulation

Atmospheric dispersion of CO_2 is in many cases very fast. However, there is a time when the atmosphere is very stable and does not lead to dispersion.

The factors involved in atmospheric dispersion are:

- Extremely unstable atmospheric conditions lead to a rapid mixing and dispersion of airborne particles, while stable atmospheric conditions inhibit mixing;

- Mechanical turbulence due to wind, uneven terrain and forests;

- Existing temperature gradient up to 30 m in the atmosphere;

- The most unfavourable condition for dispersal is the calm atmosphere of quiet nights or early morning, as well as a not too high cloud ceiling;

- The best condition for dispersal is the strong sun and wind breezes in the upper layers of the atmosphere.

- During container explosions, leaks or gas pipes, the area that is affected is not fixed, but depends on many parameters, among which are:

- Direction of the exhaust gas (vertical or horizontal); Wind direction and speed;

- General environmental conditions: day / night, clear / dark, sun / cloud, rain / humidity;

- Gas emission speed; Gas and ambient temperature;

- CO_2 concentration of the gas; Topography of the land;

The potential risks presented by the storage and transport of chemicals are realized in three stages: Risk identification; Impact analysis; Risk analysis.

Gas (CO_2) leaks into the atmosphere can be simultaneous or successive. The main parameters taken into account in the modelling are: initial gas density; type of escape: instantaneous / continuous; the type of terrain in the impact area.

Industrial security system

The project analyzed and proposed a unitary solution for the following subsystems:

- **DAS subsystem.** DigiMon will investigate how classic, currently in use, micro seismic event detection techniques perform on synthetic and real DAS data. These methods will then be extended to investigate how machine learning techniques can assist or replace the current workflows. A similar approach will be applied to event location, magnitudes and mechanisms. The algorithms will be optimized to enable near real-time processing.

- DigiMon will also investigate how ANI techniques can be extended to DAS data to improve subsurface imaging capabilities. The results will be interpreted to improve understanding of geological structure and geomechanical responses to CO2 injection. This will provide input to the geomechanical modeling.

The DAS subsystem has two subsystems:

✓ **Seismic tomography subsystem.** DigiMon will develop a new SV-wave source which will be tested in the field for comparison with existing technology (SH-wave and P-wave sources) and suitability for tomographic surveys. Data will be collected using conventional and DAS technology and monitoring designs tested for their ability to provide results with the required resolution.

The task will investigate the best deployment methods and set-ups for DAS cables in offshore settings to achieve good data quality - what type of cable should be deployed and how should it be coupled to the seafloor. The possibility coupling fiber deployments to refraction surveys and full-waveform inversion will be investigated using synthetic data, feasibility studies and, if available, field data. Existing datasets from time-lapse seismic reflection surveys and the Oseberg PRM will be investigated to determine how these surveys could be further optimised for monitoring.

✓**DCS for CO_2 leakage monitoring.** The sensors will provide the in-line measurement we need, to the desired accuracy, to exercise control over technological processes. The CO_2 sensors will provide feedback on the CO_2 in the process, without the need for sampling.

Dissolved CO_2 is a harmful and unwanted by-product that occurs naturally during cell culture processes. High dissolved CO_2 levels cause unwanted metabolic changes, growth inhibition and low productivity. The dissolved CO_2 sensor provides real-time CO_2 analysis, allowing rapid reaction to extra-specific changes in CO_2 concentration.

- **4D gravity and seafloor subsidence data acquisition system.** Information obtained from 4D gravity and subsidence monitoring provides improved decision-making in the exploitation of offshore reservoirs.

Field cases demonstrate the impact of this technology in the estimation of hydrocarbon volumes, the evaluation of risk of water breakthrough, understanding of drive mechanisms and identification of untrained compartments, the identification of infill-well targets or by the optimization of compression facilities.

4D gravity is sensitive to changes in the mass distribution in the reservoir. Gas depletion and water influx from surrounding aquifers produce an observable time-lapse gravity signal. The observed signals are independent of seismic velocities, which make this technology complementary to seismic monitoring. In addition, gravity provides a more precise quantification of mass changes than 4D seismic, and it can provide a better sensitivity to the movement of the gas-water contact.

- **Modeling framework at CCS sites.** Modeling of CO_2 capture, transport and storage allows the modeling of CO_2 pipelines and pipeline networks.

The CO2 capture and storage (CCS) assessment includes the capture of CO_2 from both existing and new CO_2 storage facilities. The pipelines in the updated model are endogenously configured to be optimally consistent with the latest capacity and cost data for the storage resource base.

The model allows the analysis of different combinations of sources, in different economic and technological scenarios. DigiMon will develop a software application of the model to assess the role of CO_2 capture, transport and storage.

- **Industrial management subsystem** - is the core of optimal management of the industrial process, informing decision makers, creates the necessary infrastructure for information flows. The subsystem comprises 3 servers: general, for Internet and external communications, for management.

- **Technology Platform Monitoring** - has the role of monitoring technological parameters, framing between functional limits, pre-alarm and alarm in case of exceeding limits, displaying information on synoptic schemes and database management, in order to prevent accidents and breakdowns. Database analysis can provide criteria for optimal operation of the installation.

The subsystem follows the quantities that characterize the technological process (pressures, differential pressures, liquid level, flows, temperatures, PHS, in areas established by the risk study, etc.). The Technological Process Subsystem could integrate:

✓ **Utilities subsystem** - has the role of monitoring the parameters that characterize the technological utilities. Considering the fact that the technological process is correlated with the functioning of the utilities, the subsystem can be included both in the function of accident prevention and in monitoring the efficiency of the technological process by highlighting the internal consumptions.

✓ **Sensors subsystem from the technological process** - has the role of monitoring the technological parameters and the concentrations of CO_2 gases escaped inside and in the immediate vicinity of the technological installations.

✓ **Sensors subsystem on the perimeter of the technological process** - has the role of monitoring the amounts of CO_2 gases released around the installations, monitoring environmental factors and forecasting the evolution of the toxic cloud in case of an accident.

The subsystem estimates the location of the accident as well as the amount of gas escaped. It allows the detection, control and identification of various emission sources as well as fugitive leaks. Analytical, meteorological and cartographic data are taken into account, which allows establishing a forecast of the diffusion of pollutants and the evolution of the CO_2 cloud according to the information taken automatically.

✓ **Independent Sensors Subsystem** - Independent sensors are located next to the critical points established by the impact study, the channel mouths which by their nature allow CO_2 leaks or leaks. The adapters to which the sensors are connected ensure a local audible alarm (hoop) and light alarm (beacon) in case of accidental leaks above the preset limit. The monitoring subsystem ensures the automatic acquisition of the quantities that characterize the independent sensors, the transmission of this information to a dispatcher, their presentation and management in a database.

✓ **Environmental monitoring and forecasting subsystem.** Environmental monitoring and forecasting subsystem. It is a subsystem made up of all the environmental sensors (CO_2) located underwater and above the water, perimeter of the technological platform that analyses the potential pollution (CO_2). Together with 3 automatic stations for measuring the weather parameters (temperature, atmospheric pressure, wind direction and speed, amount of precipitation) it can make the forecast of potential pollution.

- **Informing social partners; Subsystem Data transmissions to social decision makers** - Civil Protection Inspectorate and Environmental Protection Inspectorate - Data obtained by acquisition and processing, from transducers and sensors as well as data characterizing the evolution of the possible gas cloud are transmitted as they are transmitted specifically to social decision makers.

These data are presented on the map of the region highlighting: the place of the accident, estimating the amount of gas escaped, weather parameters in the immediate vicinity of the outbreak, highlighting possible scenarios and intervention measures.

Data flows between subsystems and social partners

Package programs "data transmissions to social partners"

The necessary information, which is transmitted, is:

a) the quantity of gases emitted into the atmosphere;

b) framing between technological limits of operation;

c) wind direction and intensity;

d) the evolution of the gas cloud superimposed on the map of the region.

The system allows the detection and modelling of accidental gas discharges that may occur in the vicinity of technological installations.

- Detection and surveillance of gas discharges in the vicinity of technological installations;
- Monitoring of METEO parameters in the meteorologically significant neighbourhood;
- Gas cloud modelling based on both real-time data taken from subsystems and performance algorithms for modelling and estimating cloud evolution.
- Remote reporting of information to decision-makers inside and outside the unit (informing the social partners) in order to make optimal decisions.

Package programs "detection and forecasting"

The system forecasting and information component performs:

- determining where the defect/outbreak occurred, the amount of gas dropped;
- determination and presentation of meteorological parameters;
- determining the shape of the cloud and its evolution;
- presentation of evolution on the map of the region;
- real-time information to decision-makers on and off the perimeter (informing the social partners);
- presenting information in a format that allows optimal decisions to be made

Package programs "chemical analysis and alarm"

The chemical alarm component achieves:

- Communication with Sensor /Translator/Analyser subsystems,
- Toxic gas monitoring;
- Monitoring of meteorological parameters
- Determination of escapes, quantities, concentrations
- Determination in points / areas, on the map of the region or inside the perimeter,
- Determination of the affected area according to weather conditions;
- Correlation escapes – quantities – concentrations – weather conditions – evolutions;

- Monitoring on synoptic schemes and map of the region in the GIS sleeve;
- Generating acoustic/visual signals (gyro far) for punctual or local accidents;
- Generating acoustic signals, gyroscope, operating barriers in case of zonally accidents;
- Management of databases on inventory of activities at risk of chemical accident;
- Management of chemical alarm scenarios;
- Simulation

Activities with a chemical accident risk factor require that, in addition to the measures that are currently being taken, safe operation, there is a control and a continuous assessment of the risk, the possible consequences, and a system for monitoring the state of operation of installations, environmental emissions and concentrations of pollutants.

Acknowledgement

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