



Steering Committee Progress Report on Hydrogen Sensor Performance Testing and Evaluation under the Memorandum of Agreement between NREL, U.S. DOE and JRC-IET, EC

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Steering Committee Progress Report

On

Hydrogen sensor performance testing and evaluation

Under the

Memorandum of Agreement

Between

NREL, DOE and JRC-IET, EC

1.0 Goal of this document

In October 2010, the Joint Research Centre (JRC), Institute of Energy and Transport (IET)¹ and the U.S. Department of Energy (DOE) National Renewable Energy Laboratory (NREL) signed a Memorandum of Agreement (MOA) to formalize collaborations in specific Thematic Areas both parties agreed to. The terms of the technical program (aims, means, and deliverables) were detailed in Technical Annexes appended to the MOA. Technical Annex 1 was titled “Hydrogen Sensor Performance, Testing and Evaluation.” As part of the MOA, each party established a Steering Committee to guide cooperative activities implemented under the MOA. The Steering Committee meets once a year to review the cooperative activities implemented, to evaluate their effectiveness, and to develop plans. The first Steering Committee meeting was held by videoconference on 22 September 2011; the second meeting is scheduled for 3 December 2012. The MOA was to be in effect for two years and subject to renewal. This report summarizes the joint activities undertaken within the framework of the MOA on hydrogen sensor performance testing. For the purposes of evaluation, these activities, results, and impacts are reported against the Objectives specified in the Technical Annex of the MOA. Suggestions for future joint activities are also proposed.

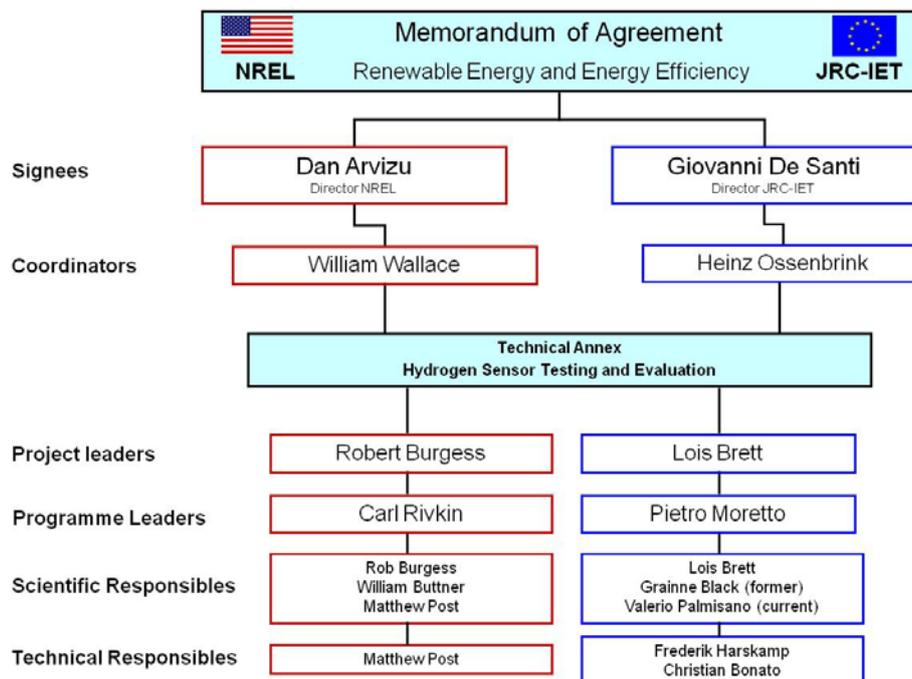


Figure 1: The NREL-JRC MOA organizational chart

¹ At the time of the MOA implementation in 2010, the IET was known as the Institute for Energy (IE)

1.1 Background

The U.S. DOE Fuel Cell Technologies Program (FCT) is a comprehensive portfolio of activities that address the full range of barriers facing the development and deployment of hydrogen and fuel cells with the ultimate goals of decreasing our dependence on oil, reducing carbon emissions, and enabling clean, reliable power generation [1]. The FCT program supports the implementation of the hydrogen infrastructure as part of the overall mission of the DOE to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions [2]. The DOE Vehicle Technologies Program recognizes hydrogen as one of six alternative and renewable fuels for advanced vehicles [3]. The European Commission (EC) also identifies the potential of hydrogen and fuel cells in the 2011 Technologies Map [4], which supports the Strategic Energy Technology (SET) Plan (the reference framework for developing energy research in Europe). The hydrogen market and infrastructure must develop safely and efficiently to ensure hydrogen is deployed successfully as an alternative fuel. A reliable safety system is composed of various elements that can include intrinsic design features (e.g., material specifications, pressure control systems, and venting systems), engineering controls (e.g., sample size minimization and deployment location) and hydrogen sensors to detect unexpected releases. To ensure hydrogen safety sensors are available, the JRC and NREL have ongoing research programs and facilities dedicated to the testing and validation of hydrogen sensor performance [5, 6] (Figure 2). The mission and goals of the hydrogen sensor test laboratories are comparable and include:

1. Independent evaluation of hydrogen safety sensor performance
2. Outreach to the hydrogen community on the proper choice and use of hydrogen sensors (support end users)
3. Participation on standards development committees to rationally guide and harmonize national and international standards

Because the JRC and NREL have similar missions and their activities overlap significantly, both laboratories entered into a collaboration that was formalized by the MOA as described in the Technical Annex on Hydrogen Sensors. This arrangement synergized the effort of each laboratory and leveraged the impact of their output by:

1. Minimizing duplicated R&D efforts to save both laboratories valuable resources and maximize throughput.
2. Increasing international exposure and visibility of results
3. Expanding capabilities and broadening the range of expertise to facilitate information exchange
4. Facilitating implementation of the hydrogen infrastructure via an expanding international collaboration among stakeholders



JRC-IET Image-used with permission



NREL PIX 18240

Figure 2: Hydrogen sensor testing facilities of JRC-IET (left) and NREL (right)

It is noted that per the policies of both laboratories, sensor performance data are treated as proprietary. Although data are openly disseminated to stakeholders via publications, presentations, and other outreach activities, no manufacturers or specific model types are to be identified.

2.0 Joint activities and achievement of objectives:

The primary goal of the NREL-JRC MOA, Technical Annex 1 was summarized as follows: “To identify and resolve issues in hydrogen sensor use and the assessment and validation of hydrogen detection technologies.” Specific objectives were defined in the Technical Annex (see Table 1). Joint hydrogen sensor activities, performed as part of this MOA, are described in this section; their contributions to the MOA objectives are also identified in Table 1. Although laboratory evaluations of hydrogen sensor technology were – and remain – a major focus for both laboratories, the respective mission of each laboratory goes beyond that to include outreach activities to educate end users on proper sensor deployment, including the rational establishment of sensor deployment requirements per national and international standards. Specific joint activities are therefore classified as (i) Sensor Technology Assessment, which includes laboratory evaluation and direct stakeholder support; or (ii) Working Groups and Outreach, which includes support for standardization.

2.1 Completed and Ongoing Activities

2.1.1 Sensor Technology Assessment

A major – but not exclusive – joint activity of the respective sensor laboratories is the laboratory evaluation of hydrogen sensor performance. The test sensor is subjected to a variety of regulated, controlled, and well-defined test protocols; then the output of the sensor is quantified to the various test conditions. Comparisons to national or international standards, as well as to application-defined requirements, may be included in this assessment. The test protocols were analogous to those specified in the international standard ISO 26142 [7]. The outcome of this work is communicated to stakeholders via presentations at national and international conferences, journal publications, and topical reports. Specific parameters that are controlled in laboratory evaluations include:

- Gas composition and flow
- Environmental parameters, including (temperature, pressure, and relative humidity)
- Experimental parameters (exposure time, logging rate)

Technology assessments may also include helping stakeholders on the proper deployment of hydrogen sensor technologies. Direct stakeholder support can include laboratory assessments per specific application requirements, as well as in-the-field deployments and assessments. A spin-off of sensor technology assessment was the feedback of results to stakeholder groups, including sensor manufacturers, end users, and project managers. In this way scientific output from the laboratories had a direct impact on in-the-field demonstration of sensor performance for end users with feedback to sensor manufacturers on the outcome to help them improve their technology.

Each sensor technology assessment can cross-cut several of the objectives identified by the MOA (see Table 1).

Many hydrogen sensor models are commercially available in the international market, and new technologies are under development. Fortunately, the number of sensing element platform types on which most commercial sensors are based is small. The main sensing element platforms used in commercial hydrogen sensors are thermal conductivity (TC), electrochemical (EC), high-temperature metal oxide sensors (MOX), combustible gas sensors (CGS), metal oxide semiconductor sensors (MOS) and palladium thin film sensors. Although specific performance can vary from one model to another, depending on the electronic sensor circuit and other controls, to a large extent the overall sensor performance is controlled

by the type of sensing platform. Thus, assessment of a relatively small number of representative sensors can provide significant insight into the basic performance characteristics of a wide range of sensor models.

2.1.1.1 Sensor Interlaboratory Comparison (SINTERCOM)

SINTERCOM was a collaborative project involving the JRC-IET and NREL. Its protocol mandated that multiple units of the same sensor platform be acquired. These were then evenly distributed to the participating laboratories and subjected to a series of well-defined test protocols. When the test protocols were completed, the sensors were exchanged between laboratories, and subjected to the same general test protocols but at the other facility. Thus, all sensor units were assessed by both laboratories. The aim of SINTERCOM was twofold: (i) it enabled the respective hydrogen sensor test facilities and methodologies to be validated through the demonstration of interlaboratory consistency; and (ii) test results were made available to relevant parties, such as end users, sensor developers, and standards organizations, to guide sensor development and use.

The results of SINTERCOM were partially presented in an interim report [8]; a more comprehensive summary is in preparation [9]. Specialized tests initiated under SINTERCOM (e.g., impact of interferents and poisons), have been expanded and will be presented separately. SINTERCOM results were also incorporated into conference presentations, publications in the scientific literature, and as direct feedback to the manufacturers, including, where appropriate, site visits. SINTERCOM data are also being surveyed to assess the ability of each major sensor platform to meet performance specifications for the various hydrogen applications [10], and, more importantly, to identify unmet performance specifications (e.g., gaps in sensor performance capabilities).

MOA Objectives addressed by SINTERCOM are indicated in Table 1.

2.1.1.2 Topical Area – Oxygen Dependence

The oxygen dependence study was initiated in direct response to a suggestion made by an end user to use a CGS to quantify spurious hydrogen releases into a nitrogen purge. Combustion requires oxygen, and thus hydrogen in a nitrogen stream is undetectable with a CGS. The inability for a CGS to operate under anaerobic conditions is intuitive, based on the CGS transduction mechanism. However, not all stakeholders who have a need to use hydrogen safety sensor have the background or expertise to realize this property. Laboratory evaluations performed at NREL or JRC, under the auspices of the MOA confirmed that the CGS and other sensor platforms were unable to detect hydrogen under anaerobic conditions and in depressed oxygen atmospheres. Oxygen dependence tests were performed on two other sensor platforms and the impact on performance was evaluated along with the potential implications on application safety. The results were presented at the 2011 International Conference on Hydrogen Safety (ICHS), and were included as a refereed publication in a special edition of the *International Journal of Hydrogen Energy* (IJHE) (references provided in Section 2.1.2). A second, more comprehensive paper on oxygen dependence in six hydrogen sensor platforms is in preparation and will be published in the IJHE.

MOA Objectives addressed by the Oxygen Dependence Study are indicated in Table 1.

2.1.1.3 Topical Area – Perks and Quirks of Sensor Miniaturization

DOE has identified a response time of 1 s as a critical analytical performance specification for several key applications [10, 11]. Although a 1 s response time remains a challenging specification, it can be achieved only by minimizing bulk-phase processes via device miniaturization. Advanced manufacturing techniques, such as micro-fabrication, have the potential to produce low-cost sensors with exceptional performance metrics (e.g., response time); however, miniaturization may cause other metrics (e.g., stability and dynamic range) to degrade.

Laboratory assessments were performed at JRC and NREL sensor facilities to evaluate and compare pertinent performance parameters (e.g., dynamic range and short-term stability) of commercial micro-

machined TC and MOX hydrogen sensors with those of their traditional counterparts. Response time measurements were also performed on the sensors using specialized custom-built fixtures at the JRC [12]. An assessment of manufacturing techniques and the promise of micro-machining were performed by the research group of Professor Frédéric Dominique in the Département de génie électrique et génie informatique, Université du Québec à Trois-Rivières (UQTR).

The results obtained at JRC and NREL confirmed that miniaturized micro-machined sensors offer improved performance characteristics in some critical metrics (e.g., response and recovery times) relative to traditionally fabricated sensors of the same platform type. However, in some sensor platform types, degradation in some performance characteristics was observed. NREL, JRC, and UQTR are finalizing a paper for publication in the IJHE in which the application of micro-machining techniques for fabricating miniature hydrogen sensors is presented along with an impartial analysis of the results of NREL and JRC experimental comparisons. The paper also addresses the challenges and potential advantages offered by micro-machined hydrogen sensors.

The preliminary results of this investigation were presented at the 2012 World Hydrogen Energy Conference. The collaboration with UQTR was supported by H2CAN [13] and the study was performed in the frame of International Energy Agency (IEA) Hydrogen implementing agreement Task 31 (see Section 2.1.2.1).

MOA Objectives addressed by the sensor miniaturization study are indicated in Table 1.

2.1.1.4 Topical Area – Interferent and Poisons

Sensor selectivity remains a critical performance specification. False alarms induced by interferents are not only a nuisance [14], but are a major cause for a lack of trust by stakeholders in chemical sensor technologies. Often false alarms arise from not understanding the limitations of the various sensor platforms, which can lead to using the wrong sensor for an application. A positive response from a chemical other than hydrogen could be misinterpreted as indicating the presence of hydrogen, whereas a negative response could suppress the indication to hydrogen (e.g., lead to a false negative), although the latter is not very common. Typically, an interferent will induce a reversible behavior such that the sensor fully recovers once the interferent is removed. Conversely, some classes of chemicals are known to induce irreversible effects on the sensor, often resulting in a total loss of sensitivity to hydrogen. However, what may be a poison on one platform type (e.g., silicon compounds on MOX and CGS) may be benign on other platforms.

As an extension of SINTERCOM, the various sensor platforms are being exposed to a variety of chemicals that may induce a response on the sensor. Common potential interferent gases include, but are not limited to, carbon monoxide, carbon dioxide, ammonia, methane, and volatile organic compounds. This study also includes potential poisons such as sulfur and silicon-containing compounds. A preliminary survey of sensor selectivity on various sensor platforms was completed by both laboratories, but a more comprehensive study is led by JRC-IET. Although experimental tests are performed primarily by JRC-IET to exploit its infrastructure for handling and disposing of toxic gases, the results are shared within the MOA to improve analysis techniques and to maximize the impact and dissemination of the scientific findings. This work is ongoing and will be jointly published in the IJHE.

2.1.1.5 Topical Area – Hydrogen Measurements via Oxygen Displacement

Hydrogen sensors are the primary and most efficient means to directly measure for the presence of hydrogen. One alternative method, employed by several research groups [15, 16, 17] is to indirectly ascertain the presence of hydrogen using oxygen sensors to measure the displacement of oxygen. This approach is even explicitly listed in the draft Hydrogen and Fuel Cell Vehicle Global Technology Regulation (GTR [18]). Although it may seem straightforward to calculate hydrogen concentrations from oxygen displacement, there are numerous drawbacks of using oxygen sensors for this purpose, including:

- A limited analytical resolution of oxygen leads to a marginal detection limit for hydrogen (and even a worse limit of quantification).
- Oxygen sensors typically have large temperature and pressure dependences.
- Oxygen sensors respond to the partial pressure of oxygen and not the volume fraction, so hydrogen released into closed systems (e.g., hydrogen fuel cell vehicles with closed windows) will be totally undetectable.

These limitations were verified in a joint NREL/JRC evaluation that was underpinned by an independent experimental comparison of direct and indirect hydrogen concentration measurements using commercial hydrogen and oxygen sensors, respectively. Experiments were performed primarily by NREL and the results are being analyzed by both laboratories in preparation for publication in the IJHE. JRC will also measure response times to compare the response times of oxygen and hydrogen sensors. The study also identified alternative hydrogen sensor platforms that exceed the capability of this approach on all critical analytical performance specifications for the detection of hydrogen releases.

2.1.1.6 Hydrogen sensor use in fuel cell electric vehicles (FCEVs) (Direct Stakeholder Support)

The National Highway Transportation Safety Administration (NHTSA) of the U.S. Department of Transportation recently performed a series of crash tests on FCEVs [19]. One purpose of the test was to verify that FCEV could be instrumented to verify compliance with the GTR safety requirements. The GTR stipulates specific performance requirements following crash tests for the FCEV fuel storage system. Specifically, the GTR mandates that for 1 hour following crash test impact, the integrity of the fuel storage must be maintained such that the hydrogen concentration in the passenger, trunk, or other vehicle compartments does not exceed 4% by volume. The crash test vehicles were successfully instrumented with hydrogen sensors to measure hydrogen release. The selected sensors not only survived the crash test but were able to operate continuously during setup, impact, and post-crash standby times. Although performed primarily by NREL, the project was reviewed by JRC colleagues before and after the test.

2.1.1.7 Performance feedback to hydrogen sensor manufacturer

In the frame of the crash tests mentioned above, feedback on the test results, specifically sensor performance during and immediately after the tests, were provided to the sensor manufacturer. The briefing was hosted by JRC and the three-way exchange of information during the briefing led to an increased insight into the technology and capabilities of the sensor. Crash test validation of this sensor's robustness enabled the testing laboratories to advise the sensor manufacturer on other niche applications for its product.

Comparable briefings, per the SINTERCOM test results, were routinely provided to sensor manufacturers via memo reports, telecoms, and if appropriate, site visits to the sensor manufacturing facility; these briefings did not include identification of other technology evaluations by NREL or JRC.

2.1.2 Working Groups and Outreach

2.1.2.1 IEA Task 19 and Task 31

The IEA-HIA Task 19 – Hydrogen Safety finished in 2011, but was renewed under the auspices of Task 31-Hydrogen Safety. Before the MOA was implemented, NREL and JRC independently participated in the IEA Task 19 activities and Experts Meetings. As the collaboration expanded under the MOA, joint summaries were presented at Task 31 Experts Meetings. One spin-off of Task 31 participation was that collaboration with UQTR and the assessments of the impact of sensor miniaturization via microfabrication were initiated. Joint presentations have been made at IEA-HIA Task 31 meetings on the hydrogen sensor collaboration, and JRC and NREL contributed to a White Paper [20] that is being prepared by the Task 31 Working Group. This White Paper illustrates how information and knowledge exchange among hydrogen safety experts is contributing to the objectives of the IEA-HIA.

2.1.2.2 Support of Standards Development Organizations

Scientific and technical support to the development of robust relevant standards is a common objective of both laboratories. Representatives from both NREL and JRC-IET participated in the ISO 197 Working Group 13 whose work culminated in the ISO 26142, a standard on hydrogen detection apparatus [5]. In this context, and as mentioned previously, response time is recognised as a critical performance parameter of hydrogen sensors. This emphasizes the importance of reproducible methods for measuring sensor response time. A proposal to amend ISO 26142, to improve the response time measurement method described in the standard, has been submitted to the Working Group chair based on experimental evaluation and improvement of the method published in the standard [13].

As an extension of this activity, JRC is participating in an IEC Working Group which is improving the response time measurement method published in IEC TC31 MT60079-29- 1 Explosive atmospheres - Part 29-1: Gas detectors - Performance requirements of detectors for flammable gases. Contribution to this Working Group will include response time measurements of oxygen and hydrogen sensors made as part of the joint activity mentioned in Section 2.1.1.5.

2.1.2.3 Joint Presentations

NREL and JRC collaborated on 6 formal presentations on hydrogen safety sensors under the auspices of the MOA. These talks were at national and international conferences, including the ICHS, the National Hydrogen Association Conference and Expo, and the World Hydrogen Energy Conference. Talks were also presented at working groups, including the IEA-HIA Task 19/Task 31 Experts Meeting and the NREL-JRC Steering Committee. A partial list of the presentations follows:

- “Round robin testing of commercial hydrogen sensor performance – Observations and results” Lois Boon-Brett, Grainne Black, Frederik Harskamp, Pietro Moretto, William J. Buttner, Robert Burgess, Carl Rivkin, and Matthew B. Post, presented at the 2010 National Hydrogen Association Conference and Expo (May 3-6, 2010), Long Beach, CA.
- “NREL/JRC Memorandum of Agreement – Hydrogen Sensor Performance Testing & Evaluation” L. Boon-Brett, G. Black, C. Bonato, F. Harskamp and P. Moretto, W.J. Buttner, R. Burgess, M.B. Post and C. Rivkin, presented at the JRC-NREL Steering Committee Meeting (September 22, 2011).
- “Hydrogen Safety Sensors – Performance under anaerobic conditions” W.J. Buttner, R. Burgess, C. Rivkin, M.B. Post, L. Boon-Brett, G. Black, F. Harskamp, P. Moretto, Presented at the 2011 International Conference on Hydrogen Safety, San Francisco (September 12-14, 2011).
- “The promise and pitfalls of micro-machined hydrogen sensors” Frederic Domingue, Hatem El Matbouly, William Buttner, Matthew Post, Robert Burgess, Lois Brett, Valerio Palmisano, presented at the 2012 World Hydrogen Energy Conference, Toronto, Canada (June 3-7, 2012).
- "Comparison of performance of MEMS versus ‘classic’ H2 sensors" Frederic Domingue, Hatem El Matbouly, William Buttner, Matthew Post, Robert Burgess, Lois Brett, Valerio Palmisano. Presented at IEA-Task 31 Experts Meeting, Paris (April 16 -18, 2012).
- “An Assessment on the Quantification of Hydrogen Releases Through Oxygen Displacement Using Oxygen Sensors” (Tentative Title) William J. Buttner, Matthew B. Post, Robert Burgess, Carl Rivkin, Lois Boon-Brett, Valerio Palmisano, to be presented at the 2013 International Conference on Hydrogen Safety, Brussels, Belgium (September 9 -11, 2013).

2.1.2.4 Joint Publications—Journal Articles and Reports

The NREL and JRC sensor laboratories have jointly published 7 papers in the open literature on hydrogen safety sensors under the auspices of the MOA. These publications included formal reports published at

NREL or at JRC, peer-reviewed papers in scientific journals, and as proceedings to conferences. These publications include:

- “Interim Report of the SINTERCOM Project” Black, G., Boon-Brett, L., Harskamp, F. , Moretto, P. Buttner, W. J., Post, M. B., Burgess, R., Rivkin, C., EUR 24854 EN – 2011 (September 2011).
- “Round robin testing of commercial hydrogen sensor performance – Observations and results” Lois Boon-Brett, Grainne Black, Frederik Harskamp, Pietro Moretto, William J. Buttner, Robert Burgess, Carl Rivkin, and Matthew B. Post, published in the proceedings of the 2010 National Hydrogen Association Conference and Expo (May 3-6, 2010), Long Beach, CA.
- “Use of Hydrogen Safety Sensors Under Anaerobic Conditions – Impact of Oxygen Content on Sensor Performance” William J. Buttner, Ph.D.; Robert Burgess; Carl Rivkin; Matthew B Post; Black, G., Boon-Brett, L., Harskamp, F. , Moretto, P." ICHS 2011 Conference Proceedings (12-14 September 2011).
- “Inter-laboratory Assessment of Hydrogen Safety Sensors Performance under Anaerobic Conditions” William J. Buttner, Ph.D.; Robert Burgess; Carl Rivkin; Matthew B Post; Lois Boon-Brett; Grainne Black; Frederik Harskamp; Pietro Moretto, International Journal of Hydrogen Energy, Volume 37, issue 22, November 2012, Pages 17540-17548.
- “Next generation micro-machined hydrogen safety sensors” H. El Matbouly, F. Domingue, V. Palmisano, L. Boon-Brett, M. B. Post, C. Rivkin, R. Burgess, and W. J. Buttner, in preparation for publication in the International Journal of Hydrogen Energy (2012).
- “An Assessment on the Quantification of Hydrogen Releases Through Oxygen Displacement Using Oxygen Sensors” (Tentative Title) William J. Buttner, Matthew B. Post, Robert Burgess, Carl Rivkin, Lois Boon-Brett, Valerio Palmisano, in preparation for publication in the International Journal of Hydrogen Energy (2012).
- “A survey of hydrogen sensor platform selectivity to interferents and poisons” Valerio Palmisano, William J. Buttner, Matthew B. Post, Robert Burgess, Carl Rivkin, Lois Boon-Brett in preparation for publication in the International Journal of Hydrogen Energy (2012).
- “Advancing the Hydrogen Safety Knowledge Base – A White Paper of the International Energy Agency Hydrogen Implementing Agreement (HIA) Task 31 – Hydrogen Safety(NREL and JRC sensor laboratory personnel are contributing authors)

2.2 Future Activities

2.2.1 Technology Evaluation and Stakeholder Support

2.2.1.1 Release Scenarios Modeling

Although general guidelines exist, rigorous guidance on sensor placement and the number of sensors required for a facility (e.g., warehouse, repair facility) remains a gap. Presently, demonstration facilities often use a high density of hydrogen sensors. For example, individual bays in the California Fuel Cell Partnership hydrogen facilities in Sacramento were deployed with 5 sensors [21]. The facility houses multiple bays. This density of sensors adds significant cost to the design and maintenance of the facility. Rational guidance on sensor deployment (e.g., location and number) will need an understanding of the fate of releases, achievable through computational fluid dynamics modeling and validation.

2.2.1.2 Wide Area Monitoring (WAM)

To date, the Technology Evaluations have focused primarily on point sensors. This was true for laboratory assessments and support of stakeholders. Other detection technologies can be classified as wide area monitors (sometimes call standoff detection). Often these are optical methods with a light source and remote detector probing across a large linear space for the target analyte. Other platform types (e.g., acoustic) are available. WAM technologies were recently surveyed [22], but this survey did not include critical assessments of the applicability of the various technologies to detect hydrogen. The advantage of WAM is the large area that can be surveyed as opposed to, for example, a large number of point sensors distributed throughout a facility. There are however, disadvantages, including the lack of commercial technology for hydrogen, detection limits, projected cost, and overall uncertain performance in the field. NREL and JRC are expanding the sensor assessment to include WAM technologies.

2.2.2 Outreach

2.2.2.1 EU/U.S. Common topic on hydrogen safety sensors

In January 2012 the European Fuel Cells and Hydrogen Joint Undertaking published its 5th annual call for proposals. This call included a topic on Hydrogen Safety Sensors inviting proposals that would facilitate the cost-effective development, testing, and application of hydrogen safety sensors. This topic was published as a joint EU/U.S. Common topic whereby EU research project proposals were required to be coordinated with a U.S. proposal submitted in parallel to DOE. A proposal was successfully submitted by a European consortium. This consortium included JRC, a sensor certification body, three SME (small and medium-sized enterprises) sensor manufacturers, and a sensor end user. The consortium will coordinate with a similar U.S. project coordinated by NREL. As part of the EU research project, a workshop will be held and will include a presentation from an NREL representative as a U.S. hydrogen sensor expert.

2.2.2.2 Presentations

The 5th International Conference on Hydrogen Safety conference will be held in Brussels in September 2013 and is being hosted by JRC-IET. A joint presentation will be submitted by JRC and NREL on the use of oxygen sensors for indirect hydrogen measurement. Additional presentations at other conferences and workshops will be jointly given as appropriate.

2.2.2.3 Publications

The outcome of the NREL/JRC collaboration will continue to be communicated to the hydrogen community via open publications, including formal JRC reports, formal NREL reports, and journal articles. An oral presentation proposal will be submitted before the end of 2012 on “An Assessment on the Quantification of Hydrogen Releases Through Oxygen Displacement Using Oxygen Sensors” (Tentative Title) William J. Buttner, Matthew B. Post, Robert Burgess, Carl Rivkin, Lois Boon-Brett, Valerio Palmisano, to be presented at the 2013 International Conference on Hydrogen Safety, Brussels, Belgium (9 to 11 September 2013). This work and other ongoing studies (e.g., impact of interferents) will be published in the IJHE or other relevant journals.

The NREL/JRC collaboration will intensify in the next 12 months following agreement to coauthor, together with BAM (Germany) a CRC Press book titled *Sensors for Process Control and Safety in Hydrogen Technologies*. The manuscript is expected to be submitted by 31 December 2013.

3.0 Summary and Conclusion

The sensor laboratories at NREL and the IET have just completed the first two years of the MOA. The activities of both laboratories undertaken with the frame of this agreement have been summarized in this report. These joint activities have resulted in:

- Leveraged scientific output through performance of repetitive and complementary sensor testing

- More effective and efficient use of mutual resources
- Enhanced dissemination and impact of research findings
- Increased visibility in the scientific community
- Exchange of knowledge, technical know-how, and ideas

Under the MOA, NREL and the IET were able to provide extensive support for the safe implementation of the hydrogen infrastructure, including:

- Active participation on standards development organizations
- More than 6 presentations at national and international conferences
- More than 7 publications in the open literature (reports, journal articles, conference proceedings) on hydrogen sensor performance
- Initiation of 5 topical studies on the proper use of hydrogen sensors to serve as a guide to stakeholders
- Sensor technologies evaluations for deployment in FCEV crash tests in support of the GTR
- Expanded international cooperation on hydrogen safety and hydrogen sensor technology.

DOE and JRC are pursuing a formalized agreement for a more extensive Collaboration Arrangement with the intention to rationalize and formalize all prioritized activities shared by JRC (all Institutes) and DOE (covering all national laboratories). In this context, and in consideration of the successful results from the NREL/JRC hydrogen sensor collaboration, it is strongly recommended that this collaboration continue, possibly under the new DOE/JRC Collaborative Arrangement.

Acknowledgements

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List of Abbreviations and Acronyms

CGS	Combustible Gas Detector
DOE	Department of Energy
EC	European Commission
EU	European Union
FC&HE	Fuel Cell and Hydrogen Energy Association
FCEV	Fuel Cell Electric Vehicle
FCT	Fuel Cell Technologies
GTR	Global Technology Regulation
HIA	Hydrogen Implementing Agreement
ICHHS	International Conference on Hydrogen Safety
IE	Institute for Energy
IEA	International Energy Agency
IET	Institute for Energy and Transport
IJHE	International Journal of Hydrogen Energy
JRC	Joint Research Centre
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MOX	Metal Oxide
NREL	National Renewable Energy Laboratory
SINTERCOM	Sensor Interlaboratory Comparison

TC Thermo Conductivity
UQTR Université du Québec à Trois-Rivières
WAM Wide Area Monitoring

Table 1: MOA Sensor Task Objectives and Sensor Laboratories Activities

Planned Objectives (in TA of MoA)	Technology Assessment										Working Groups and Outreach				
	SINTERCOM ^A	O2 Dependence ^A	Sensor Miniaturization ^B	Response Time ^B	Interferents & Poisons ^C	H2 levels via O2 Sensors ^A	Vehicle Crash Test ^A	Feedback to manufacturers ^B	Wide Area Monitoring ^C	Modeling of releases ^C	IEA Task 31 Experts Meeting ^C	ISO 26142 and other SDOs ^B	Oral Presentations ^B	Publications ^B	Common Call ^C
a) To obtain scientific data needed for a better understanding of the requirements for safe use of hydrogen systems, with specific accent on gas detection techniques for hydrogen applications in confined spaces.	X	X			X	X			X	X					
b) To improve the co-ordination and effectiveness of co-operation efforts between NREL and the Commission in the field of hydrogen detection, through inter-laboratory comparison of data and validation of testing facilities, methods and practices.	X														X
c) To use the results from this collaborative work to leverage output and support to JRC and NREL's mutual policy makers.	X					X	X				X	X			
d) To promote mutual interest and co-operation in understanding and resolving issues that can help outlining gaps in the existing standards and regulations, thus enabling to express recommendations on pre- and co-normative research needs.						X		X	X		X	X			
e) To deepen the understanding of scientific and technical issues relating to hydrogen detection technologies, assessing their current performances and potentialities and helping further Research and Development goals to be met.		X	X	X	X	X		X	X	X		X			
f) Using knowledge generated to provide assistance and advice in determining of hydrogen detector performance targets for applications.	X	X		X	X			X					X	X	
g) To test and demonstrate the proficiency of both laboratories in hydrogen detector testing methods and illustrate their competence in this area.	X														
h) To make visible to stakeholders the importance of hydrogen detection for safety and to make available the results and conclusions from this collaboration.											X	X	X	X	X

^A Completed activity, excluding submission of publication

^B Ongoing activity

^C Future activity (not started as of December 2012)

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Appendix 1
The MOA between NREL and JRC



**MEMORANDUM OF AGREEMENT
UNDER INTERNATIONAL IMPLEMENTING
ARRANGEMENTS**

**RENEWABLE ENERGY AND ENERGY EFFICIENCY
SCIENTIFIC COLLABORATIONS AND RESEARCHER
EXCHANGES**

between

The Institute for Energy of the Joint Research Center
European Commission
under the
European (Atomic Energy) Community

And

The National Renewable Energy Laboratory
under the
United States Department of Energy

**MEMORANDUM OF AGREEMENT
UNDER INTERNATIONAL IMPLEMENTING ARRANGEMENTS**

**RENEWABLE ENERGY AND ENERGY EFFICIENCY
SCIENTIFIC COLLABORATIONS AND RESEARCHER EXCHANGES**

Between

The National Renewable Energy Laboratory
United States Department of Energy

And

Institute for Energy of the Joint Research Center
European Commission
European (Atomic Energy) Community

SUBJECT: Scientific Collaborations and Researcher Exchanges in Energy Related Fields

This Memorandum of Agreement (MOA) is entered into in pursuant to the international IMPLEMENTING AGREEMENT BETWEEN THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA AND THE EUROPEAN COMMISSION FOR NON-NUCLEAR ENERGY SCIENTIFIC AND TECHNOLOGICAL COOPERATION dated October 14, 1998 and in accordance with the AGREEMENT FOR SCIENTIFIC AND TECHNOLOGICAL COOPERATION BETWEEN THE EUROPEAN COMMUNITY AND THE GOVERNMENT OF THE UNITED STATES OF AMERICA AND ANNEX signed December 5, 1997, entered into force on October 14, 1998, and extended and amended on March 30, 2009.

This MOA for Scientific Collaborations and Researcher Exchanges is entered into between the following entities:

- (1) The Institute for Energy of the **Joint Research Centre (JRC)** of the European Commission which represents the European (Atomic Energy) Community. The JRC's Institute for Energy is based both in Petten, the Netherlands and Ispra, Italy.
- (2) The **National Renewable Energy Laboratory (NREL)** is a United States Department of Energy national laboratory managed and operated by the Alliance for Sustainable Energy, LLC, under DOE Contract No. DE-AC36-08GO28308. NREL is based in Golden, Colorado, USA.

Integral to its mission for the U.S. Department of Energy, **NREL** conducts research and development in renewable energy and energy efficiency technologies and practices, advances related science and engineering, and transfers knowledge and innovation to address the United States' energy and environmental goals. NREL is supported by funding from the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE).

Integral to its mission for the European Commission, representing the European (Atomic Energy) Community, **JRC** provides customer driven scientific and technical support for the conception, development, implementation and monitoring of European Union policies. It functions as a reference centre for science and technology for the European Union. It serves the common interests of the Member States of the European Union while being independent of special interests. Through its Institute for Energy in Petten (NL) and Ispra (IT), the JRC provides scientific technical support for the conception, development, implementation and monitoring of community policies related to energy. Special emphasis is given to the security of energy supply and sustainable and safe energy production.

Either JRC or NREL shall be referred to as a "Participant". Both JRC and NREL shall be collectively referred to as "Participants."

BACKGROUND

This MOA between NREL and JRC expresses the Participants' intent to synergize their independently programmed activities to maximize the benefit of their respective institutional interests through cooperative activities, including Scientific Collaborations and Researcher Exchanges in the field of Energy.

NOW, THEREFORE, the Participants hereby agree as follows:

ARTICLE 1 – SCIENTIFIC COLLABORATIONS

The general objective of Scientific Collaborations to carry out cooperative activities implemented under this MOA is to contribute more effectively to understanding and resolving issues in the Energy field.

The JRC and NREL have identified a non exhaustive list of thematic areas within which collaboration is possible and mutually beneficial:

- Solar energy (PV & CSP)
- Bioenergy (biofuels)
- Hydrogen and Fuel Cells
- End-use efficiency
- Energy technologies and energy systemic modelling"
- Establishment and operation of a technology validation and assessment framework for energy technology demonstration projects
- Energy Storage (battery, solid and hybrid storage)

In the case where collaboration in a specific Thematic Area has been agreed upon by NREL and JRC, the details of the technical programme (aims, means and deliverables) are given in the Annexes to the present MOA.

ARTICLE 2 – RESEARCHER EXCHANGES

1. Each Participant will be responsible for its own personnel in relation to Researcher Exchanges to carry out cooperative activities implemented under this MOA.
2. When it is appropriate for personnel from NREL or the JRC to visit the other Participant's facilities for brief periods in carrying out cooperative activities implemented under this MOA, each Participant shall adhere to the conditions of the host institution's separate written facility access and visiting professional policies, procedures, and other guidance for invitation of personnel to carry out cooperative activities at the host institution.
3. Each Participant shall adhere to the standard regulations, policies, and procedures of the host institution that address the regulation of mutual rights and obligations (including confidentiality, intellectual property in carrying out cooperative activities implemented under this MOA), the conditions of cooperation and decorum, the conditions of security and safety, and all other terms under which personnel are authorized to participate in Researcher Exchanges at the host institution.
4. Each Participant is responsible to continue the employment relation with its staff member for the duration of the Researcher Exchange and to assure that its personnel carrying out cooperative activities implemented under this MOA comply with the regulations, policies, and working conditions of the host institution.

5. Each Participant has sole responsibility for its personnel carrying out cooperative activities implemented under this MOA at the host institution, including but not limited to: immigration support, travel, suitable living accommodations, and appropriate insurance coverage. To the extent possible, the host Participant will assist, in meeting the personal and professional needs of personnel for Researcher Exchanges including immigration support, research support, office space and equipment, and access to facilities within the context of the regulations in force at the host institution.

ARTICLE 3 – FUNDING AND SCOPE

1. Unless otherwise determined by writing, each Participant is responsible for the costs it incurs in carrying out the cooperative activities implemented under this MOA, including all administrative costs, overhead expenses, labor costs, insurance costs, travel and living expenses, and similar or related costs.
2. This MOA is neither a fiscal nor a funds obligation document. Nothing in this MOA authorizes or is intended to obligate the Participants to expend, exchange, or reimburse funds, services, or supplies or transfer or receive anything of value. This MOA is not to be used to obligate or commit funds and is not to be used as a basis for the transfer of funds between the Participants.
3. This MOA in no way restricts either of the Participants from participating in any activity with any other public or private organization.

ARTICLE 4 – REPORTS, DOCUMENTS AND RELEASE OF INFORMATION

1. Each Participant intends to carry out cooperative activities implemented under this MOA in a manner that facilitates exchanges of publicly available, non-proprietary information. Subject to applicable laws and regulations, the Participants intend that information, data, and reports of cooperative activities implemented under this MOA may be released by either Participant with the written concurrence of the other Participant.
2. Cooperative activities implemented under this MOA that may involve sharing of proprietary or confidential information and transfer of rights and interest in intellectual property are excluded from the purview of this MOA.

ARTICLE 5 – DISCLAIMER

Information transmitted by one Participant to the other under this MOA should be accurate to the best knowledge and belief of the transmitting Participant. Neither Participant makes any warranty, express or implied, nor assumes any responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe upon privately owned rights.

ARTICLE 6 – INTELLECTUAL PROPERTY

1. The Participants do not intend, or expect, to create intellectual property under this MOA. If it appears that cooperative activities implemented under this MOA may result in the creation of intellectual property, the Participants are to restructure the cooperative activities to avoid the creation of intellectual property.
2. In the event that intellectual property results from cooperative activities implemented under this MOA, the rights related to any form of intellectual property arising under this MOA shall be allocated in conformity with the rules and procedures set out in the AGREEMENT FOR SCIENTIFIC AND TECHNOLOGICAL COOPERATION BETWEEN THE EUROPEAN COMMUNITY AND THE GOVERNMENT OF THE UNITED STATES OF AMERICA AND ANNEX signed December 5, 1997, entered into force on October 14, 1998, and extended and amended on March 30, 2009, which forms an integral part of this MOA.

ARTICLE 7 – EXPORT CONTROL

Each Participant acknowledges that it is responsible for its own compliance with all countries' export control laws and regulations. Each Participant acknowledges that it will not knowingly export directly or indirectly, through its personnel, agents, or other affiliates, any export-controlled hardware, software, or technical data in the performance of cooperative activities implemented under this MOA without a required license/authority, which will be obtained by the responsible Participant from the appropriate country's authorities.

ARTICLE 8 – WARRANTIES AND RELEASE/LIMITATION OF LIABILITIES

1. The Participants hereby represent and warrant to each other that they have the power to enter into this MOA and to perform according to its terms, and that the representative signing this MOA has the authority to do so. Provided, however, that all actions undertaken by NREL must be consistent with the terms and conditions of the Management and Operating Contract for NREL between the Alliance for Sustainable Energy, LLC and the U.S. Department of Energy.
2. Any loss, damage, or injury of any origin whatsoever suffered by one Participant arising in any way out of or related to this MOA or any other related agreements, and the performance thereof, shall be borne exclusively by such Participant. If the loss, damage, or injury is caused by a sending Participant's personnel participating in a Researcher Exchange at a host institution, the sending Participant shall be exclusively liable.
3. Each Participant shall be exclusively liable for any loss, damage, or injury of any origin caused by its personnel, agents, or other affiliates to third parties and arising in any way out of or related to this MOA or any other related agreements and the performance thereof.
4. Neither Participant shall be liable to the other Participant for any direct, indirect, incidental, consequential, special or punitive damages arising in any way out of or related to this MOA or any other related agreements, and the performance thereof, whether under theory of contract, tort, warranty, intellectual property, or otherwise, and whether or not the Participants had advance notice of the possibility of such damages.

ARTICLE 9 – RESOLUTION OF DISPUTES AND LIMITATION OF LIABILITY

1. The Participants agree to work cooperatively and in good faith to achieve the goals of this MOA. If disputes do arise in administering this MOA, the designated points of contact shall settle such dispute by mutual agreement.
2. In the case of no settlement, upon mutual agreement of the Participants, the Participants may submit a dispute or disagreement under this MOA to an arbitral tribunal for binding arbitration in the country in which the major part of the cooperative activities that have given rise to the dispute or disagreement are

executed. *Notwithstanding the foregoing, the arbitral tribunal and the law applicable to the arbitration must always be that of a member state of the European Union or that of the United States of America.* The language of the arbitration shall be the English language.

ARTICLE 10 – COMMENCEMENT, EXTENSION, REVISION, AND DISCONTINUATION

1. Scientific Collaborations and Researcher Exchanges for cooperative activities implemented under this MOA may commence upon the later date of the Participants' signatures, may continue for an initial period of two (2) years, and may be extended for additional periods by the Participants' joint determination in writing.
2. The Participants may revise this MOA at any time by mutual consent in writing.
3. The Participants may discontinue this MOA at any time by mutual consent in writing. A Participant that desires to discontinue its participation in this MOA should endeavor to provide the other Participant at least 90 days advance written notice.

ARTICLE 11 - CONTACTS AND NOTICES

1. All notices, communications and coordination under this MOA shall involve, at a minimum, the following individuals, their successors and/or designees as follows:

(a) For the National Renewable Energy Laboratory:

Dan Arvizu, President and NREL Laboratory Director
Alliance for Sustainable Energy, LLC
1617 Cole Boulevard
Golden, CO 80401
Tel: 1 303 275 3016

(b) For the Joint Research Centre, Institute for Energy

Giovanni De Santi, Director
P.O. Box 2
1755ZG Petten
Netherlands
Tel: +31 224 56 5401

- 2. Any notice given under this MOA shall be in writing and shall be deemed given when sent by confirmed facsimile or two (2) working days after deposit with a commercial overnight carrier with confirmed verification of receipt. All communications shall be sent to the addresses set forth above or to such other address as may be designated by either Participant.

ARTICLE 12 - STEERING COMMITTEE AND COORDINATORS

- 1. The Participants shall establish a Steering Committee to guide cooperative activities implemented under this MOA. The Steering Committee shall meet at least once a year to evaluate past cooperative activities, develop future plans, and discuss any matter concerning the interpretation or implementation of this MOA. The Steering Committee shall be composed of Directors from NREL and JRC-IE.
- 2. At least once a year, the Steering Committee shall review the cooperative activities implemented under this MOA as a means to ascertain their effectiveness, document achievements and lessons learned, recognize technical personnel, and identify and plan for better fulfilling the objectives of this MOA.
- 3. To this end, each Participant has designated one (1) person to serve as its coordinator with responsibility to coordinate, prepare for, and attend the Steering Committee. The Participants shall communicate to each other in writing any changes with regard to the designated coordinators.
 - a. The coordinator for NREL shall be Dr. William Wallace.
 - b. The coordinator for the JRC shall be Dr. Heinz Ossenbrink.

ARTICLE 13 - GENERAL PROVISIONS

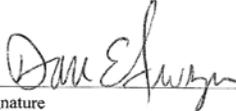
- 1. Relationship of the Participants. Neither Participant to this MOA intends that any agency, joint venture or partnership relationship shall be created between them by this MOA. Nothing in this MOA shall be construed as an authorization by one Participant for the other Participant to act as agent for that Participant.
- 2. Revisions. No modifications, alteration or revisions shall be effective unless confirmed in a written agreement signed by an authorized representative of each Participant (as applicable).

- 3. Force Majeure. Neither Participant shall be liable for any unforeseeable event beyond its reasonable control not caused by the fault or negligence of such Participant, which causes such Participant to be unable to perform its obligations under this MOA and which it has been unable to overcome by the exercise of due diligence.
- 4. Entire Agreement. This MOA embodies the entire understanding of the Participants to this MOA and shall supersede all previous or contemporaneous communications, either verbal or written, between them relating to this MOA.

IN WITNESS WHEREOF, the Parties have executed this Memorandum of Agreement by signature below.

National Renewable Energy Laboratory
 managed and operated by the
 Alliance for Sustainable Energy, LLC
 for the United States Department of Energy

Joint Research Center Institute for Energy
 European Commission, representing the
 European (Atomic Energy) Community



 Signature

Dan E. Arvizo
Director

12 October 2010

 Date Signed



 Signature

Giovanni De Santi
Director

 Date Signed

Technical Annex 1 to JRC/NREL Memorandum of Agreement

“Hydrogen Sensor Performance Testing and Evaluation”

Project Leaders: L. Brett (JRC-IE) R. Burgess (NREL)	
Title & short Summary	Hydrogen Sensor Performance Testing and Evaluation To identify and resolve issues in hydrogen sensor use and the assessment and validation of hydrogen detection technologies
Objectives	<ul style="list-style-type: none"> a) To obtain scientific data needed for a better understanding of the requirements for safe use of hydrogen systems, with specific accent on gas detection techniques for hydrogen applications in confined spaces. b) To improve the co-ordination and effectiveness of co-operation efforts between NREL and the Commission in the field of hydrogen detection, through inter-laboratory comparison of data and validation of testing facilities, methods and practices. c) To use the results from this collaborative work to leverage output and support to JRC and NREL's mutual policy makers. d) To promote mutual interest and co-operation in understanding and resolving issues that can help outlining gaps in the existing standards and regulations, thus enabling to express recommendations on pre- and co-normative research needs. e) To deepen the understanding of scientific and technical issues relating to hydrogen detection technologies, assessing their current performances and potentialities and helping further Research and Development goals to be met. f) Using knowledge generated to provide assistance and advice in determining of hydrogen detector performance targets for applications. g) To test and demonstrate the proficiency of both laboratories in hydrogen detector testing methods and illustrate their competence in this area. h) To make visible to stakeholders the importance of hydrogen detection for safety and to make available the results and conclusions from this collaboration.

Activities	<ol style="list-style-type: none"> 1. Initiate and maintain a dialogue on matters of hydrogen safety technologies, with specific accent on hydrogen detection measures and devices, exploring possibilities for developing research projects of mutual interest. 2. Exchange of appropriate, non-proprietary scientific and technological information. 3. Harmonise established testing procedures and promote these methods to end-users internationally. 4. Work jointly to develop initiatives to identify and implement research projects of mutual interest. 5. Participate in the execution of on-going programs, projects and related activities of mutual interest to the Parties including inter-laboratory comparisons and round robin testing. 6. Exchange of scientific/technical personnel to facilitate effective sharing of skills, scientific and technological developments between both laboratories. 7. Joint participation in national and international scientific conferences.
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