Optical fiber based monitoring system for high pressure composite vessels for hydrogen storage

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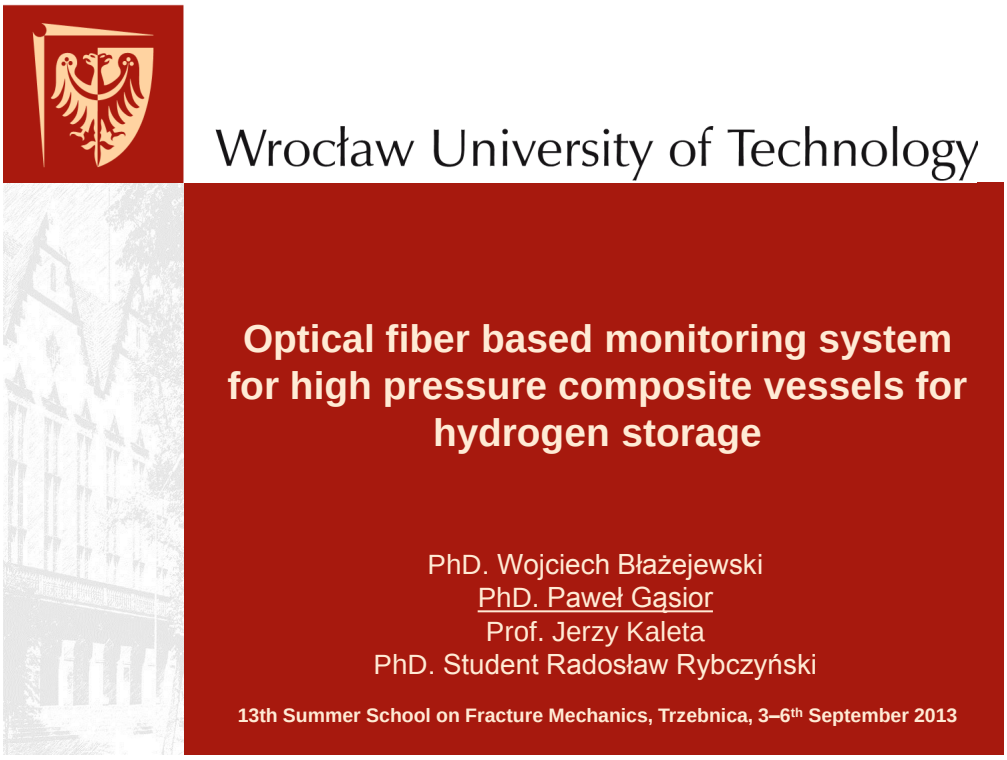
Trzebnica, 3–6 th September 2013



*Wrocław University of Technology, Institute of Materials Science and Applied Mechanics

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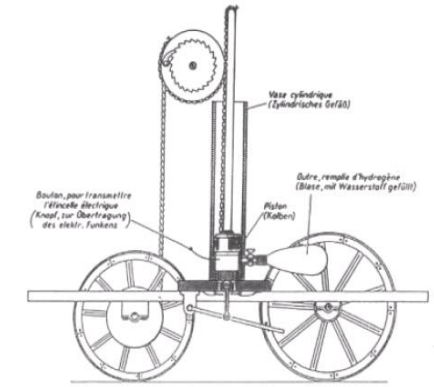
A bit of history… the first experimental vehicle powered by hydrogen gas



Darstellung eines Kraftfahrzeugs von Rivaz mit einem atmosphärischen Flugkolbenmotor, nach der Patentschrift vom 30. Januar 1807; Rivaz bezeichnete die Idee seines Motors als Anwendung der „Pistole, dit de Volta"

In 1807 Francois Isaac de Rivaz (French engineer) designed the first internal combustion engine that ran inside the first automobile. The Rivaz car stored compressed hydrogen gas in a balloon and it had an electrical Volta cell ignition.

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Modern hydrogen cars


DC Hygenious F600


Audi A2 FC Hybrid


MAN H_2 ICE Bus


Hyundai ix35


GM HyWire


DC FC Citaro


VW
FC Touran HyMotion


BMW LH_2 ICE


DC FC Sprinter

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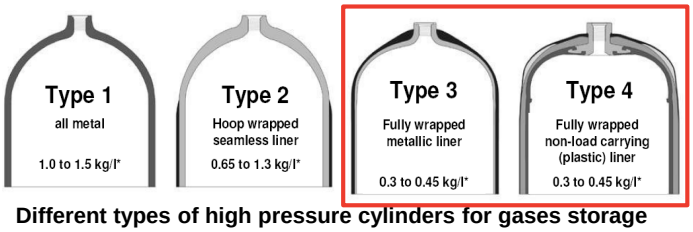
Cylinder designs and its applications

CNG or CH2 storage for automotive and stationary applications

Rescue and sport equipment



Different types of high pressure cylinders for gases storage

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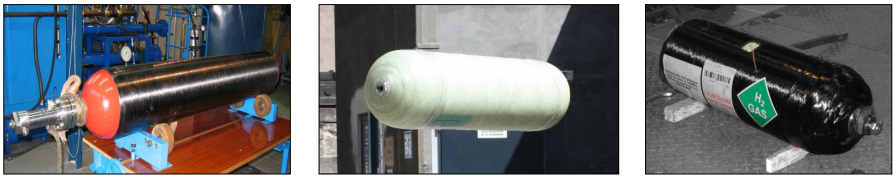
High pressure vessels for hydrogen storage. Main parameters

Nominal Working Pressure: **up to 700 bar**
Burst pressure: **≥ 1645 bar (CH2)**
Cyclic test pressure: **1.25 x NWP**
Number of cycles: **45000**
Temperature : **-45ºC ÷ 90ºC**
Humidity: **0 ÷ 95%**

Test vessel after burst test



High pressure vessels for CH2 and CNG storage – type II, III i IV

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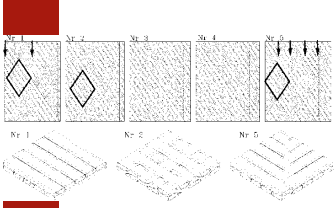
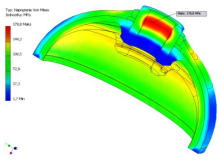
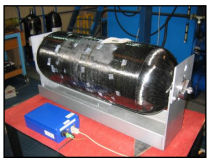
WUT experience in European and National „vessels" projects (FP6, FP7, EIT – KIC, etc.)

- testing of high pressure vessels
- optimization of winding geometry of composite layers
- ''on-line" monitoring sensor system
- new material testing
- modelling of composite structures and running damage processes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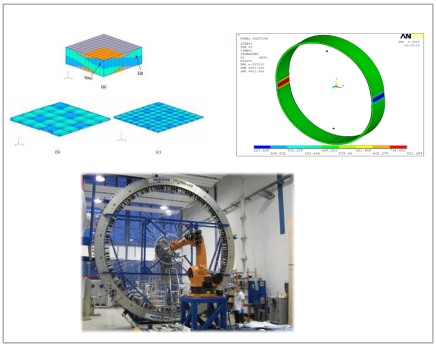
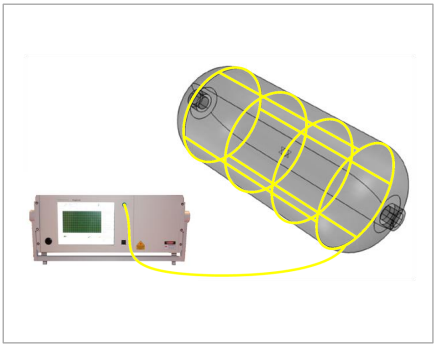
Smart composite high-pressure vessels. How to reduce weight, costs and make them safe at the same time?

Large scale application of high-tech composite vessels requires effective solutions to several problems. The most important are:

- **optimization of production technology** with a view to reducing their weight and production costs, ensuring mass application of such vessels,
- **ensuring safety** of 10-to-15-year exploitation of the vessels (Smart vessels with integrated on-board monitoring system).

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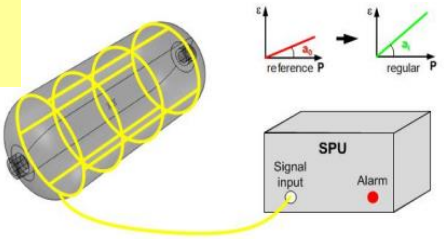
Concept of vessel's on-board monitoring system. Requirements

- Low cost on-board system
- Detection of critical parameters
- Control of degradation processes in composite structure
- Prediction of a lifetime

Standard NDT methods such as interferometric holography, ultrasonic scanning, ESPI, acoustic emission or visual inspection **do not prove precise enough** in the process of on-line monitoring of high pressure vessels.



Concept of the monitoring system for high pressure vessels

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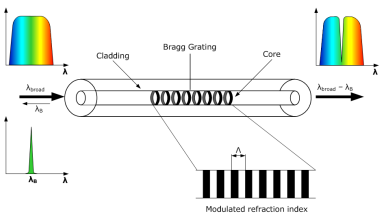
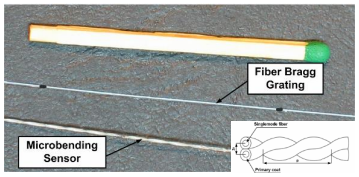
Optical fiber based monitoring systems for vessels monitoring. FBG & interferometric (SOFO®) sensors

SHORT-GAGE SENSOR

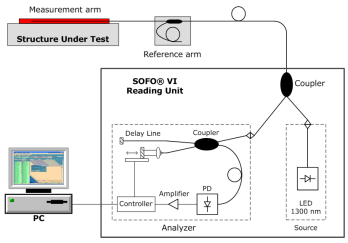


Working principle of FBG



Bare fiber sensors

LONG-GAGE SENSOR



Working principle of SOFO® interferometric system

SOFO® SMARTape

SMARTEC

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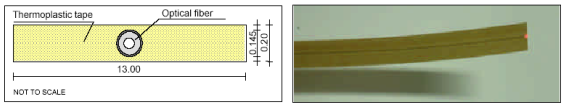
Advantages of optical fiber based measurements methods

- High strain (-3%.. 3%, resolution 1 με) and temperature (-270 .. +800°C, resolution 0.1 K) sensitivity.
- Linear strain and temperature characteristics.
- Advantages connected with optical fiber features:
  - insensitive to high temperature, EM fields, corrosion,
  - no spark (safe for flammable materials),
  - lightweight and small dimension,
  - easy to integrate with monitored objects,
  - resistance for a cyclic loads.



Optical fiber sensors (FBG) for strain measurements

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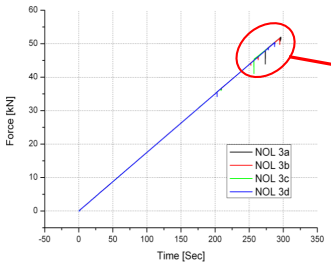
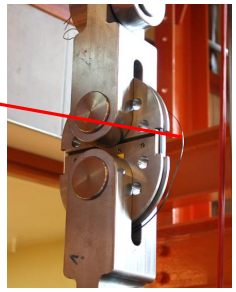
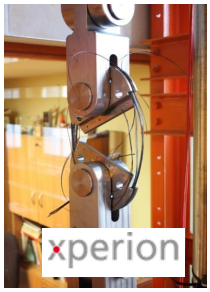
Verification of testing method (1). NOL specimens

- Composite NOL specimen simulates cylindrical part of high pressure vessels.
- Calibration of strain measurements done by OFS with Acoustic Emission in order to register damage accumulation process.







NOL specimens during slow tensile test

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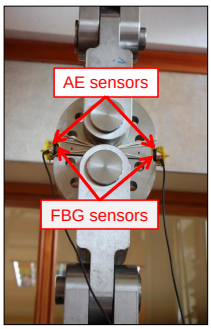
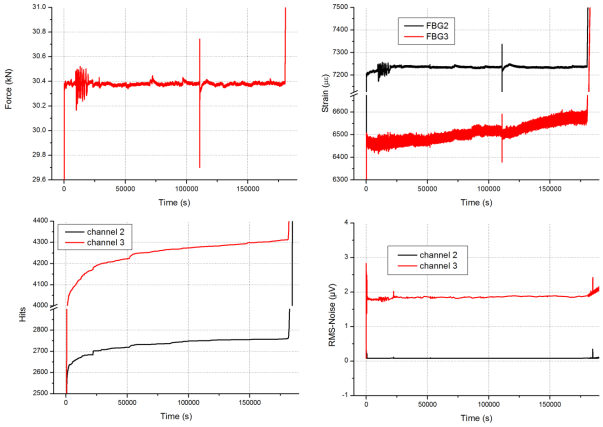
Verification of testing method (2). Creep test of NOL specimens



FBG and AE sensors installed on NOL specimen



Applied constant load (30,38 kN) was equal to 60% of an avarage value of maximum forces.

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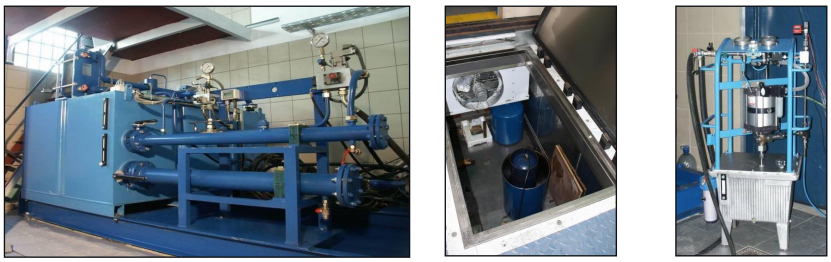
Testing of high pressure vessels for CNG and CH2 storage (1)

Standard tests of high pressure composite vessels:

- Cyclic test (ambient and extreme temperature pressure cycling)
- Quasi-static test (burst test)
- Test with programmed defects (flaws and delamination) – quasi-static and cyclic



Hydraulic equipment for cycling and quasi-static tests at ambient and extreme temperature

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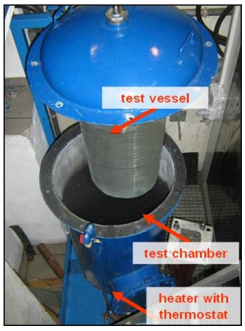
Testing of high pressure vessels for CNG and CH2 storage (2)

Impact damage test (Drop test):

- Three different kind of drops (horizontal, vertical, at 45° angle)
- Cyclic test at ambient conditions

Accelerated stress rupture test:

- Cylinder pressurised to 26 MPa while immersed in water at 65 °C and hold for 1,000 hours
- Burst test



High temperature creep test :

- Cylinder pressurised to 26 MPa and held at temp. 100 °C for not less than 200 hours
- Hydrostatic expansion test
- Leak test
- Burst test

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Other standard and non-standard tests

Burst tests at the test range conditions

Penetration test (cal. 7.62 mm)

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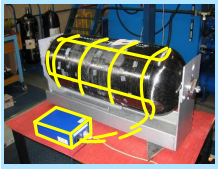
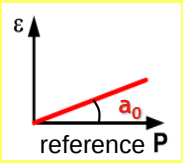
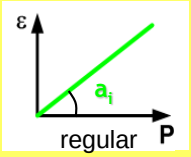
Concept of monitoring strategy for high-pressure vessels



1. Sensors installation (configuration should be proceeded by simulations, i.e. FEM analysis).

2. Measurements





3. Calculation

$$|a_{on} - a_{in}| = ABS_{in}$$

where:
i – measurand number
n – sensor number

4. Analysis (comparison with specified threshold level lets identify if there are any defects in the object).

The threshold determination should be connected with the vessel's modeling results (i.e. by FEM analysis), taking into account the vessel's construction, geometry, experience of the producer, measuring errors, etc.

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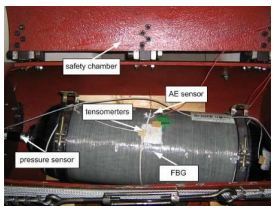
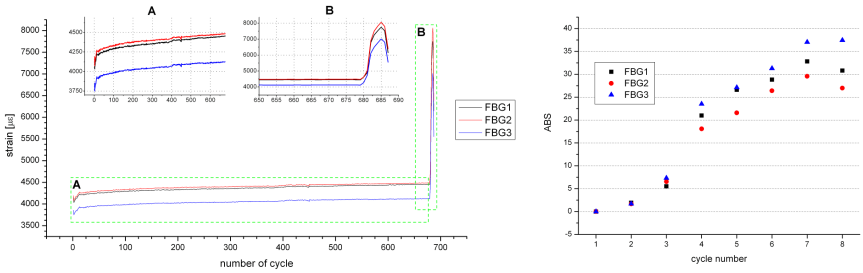
Ambient Temperature Pressure Cycling Test for type 3 vessel



Test vessel inside safety chamber and after the test



Change of maximum local circumferential strains (for Pmax = 875 bar) in function of cycle number and ABS parameter analysis for the same vessel

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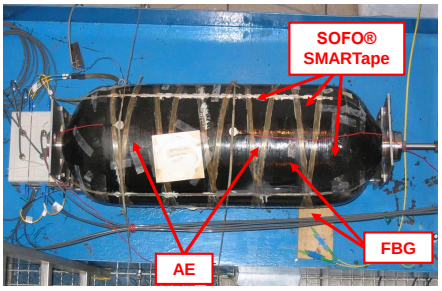
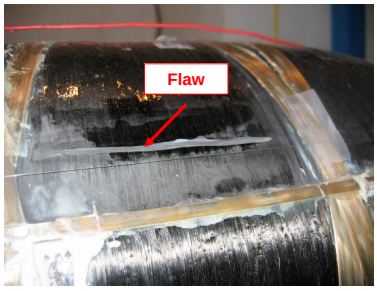
Static tests of type 3 and 4 composite pressure vessels with programmed defects: flaws and delaminations





Pressure vesssel with integrated optical fiber sensors and programmed defects

Tests plan:

- Step 1 – vessel without defects (reference measurements),
- Step 2 – flaws in longitudinal direction (8 cm length, 2 mm deep),
- Step 3 – delamination by drop hammer
- Step 4 – increase of each programmed defect

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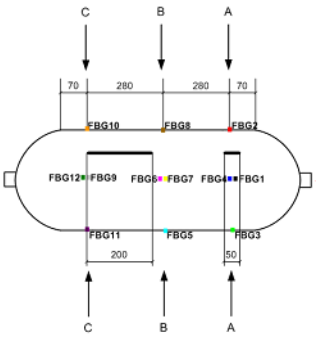
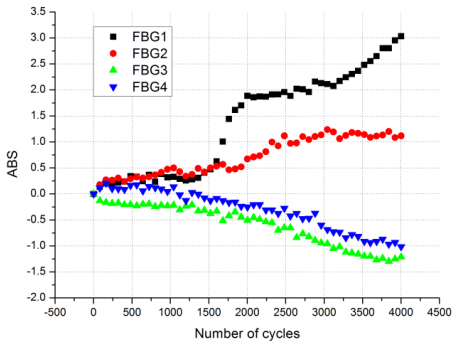
Composite high pressure vessel with programmed defects

- Ambient temperature pressure cycle test in pressure range from 20 to 258,5 bar (1,25 x NWP, NWP = 3000 psi). Test was stoped after 4050 cycles.





ABS parameter analysis in function of number of pressure cycles for selected FBG sensors

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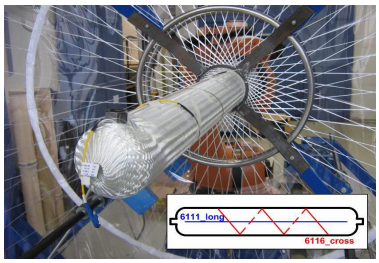
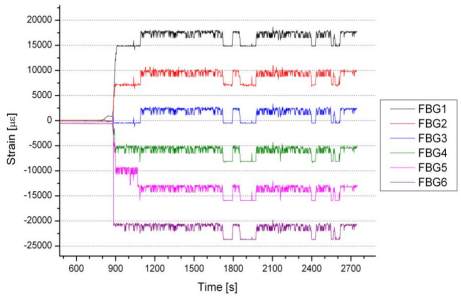
Production of high-pressure vessels by braiding technique (1) Integration of OFS and production process monitoring





Local strains registered by OFS sensors during braiding process

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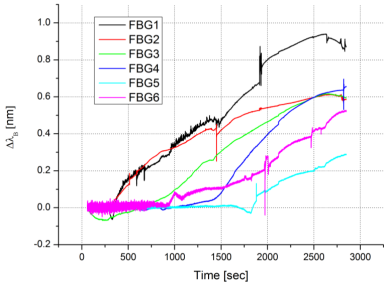
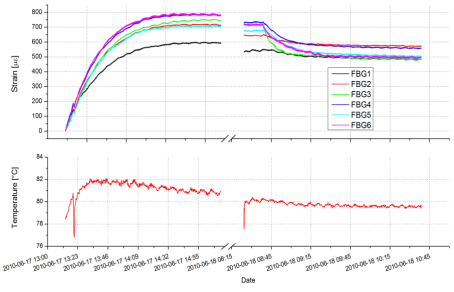
Production of high-pressure vessels by braiding technique (2) Infiltration and hardening procsess



Vessel monitoring during infiltration process (with epoxy resin)



Vessel monitoring during hardening process at high temperature

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Summary for manufacturing process monitoring

Thanks to the structural monitoring of composite pressure vessel during all manufacturing processes it is possible to:

- **register strain field distribution** at the vessel surface and inside composite
- control **the tension in composite roving** during braiding (or winding)
- identification of **areas without pre-tensioned** reinforcement (with internal defects)
- **check the repeatability** of the production process and its control at structural level
- structural monitoring of vessel **in daily use**

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Summary

- Structural Health Monitoring system for composite pressure vessels based on Optical Fiber Sensors was created and its efficiency was verified by experimental methods.
- It was shown that the measurements of selected components of strain of highly stressed composite layer allows the assessment of the degradation level during its use, and thus can determine the safe lifetime.
- It was attempted to assess the damage accumulation of composite layer of high pressure tanks, using the calibration of strain measurements by acoustic emission.
- It was demonstrated that integration of OFS inside composite structure during production of high pressure vessel is possible.

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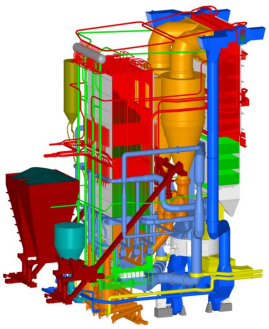
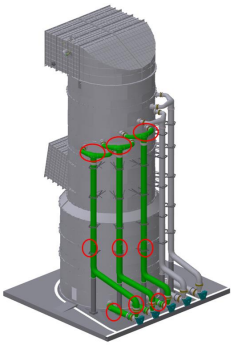
Selected „side effects" – application of OFS based Structural Health Monitoring systems in industry



SHM system for power boiler monitoring in Siersza Power Plant (together with RAFAKO S.A.)



SHM system for a Power Engineering composite pipelines in Bełchatów Power Plant (together with RAFAKO S.A.)

SHM system for pipelines and buffer tank in waste hydrogen power plant in ZAK S.A. (together with SKOTAN S.A.)

P. Gąsior, J. Kaleta i A. Przygoda, „Układ do kontroli naprężeń w konstrukcji kotła przepływowego". zgłoszenie patentowe nr P.390651, Polska 2010