Project No: 209481

Project acronym: ZEOCELL

Project Full Name: NANOSTRUCTURED ELECTROLYTE MEMBRANES BASED ON POLYMER / IONIC LIQUIDS / ZEOLITE COMPOSITES FOR HIGH TEMPERATURE PEM FUEL CELL

FINAL REPORT

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Project Coordinator name: Dr. Jesús Santamaría
Project Coordinator organisation name: Institute of Nanoscience of Aragon (INA) - University of Zaragoza (UNIZAR)

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- **Executive summary**

ZEOCELL (http://ina.unizar.es/zeocell) puts forward an innovative concept to overcome the current limitations of commercial available PEMFCs based on the use of multifunctional nanostructured materials, capable to withstand temperatures in the range 130º - 200º C. Up to **seven electrolyte membrane compositions** have been studied (see Figure 1). All of the electrolyte membranes comprise at least one of the following basic materials: **poly-benzimidazole** (PBI), **protic ionic liquids** and **zeolites/zeotypes** (Figure 2).

As the polymer membrane architecture plays the key role to ensure proton transport through heterogeneous media, **dense and porous** (random or straight pores) **PBI films** have been deployed as proton conductor supports (see Figure 3). For proton conduction purposes, **phosphoric acid doping** and/or **protic ionic liquid embe**dding have been mainly studied in the project. The incorporation of microporous materials either as **inorganic fillers** to the membrane casting solution or as **thin film coatings** onto pre-existing porous PBI membranes has been considered (see Figure 4).

To gain insight the synergic effects provided by materials combination, different membrane categories, ranging from **1 component** (i.e. Pure Polymeric Ionic Liquid Films), through **binary** (supported ionic liquid membranes in track-etched porous PBI substrates, supported ionic liquid membranes in randomly porous PBI substrates, reinforced polymeric ionic liquid membranes on porous PBI supports, acid doped track-etched porous PBI substrates), **ternary composites** (hybrid acid doped dense or porous PBI and hybrid dense or porous PBI embedding ionic liquid) to the final nanostructured electrolyte membranes based on **four components** (i.e. PBI, phosphoric acid, ionic liquid and microporous materials) have been deeply studied. The best conduction performance of 1 component-membranes is exhibited by polymeric ionic liquid films prepared from ImSF0108b (350 mS/cm at 200ºC after 1000 h working). For 2 components-membranes, it is clearly outstanding the conduction behaviour of poly[ImSF0108b] on randomly porous PBI supports (275 mS/cm at 200ºC after 1,000 h working).Thus, both membrane categories effectively accomplish with the durability and conductivity targets. Concerning 3 components-membranes, Hybrid Randomly Porous Doped PBI 75% in porosity prepared from TPP porogen including a 3% wt. of colloidal NaY type zeolite encapsulating 1-H-3-methylimidazolium bis(trifluoromethanesulfonyl)imide as inorganic filler shows 223 mS/cm at 150ºC as in-plane conductivity. The 4-components nanostructured electrolyte membrane based on phosphoric acid doped porous PBI (80% in porosity) embedding 1-H-3-vynilimidazolium bis(trifluoromethanesulfonyl)imide as proton conductor with ETS-10 titanosilicate type coatings as top layers allows to attain 100 mS/cm at 150ºC. In addition to conduction requirements which have been successfully addressed, the hybrid doped PBI membranes and the nanostructured electrolyte membranes stand up as the most adequate in terms of methanol and hydrogen cross-over respectively. Overall, the most promising electrolyte membranes are those based on **polymeric ionic liquids** although further efforts to reduce fuel cross-over at temperatures above 120ºC are required. The cost assessment results clearly indicate that the aforementioned membranes would be competitive in the high temperature PEMFC stationary applications market. The business analysis of stacks based on Zeocell membranes in the Micro-Combined Heat and Power Systems and Backup/supplemental power for Telecom Applications has foreseen encouraging benefits in a hypothetical scenario with a 2% and 6% penetration in both markets respectively.

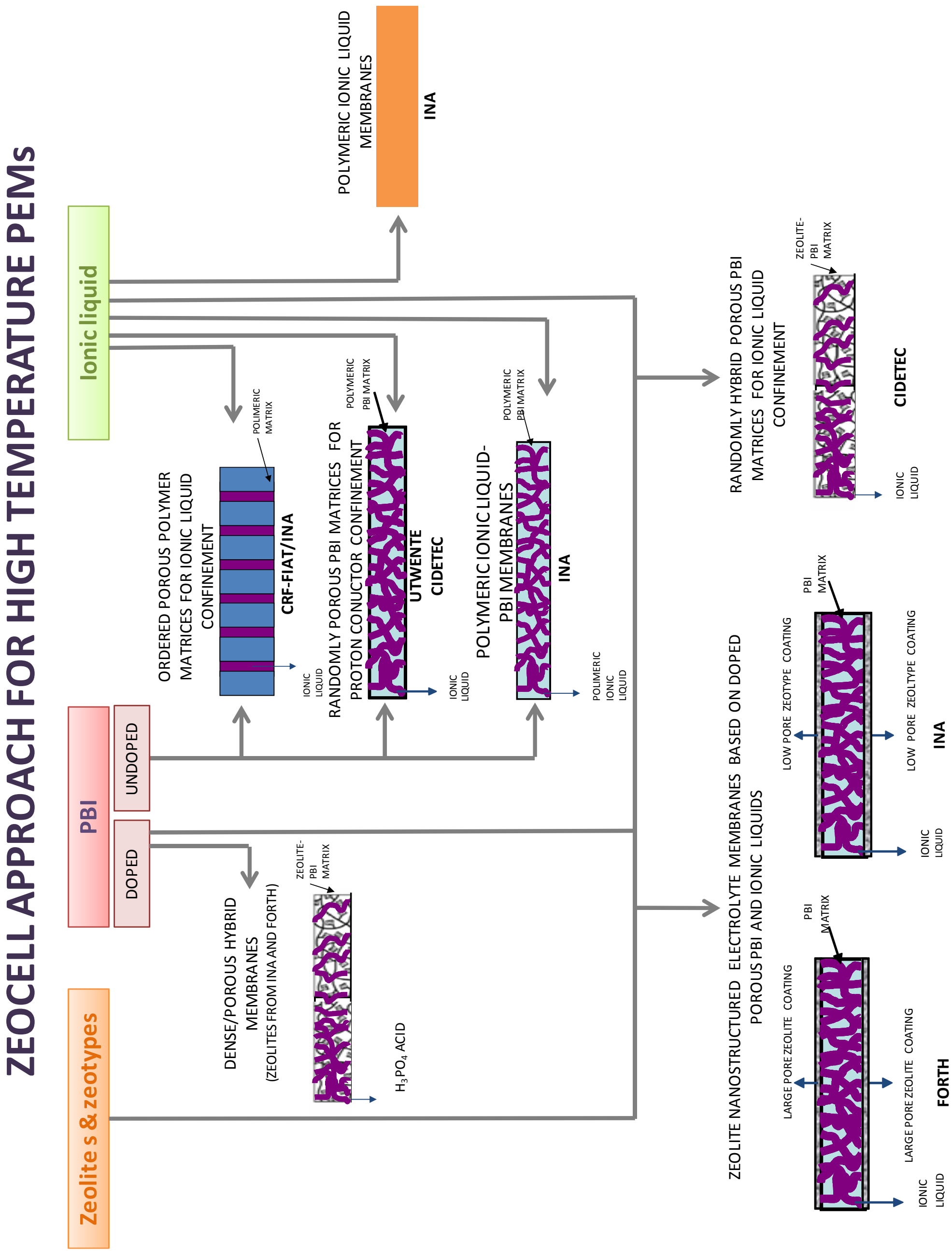


Figure 1. General overview of the different electrolyte membranes developed in Zeocell.

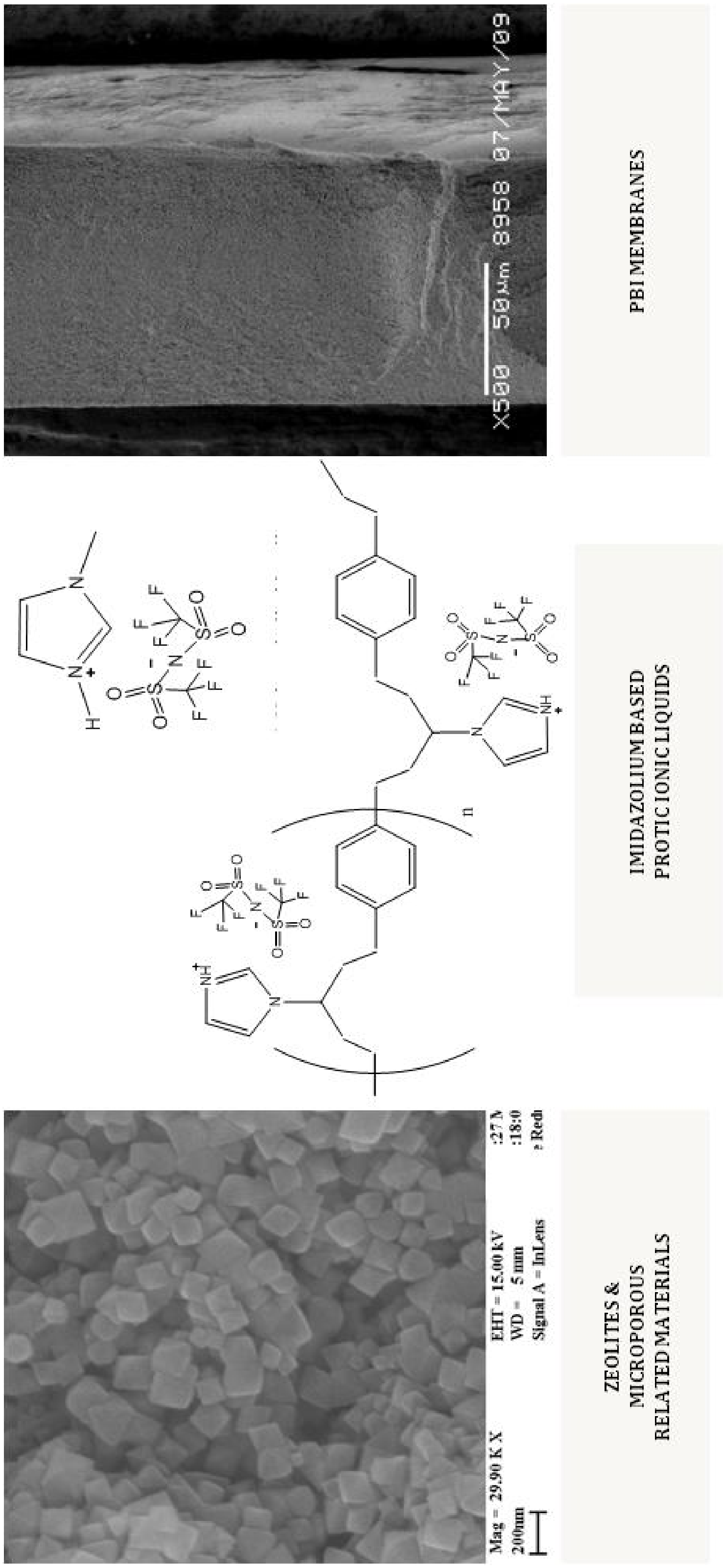


Figure 2. Individual materials for ZEOCELL membranes

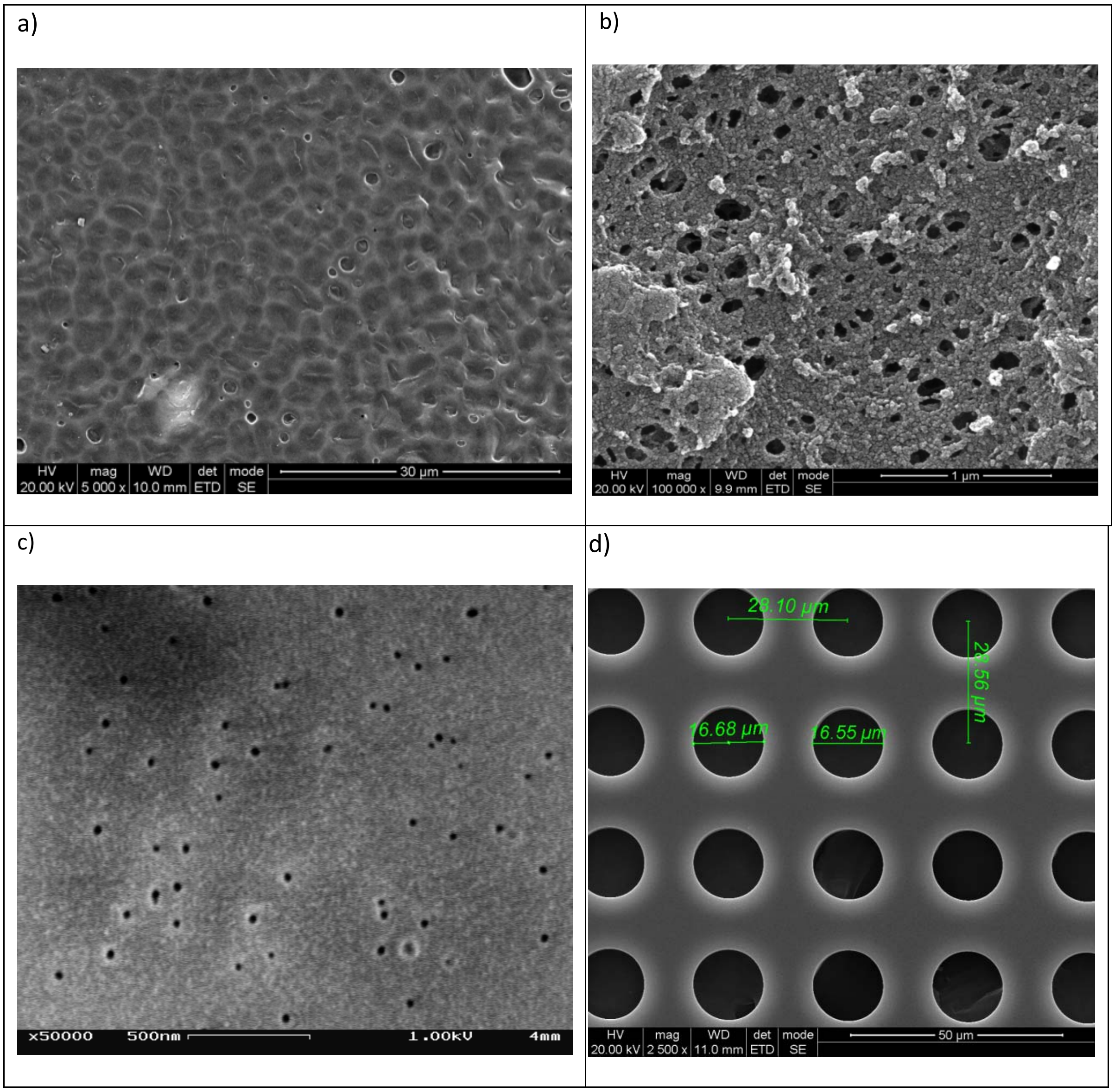


Figure 3. Top view of Porous PBI films prepared by: a)leaching out a porogen (75% DBP); b) delayed-demixing (80% porosity); c) ion-track etching (1% porosity); d) microtransfer moulding (30% porosity).

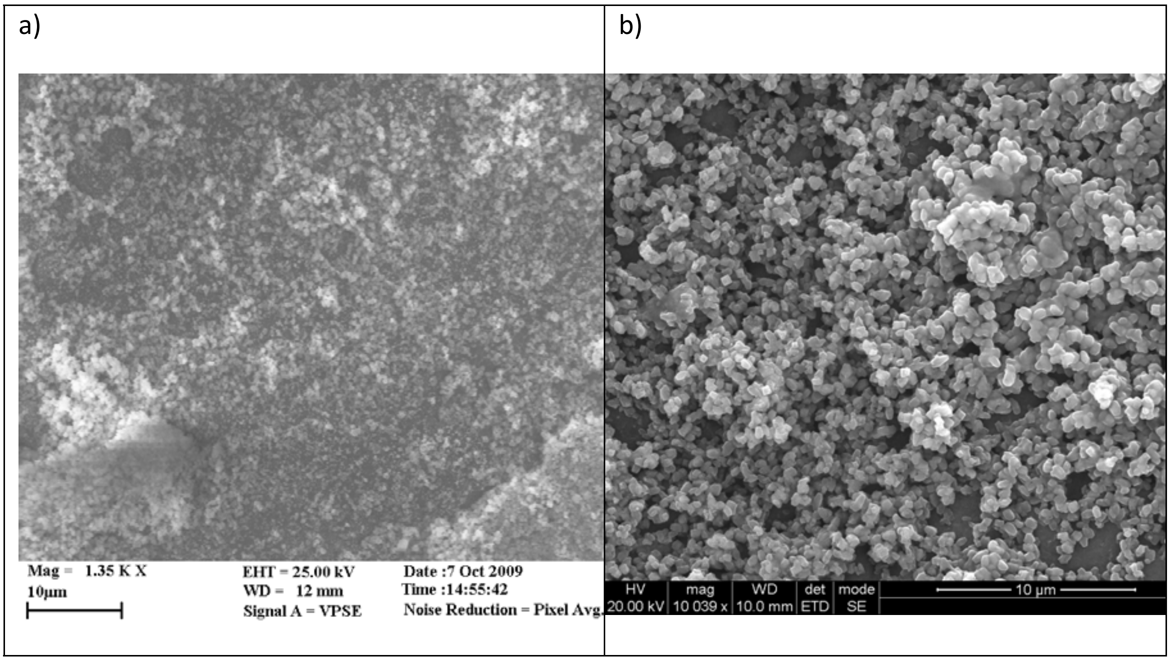


Figure 4. SEM analyses of Nanostructured electrolyte membranes combining doped PBI porous membranes, protic ionic liquid and microporous coatings. Top view for: a) NaY coating by vacuum filtration, and b) ETS-10 coating by covalent linkage over porous PBI substrates.

- **Summary description of project context and objectives**

The European Council in 2007 adopted ambitious energy and climate change objectives for 2020 including the reduction of greenhouse gas emissions by 20%, increasing the share of renewable energy to 20%, and making a 20% improvement in energy efficiency. The European Council has also given a long-term commitment to the decarbonisation path with a target for the EU and other industrialised countries of 80 to 95% cuts in emissions by 2050. Nevertheless, the existing strategy is currently unlikely to achieve all the 2020 targets, in particular those related to energy efficiency[1]. EU energy and climate goals have been incorporated into the Europe 2020 Strategy for smart, sustainable and inclusive growth, adopted by the European Council in June 2010[2]. The development of economically feasible more efficient energy conversion systems, is one of the most important technological challenges for the XXI century. The European Strategic Energy Technology (SET) Plan has identified fuel cells and hydrogen among the technologies needed for Europe to achieve the 2020 targets. Much of the research on new materials for PEMFC membranes, while promising, may be too far away from commercialization to meet this timeframe, and could be the next generation technology. Certainly, fuel cells and hydrogen are medium and long-term energy technology options and, therefore, their contribution to meet the 2020 EU targets on greenhouse gas emissions, renewable energy and energy efficiency will be limited. However, they are expected to play an important role in achieving the EU vision of reducing greenhouse gas emissions by 60-80% by 2050. By that time it is expected that the critical barriers preventing commercialisation of these technologies (i.e. cost and durability of fuel cells, availability of large amounts of emissions-free, affordable hydrogen, development of a long term stable regulatory framework) will be overcome and their full socio-economic and environmental benefits realized.

Among FCs, proton exchange membrane fuel cells (PEMFC)[3] are favorably identified in three out of four priorities (i.e. Transport & Refuelling Infrastructure, Stationary Power Generation & Combined Heat and Power (CHP) and Early Markets) settled in the Multi-annual Implementation Plan 2008-2013 adopted by FCH JU[4]. However, cost reduction seems to be the main challenge to a widespread PEM Fuel Cell commercialization, which is based on four main pillars with strong interdependencies: i) manufacturing costs reduction through the use of new materials with lower costs and suitable for mass production; ii) efficiency increase to allow reducing operation costs and equipment size through the use of new materials with improved properties or new concepts for stack configuration; iii) durability increase; and iv) fuel availability to become a real alternative to fossil fuels. In fact, the benefits imposed by the use of electrolyte membranes developed within this project are mainly related to the three former issues.

The low temperature proton exchange membranes present some disadvantages that may reduce their effectiveness in fuel cell applications (see Figure 5). These disadvantages can be overcome by adopting high temperature operation of the membrane[5]. The advantages of high temperature Polymer Electrolyte Membrane (PEM) fuel cells include the simplifications of the balance of plant, the generation of more useful high-grade waste heat and improvements in the catalyst activity. With respect to the balance of plant, a membrane not dependent on water to maintain fast-ion transport processes would allow significant simplification of the system. The energy-cost associated with humidifying hydrogen and air would be reduced, resulting in a net efficiency gain. The waste heat produced in the stack would be more easily collected and removed and could provide useful heat (CHP applications) or more straight forward removal to the environment with smaller forced-convective radiators and air blowers (demanding less energy from the system). Operation at higher temperatures would also enhance the properties of the catalysts within the fuel cell stack. For the anode, fuelling options would become more flexible as the anode catalyst becomes more tolerant to impurities present in primary reforming streams. This leads to reductions in cost, complexity of the system balance of plant and improvements in the net efficiency. The cathode performance will also be enhanced. Provided the level of water within the stack remains low, improvements in electro-kinetic performance are expected at elevated temperatures. The term 'high temperature' refers to the temperature range, 100º–200ºC (150º-200ºC for some authors[6]) which does not appear to be high from an engineering point of view. However, in the current state of the art, development of high temperature PEM for fuel cells is very important in the field of materials science and engineering.

PEMFC Advantages	PEMFC Disadvantages
• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up • Uses Hydrogen based fuels	• Requires expensive catalysts (at low temperatures, noble metals are needed) • High sensitivity to fuel impurities • Low temperature waste heat

Benefits of T increase	Problems/specific challenges
• Reaction Rate Increase • CO tolerance Increase (fuel treatment systems can be simplified) • Operating Voltage Increase • Polarization effect Reduction • Cogeneration possibilities	• Corrosion • Electrocatalysts sintering and recrystallization • Electrolyte loss by evaporation • Fuel cross-over (Utility decrease)

Figure 5. Main features of High Temperature PEMFCs

Over the past decade, several basic research projects supported by the EU have been focused on the High-Temperature PEMFC topic. FURIM project funded by FP6 developed new high temperature polymer electrolyte membrane fuel cells based on acid-base blend membranes (30% SFS and 70%PBI) with H3PO4 imbibed[7,8]. Conductivity values up to 87.5 mS/cm (180ºC/ 5% RH) were attained. However, durability tests revealed the MEA performance decayed after 300 hours for operation at 200ºC/1000 hours at 180 ºC/ 5000 hours at 150ºC[9]. CARISMA network was focused on MEAs development for high temperature applications (100ºC, 110ºC and 120ºC) while maintaining reasonable performance at lower temperatures (80ºC and 60ºC). Thus, a new perfluorosulfonic acid membrane (PFSA) called E79-03S developed by Solvay Solexis were successfully incorporated into MEAs showing significant performance improvements (0.5 W cm-2 at 0.65 V, 500 hours steady state durability at 110ºC with stable performance in presence of 17% RH). Polysulfone membranes were also tested (polysulfone-graft-poly(vinylphosphonic acid) with proton conductivities of 10 mS/cm at dry conditions and 100 mS/cm at 100% RH and 120ºC by doping with 2-5% sulfonated polymer (Nafion N11) at the expense of lower durability. PFSA membranes were also developed as

Hyflon Ion E87 from Solvay Solexis with similar performance to Nafion 117. However, long time test at dry conditions results in a loss of performance (30% decay at 100ºC/700h; 50% decay at 120ºC/375h). The incorporation of ZrO_2 with phosphotungstic acid imbibed to Nafion was also studied without any significant improvements. Funded by FCH JU, the objective of MAESTRO (2010-2012) (http://www.maestro-fuelcells.eu/) is to improve the mechanical properties of state of the art perfluorosulfonic acid membranes by using chemical and thermal processing and filler reinforcement methodologies, since due the most relevant failure mode in extended life time operation is associated with membrane mechanical failure. More recently (2011-2013), STAYERS project (www.stayers.eu) pursues stationary PEMFCs with lifetime beyond 5 years. To reach the high goals of the project, basic material research is given maximum attention. The durability of all components of a stack of PEM fuel cells, especially that of the Membrane Electrode Assembly (MEA) supplied by Solvay Solexis, rims and seals, cell (bipolar) plates, and flow field is of paramount importance for a stationary power generator. APOLLON-B project (2006-2009) aimed to develop new materials for high-temperature PEMFCs (130º-200 °C). Novel polymers comprising aromatic polyethers with pyridine units were synthesised and evaluated. A new polymer from Advent, now commercially available ADVENT TPS®, revealed exceptional continuous operating stability, with no decay in performance for over 2,000 hours at 180 °C under H2/air feed. Funded by FCH JU, the objective of DEMDEA (2010-2012) (http://demmea.iceht.forth.gr) is to understand the functional operation and degradation mechanisms operating in high temperature PEMs based on H3PO4 imbibed PBI, and its electrochemical interfaces; and advanced state of the art MEAs based on aromatic polyethers bearing pyridine units.

Similarly, the U.S. Department of Energy between 2003 and 2007 funded the project "Development of Polybenzimidazole-Based High-Temperature Membrane and Electrode Assemblies for Stationary and Automotive Applications" managed by Plug Power Inc. The investigation was focused on the high-temperature polybenzimidazole (PBI) membrane optimization supplied by BASF to meet the performance, durability and cost targets required for stationary fuel cell applications. Conductivity values up to 270 mS/cm (160ºC/ 70% RH) were attained. The long time durability studies gave a loss of performance in 400 hours of 2.77% at 160ºC, which made impossible to achieve the durability goal for the project (20000 hours). BASF longer tests exhibited a loss performance >16% in 12000 hours.

In this context, the purpose of ZEOCELL project is the development of nanostructured electrolyte membranes based on the synergic combination of zeolites, ionic liquids and polymers able to operate at 130º-200ºC with the following features:

High ionic conductivity: higher or equal than 100 mS/cm at 150ºC.

Suitability for operating at temperatures between 130-200ºC (the membrane materials are expected to be thermally stable up to 200ºC. Membrane performance will be validated on single cells at temperatures of at least 150ºC).

Good chemical, mechanical and thermal stability up to 200ºC.

Durable (<1% of performance degradation during the first 1000 working hours).

Low fuel cross-over (<five times lower than Nafion methanol permeability lower or equal than $3x10^{-7}$ cm^2 s^{-1})

Reduced manufacturing costs (< 400 EUR/m^2).

For such purposes, the work-programme/methodology depicted in Figure 6 has been followed. Among the different electrolyte membrane concepts studied along the project (see Figure 1), three membrane configurations fulfil all the ST requirements quoted above with the exception of durability issues which are briefly described below:

1) **Hybrid Randomly Porous PBI Membranes** doped with phosphoric acid (PCT/EP2010/064857; priority date 05/10/2010): endurance properties are under investigation.

2) **Nanostructured Electrolyte Membranes** based on randomly porous acid doped PBI membranes with tortuous pores filled with protic ionic liquid and two microporous ETS10 coatings on top surfaces: test at 150º and 200ºC revealed severe performance decay after 150 h operation

3) **Reinforced Polymeric Ionic Liquid Membranes on Porous PBI supports**: a continuous stepwise loss in performance was observed during the first 500 h at 200ºC, but afterwards conductivity value remained constant at around 275 mS/cm.

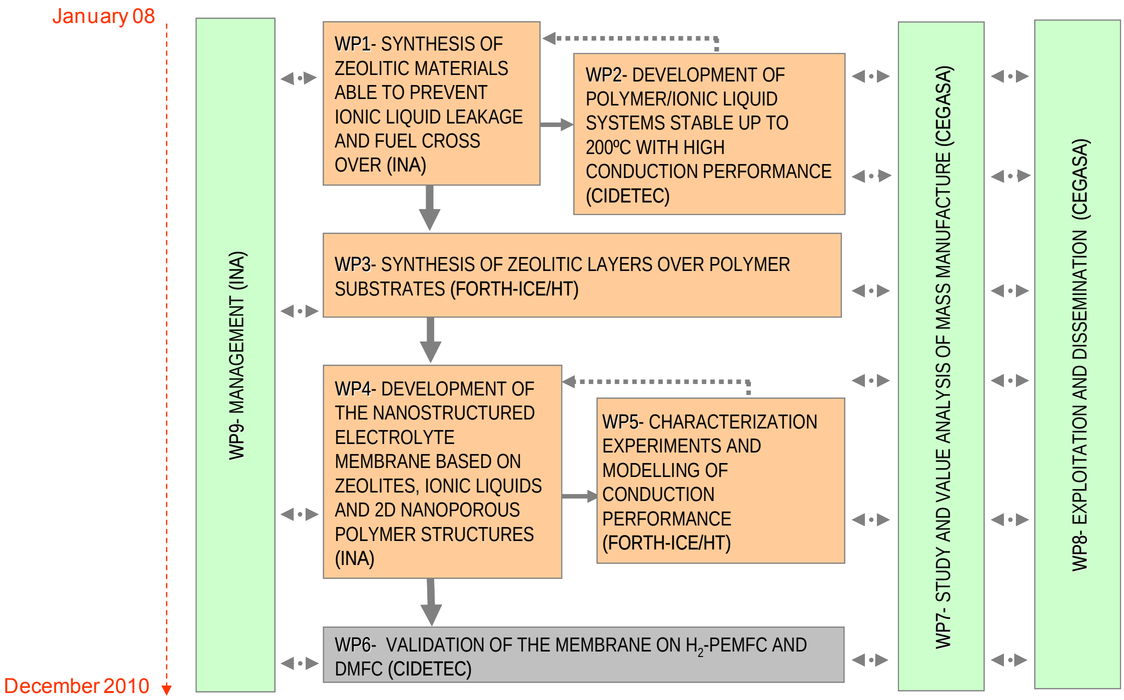


Figure 6 Work-programme schedule proposed for Zeocell Project.

For such promising candidates, their manufacturing process has been evaluated from an industrial point of view in an attempt to identify the next steps for the final implementation and industrial exploitation of the developed technologies. PEM fuel cells are commonly applied in transportation, stationary applications, and portable power generation. The integration of HT-PEMFC technology in the mentioned sectors is considered highly interesting because it reduces drastically the overall system complexity (see Figure 7).Within the Zeocell framework, the exploitation plans for high temperature PEMFCs have been mostly focused on two stationary markets: Backups and micro or domestic Combined heat and power (micro-CHP or dCHP) systems.

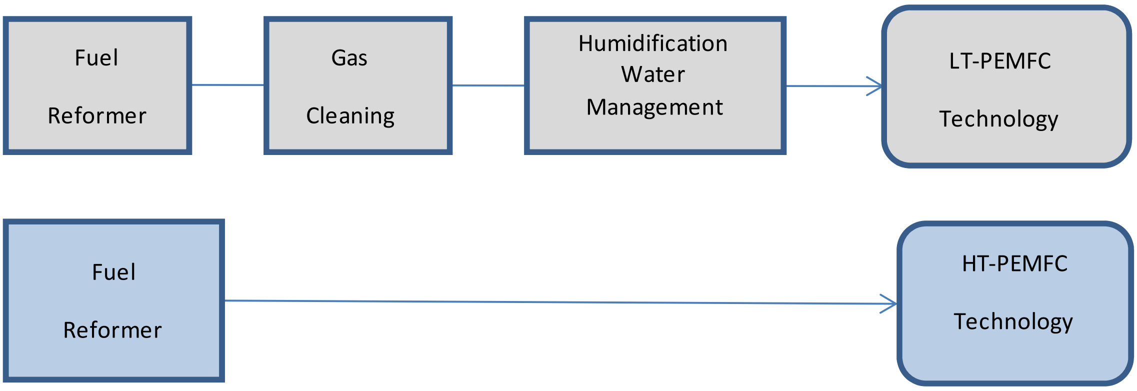


Figure 7. System complexity reduction by using HT-PEMFC technology.

Application Area	Targets 2010	Targets 2015	
		Volume	Cost and Technology
Transport & Refuelling Infrastructure	~10 additional road vehicles (single site) plus mobile deployment to sites with existing refuelling infrastructure capable of refuelling up to 50 vehicles ~20 buses on 3 sites with appropriate refuelling capacity	~ 500 Light Duty Vehicles (mainly cars) at 3 additional sites with 3 new stations ~500 buses at 10 EU sites (of which at least 7 new ones) with refuelling stations (daily refuelling capacity >400kg)	System cost of approx. € 100/kW Durability in car propulsion systems 5000 hours Roadmap for the establishment of a commercial European hydrogen refuelling infrastructure
Hydrogen Production & Distribution	Appropriate H2 supply chain (including fuel purity) to match Transport, Stationary and Early Markets requirements. For 2015 10 - 20% of general H2 demand should be produced via carbon free/carbon lean processes		Cost of H2 delivered at refuelling station < €5/kg (€ 0.15/kWh) Improved system density for H_2 storage (9 %wt of H_2)
Stationary Power Generation & CHP	3 - 7 MW installed electrical capacity in the EU for pre-commercial demonstration	~ 100MW installed electric capacity	Cost of € 4,000 - 5,000/kW for micro CHP Cost of € 1,500 - 2,500/kW for industrial/commercial units
Early Markets	500 new units in the EU-Market: ♦ 50 UPS/back-up power ♦ 20 industrial and off highway vehicles ♦~ 400 portable & micro FCs	14,000 new units in the EU market: ♦ 1000 UPS/back-up power ♦ 500 industrial and off-highway vehicles ♦ 12,000 - 13,000 portable and micro FC's	

Figure 8. Multi Annual Implementation Plan Targets for the FCH JU.

According to the Multiannual Implementation Plan Targets of the FCH JU (see Figure 8), both of them are included within the RTD priorities. In fact, 2015 targets are 1000 UPS/back – up units and 4000-5000 €/kW for dCHP systems respectively. With the rapid expansion of wireless communication systems worldwide, and the increasing socioeconomic benefits of mobile technology, the need for dependable and economical backup power is critical. Electric grid loss throughout the year, whether from severe weather, natural disasters, or limited grid capacity, is an ongoing challenge for network operators. Traditional telecom backup power solutions include batteries for short duration backup and diesel and propane generators for longer duration backup. Batteries are relatively inexpensive for 1 to 2 hours of backup power. However, batteries are not ideal for longer duration backup power applications because they can be expensive to maintain, unreliable after aging, temperature sensitive and hazardous to the environment after disposal. Diesel and propane generators are capable of longer duration backup power. However, generators are unreliable, maintenance intensive, and environmentally unfriendly. Thus, clean fuel cell technology is the clean solution with minimal environmental impact. Fuel cells are reliable, with fewer moving parts and a wider operating temperature range than a battery. In addition, a fuel cell system has a lower lifetime cost than a generator.

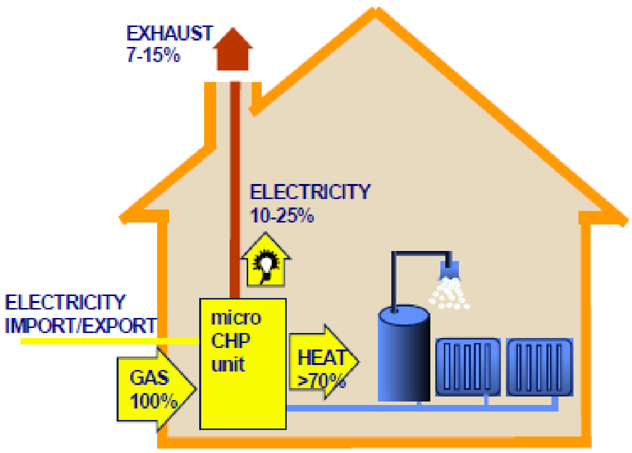


Figure 9. Diagram of a micro CHP application.

Combined heat and power (CHP) systems based on fuel cells offer high efficiency, low emission, and decentralized power and heat supply for buildings (see Figure 9) and industries. They can operate from the existing natural gas distribution network, using a reformer to convert methane gas to hydrogen thus minimizing infrastructure requirements. There is considerable interest in installing CHP systems in domestic environments[10], and also for large scale applications such as community heating or industries. It is expected that by 2050 combined heat and power (CHP) generation and dCHP will become increasingly important as smart grids integrate a large number of distributed power generation units in "virtual plants". Ultimately, stationary fuel cells will establish themselves as the reference technology for on-demand power generation in the residential and industrial sector. Globally, pre-commercial projects have already been initiated for the implementation of dCHP systems on the larger scale. A combination of low-temperature reforming with a high-temperature PEMFC (120°C – 180ºC) opens a unique perspective in thermal management for both domestic (up to 10kW) and industrial (up to 150kW) CHP systems, with a total efficiency yield of primary energy above 80%. The high temperature operation of the PEMFCs tolerates higher impurity levels in the fuel, and thereby simplifies the reforming system (fuel cell and reformer synergy).

To evaluate their potential share in the market, the cost evaluation for the 2kW HT-PEMFC based stack has been compared with the current manufacturing processes considering different aspects: cost (€/kW), number of membranes manufactured and necessary equipment. In general terms, fuel cell systems integrating the membranes developed in ZEOCELL would be cost-competitive by the implementation of a mass manufacturing process; although further efforts on endurance properties are required. Economical use of PEM fuel cell power for stationary applications demands a lifetime of the fuel cells of at least 5 years, or more than 40,000 hours of continuous operation. For the stationary use, especially in the chemical industry and in remote areas, robustness, reliability, and longevity are often more important than the cost of the initial investment. For stationary generators the yearly cost of maintenance and overhaul are expected to be much larger than for intermittent applications such as automotive- and back-up power. Currently, most fuel cells exhibit major performance decay after around a thousand hours of operation. The DOE targets pursue a life time of 40,000 h by 2011 with 40% efficiency for distributed power and $1500/kW for stationary applications. According to Zeocell estimations, the costs for high temperature PEMFC stack (2 kW) are estimated at 214 €/kW for automated manufacturing process on a 500.000 units/year basis. The foreseen total units sold globally by 2015 for both applications, could reach 360,000 and 43,000 for micro-CHP and back-ups respectively, considering from the micro-map study "mini and micro CHP market assessment and development plan" (supported by the European Commission SAVE Programme) and Ballard Power System reports[11] and assuming a high temperature PEMFC technology share in the market of 10% and 20% respectively. Within this scenario, and considering the Zeocell membranes cost and the manufacturing process layouts; it is worthwhile to reconsider the business opportunities in the medium term (2015-2025).

- **Description of main S & T results/foregrounds**

  - BACKGROUND

The PEMFC technology represents one of the most promising opportunities in the field of the alternative fuels for an environmentally friendly energy production. However, fuel cells and hydrogen are definitely medium and long-term energy technology options. During the past few years, many advances have been made but there are still technical and economic obstacles in the commercialization of fuel cell. In this regard, many efforts have been made to develop membranes for PEMFC's with excellent performance and durability and low cost. Particularly, good ionic conductivies at high temperatures and low humidity, low gas permeability, low electro osmotic drag coefficient, good chemical/thermal stability and mechanical properties, excellent fuel cell performance are being pursued by scientific-industrial partnerships. As already stated ZEOCELL aims to put forward an innovative concept based on the use of multifunctional nanostructured materials to overcome the existing drawbacks of PEMFCs. Particularly, a synergic combination of microporous zeolite type materials, protic ionic liquids (PILs) and porous polymers is proposed to develop improved and mass manufacturable electrolyte membrane materials capable to withstand temperatures in the range of 130-200ºC. Operation at this temperature is desirable since at temperatures over 120ºC most of the functional problems currently associated with PEMFCs such as catalyst CO poisoning, water management, efficiency (polarization effects and electrochemical reaction rates), and cogeneration possibilities (see Table 1) can be overcome.

Table 1. Comparison between HT-PEMFC and LT-PEMFC.

HT-PEMFC (100º – 200ºC)	**LT-PEMFC (< 90ºC)**
Tolerance to fuel impurities	Tolerance to fuel impurities
• CO up to 3%	• CO below 100ppm
• H_2S up 10 ppm	• H_2S below 0.1 ppm
• CH_3OH up to 10%	• CH_3OH below 1%
No external humidification	Humidification issue
No stability issue of membrane	Membrane degradation
Simplified systems	Complex fuel cell systems
Effective co-and tri-generation	Complex co-and tri-generation
Simple thermal integration of reformer & stack	

In this "new" high temperature scenario, the most important challenges are related to the electrolyte performance and durability, and also to the fuel utility (cross-over phenomena). Table 2 summarizes the proton conductivity of "state of the art" membranes used in fuel cell under high temperature operation. Apart from sulfonated aromatic hydrocarbon polymers, organic-inorganic composite membranes (mostly based on Nafion and Silica) and polymer blends; acid-base Polybenzimidazole membranes are among the most studied for HT-PEMFCs. PBI membranes impregnated with phosphoric acid have been studied as electrolytes in high temperature PEMFCs [5-9] for more than a decade. PBI polymer is commercially available at a relative low cost (150-220 €/kg), exhibits excellent stability in both reducting and oxidizing environments and its glass transition and decomposition temperature values are between 425-435ºC and above 600ºC respectively. Being a basic polymer (pK equals approximately 6.0), it easily captures oxo- acids (phosphoric or sulphuric acid), which helps stabilization and provides with proton conductivity. The first patent related to phosphoric acid doped PBI membranes for high temperature PEMFCs belongs to Savinell & Litt [12] and dates back to 1996; since then, numerous patents have emerged from this group. A high acid concentration provokes a drastic worsening in the membrane mechanical resistance due to the soaking process that takes place provoking separation among the polymer chains and reduction of intermolecular interactions. Therefore, an optimal doping of the membrane implies an improvement in conductivity without affecting the mechanical properties. Moreover, phosphoric acid autodehydration at temperatures above 140ºC is a serious limitation due to the formation of lower conductivity oligomers like pyrophosphoric acid ($H_4P_2O_7$). Among the main strategies to improve the performance of current PBI membranes, the most studied are: i) ionic cross-linking of polymeric acids and polymeric bases; ii) use of covalently cross-linked acids or halides; iii) composite organic-inorganic membranes from PBI and inorganic fillers. Accordingly, a new generation of advanced PBI membranes are currently commercially available (i.e. Celtec®-P1000 MEA from BASF and HT-PEM fumea® generation II from FumaTech).

Table 2. In Plane Proton Conductivity properties of high temperature proton exchange membranes (adapted from [5])

Membrane Type	Operational temperature (ºC)	Relative humidity (%)	In Plane Proton conductivity (mS/cm)	Reference
Functionalized PDMS (APP 414)	130	100	72	Ghil LJ, Kim CK, Rhee HW. Phosphonic acid functionalized poly(dimethyl siloxane) membrane for high temperature proton exchange membrane fuel cells. Curr Appl Phys 2009;9:e56–9.
SPES/BPO4 composite	120	-	38	WenS,GongC,TsenWC,ShuYC,TsaiFC.Sulfonatedpoly(ether sulfone) (SPES)/boronphosphate(BPO4) compositemembranes for high-temperatureproton-exchangemembranefuelcells.IntJ Hydrogen Energy2009;34:2982–91.
SPFEK–SiO2– HPMC hybridmembrane	120	50	19,8	Zhang YF, Wang SJ, Xiao M, Bian SG, Meng YZ. The silica- doped sulfonated poly(fluorenyl ether ketone)s membrane using hydroxypropyl methyl cellulose as dispersant for high tempera- ture proton exchange membrane fuel cells. Int J Hydrogen Energy 2009;34:4379–86.
Disulfonated poly(arylene ether sulfone)/ZrP composite	130	100	130	Hill ML, Kim YS, Einsla BR, McGrath JE. Zirconium hydrogen phosphate/disulfonated poly(arylene ether sulfone) copolymer composite membranes for proton exchange membrane fuel cells. J Membr Sci 2006;283:102–8.
Sulfonated polyimides	140	10–20	0,5	Ye X, Bai H, Winston Ho WS. Synthesis and characterization of new sulfonated polyimides as proton-exchange membranes for fuel cells. J Membr Sci 2006;279:570–7.
	160	5–12	2	
Nafion/ZrSPP composite	110	50	≥5	Kim YT, Kim KH, Song MK, Rhee HW. Nafion/ZrSPP composite membrane for high temperature operation of proton exchange membrane fuel cells. Curr Appl Phys 2006;6:612–5.
	110	98	≤50	
PBI/ZrP composite	200	5	96	He R, Li Q, Xiao G, Bjerrum NJ. Proton conductivity of phosphoric acid doped polybenzimidazole and its composites with inorganic proton conductors. J Membr Sci 2003;226:169–84.
S-polyoxadiazole/mesoporous silica (MCM-41)	120	25	34	Gomes D, Marschall R, Nunes SP, Wark M. Development of polyoxa- diazole nanocomposites for high temperature polymer electrolyte membrane fuel cells. J Membr Sci 2008;322:406–15.
Krytox-Si–Nafion hybrid membrane	130	Ambient condition	1.72×10−1	Gosalawit R, Chirachanchai S, Manuspiya H, Traversa E. Krytox- Silica–Nafion composite membrane: A hybrid system for maintain- ing proton conductivity in a wide range of operating temperatures. Catal Today 2006;118:259–65.
Nafion/sulfonated poly(phenylsilsesquioxane) (sPPSQ) nanocomposites	120	100	157	Nam SE, Kim SO, Kang YK, Lee JW, Lee KH. Preparation of Nafion/sulfonated poly(phenylsilsesquioxane) nanocomposite as high temperature proton exchange membranes. J Membr Sci 2008;322:466–74.
Nafion/silica (SBA-15)	140	10	8.52×10−1	Park SJ, Lee DH, Kang YS. High temperature proton exchange membranes based on triazoles attached onto SBA-15 type mesoporous silica. J Membr Sci 2010;357:1–5.
Heteropolyacid (HPA)/sulfonated BPSH composite	130	-	150	KimYS,WangF,HicknerM,ZawodzinskiTA,McGrathJE. Fabrication andcharacterizationofheteropolyacid(H3PW12O40)/directly polymerized sulfonatedpoly(aryleneethersulfone)copolymer composite membranesforhighertemperaturefuelcellapplica- tions. JMembrSci2003;212:263–82.
Polyimide Containing Pendant Sulfophenoxypropoxy	120	100	1000	Miyatek K, Yasuda T, Hirai M, Nanasawa M, Watanabe M. Synthesis and properties of a polyimide containing pendant sulfophenoxypropoxy groups. J Polym Sci Part A Polym Chem 2007;45:157–63.
Groups poly(benzimidazole-co-aniline)	120	100	167	Bhadra S, Kim NH, Lee JH. A new self-cross-linked, net-structured, proton conducting polymer membrane for high temperature proton exchange membrane fuel cells. J Membr Sci 2010;349:304–11.
PPO/poly(styrene-b-vinylbenzylphosphonic acid)	140	100	280	Cho CG,KimSH, Park YC,KimH, Park JW. Fuel cellmembranes based on blends of PPO with poly(styrene-b-vinylbenzylphosphonic acid) copolymers. J Membr Sci 2008;308:96–106.
Perfluorocyclobutyl containing polybenzimidazoles	140	Without humidification	120	Qian G, Smith Jr DW, Benicewicz BC. Synthesis and characterization of high molecular weight perfluorocyclobutyl containing polybenzimidazoles (PFCB–PBI) for high temperature polymer electrolyte membrane fuel cells. Polymer 2009;50:3911–6.
Polybenzimidazole (PBI) containing bulky basic benzimidazole side groups	180	Without humidification	160	KimSK,KimTH, Jung JW, Lee JC. Polybenzimidazole containing ben- zimidazole side groups for high-temperature fuel cell applications. Polymer 2009;50:3495–502.
Imidazole intercalated into sulfonated polyetherketone membrane	120	Without humidification	10	Kreuer KD, Fuchs A, Ise M, Sapeth M. Imidazole and pyrazole- based proton conducting polymers and liquids. Electrochim Acta 1998;43:1281–8.
	200	Without humidification	20	

- ZEOCELL: A BASIC RESEARCH PROJECT ON MULTIFUNCTIONAL MATERIALS

Starting from the well-known PBI polymer, Zeocell pushes the "state of the art" with the development of nanostructured electrolyte membranes based on the synergic combination of porous PBI, protic ionic liquids and microporous inorganic nanocrystals (see Figure 10). The final aim is to use the advantages of each primary building block by choosing a proper electrolyte membrane configuration. Up to seven electrolyte membrane compositions have been studied (see Figure 1).

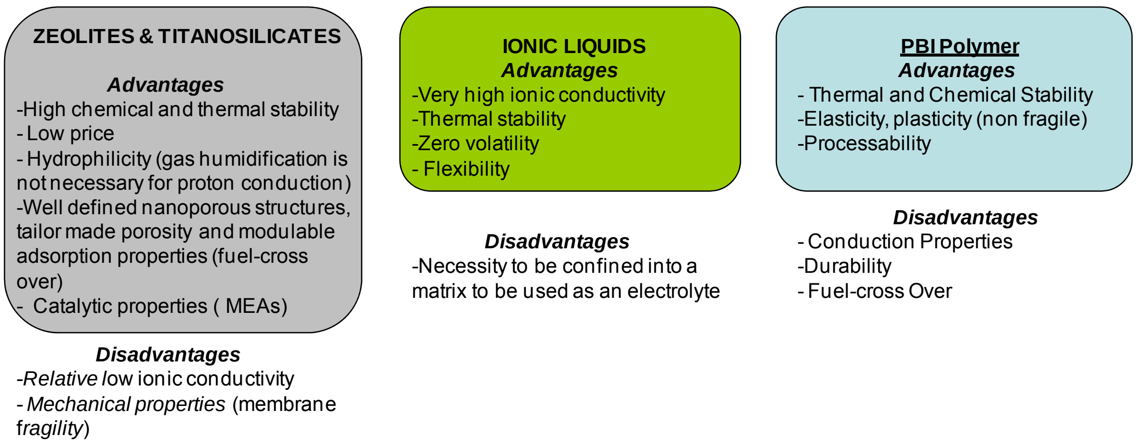


Figure 10. General properties of the three primary building units used in Zeocell Project.

For proton conduction purposes, mainly phosphoric acid doping and/or protic ionic liquid embedding have been studied in the project. Since phosphoric acid autodehydration is a serious limitation for operation above 140ºC, when less conductive oligomers are formed, the deployment of Protic Ionic Liquids as proton carriers has been demonstrated as clearly beneficial due to its physical and chemical properties. The synthesized Protic Ionic Liquids exhibiting decomposition temperatures above 300ºC have revealed highly attractive possibilities, not only as embedded proton carriers in porous PBI due to its conductive properties (see Figure 11), but also as guest molecules inside large pore zeolites to eventually improve the proton conduction properties of these microporous inorganic materials.

Molecular dynamics simulations show that the protic ionic liquids fit energetically inside the faujasite cells and their ions are mobile within the zeolite framework (see Figure 12). The protic ionic liquid entrapped in large pore zeolites shows a gradual increase of conductivity up to a maximum followed by a decrease with temperature (see Figure 13). Thus, synergic-inhibition effects between both proton conductors (i.e. protic ionic liquids and H_2O molecules) coupled to protic ionic liquid dragging by water desorption, explain the observed behaviour. The temperature, at which the conductivity of the composite starts to decrease, depends on the hydrophilicity not only of the zeolitic host but also on the ionic liquid itself[13]. Furthermore, polymeric ionic liquid based membranes with excellent proton conduction properties have been fabricated to address durability and lifetime requirements.

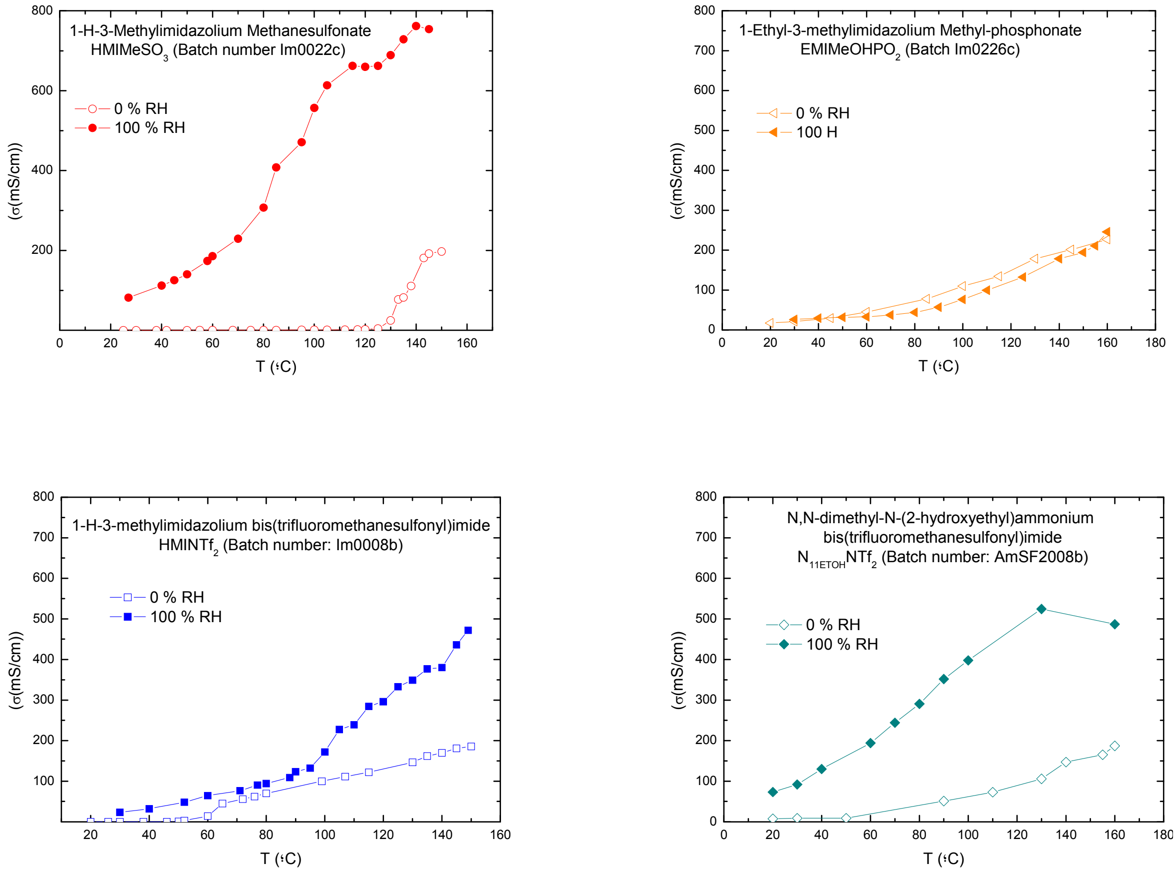


Figure 11. Conduction Performance of selected Protic Ionic Liquids synthesized by SOLVIONIC.

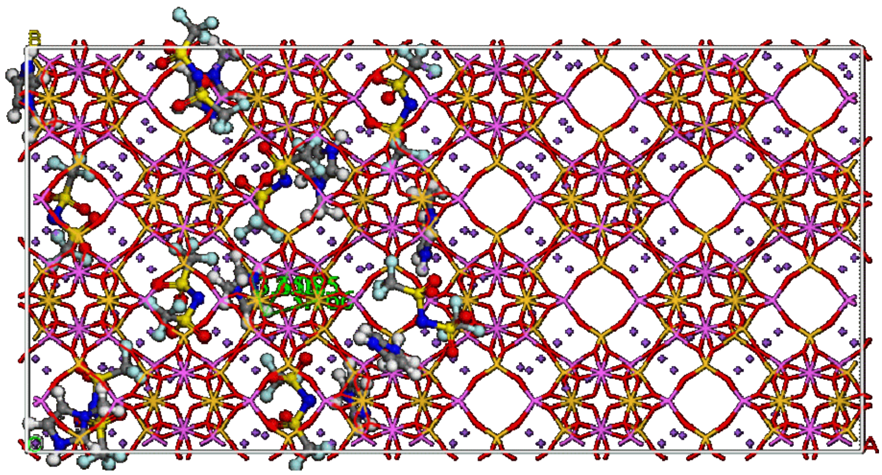


Figure 12. Super-cell structure constituted of two adjacent faujasite unit cells in zeolite type Y, one of which (left) was initially full of Im0008b protic ionic liquid, while the other one (right) was initially empty.

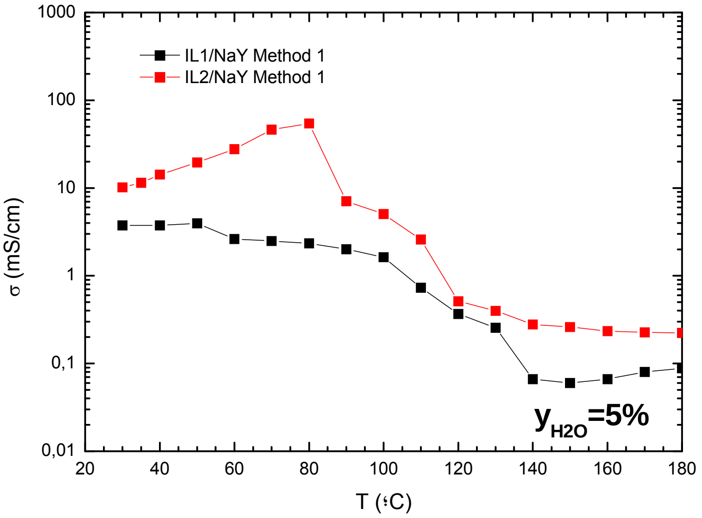
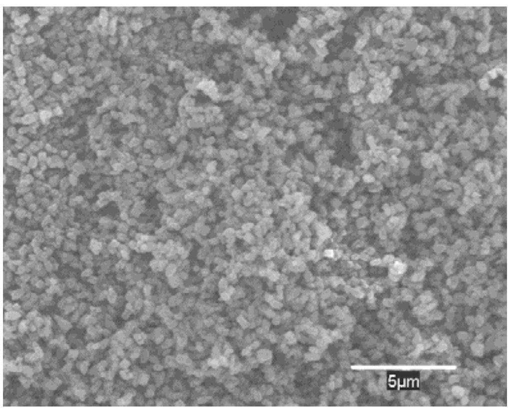


Figure 13. Conduction performance of ammonium based protic ionic liquids encapsulated in NaY zeolites.

As it has already been pointed out, one of the strategies to improve the performance of acid doped PBI membranes relies on the addition of inorganic fillers (zirconium phosphates, phosphotungstenic acid, silicotungstenic acid, zirconium tricarboxilphosphate, polyoxometals, sulfonic silica nanoparticles) followed by phosphoric acid doping[14,15,16,17,18]. Following a similar approach, the Zeocell contingency plans involve the addition of zeolites and titanosilicates nanocrystals[19] (see Figure 14) to the PBI casting solution.



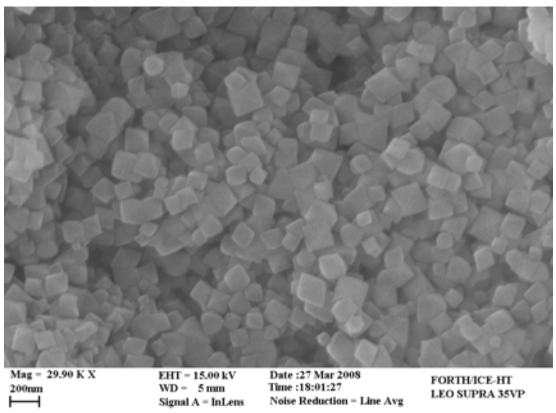


Figure 14. SEM images of titanosilicates (left) and colloidal FAU zeolites (right); the main microporous solids used in the Project.

However, the addition of inorganic particles to a polymer results in a greater rigidity of the final polymeric membrane and eventually provokes the appearance of undesired voids at the organic-inorganic interface. Therefore, adequate surface properties coupled to small particle sizes are two of the main requirements for the inorganic fillers when preparing electrolyte membranes with suitable transport selectivity and mechanical properties.

The most widely studied chemical interactions between zeolites and polymer surfaces are those involving covalent linkages. For such reason in this project, the external surface of zeolites and titanosilicates has been modified by means of reaction with organosilanes to: i) promote their ionic conductivity, ii) facilitate chemical interactions with PBI chains, iii) improve the compatibility at the organic-inorganic interface; and, iv) enhance the mechanical strength of the composite membranes. Specific functionalization protocols of the microporous materials have been established by grafting and filming techniques in order to ensure an adequate degree of surface coverage. As an example, the improvement in the proton transport properties due to the presence of sulfonic groups attached to the external surface of ETS10 crystals is shown in Figure 15.

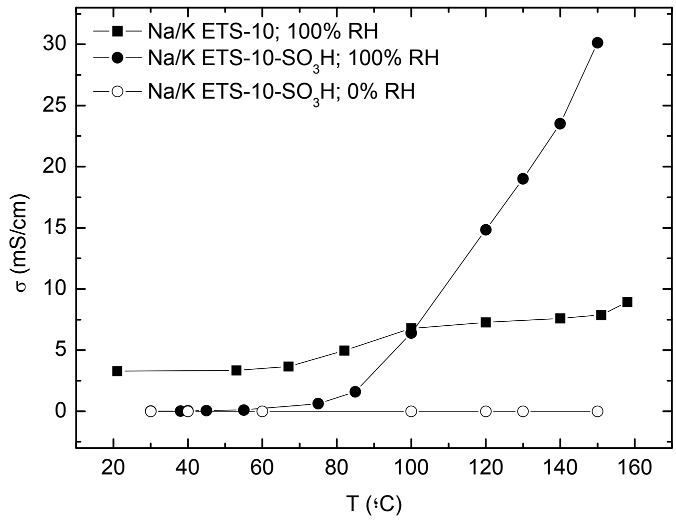


Figure 15. Proton conductivity of Na/K ETS-10 crystals before and after sulfonation of the external surface.

Because the polymer membrane architecture plays the key role to ensure proton transport through heterogeneous media, dense and porous PBI films (prepared from Fumion powder) have been systematically deployed as proton conductor supports (see Figure 3). Randomly porous PBI membranes have been prepared by leaching out a porogen (CIDETEC route) and also by delayed demixing (UTWENTE route). In the former approach, PBI membranes are obtained by casting from a polymer solution (5 wt% in DMAc) containing the porogen (dibutylphthalate or triphenylphosphate) in %wt. ranging from 30% to 75% on a glass plate support. After peeling and solvent removal, the leaching of the porogen was induced by immersion in ethanol for 3 h at 50º C (see Figure 16) rendering in porous membranes (see Figure 17) with controlled thickness between 45 and 100 µm.

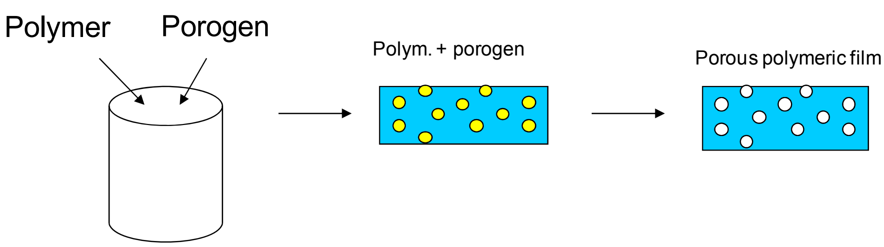


Figure 16. General scheme for the preparation of porous membranes by porogen leaching.

In the second approach, randomly porous PBI membranes were prepared by the inverse-phase method (UTWENTE route). For such purposes, a 12 wt % Fumion solution was prepared at 160°C under reflux in NMP. The inclusion of additives (PVP K30 and PVP K90) to the casting solution as weak solvents is demonstrated to promote pore interconnectivity and to suppress macro-void formation during the phase separation process. The membrane casting was performed at 20°C over the surface of glass plates previously cleaned by using a 0.1 μm casting knife, and immediately placed in the coagulation bath. First, the cast polymer solution was immersed in NMP / Water (50/50) mixture during 30 minutes. Subsequently, the membrane formation was completed in a second coagulation bath containing DD water for 1 h. Finally the membrane was immersed in DD water to rinse out the last traces of solvent and stored in pure water (see Figure 17). The most remarkable feature is that no macrovoids are identified along and across the membrane confirming the viability of both preparation procedures (see Figure 17 and Figure 18).

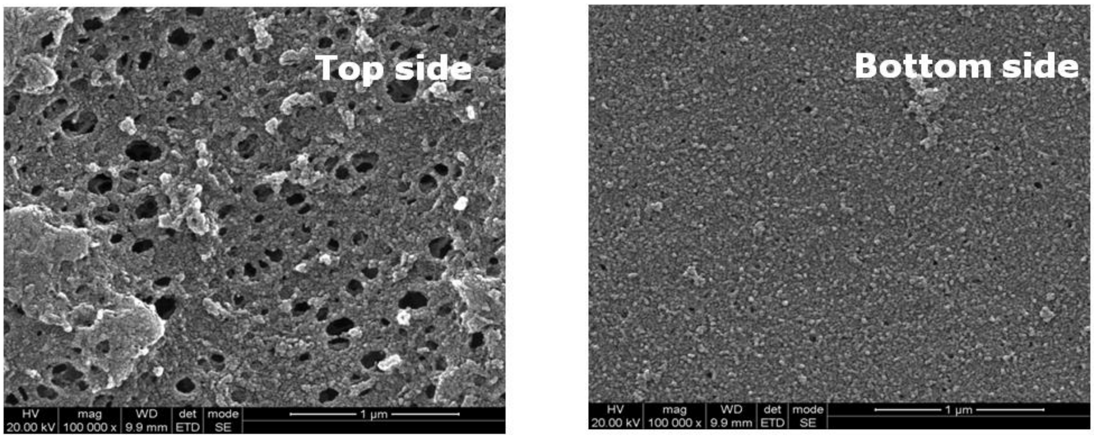


Figure 17. SEM top view of 80% porous PBI prepared by delayed demixing.

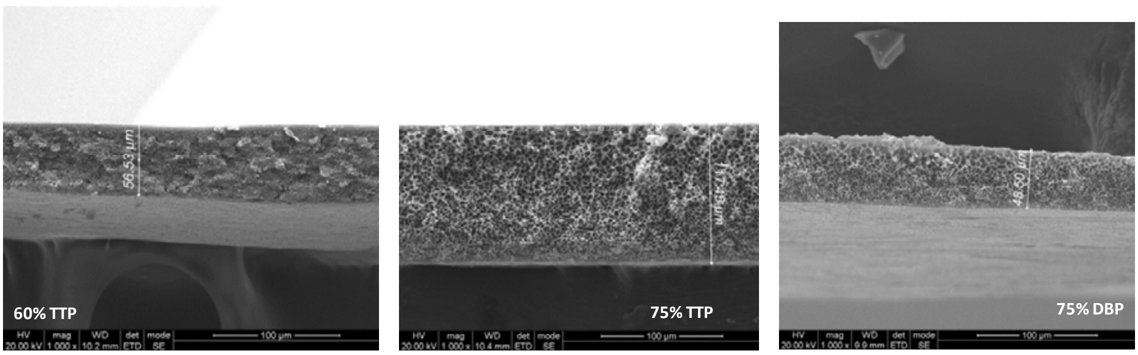


Figure 18. SEM cross section view of porous PBI membrane thickness prepared by porogen leaching.

The application of the as prepared randomly porous PBI is potentially attractive in the field of gas separations at high temperature and pressure conditions. In addition, by taking advantage of the asymmetric porous structures exhibited by porous PBI membranes prepared by chemical routes, liquid phase separations are also feasible. In both cases, the porous PBI membrane could play the role of a material separation agent capable to separate selectively the components in the feed mixture thanks to a driving force. One of the project side results in this respect was the ability of the porous PBI membranes (prepared by leaching out a porogen) with a short non-porous PBI skin (see Figure 19) to successfully separate H_2 / CO_2 mixtures at temperatures up to 200ºC (see Figure 20) with permselectivity values around 25. Indeed, the separation of H_2/CO_2 at high temperatures is extremely important because it opens the potential of developing membrane reactors for the Water Gas Shift Reaction.

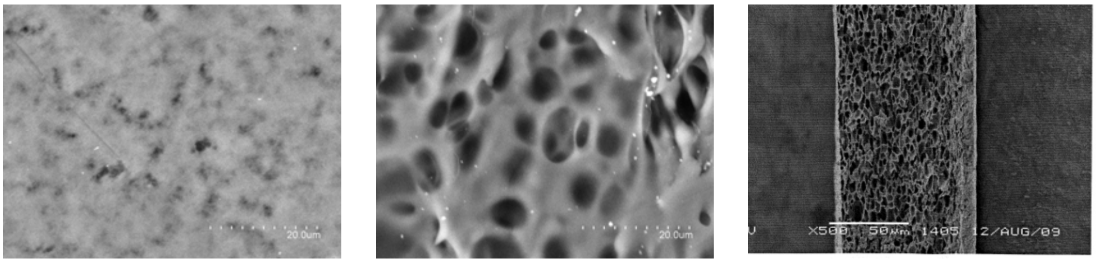


Figure 19. Asymmetric Porous PBI membranes (60% in porosity) prepared by leaching out a porogen.

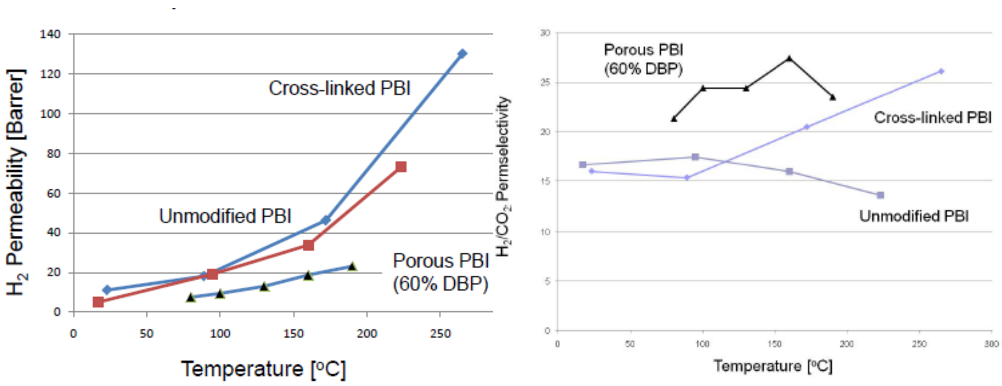


Figure 20. Porous PBI membrane (60% in porosity) Perfomance for H2/CO2 separation.

On the other hand, straight porous PBI supports have been prepared either by track-etching[20] technology (CRF-FIAT route) or micro-transfer moulding[21] (INA route). Herein, it is worthwhile to underline that both methods have been applied for the first time to PBI films within the framework of this project. Ion track technology (see Figure 21) is widely used for the industrial production of filters (Whatman, Trackpore), printed circuit boards (IST), and other devices. It opens a low-cost route to micro and nanotechnology as a vertically cutting tool, enabling high aspect ratio structures, distributed at arbitrary number density. In this field, the main outcome of Zeocell has been the possibility to track-etch PBI films with thickness below 30 microns to obtain nano-porous (30-50 nm in pore size) membranes (see Figure 22). The application of APA masks has proved to be not feasible due to the angular divergence of the incident beam and to charging and damaging phenomena on the alumina support. Thus, the pore distribution in the plane parallel to the polymeric layer is disordered, but the pore shape is straight and the aspect ratio of the channels is about 1000. Ion-track technology on PBI polymer could also be explored for the production of Li-ion batteries separators. In fact, advanced separators, able to block the thermal runaway of the lithium ion batteries are of extreme importance for the safety of the device itself.

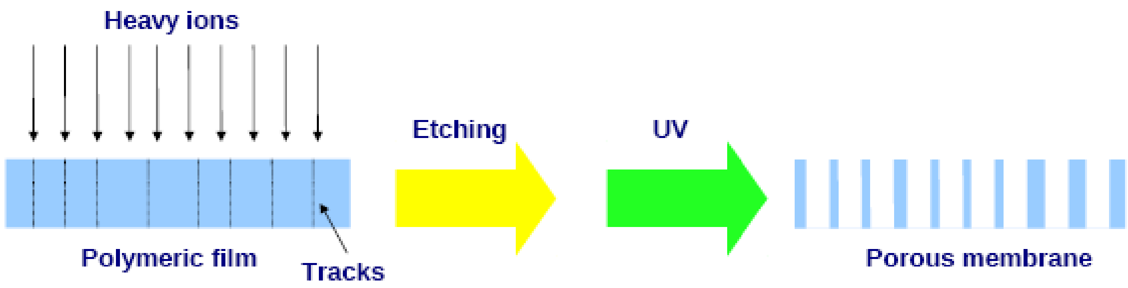


Figure 21. Nanoporous Formation on Polymer Films by Track-Etching Technology.

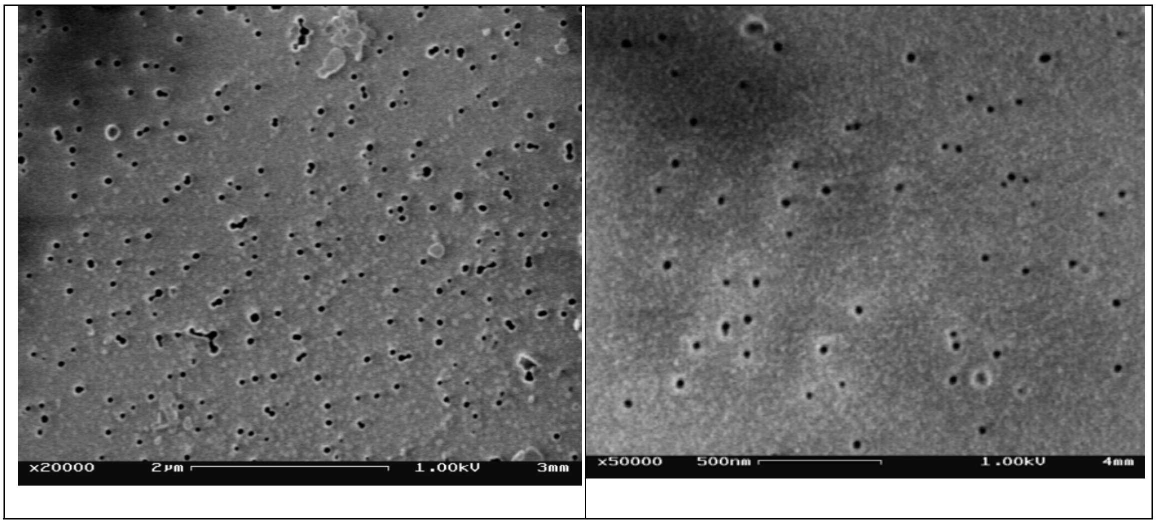
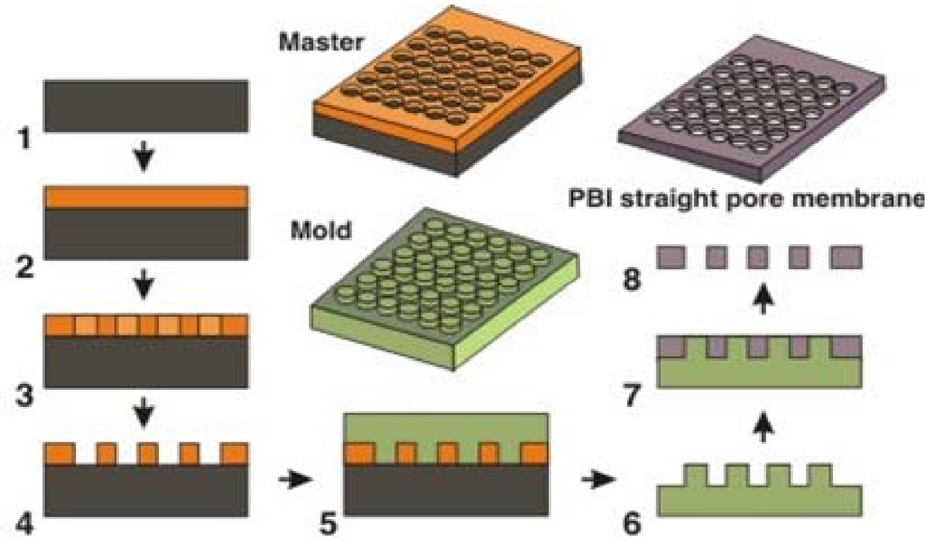


Figure 22. SEM top view analyses of track-etched PBI membranes with 50 microns in thickness (dead-end pores) on the left side, and 28 microns in thickness (interconnected pores) on the right side.

2D ordered porous PBI structures have been successfully prepared by soft lithography techniques. In particular, the application of microtransfer moulding technique (see

Figure **23**) has allowed developing replicas by using a relief pattern of a flexible mould (PDMS). By this fabrication route, porous PBI membranes with 25% of porosity, 15 micron in pore diameter and 30 micron in pitch have been successfully prepared (see Figure 24). Among the potentialities of this new type of micro-patterned PBI films, it is noteworthy the use as structural layer for applications demanding harsh conditions (high temperature, extreme pH or oxidant-reducing conditions) thanks to the intrinsic properties of PBI polymer. A new research path emerges on micro-patterned PBI films to fill the existing gap in lab on chip applications, mainly dealing with biomedical applications. More specifically, Lab on chip, Micro Total Analytical Systems, Flexible Structured Micro Reactor and Micro fuel cells based on microstructured PBI films are envisioned in the short term. Holdcroft and co-workers [22] were the first to propose the concept of making PEMs from curable liquid precursors and pointed out that such a liquid-to-PEM approach may enable the formation of PEMs conformable by injection molding, formed as microchannels and unique shapes, or strongly adhering to the catalyst layer without hot pressing. The fabrication of MEAs from these PEMs resulted in fuel cells outperforming those based on commercial materials[23]. The patterned membranes provided a larger interfacial area between the membrane and catalyst layer than standard flat counterparts and demonstrated higher power densities without an increase in the macroscopic area of the fuel cells.



1. Si wafer washing process
2. SU-8 deposition
3. UV exposure
4. SU-8 exposed development
5. PDMS deposition/dried process
6. PDMS final product (pattern)
7. PBI deposition
8. PBI final product

Figure 23. Microtransfer moulding process to prepare microstructured PBI films.

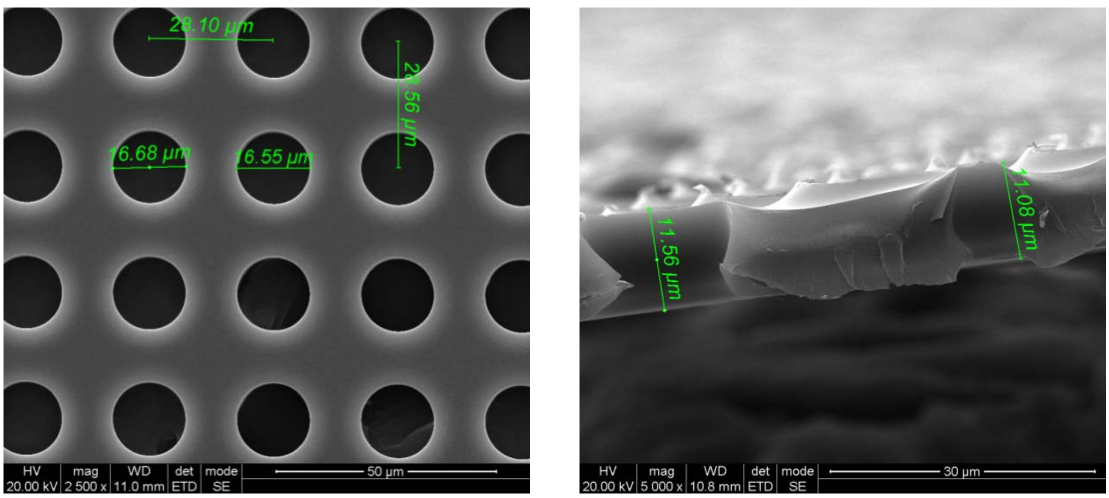


Figure 24. SEM micrographs of straight porous PBI membranes prepared by micro transfer-moulding.

- ZEOCELL GOAL: DEVELOPMENT OF NANOSTRUCTURED ELECTROLYTE MEMBRANES FOR HIGH TEMPERATURE PEMFCs.

The electrolyte membranes developed within the framework of this project for high temperature operation are included in Figure 1. Nearly all samples prepared comprise PBI as base polymer. Different membrane structures have been obtained: dense PBI membranes, randomly **porous PBI** membranes prepared by **delayed demixing** and also by **leaching out a porogen**, **track-etched porous PBI** membranes and **micropatterned PBI** membranes. For proton conduction purposes, phosphoric acid doping and/or 1-H-3-methylimidazolium bis(trifluoromethanesulfonyl)imide (Im0008b) ionic liquid embedding have been mainly studied in the project. The phosphoric acid autodehydration is a serious limitation for operation above 140ºC, where lower conductivity oligomers like pyrophosphoric acid are generated. Thus, the deployment of **protic ionic liquids** as proton carriers has been demonstrated as clearly beneficial due to its physical and chemical properties. In a step further, in an attempt to improve endurance properties, and considering the successful UV assisted polymerization of monomers prepared from Im008b ionic liquid, **polymeric ionic liquid** (PIL) based membranes have also been developed. In particular, pure dense PIL-membranes, and reinforced PIL on porous PBI supports have revealed enormous possibilities as proton conductors. The incorporation of **microporous materials** either as **inorganic fillers** to the membrane casting solution (contingency plan) or as **thin film coatings** onto preexisiting porous PBI membranes has been considered. In the first case, conduction/durability issues of acid doped PBI membranes were pursued. On the other hand, the role of microporous top layers was mainly related to fuel cross-over and ionic liquid leakage with time on stream.

To gain insight on the synergic effects provided by materials combination, different membrane categories, ranging from 1 component (i.e. Pure Polymeric Ionic Liquid Films), through binary (supported ionic liquid membranes in track-etched porous PBI substrates, supported ionic liquid membranes in randomly porous PBI substrates, reinforced polymeric ionic liquid membranes on porous PBI supports, acid doped track-etched porous PBI substrates), ternary composites (hybrid acid doped dense or porous PBI and hybrid dense or porous PBI embedding ionic liquid) to the final nanostructured electrolyte membranes based on four components (i.e. PBI, phosphoric acid, ionic liquid and microporous materials) have been studied in detail in most cases, **morphological** (SEM), **physicochemical** (TGA-DSC, H_2 and methanol permeabilities), **mechanical** (DMA) and **electrochemical** (in plane and through-plane proton conductivity and durability) properties have been evaluated. Table 3, Table 4 and Table 5, summarize the main properties of the as prepared membranes at 50ºC, 100ºC and 150ºC; where dense PBI membranes and Nafion are also included for comparison purposes. The technical targets for the Zeocell membranes as laid out in the project proposal were the following:

- high ionic conductivity (100 mS/cm at 150ºC vs. 100 mS/cm exhibited by Nafion® at 80ºC),
- low fuel cross over (five times lower than Nafion®),
- suitability for operating at temperatures between 130-200ºC (the membrane materials are conceived to exhibit mechanical, thermal and chemical stability up to 200ºC and the membrane performance will be validated on single cells at temperatures up to 150ºC minimum) for extended period (<1% of performance degradation during the first 1000 hours working)

For a better understanding, the most outstanding features in relation to the defined technical targets, the MEA performance and the estimated manufacturing costs (if available) for a future exploitation are separately discussed for each membrane type in the subsequent sections below. The best performances in any given category are also underlined by highlighting the corresponding cells in tables 3 to 5. Although the core of the project is focused on high temperature applications, the performance of porous polyimide membranes developed within the framework of the project and capable to withstand temperatures up to 120ºC, is firstly reviewed due to the considerable improvement of performance obtained in comparison with Nafion 212.

Table 3. Main properties of of Zeocell electrolyte membranes at 50ºC

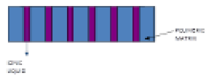
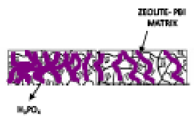
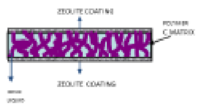
50 ºC			Beneficiary involved (materials)	Conductivity mS/cm (in plane) 50ºC	Conductivity mS/cm (through plane) 50º	Methanol permeability 50ºC mol/cm.s.bar	H2 permeability 50ºC mol/cm.s.bar	Storage modulus MPa (209ºC)	Durability	Transport selectivity (MS.s.bar/mol) In plane//throughplane
One-component	PIL membranes		INA	0% HR 0.12	0% HR 0 5% HR 8	☹	<LOD	n.a.	1000h//200ºC 325 mS/cm	n.a.
Two-components	PIL + PBI (80% porous)		INA	0% HR 0.82	5% HR 8	1.91 10^{-9}	2.74 10^{-8}	n.a.	1000h//200ºC 260mS/cm	0.42// 4.18
	Track-etched membranes		CRF-FIAT// INA (PBI 1% porous/Im008b)	n.a.	5% HR 0.14	n.a.	n.a.	n.a.	150h//150ºC 0.5 mS/cm ☺	n.a.
			INA APA 35% porous/Im008b)	n.a.	5% HR 10	n.a.	n.a.	n.a.	170h//120ºC 22mS/cm ☺	n.a.
	Supported IL on Randomly porous PBI		INA// TWENTE (80% porous//Im008b)	n.a.	5% HR 1	n.a.	n.a.	598.7	150h//170ºC 6mS/cm	n.a.
Three-components	Dense hybrid membranes		INA 3 %ETS10-SO3H	0% HR 5	5% HR 5	4.2 10^{-10}	n.a.	n.a.	n.a.	11.9// 11.9
	Porous hybrid membranes		CIDETEC 3% NaY-Im008b 75% Porous DBP	0% HR 60	n.a.	1.3 10^{-9} 45%DBP ETS-10	n.a.	924	n.a.	46.1// n.a.
			CIDETEC 3 %ETS10-SO3H 45%Porous DBP	0% HR 32	n.a.	1.3 10^{-9}	n.a.	2867 45%DBP NaY	n.a.	24.6// n.a.
Four components	Nanostructured Electrolyte Membranes		INA (75% Porous DBP-ETS-10 coatings//Im008b)		5% HR 30	7.4 10^{-10}	n.a.	n.a.	n.a.	n.a.// 40.5
			INA (80% Porous – ETS10 coatings/Im008b)	0% HR 21	0% HR 28 5%HR 28	9.65 10^{-10}	5.58 10^{-9}	82.3	500h//150ºC 15 mS/cm	21.7// 29
Reference	Nafion 212			n.a.	5%HR 16.8	4.48·10^{-9}	<LOD	n.a.	n.a.	n.a.// 3.75
	PBI			0% HR 5	5%HR 0.5	1.7·10^{-10}	5.7·10^{-8}	n.a.	150h//150ºC 4.3 mS/cm	29.4// 2.94

Table 4. Main properties of Zeocell electrolyte membranes at 100ºC.

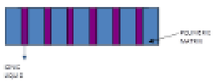
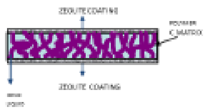
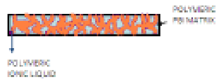
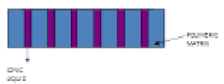
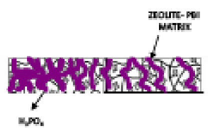
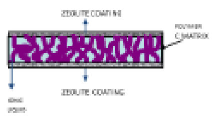
100 ºC			Beneficiary involved (materials)	Conductivity mS/cm (in plane) 100ºC	Conductivity mS/cm (through plane) 100ºC	Methanol permeability 100ºC mol/cm.s.bar	H2 permeability 100ºC mol/cm.s.bar	Storage modulus MPa (209ºC)	Durability	Transport selectivity (MS.s.bar/mol) In plane//throughplane
One-component	PIL membranes		INA	0% HR 1.13	0% HR 325 5% HR 320	☹	1.5 10^{-7}	n.a.	1000h//200ºC 325 mS/cm	n.a.
Two-components	PIL + PBI (80% porous)		INA	0% HR 5.2	5% HR 10	1.72 10^{-9}	3.39 10^{-8}	n.a.	1000h//200ºC 260mS/cm	3.02// 5.81
	Track-etched membranes		CRF-FIAT// INA (PBI 1% porous/Im008b)	n.a.	5% HR 0.32	n.a.	n.a.	n.a.	150h//150ºC 0.5 mS/cm ☺	n.a.
			INA APA 35% porous	n.a.	5% HR 30	n.a.	n.a.	n.a.	170h//120ºC 22mS/cm ☺	n.a.
	Supported IL on Randomly porous PBI		INA// TWENTE (80% porous//Im008b)	n.a.	5% HR 10	n.a.	n.a.	598.7	150h//170ºC 6mS/cm	n.a.
Three-components	Dense hybrid membranes		INA 3 %ETS10-SO3H	0% HR 26	5% HR 8	2.38 10^{-10}	n.a.	n.a.	n.a.	109// 33.6
	Porous hybrid membranes		CIDETEC 3% NaY-Im008b 75% Porous DBP	0% HR 190	n.a.	1.11 10^{-9} 45%DBP ETS-10	n.a.	924	n.a.	171// n.a.
			CIDETEC 3 %ETS10-SO3H 45%Porous DBP	0% HR 57	n.a.	1.11·10^{-9}	n.a.	2867 45%DBP NaY	n.a.	51.3// n.a.
Four components	Nanostructured Electrolyte Membranes		INA (75% Porous DBP-ETS-10 coatings//Im008b)		5% HR 32	6.39 10^{-10}	n.a.	n.a.	n.a.	n.a.// 50.1
			INA (80% Porous – ETS10 coatings/Im008b)	0% HR 60	0% HR 38 5%HR 38	7.91 10^{-10}	4.12 10^{-8}	82.3	500h//150ºC 15 mS/cm	75.8// 48
Reference	Nafion 212			n.a.	5%HR 4	3.13 10^{-10}	<LOD	n.a.	n.a.	n.a.// 12.7
	PBI			0% HR 45	5%HR 0.7	1.32 10^{-10}	6.0·10^{-8}	n.a.	150h//150ºC 4.3 mS/cm	341// 5.30

Table 5. Main properties of Zeocell electrolyte membranes at 150ºC.

150 ºC			Beneficiary involved (materials)	Conductivity mS/cm (in plane) 150ºC	Conductivity mS/cm (through plane) 150ºC	Methanol permeability 150ºC mol/cm.s.bar	H2 permeability 150ºC mol/cm.s.bar	Storage modulus MPa (209ºC)	Durability	Transport selectivity (MS.s.bar/mol) In plane//throughplane
One-component	PIL membranes		INA	0% HR 3.70	0% HR 350 5% HR 400	☹	1.4 10^{-7}	n.a.	1000h//200ºC 325 mS/cm	n.a.
Two-components	PIL + PBI (80% porous)		INA	0% HR 12	5% HR 260	1.56 10^{-9}	1.15 10^{-7}	n.a.	1000h//200ºC 260mS/cm	7.69// 166
	Track-etched membranes		CRF-FIAT// INA (PBI 1% porous/Im008b)	n.a.	5% HR 0.65	n.a.	n.a.	n.a.	150h//150ºC 0.5 mS/cm ☺	n.a.
			INA APA 35% porous	n.a.	5% HR 65	n.a.	n.a.	n.a.	170h//120ºC 22mS/cm ☺	n.a.
	Supported IL on Randomly porous PBI		INA// TWENTE (80% porous//Im008b)	n.a.	5% HR 18	n.a.	n.a.	598.7	150h//170ºC 6mS/cm	n.a.
Three-components	Dense hybrid membranes		INA 3 %ETS10-SO3H	0% HR 55	5% HR 10	7.15 10^{-10}	n.a.	n.a.	n.a.	76.9 // 13.9
	Porous hybrid membranes		CIDETEC 3% NaY-Im008b 75% Porous DBP	0% HR 223	n.a.	7.25 10^{-10} 45%DBP ETS-10	n.a.	924	n.a.	307// n.a.
			CIDETEC 3 %ETS10-SO3H 45%Porous DBP	0% HR 73	n.a.	7.25 10^{-10}	n.a.	2867 45%DBP NaY	n.a.	101// n.a.
Four components	Nanostructured Electrolyte Membranes		INA (75% Porous DBP-ETS-10 coatings//Im008b)		5% HR 45	5.25 10^{-10}	n.a.	n.a.	n.a.	n.a.// 85.7
			INA (80% Porous – ETS10 coatings/Im008b)	0% HR 100	0% HR 49 5%HR 55	6.76 10^{-10}	8.53 10^{-10}	82.3	500h//150ºC 15 mS/cm	147// 81.3
Reference	Nafion 212			n.a.	5%HR 0.46	2.69 10^{-9}	<LOD	n.a.	n.a.	n.a.// 0.17
	PBI			0% HR 64.8	5%HR 1.3	9.25 10^{-11}	6.19 10^{-8}	n.a.	150h//150ºC 4.3 mS/cm	701// 14

1. Porous sPEI based membranes for low-medium temperature applications

Porous sulfonated naphthalenic copolyimides (sPEI) films (15%-60% nominal porosity) with controlled thickness between 60 and 100 µm have been prepared by casting from a polymer solution containing DBP porogen-type molecules. Series of tough sulfonated polyimide films are obtained with controlled thickness between 45 and 50 µm. Previous to characterization, the membranes are acid-treated with 0.1 M H_2SO_4 solution at room temperature for 14 h and then rinsed with DDW. The conduction properties of the as prepared porous PEI membranes up to 120ºC are shown in Figure 25. As can be observed, the behaviour is clearly outperforming Nafion. However, at temperatures higher than 90 ºC the membranes become fragile, and for this reason, they have rejected as solid electrolyte for high temperature PEMFC. In spite of this result, these membranes are really promising as electrolyte for low temperature PEMFCs, since their conductivity values at 60 ºC are considerably higher than available commercial membranes (up to 1.6 times the Nafion 212 values). The polarization curves at 70ºC of the as prepared sPEI membranes on commercial electrodes and GDLs are quite similar to Nafion212 used as benchmark (see Figure 26). Despite the potential applications of porous polyimides membranes (fluorine free) are in the medium temperature (80-120ºC) range, i.e. outside the scope of this project, these co-lateral results are highly promising and we consider them as exploitable foreground.

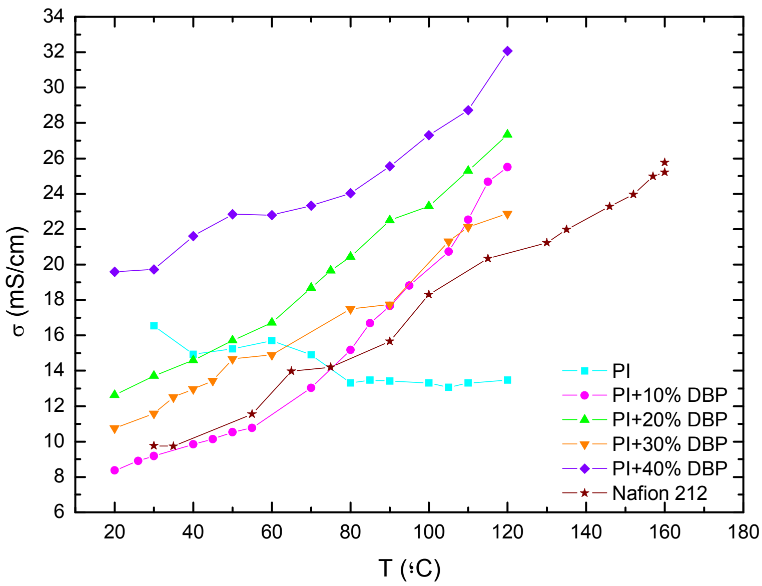


Figure 25. Through-plane proton conductivity of porous sPEI membranes at 100% RH.

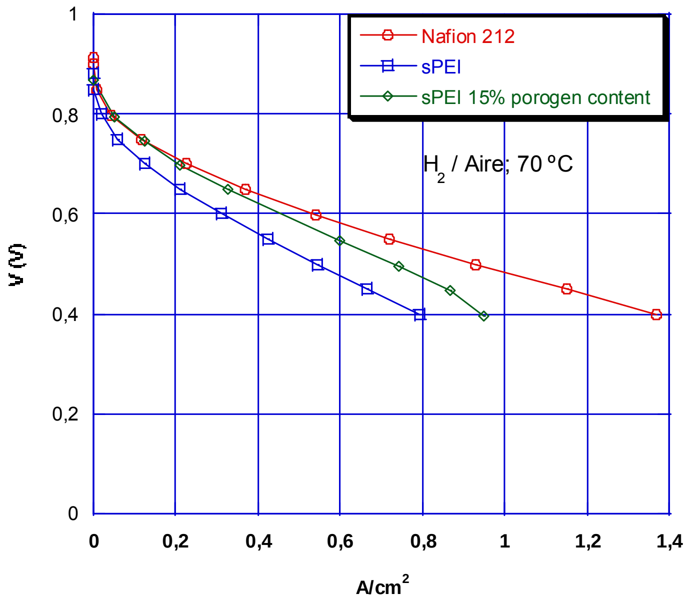


Figure 26. Polarization curves for MEAS prepared from dense and porous (15% porogen content) sPEI membranes + commercial electrodes (ELATV2.1) at 70ºC and atmospheric pressure with humidification at 60ºC.

2. Electrolyte Membranes from single materials: Polymeric Ionic Liquid (PIL) Membranes

This electrolyte membrane category has been the result of a modified work-programme in accordance to the periodic risk assessment carried out by the project steering committee (see Figure 27). Finally, the preparation of highly proton conducting polymeric ionic liquid membranes based on the selected protic ionic liquid Im0008b has been successfully achieved (see Figure 28). In general, the proton conductivity decreases with increases in the cross-linker percentage (i.e. 1000 mS/cm to 0.64 mS/cm at 150 ºC). On the other hand, higher CL degree increases the rigidity/fragility of the membrane. Therefore, an optimization of the cross-linker content was performed.

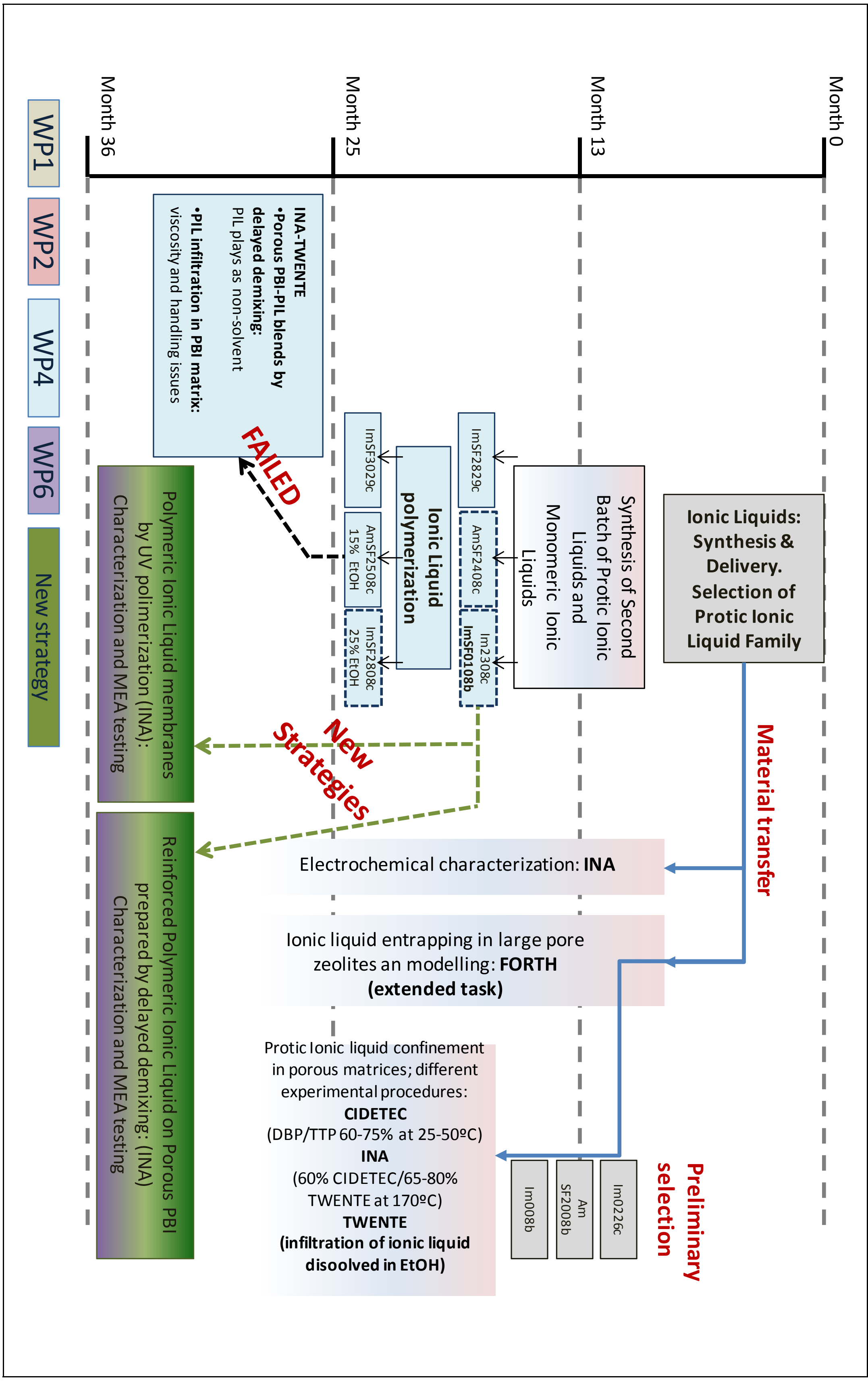


Figure 27. Progress of the work related to protic ionic liquid and polymer ionic liquid based membranes.

Figure 28. Appearance of Polymeric ionic liquid films as a function of %wt-cross-linker (from left to the right).

The membrane properties in relation to the technical Zeocell targets are the following:

☑ High ionic conductivity (see Figure 29): 342 mS/cm at 150ºC without external gas humidification (the target was 100 mS/cm)

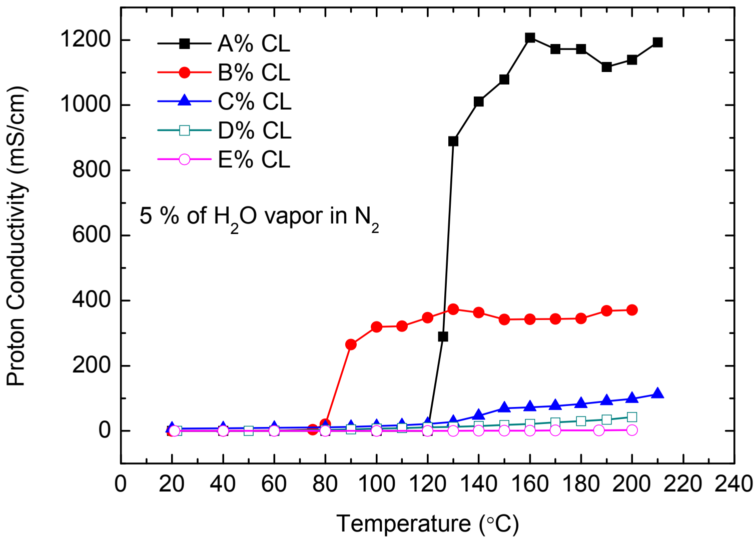


Figure 29. Through-Plane Proton conductivity measurements Polymer Ionic Liquid films based on Im008b ionic liquid as a function of %wt-cross-linker.

☑ Suitability for operating at temperatures between 130-200ºC: the glass transition temperature is above 300ºC and the polymer degradation temperature is at 400ºC (see Figure 30) (the target was up to 200ºC).

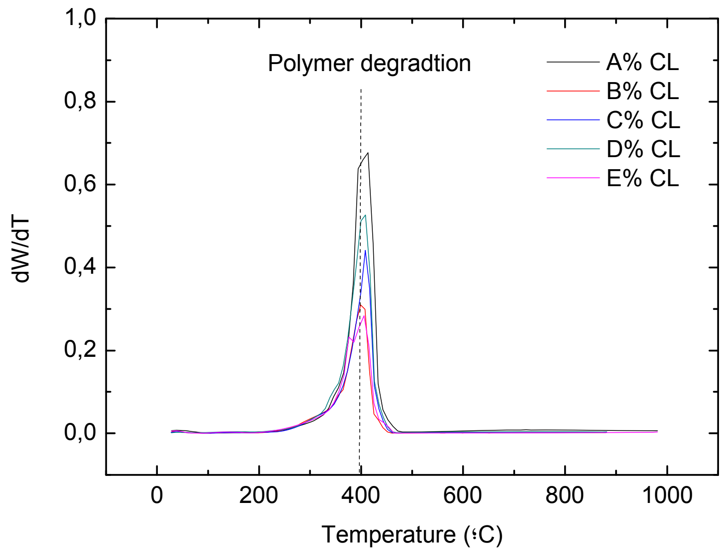


Figure 30. TGA of Polymer Ionic Liquid films based on Im008b ionic liquid as a function of %wt-cross-linker.

☑ Durability tests at 200ºC for more than 1000 hours reveal a 12% decay in performance after 350 h (see Figure 31). Although the target was established in less than 1% of performance degradation during the first 1000 working hours; afterwards, a stable value at 350 mS/cm is attained.

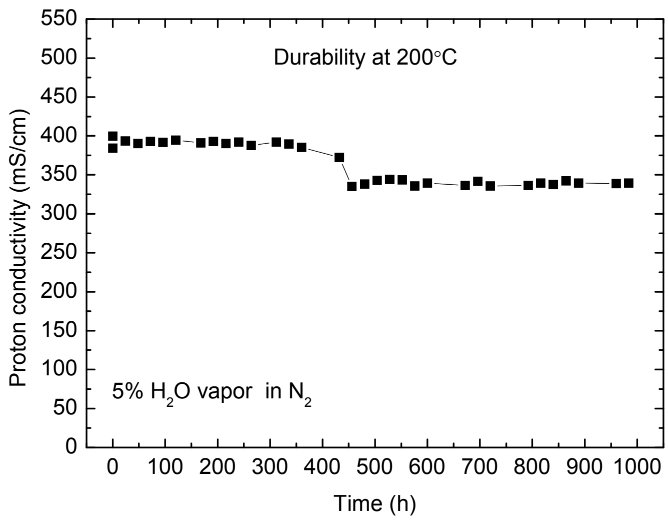


Figure 31. Time on stream conduction performance of Polymer Ionic Liquid films based on Im008b ionic liquid and 1 %wt of cross-linker.

☒ Limited chemical stability of the PIL membranes in presence of solvents such as methanol vapors. These membranes are excluded for DMFCs applications

☐ The H_2 cross-over properties at temperatures below 100ºC are comparable to those of Nafion.

☑ Reduced fabrication costs compared to current technology (<400 EUR/m^2) due to the simplicity of the manufacturing process and the low unit cost of monomeric ImSF0108 (95.55 €/kg).

The evaluation in H_2-FC performance (with 2.5cm*2.5cm of electroactive area) has been compared with commercial MEAs from Advent (Figure 32) at 120ºC. Comparing with pure PBI MEAs and commercial Advent MEAs, the PILs based MEAs performance seems quite encouraging. Thus, the "proof of concept" has been successfully demonstrated even better results can be expected by electrode optimization and improvements in fuel-cell components (i.e. bipolar plates). As the power density obtainable increased as a function of temperature, the deposition of PBI dense thin layers by spin coating (see Figure 33) over the top surfaces of PILs based membranes is being pursued to minimize H_2 cross over.

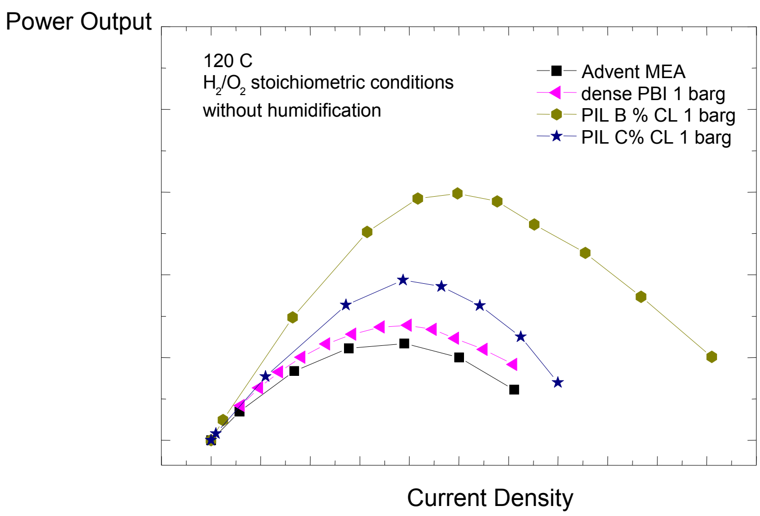


Figure 32. Power output curves in H2/O2 single cell for MEAs based on polymeric ionic liquid membranes and electrodes prepared by CIDETEC.

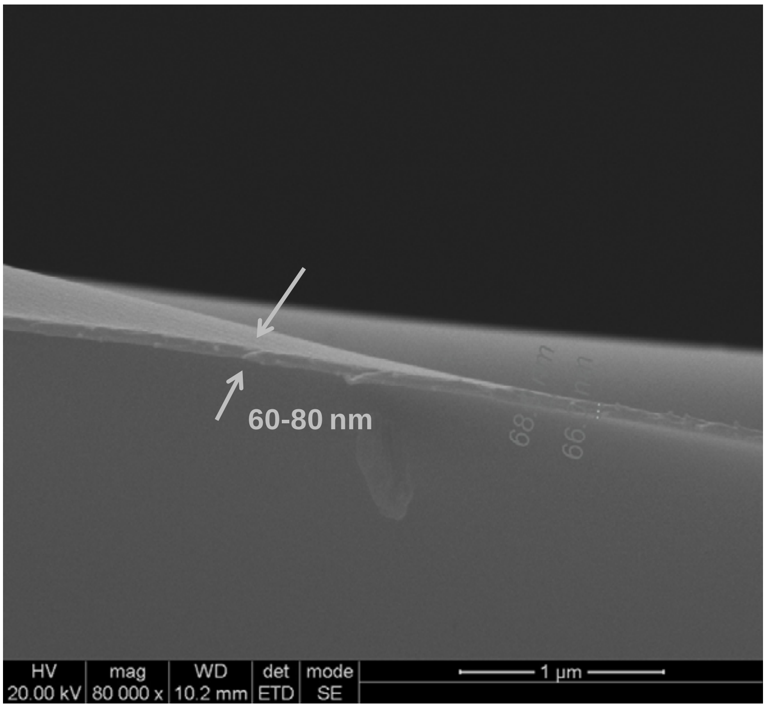


Figure 33. Peeled Dense thin PBI films prepared by spin coating over Si wafers.

3. Electrolyte Membranes from two components: Reinforced Polymeric Ionic Liquid onto Porous PBI Membranes (PIL-PBI)

This electrolyte membrane category has been conceived as a consequence of the experimentation carried out with pure polymer protic ionic liquid membranes (see **¡Error! No se encuentra el origen de la referencia.**). More specifically, the main purpose of reinforced polymer ionic liquids is to enhance not only the chemical stability of pure PIL in presence of solvents, but also the mechanical properties and at the same time to take advantage of the conduction performance of pure polymer ionic liquid. Thermogravimetric analysis of the as prepared membranes in comparison with pure PIL membranes and undoped PBI porous support are depicted in Figure 34. The evaluated PIL/PBI weight ratio is circa 2. Moreover, the use of PBI as support is justified by the existence of commercial membranes and MEAs based on this high temperature resin type polymer. For such reasons, the eventual implementation of PIL-PBI membranes into the standard MEA procedures already developed at industrial scale for PBI will be facilitated.

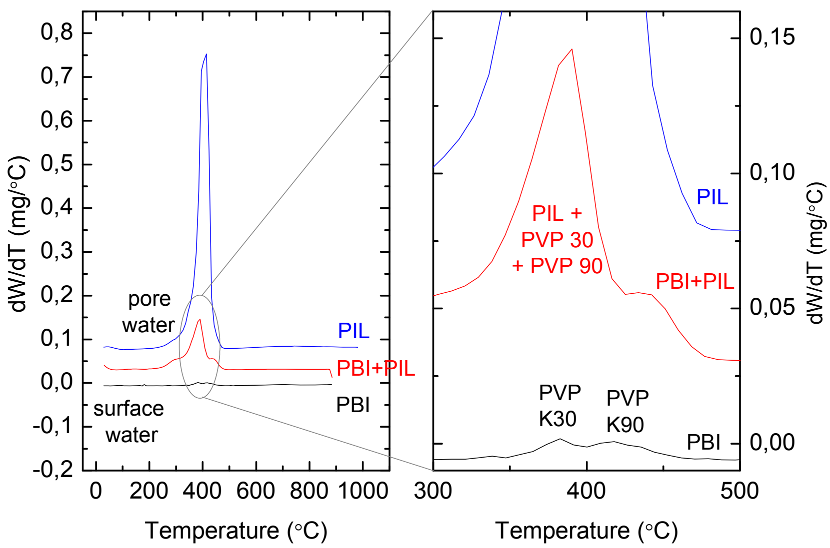


Figure 34. Differencial thermograms of porous PBI supports and reinforced PIL membranes.

As expected, the conduction-temperature dependence is similar to the observed for pure PIL without CL. For reinforced PIL-PBI membranes conductivity values up to 250 mS/cm and 340 mS/cm at 150 ºC and 200 ºC respectively, are achieved in presence of 5% of water partial pressure (see Figure 35). Similarly, reinforced PIL membranes on track-etched APA supports from Anodisc® (35% in porosity, 100 - 200 nm in pore size) have also been prepared. However, the expected conductivity values through straight APA pores are somewhat hindered due to poor APA wetability. In spite of this, conductivity values as high as 25 mS/cm has been attained at 200ºC. This behaviour agrees with the "apparent" proton transport activation energies calculated in Figure 36. For reinforced PIL onto porous PBI supports the activation energy is twice that evaluated for pure PIL membranes indicating that the length of percolating pathways are higher for the former. On the other hand, for straight APA pores, the limited number of percolating pathways increases five-fold the activation energy required for proton hopping.

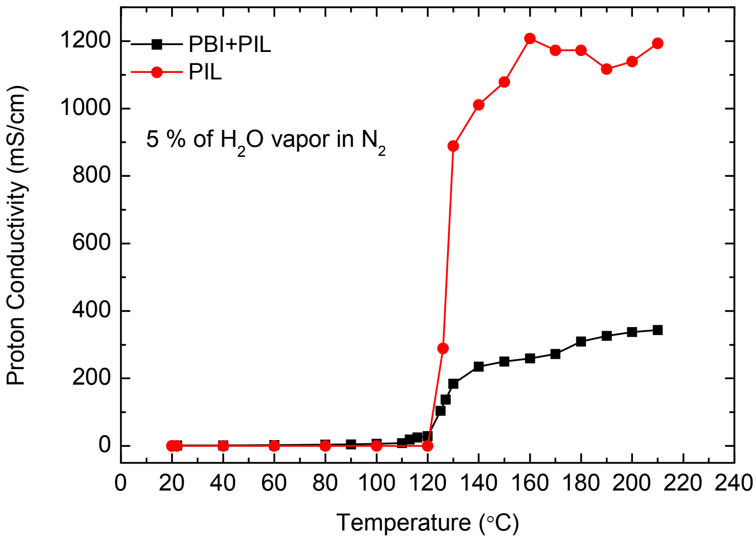


Figure 35. Comparison of proton conductivity measurements for supported and unsupported PIL.

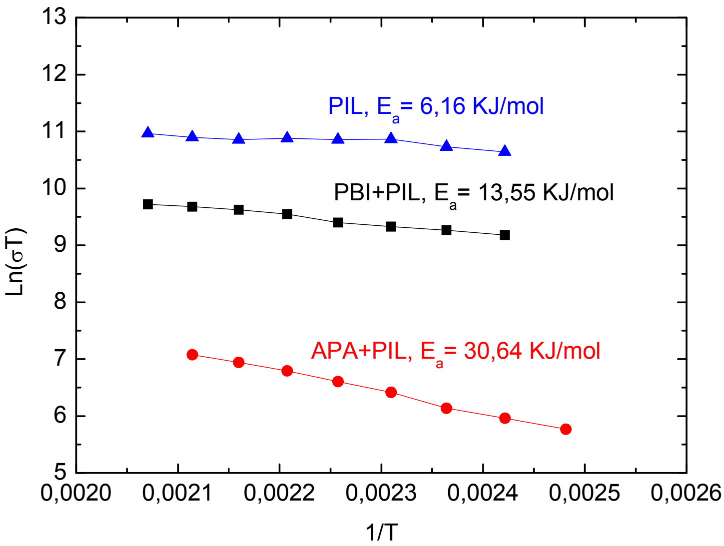


Figure 36. Apparent Activation energy for proton transport through PIL based membranes.

Methanol cross-over through reinforced PIL membranes has been notably improved in comparison with pure PIL membranes. The most outstanding feature for these membranes was the decrease of methanol permeability with temperature. This pattern strongly suggest: i) the absence of non-selective free voids; and ii) a permeation process mainly controlled by diffusion-solution mechanism. These hypotheses are also in agreement with the lower permeation rates exhibited in comparison with the porous PBI support at temperatures above 50ºC. To summarize, the PIL-PBI membrane properties in relation to the technical targets of Zeocell are the following:

☑ High ionic conductivity: 250 mS/cm at 150ºC (see Figure 35)

☑ Suitability for operating at temperatures between 130-200ºC. The glass transition temperature is above 300ºC for PIL and 380ºC for PBI respectively. The temperature values for both polymer degradation are higher than 400ºC. (see Figure 34)

☑ Durability tests at 200ºC for more than 1000 hours reveal a continuous stepwise, loss in performance during the first 500 h. Afterwards, steady state conductivity value at around 275 mS/cm is attained (see Figure 37), still above the conductivity target (100 mS/cm at 150ºC).

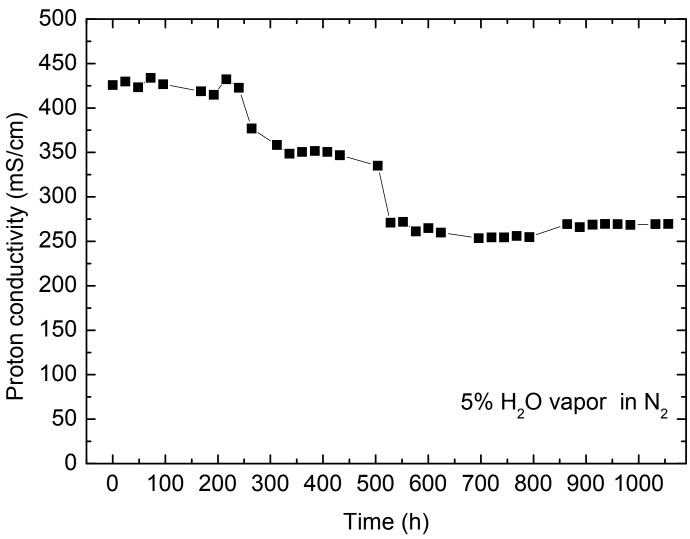


Figure 37. Durability test for conduction performance at 200 ºC for PIL-PBI membranes.

☒ Low Cross-over (5 times lower than Nafion): methanol permeability is three-folds and two-folds lower than Nafion117 at 25ºC and 150ºC respectively. Therefore a very significant improvement was achieved through the target was not met.

☑ The transport selectivity of the as prepared reinforced PIL based membranes calculated as the "through-plane" conductivity/methanol permeability ratio is noticeable higher than their Nafion counterparts (3,7E+09 and 1,6E+11 mS·s·bar/mol at 100º and 150ºC respectively vs. 3,8E+08 and 6,3E+07 mS·s·bar/mol)

☐ The H_2 cross-over properties at temperatures below 50ºC are similar to those of Nafion. However they present selective CO_2/H_2 permeation properties (7-8 as CO_2/H_2 separation factor) opening up new applications in the field of Gas Separation.

- ☑ Reduced fabrication costs compared to current technology: reduction of cost from 253 EUR/m^2 to 18 EUR/m^2 is estimated considering an annual production rate from 10.000 m^2 to 2.000.000 m^2 respectively.

The H_2-FC performance (with 2.5cm*2.5cm of electroactive area) has been evaluated at 120ºC (see Figure 38). Thus, the "proof of concept" has been deemed successful by comparison with commercial counterparts (Advent); and, even better results can be expected by electrode optimization and improvements in fuel-cell components (i.e. bipolar plates).

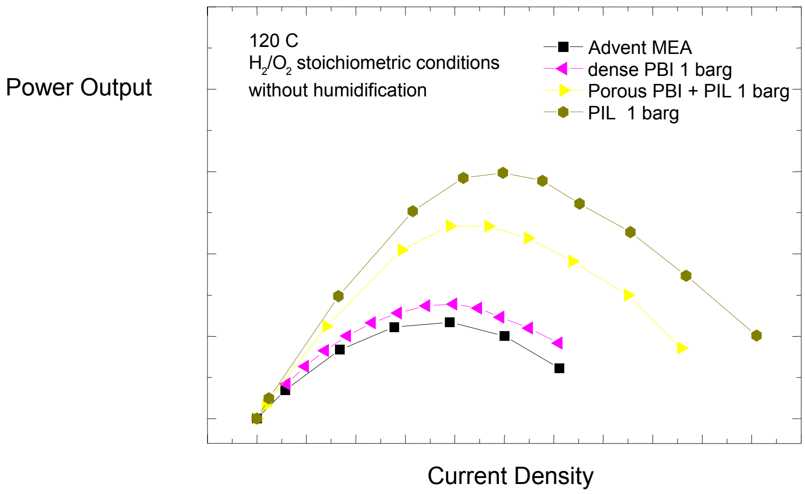


Figure 38. Power output curves in H2/O2 single cell for MEAs based on PIL-PBI membranes and electrodes prepared by CIDETEC.

4. Electrolyte Membranes from two components: Supported Protic Ionic Liquid Membranes onto Porous PBI supports

The conduction properties of bulky protic ionic liquids coupled to their physical and chemical properties have been the main factors that motivated the study of supported liquid membranes on porous PBI as supports. The development of experimental procedures (assisted by vacuum and/or temperature) to achieve a complete filling of the porous supports by protic ionic liquids and avoids its leakage, is one of the main challenges for this dual system.

In addition, proton conduction over Im008b Protic Liquid Supported Membranes, unlike phosphoric acid doped porous PBI membranes, primarily depends not only on support porosity but also on pore connectivity (coordination number) as revealed by modelling studies (see Figure 39). In general, the conductivity values of heterogeneous media increase markedly with porosity for values above the percolation threshold. Therefore, the conduction performance of the supported Protic Ionic Liquid Membranes has been somewhat limited due to the availability of adequate PBI porous supports. Figure 40, Figure 41, Figure 42 illustrate schematically the work progress in the preparation of porous PBI supports, the difficulties encountered and the contingency solutions in accordance to the periodic risk assessment carried out by the project steering committee.

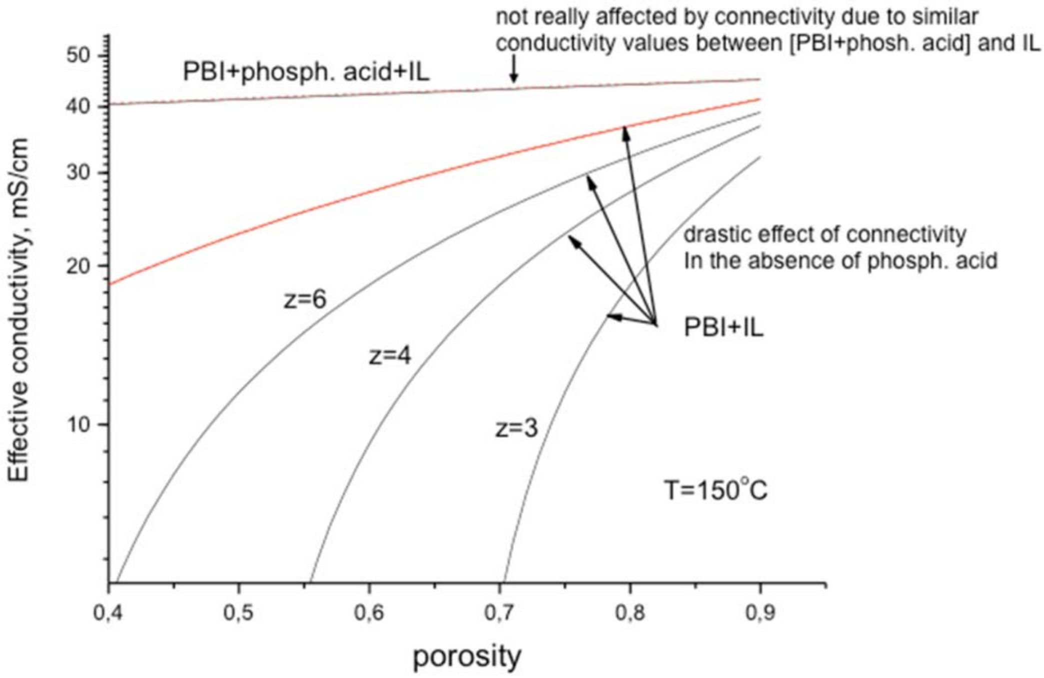


Figure 39. Modeling results of conduction performance on porous media by Effective Medium Theory.

Figure 40. Progress of the work related to randomly porous PBI preparation by delayed demixing for protic ionic liquid confinement.

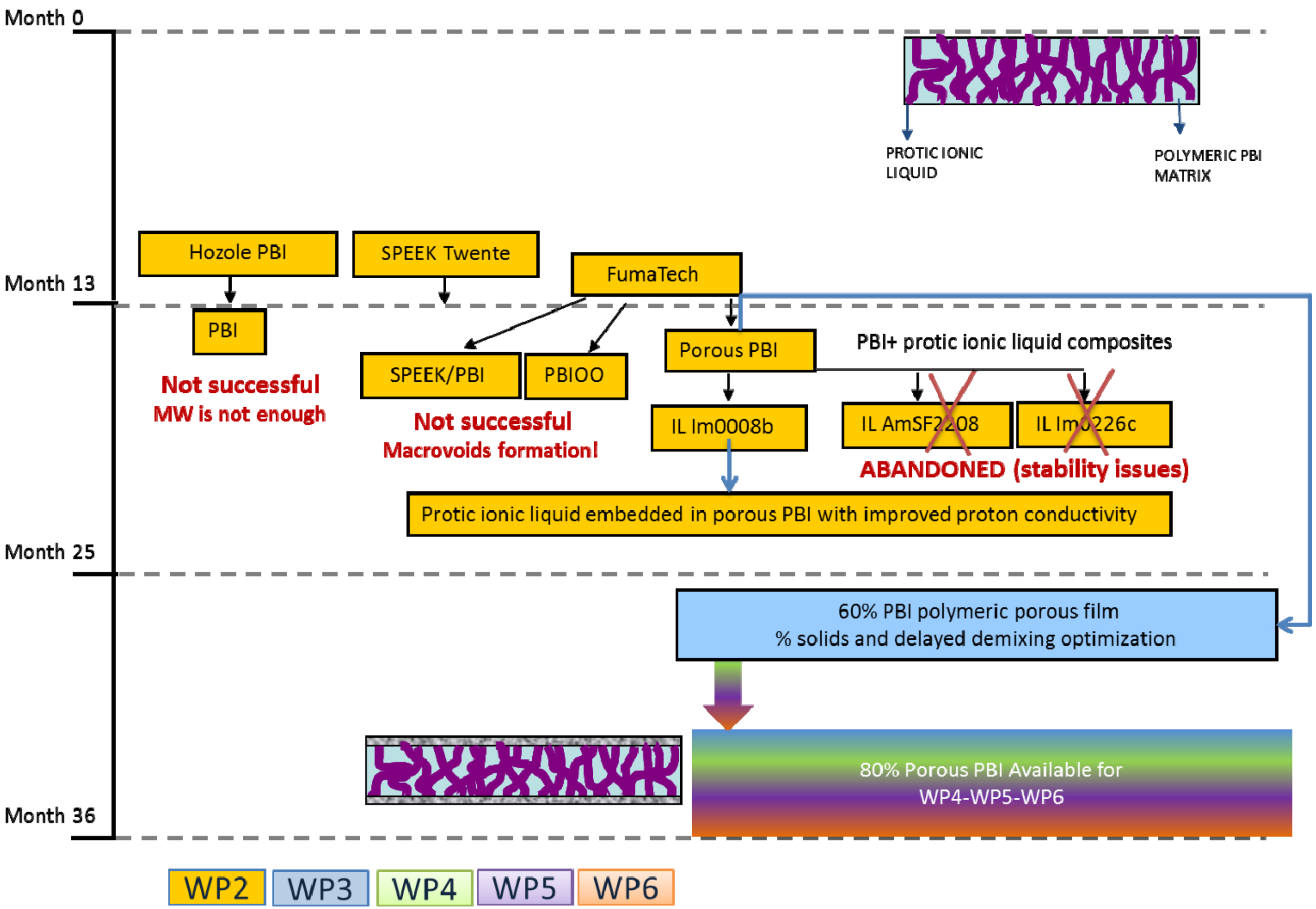


Figure 41. Progress of the work related to randomly porous PBI preparation by porogen leaching for protic ionic liquid confinement.

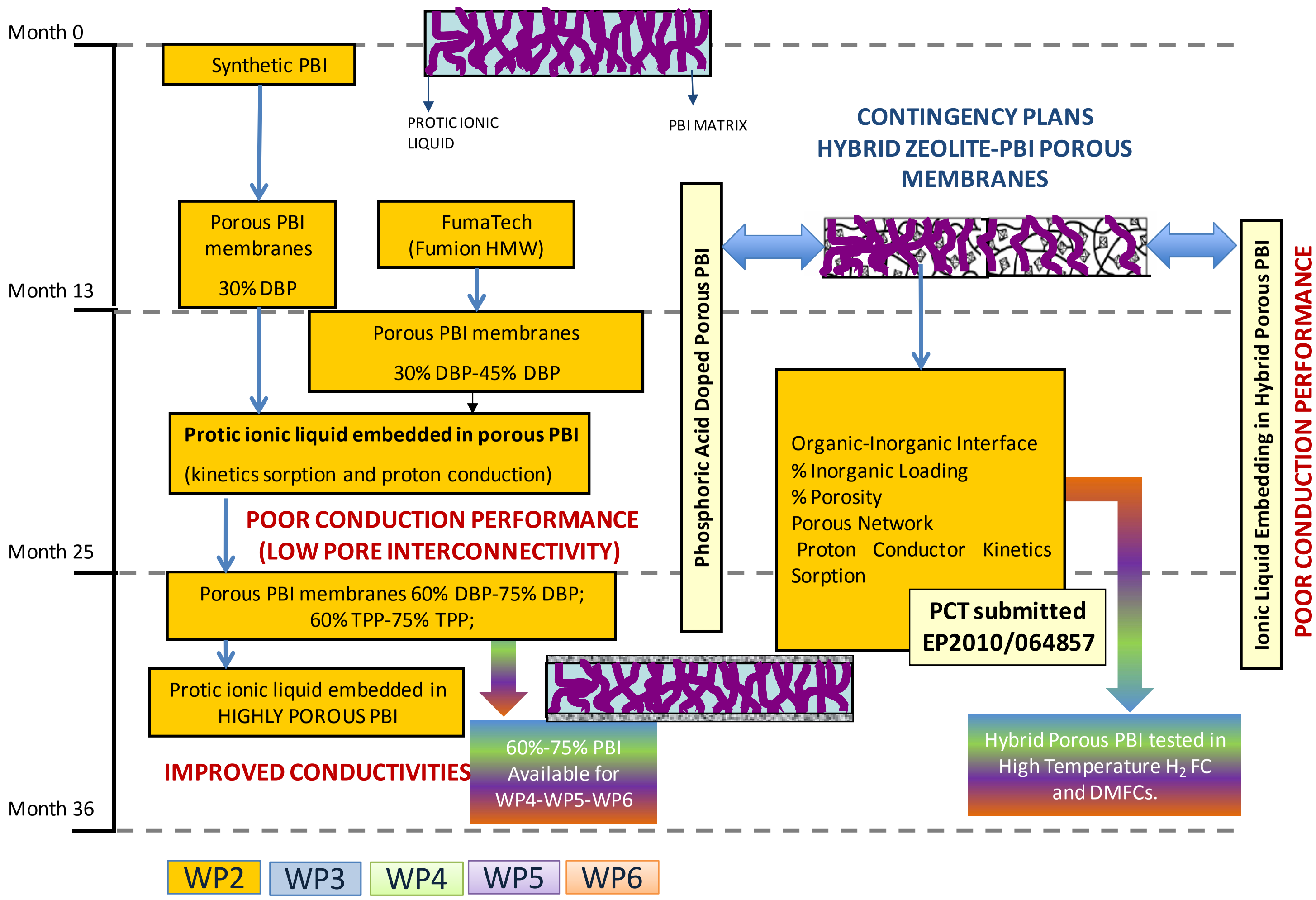


Figure 42. Progress of the work related to straight porous PBI preparation for protic ionic liquid confinement.

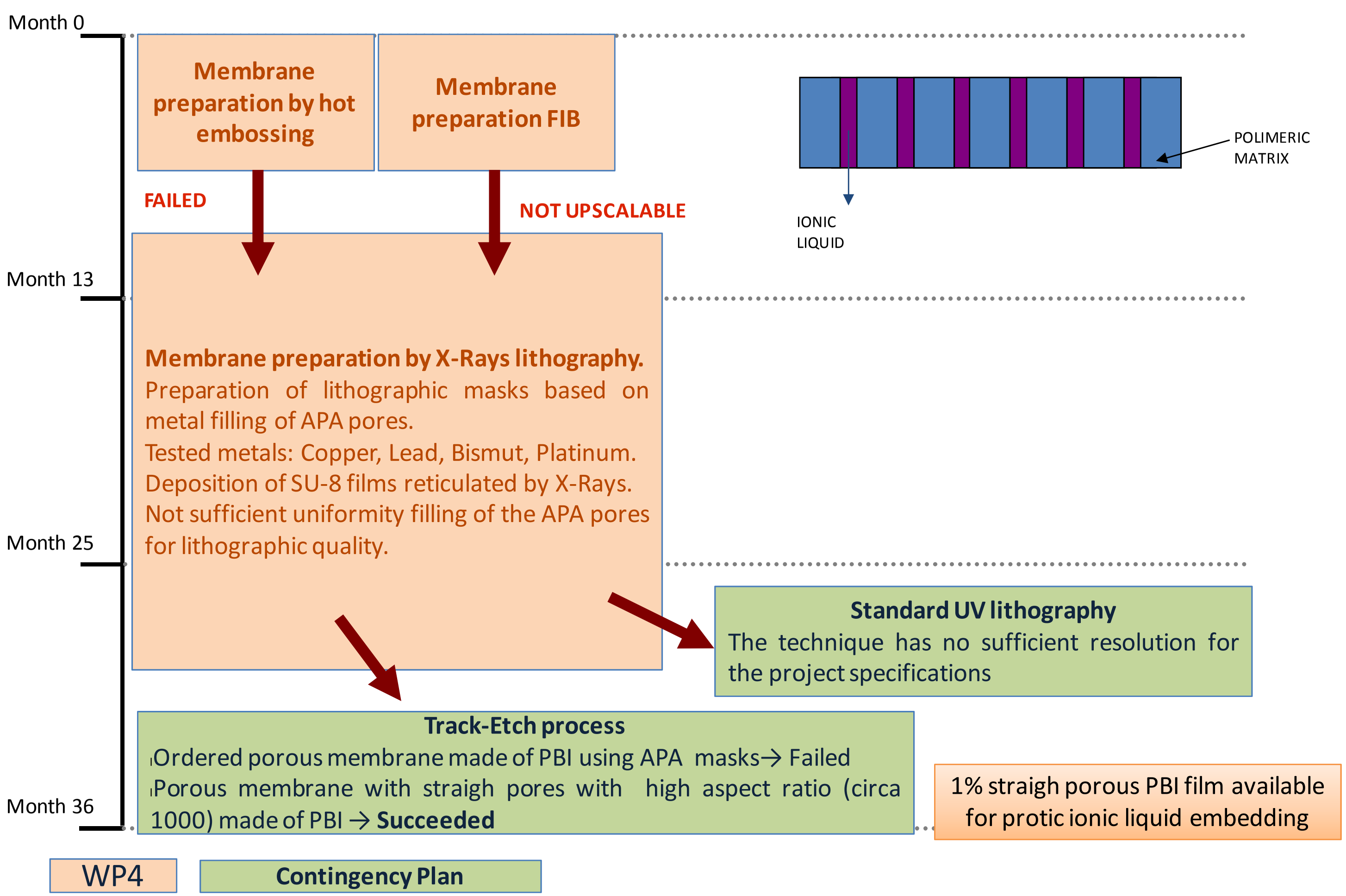


Figure 43 shows comparatively the conduction properties of the best supported Im008b liquid membrane on random and straight pore PBI supports respectively. Conductivity values up to 20 mS/cm at 150ºC have been achieved for the imbibed on 80% porous PBI membranes and 100 nm in pore size. This behaviour is in agreement with the pore architecture attained by delayed-demixing membrane process. Nevertheless, the conductivity decreases with time on stream (below 6 mS/cm at 150ºC after 150 h) for all samples prepared due to Im008b leakage and/or water dragging effect during testing in presence of 0.05 water molar fraction. The 80% porous support provides better performance than the track-etched membranes with 1% porosity (almost 10 times higher). However the amount of ionic liquid encapsulated is not comparable at all due to porosity differences.

For a real assessment on the benefits imposed by track-etched pores, Figure 44 shows the intrinsic proton conductivity dependence with temperature for all supported Im008b liquid membranes. In this case, the bulk Im008b performance is also included as reference. As expected, higher values are attained by using track-etched supports due to the shorter proton diffusion pathways. In addition, the endurance properties of the supported liquid membrane on 50 nm track-etched pores, are notably improved. Thus, the proton conductivity at 150ºC remains nearly constant after 150h at about 0.6 mS/cm (membrane support with 1% in porosity). Thus, supports with low pore diameters are clearly preferred for durability at the expense of a lower porosity and conductivity. In this region, only track-etched technology is feasible although up to now it has been scarcely explored for PBI type polymers. Acid doped track-etched porous PBI membranes have also been studied. A clear improvement was observed when compared with doped dense PBI membranes prepared under identical conditions. Thus, 1 % of porosity allows up to 25-fold enhancement of through-plane conductivity at 180 ºC. This fact is related to proton transport kinetics aided by wetted wall straight cavities with H_3PO_4 molecules.

Theoretical conductivity calculations have been carried out over straight porous PBI membranes with 25% of porosity and 15 μm in pore diameter prepared by micro-moulding. Thus, 45 mS/cm and 64 mS/cm are calculated for Im008b supported on patterned PBI at 170ºC and 200ºC respectively. In addition, the porosity value required to fulfil Zeocell technical targets in term of conductivity is technologically feasible. Acid doped micro-moulded PBI membranes have also been studied. A clear improvement was observed when compared with doped randomly porous PBI membranes with similar porosity values. Thus, 25% porosity allows up to 2-fold enhancement of through plane conductivity at 180ºC. This field constitutes one of the main exploitable foregrounds not only for FC applications but also in the “Smart Microsystems” field.

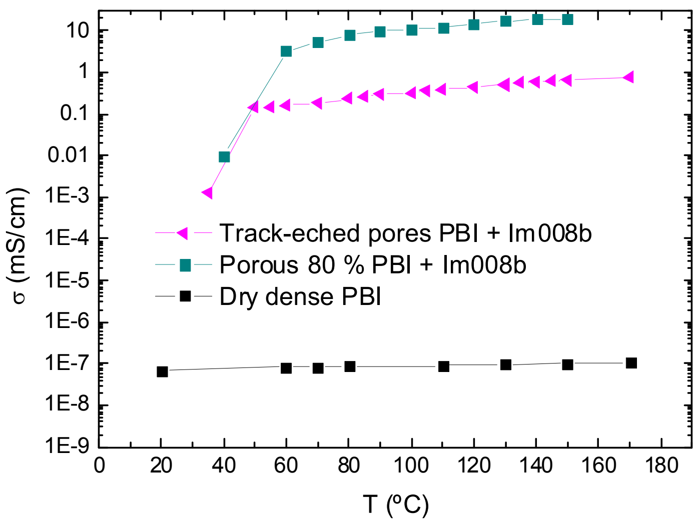


Figure 43. Through plane proton conductive values of supported Im008b liquid membranes on porous PBI (dense membrane is also included as a reference).

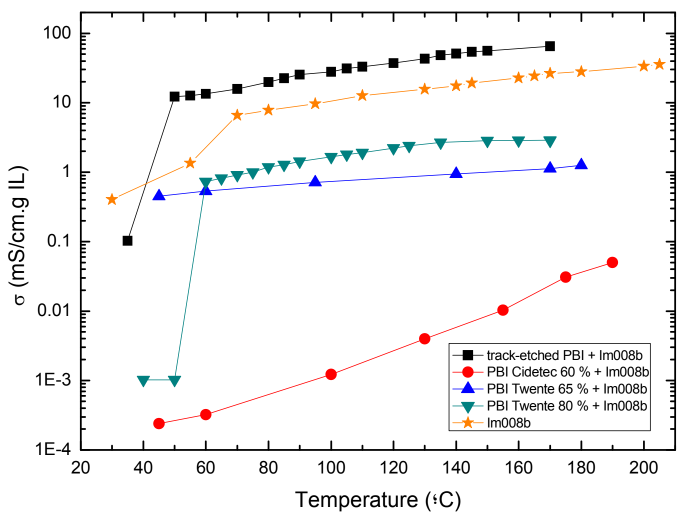


Figure 44. Through-plane “intrinsic” proton conductivity values (expressed per IL).

5. Electrolyte Membranes from three main components: Phosphoric Acid Doped Hybrid PBI Membranes

Hybrid membranes based on acid doped PBI and microporous materials (see Figure 45) have been successfully developed as a results of the contingency plan for HT PEMFCs applications (see Figure 41). In fact, this electrolyte concept has been intellectually protected (PCT/EP2010/064857; priority date 05/10/2010). Basically two fillers have been mainly studied: ETS-10 titanosilicate type material externally functionalized with sulfonic groups and NaY type zeolite embedded in Im008b. Thus, the organic functionalization of the external surface of microporous ETS-10 crystals (circa 4%wt loading), has allowed to improve the intrinsic conductivity of the inorganic loading attaining proton conductivity values as high as 30 mS/cm at 150ºC under saturated conditions. This fact is due to the coexistence of the two main conduction mechanisms: vehicle –type mechanism (with H_2O as proton carrier) and hopping- type mechanism (through $-SO_3H$ terminal groups + H_2O molecules).

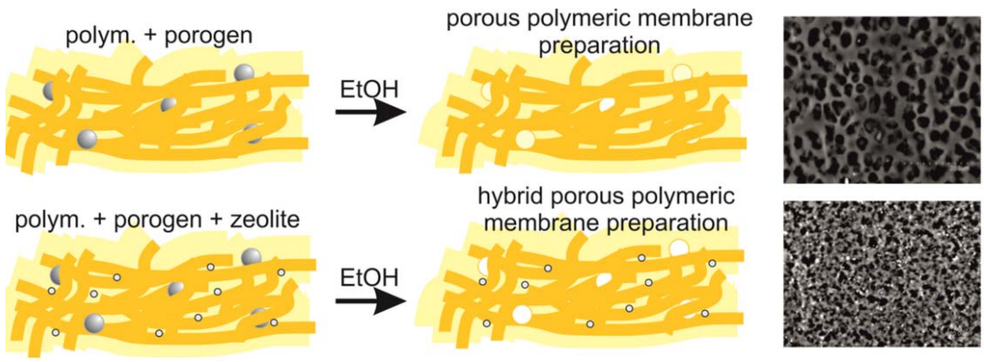


Figure 45. Porous PBI and hybrid porous PBI films formation procedures by leaching out the porogen with ethanol (reprinted from ref. 19).

Similarly, the presence of Im008b in the NaY framework structure also enhances the membrane conduction properties due to the hydrophilicity of NaY crystals and the new conduction pathways provided by proton donor-acceptor sites encapsulated within its framework. A parametric study on the inorganic loading effect onto conduction performance of dense membranes has been carried out to identify an optimum value around 3% wt. referred to the polymer in the studied range (1-20% wt.). In a subsequent step, with the aim to further promote the conductivity of hybrid membranes, porous based PBI membranes with porosity values ranging from 30% to 75% have also been prepared by leaching out a porogen (DBP or TPP). Higher proton conductor uptakes values do not necessary involve higher conductivity. This fact is related to the phosphoric acid leakage during handling and the limited number of percolating pathways. It is important to remark that 3% of inorganic loading was identified as the optimum value for the 30% porous data set[19]; and it seems likely that higher porosity values would demand a higher amount of filler to ensure the beneficial effects.

The analyses of intrinsic proton conductivity values (expressed per phosphoric acid doping %wt.) versus porosity values for the two porogen molecules (i.e., pore connectivity degree) has allowed to quantify the "porous structure" effect for a given inorganic filler. In particular, a most effective acid doping is shown by porous membranes prepared from TPP porogen.

Table 6. In-plane conduction properties of porous doped based PBI membranes after H_3PO_4 doping.

			H_3PO_4 doped at 25ºC			H_3PO_4 doped at 50ºC		
Sample			% doped	σ (mS/cm) At 80ºC	σ (mS/cm) At 150ºC	% doped	σ (mS/cm) At 80ºC	σ (mS/cm) At 150ºC
DBP	45%	pure PBI	202	7.7	47.3	220	23.1	59.7
		Hybrid (ETS-10 3%wt.)	264	27.2	79.3	302	32.8	73.3
		Hybrid (NaY 3%wt.)	281	-	-	289	14.5	51.4
	60%	pure PBI	240	26.3	112.4	263	30.5	89
		Hybrid (ETS-10 3%wt.)	365	50.2	110.1	338	62.2	120.6
		Hybrid (NaY 3%wt.)	365	-	-	385	20.8	63.1
	75%	pure PBI	592	134.1	281.4	630	66.5	142.1
		Hybrid (ETS-10 3%wt.)	609	71.2	126	702	62.2	133.3
		Hybrid (NaY 3%wt.)	550	-	-	649	60.4	130.5
TPP	45%	pure PBI	172	10.1	72.1	180	11.6	29.9
		Hybrid (ETS-10 3%wt.)	164	0.8	2.7	175	11.1	68.9
		Hybrid (NaY 3%wt.)	181	-	-	188	13.9	81.9
	60%	pure PBI	228	17.9	83.7	243	18.9	107.9
		Hybrid (ETS-10 3%wt.)	263	10.9	66.9	284	40.0	109.4
		Hybrid (NaY 3%wt.)	227	-	-	253	41.7	106.2
	75%	pure PBI	448	79.8	149.6	563	99.4	188.4
		Hybrid (ETS-10 3%wt.)	482	60	123.3	516	83.3	182.8
		Hybrid (NaY 3%wt.)	383	-	-	401	121.5	213.2

The performances of hybrid PBI membranes in relation to the technical Zeocell targets are as follows:

- ☑ High ionic conductivity: >100 mS/cm at 150ºC without external humidification for highly porous PBI membranes (60% and 75% porosity) prepared from DBP or TPP porogen (see Table 6).
- ☑ Suitability for operating at temperatures between 130-200ºC. The mechanical properties for porous membranes are similar to those reported in the literature for high temperature PEMs. The benefits attained by the inclusion of microporous fillers in the doped PBI membranes are remarkable in the high temperature region (above 150ºC) (see Figure 46).The phosphoric acid oligomerization usually leads to the formation of pyrophosphoric acid and the conductivity drops. However, this effect is strongly reduced for hybrid samples due to: i) the presence of hydrophilic inorganic domains, the most effective acid-doping of PBI polymer (sulfonic-phosphoric acid interactions forPBI-ETS10) and the provision of new conduction pathways.

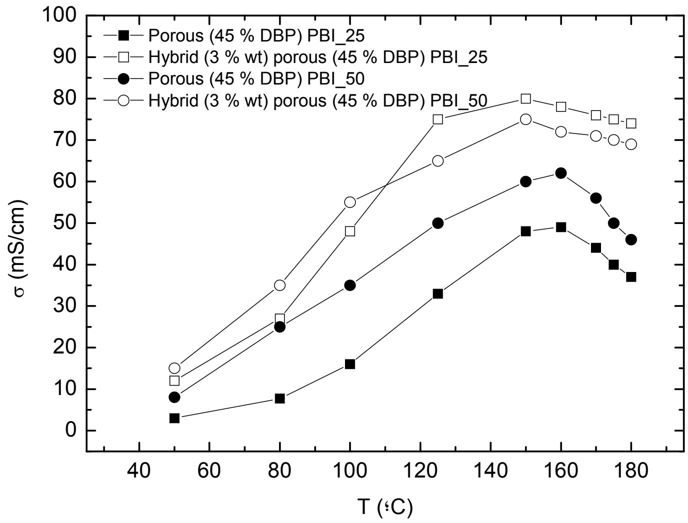


Figure 46. In-plane conductivity measurements of porous systems (45% in porosity) after phosphoric acid doping at 25ºC and 50ºC: pure PBI membrane vs. Hybrid PBI membrane with 3% wt. of SO3H-ETS-10 (reprinted from ref. 19).

☐ Durability tests: post-project collaboration among the partners will enable this evaluation.

☑ Low Cross-over (5 times lower than Nafion): methanol permeability is about one-tenth (for porous membrane) / one hundredth (for dense membrane) of the value reported for Nafion 117 over the full temperature range (see Figure 47).

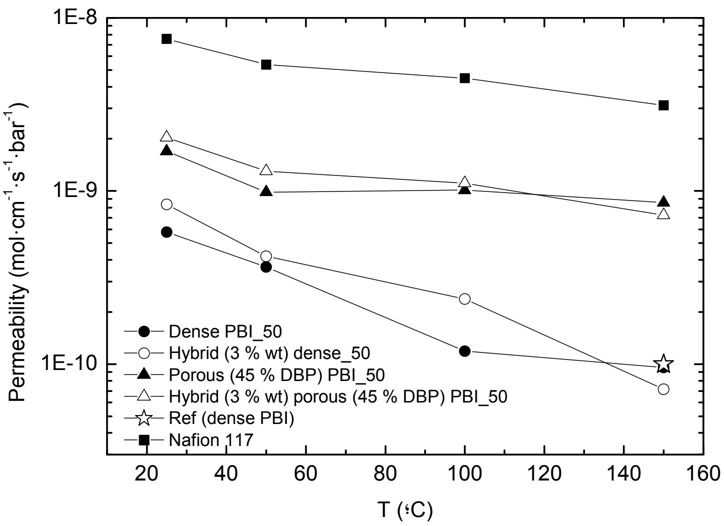


Figure 47. Methanol permeability for dense and porous PBI based membranes after phosphoric acid doping.

☑The transport selectivity of some of the as prepared hybrid porous membranes (calculated as the "in-plane" conductivity/methanol permeability ratio) is two to four orders of magnitude higher than Nafion. As an example, for Hybrid 3% ETS-10 Porous PBI 45% DBP, the evaluated transport selectivity values are 4,5E+10 and 1,6E+11 mS·s·bar/mol at 100º and 150ºC respectively vs. 3,8E+08 and 6,3E+07 mS·s·bar/mol for Nafion 117.

☑Reduced membrane fabrication costs compared to current technology: from 296 EUR/m^2 to 22 EUR/m^2 considering an annual production rate from 10.000 m^2 to 2,000,000 m^2 respectively.

☑Reduced manufacturing costs for high temperature 2 kW PEMFC stacks compared to DOE targets: 1000 EUR/kW to 217 EUR/kW considering an annual production rate from 1000 to 500,000 stack units respectively.

Different porous membranes have been assembled on Freudenberg Carbon Paper recommended for High temperature H_2 PEMFCs and DMFCs. Among the tested, the most outstanding H_2 PEMFC performance (see Figure 48) is exhibited by MEAs prepared for porous PBI membranes, 60% DBP content (0.5 V/ 0.704 A/cm2 vs. 0.5 V/ 0.47 A/cm2 at 160ºC and non humidified conditions). This result is in accordance with the reported values for commercial and state of the art HT H_2-PEMFCs. Eventually, further improvements are expected in the short-term by means of electrode and MEA assembly optimization.

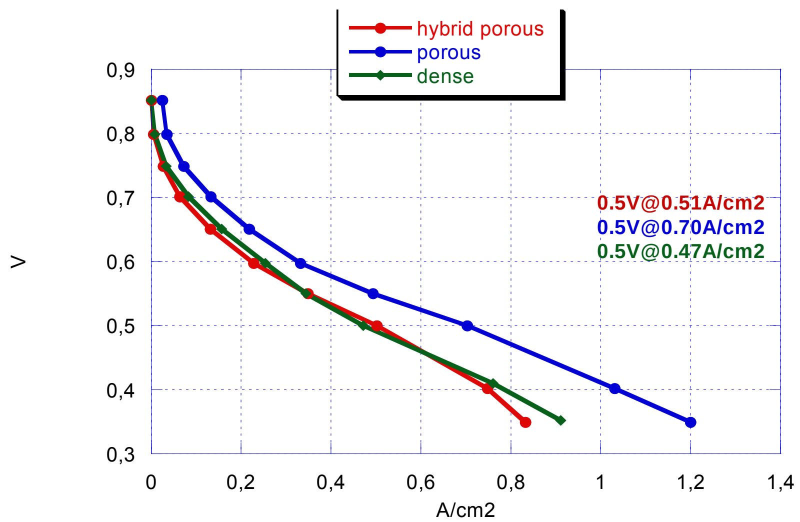


Figure 48. H2 FC Performance of Dense, porous 60% and hybrid porous 60% membranes at 160º C and non humidified conditions.

A similar work-programme has been followed for high temperature DMFCs. In this case the electrolyte membrane porosity seems to have an adverse effect over DMFC performance and time on stream behaviour (cracks formation). Among the samples tested (see Figure 49), the best high temperature DMFC performance was exhibited by MEAs prepared for dense PBI membranes (0.3 V/ 0.170 A/cm2 at 150ºC), which can be considered as an outstanding result.

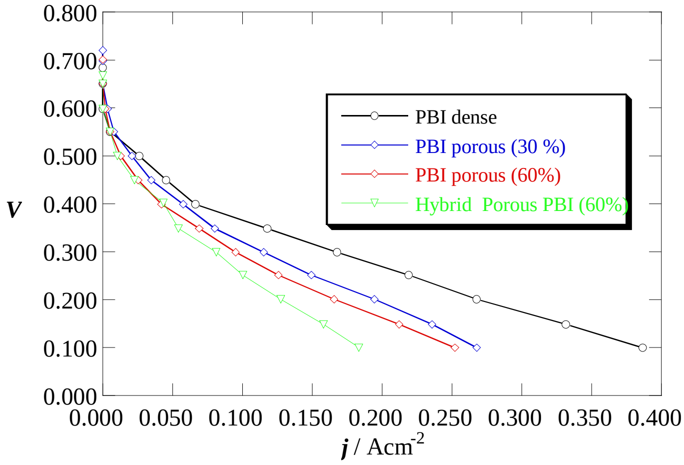


Figure 49. DMFC Performance of Porous PBI Based Membranes.

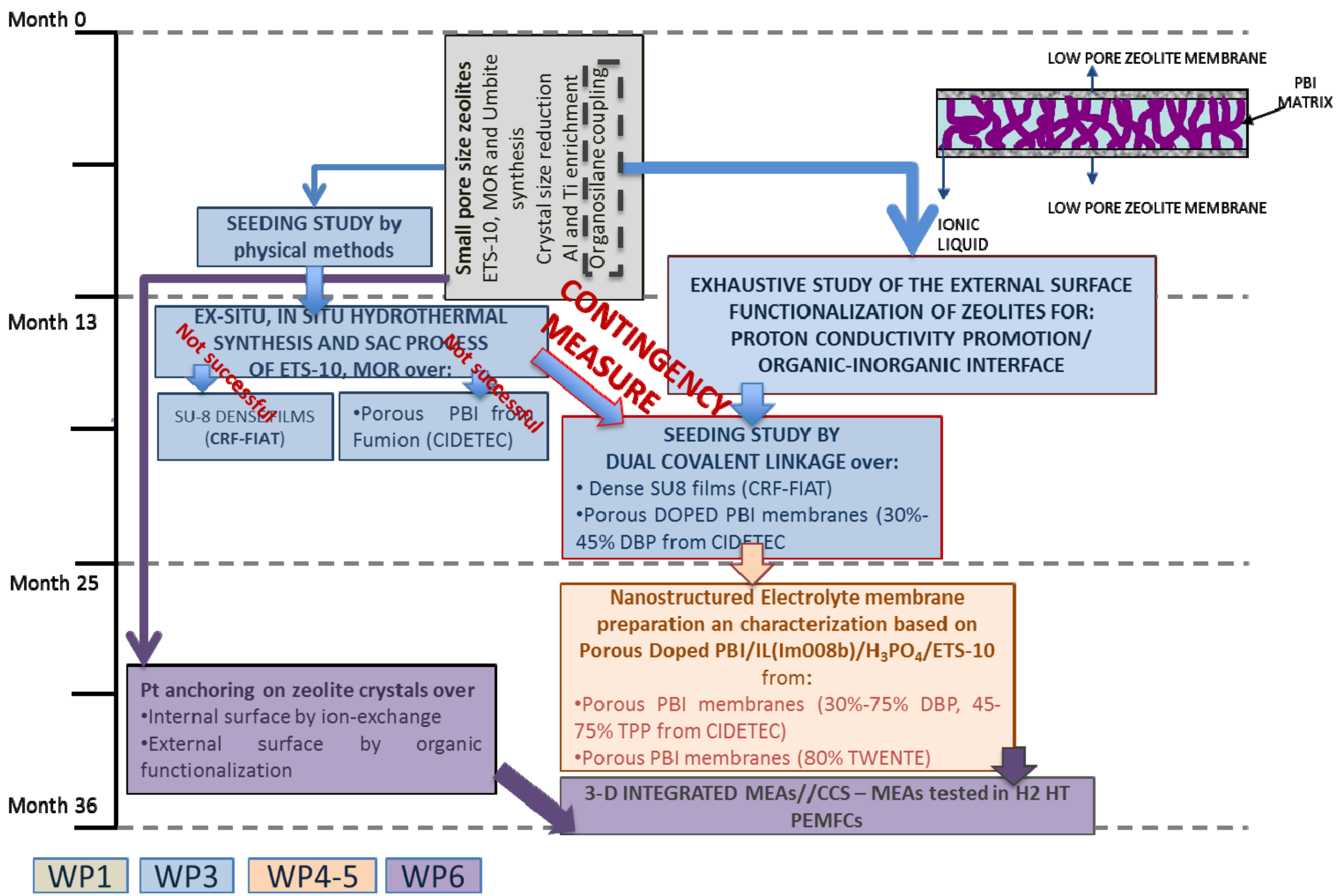
6. Electrolyte Membranes from three main components: Protic Ionic Liquids embedded in Hybrid Porous PBI Membranes

Hybrid membranes based on PBI and microporous materials impregnated with protic ionic liquid have been also tested (see Figure 41). This membrane system could be considered as a supported liquid membrane, where the porous hybrid PBI is the inert container and the protic ionic liquid is the selective carrier from proton transport. Therefore, the pore connectivity of the PBI framework has to ensure a continuous conduction pathway through the protic ionic liquid network. Unfortunately, the exhibited conduction performance is far below the Zeocell requirements, whatever the porosity and porogen used in spite of the reported Im008b uptake values. This fact is in agreement with: i)the prevailing role of free Im008b molecules on proton transport, ii) the existence of a specific percolation threshold limit that has to be overcome, and, iii) the limited number of percolation pathways exhibited in the porous architectures prepared by leaching.

7. Electrolyte Membranes from four main components: Protic Ionic Liquids embedded in Phosphoric Acid Doped Porous PBI Membranes with Zeolite Coatings

The Zeocell project puts forward an innovative electrolyte membrane concept based on the synergic combination of porous PBI supports containing protic ionic liquids as intrinsic conductors and zeolite coatings ETS-10 as diffusional barriers over PBI top surfaces to prevent the conductor leakage/dragging with time on stream. Due to the technical difficulties to fabricate ordered porous PBI supports, all the experimentation on this topic has been carried out with **ramdonly porous PBI** prepared either by **leaching out DBP or TPP porogen molecules** (CIDETEC route) or by **phase separation process** (UTWENTE route). Figure 50 and Figure 51 schematically illustrate the progress of the work in the preparation of nanostructured electrolyte membrane, the encountered difficulties and the contingency solutions in accordance to the periodic risk assessment carried out by the project steering committee.

Figure 50. Progress of the work related to the preparation of nanostructured electrolyte membranes based on low pore zeotype coatings



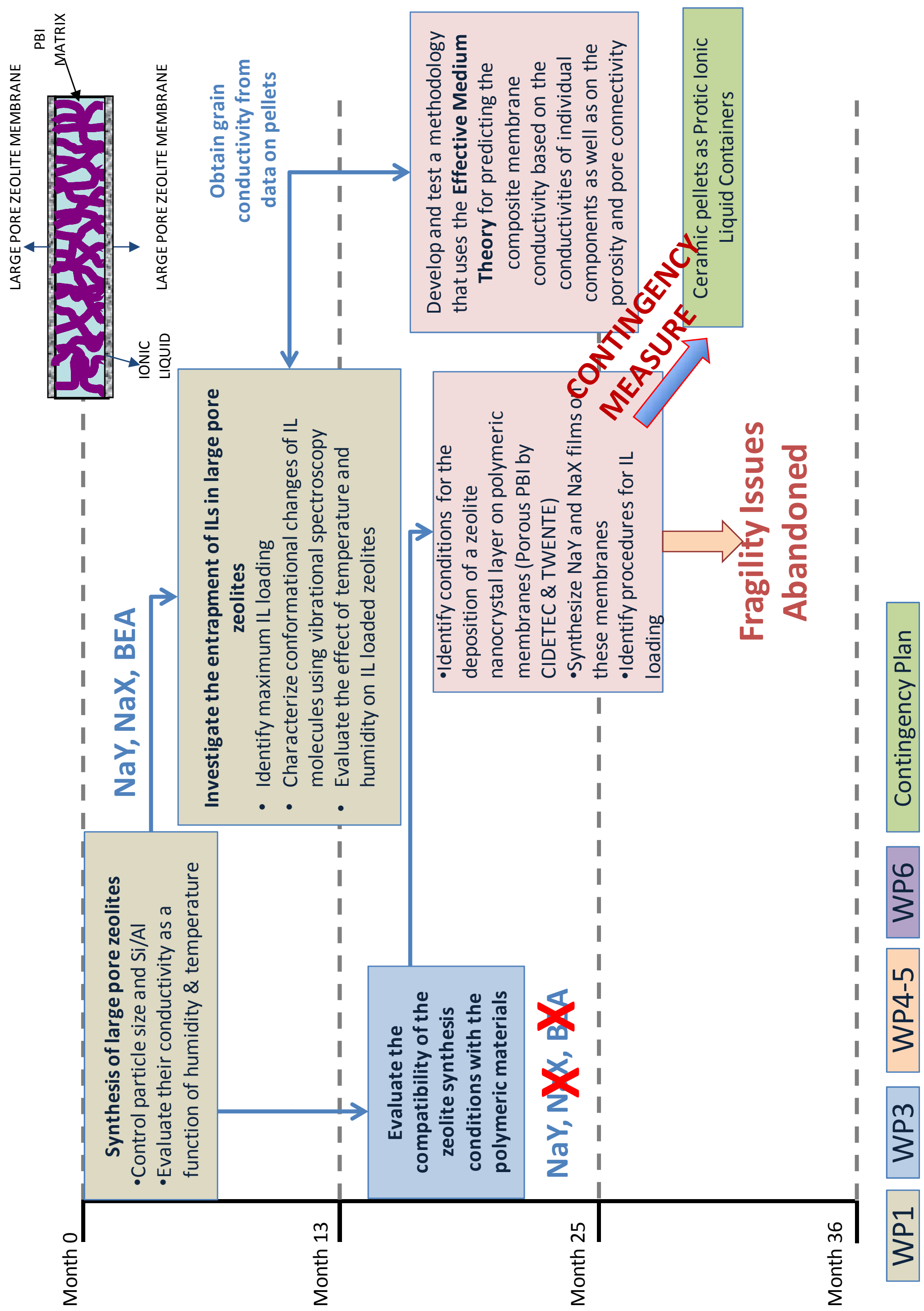
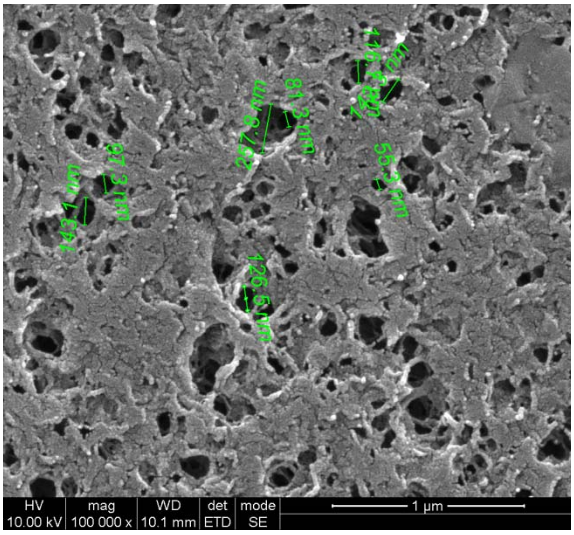


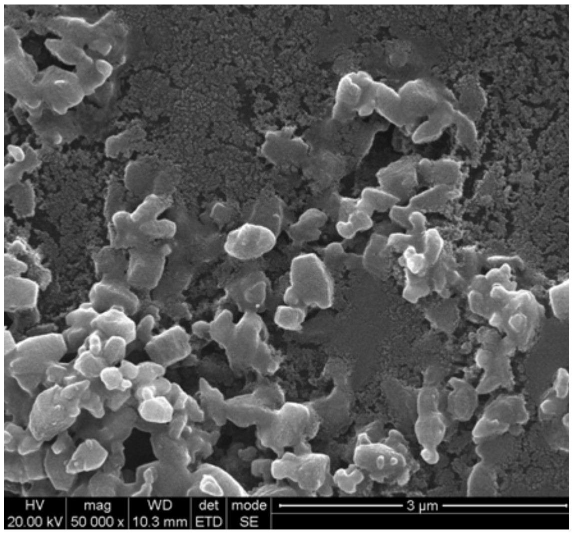
Figure 51. Progress of the work related to the preparation of nanostructured electrolyte membranes based on large pore zeolyte coatings.

From the preliminary results, it appears that membrane porosity values higher than 60% provide the best conduction performances. TPP porogen renders sponge-like pores more adequate for ionic liquid filling but also more prone to leakage. On these samples, a trade-off between durability and conductivity should be considered. Thus, the most interconnected porosity attained on TPP samples, the higher embedding and proton transport properties, at the expense of a higher leakage risk during operation. Moreover, electrolyte membranes based on porous PBI 80% prepared by delayed de-mixing outperform CIDETEC membranes.

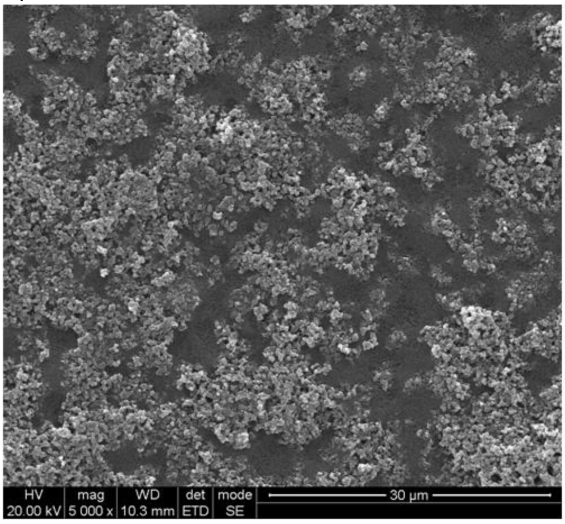
In addition, two different coatings have been deployed over the polymer surface. The FORTH procedures involve the infiltration of colloidal NaY seeds, whereas, ETS10 coatings by covalent-linkage over acid doped PBI polymer were prepared by INA. In the former case, conductivity values up to 10 mS/cm have been reported. On the other hand, up to 100 mS/cm and 60 mS/cm at 150ºC for in plane and through plane conductivities respectively have been attained by following optimized INA procedures over porous PBI 80% prepared by delayed de-mixing. The optimized preparation method comprises four main steps (see Figure 52):

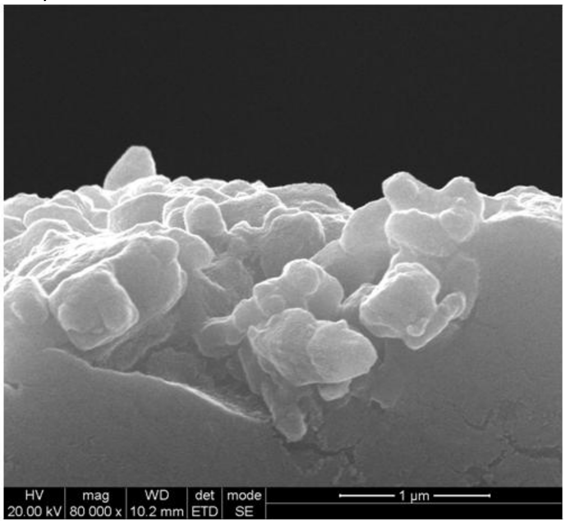
1) Phosphoric Acid Doping of porous PBI membranes with 11M solution for 24 h at room temperature followed by drying at 120ºC under vacuum for 12 hours.
2) Immobilization of ionic liquid by assisted vacuum filtration at 170ºC onto doped PBI membranes previously evacuated. The filtration procedure is carried out during 8 h at the fixed temperature. Finally, the system is evacuated at 0.5 mbar until most of the ionic liquid pass through the membrane ensuring that the pores are filled with it. The resulted composite membrane is dried at room temperature for 3 hours. Sweeping the excess of ionic liquid of the PBI surface was then performed using sorbent paper soaked in dry acetone.
3) Two steps of covalent linkage of functionalized epoxy-ETS10 crystals over the PBI surface.
4) Phosphoric acid doping of composite IL-ETS10-PBI membranes with 11M solution for 15 minutes at room temperature followed by drying at 120ºC under vacuum for 3 hours.





A) B)





B) D)

Figure 52. SEM analyses of the nanostructured electrolyte membrane prepared from porous PBI (80%): A) after 2nd step; B) after 3rd step; C) and D) after 4th step.

To summarize, the performance of the best nanostructured electrolyte membrane in relation to the technical Zeocell targets are the following:

☑ High ionic conductivity: in plane conductivity values up to 100 mS/cm at 160ºC without external humidification (see Figure 53).

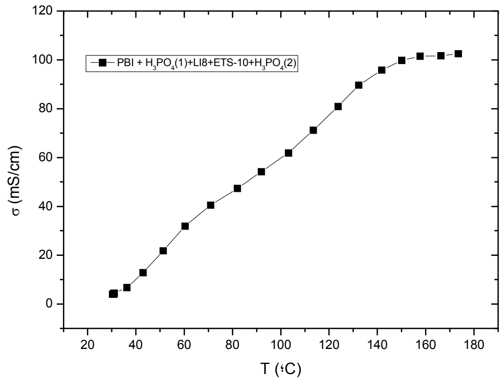


Figure 53. In plane proton conductivity measurements of the optimal nanostructured electrolyte membranes based on porous PBI (80%).

☑ Suitability for operating at temperatures between 130-200ºC. The mechanical properties for the as prepared nanostructured electrolyte membranes are similar to those reported in the literature for high temperature PEMs. The benefits imposed by the use of protic ionic liquid as major proton conductors are notorious at temperatures above 160ºC.

☒ Durability tests: through-plane proton conductivity performance at 200ºC remains constant with time on stream during 24 h (44 mS/cm). However, a drastic loss in performance is observed at 200ºC (90 % decay) after 100 h. Afterwards, a steady state value is attained at 6 mS/cm. For operation at 150ºC, 67 % losses appear after 150 h, and then, proton conductivity remains nearly constant at 15 mS/cm.

☑ Low Cross-over (5 times lower than Nafion): nanostructured electrolyte membranes exhibit 4.6-5.6 times lower methanol cross over than commercial Nafion 117 in the full temperature range (see Figure 54).

☑ The transport selectivity of the best nanostructured electrolyte membrane membranes (calculated as the “through-plane” conductivity/methanol permeability ratio) is one-three orders of magnitude higher than Nafion counterparts. As an example, for nanostructured Twente membranes, the evaluated transport selectivity values are 2.65E+10 and 5.77E+10 mS·s·bar/mol at 100ºC and 150ºC respectively vs. 3,8E+08 and 6,3E+07 mS·s·bar/mol for Nafion 117.

☐ The H_2 cross-over properties at temperatures below 50ºC are similar to those of Nafion. At temperatures above 100ºC, the barrier effect imposed by the microporous coating provides a decrease of the H_2 permeability of three orders of magnitude in comparison with reinforced PIL based membranes ($8{,}53.10^{-10}$ mol/cm·s·bar vs. $1{,}15.10^{-07}$ mol/cm·s·bar for nanostructured and PIL-PBI membranes respectively).

☑ Reduced membrane fabrication costs compared to current technology: from 322 EUR/m^2 to 23 EUR/m^2 considering an annual production rate from 10,000 m^2 to 2,000,000 m^2 respectively.

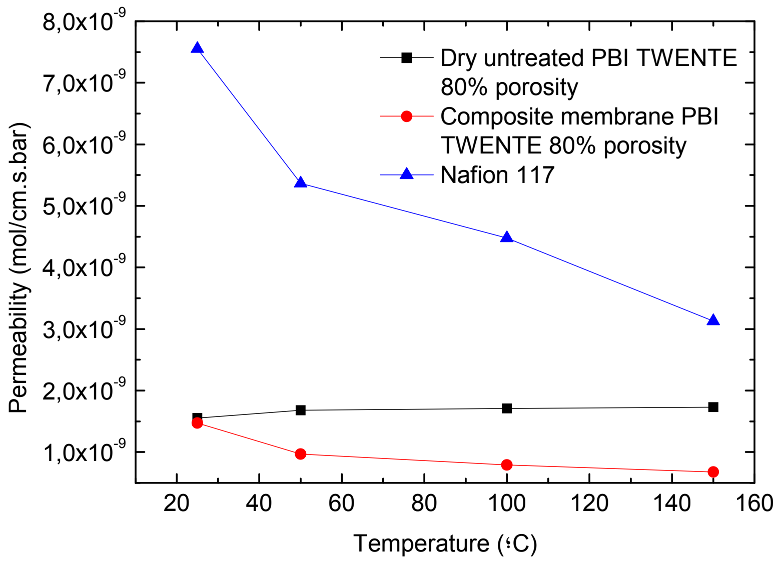


Figure 54. Comparison of Methanol Permeation for the Nanostructured Electrolyte Membranes based on Porous PBI TWENTE (80%) and Nafion 117.

The H_2-FC performance (with 2.5cm*2.5cm of electroactive area) has been evaluated at temperatures up to 180ºC. By comparison with pure PBI MEAs and commercial MEAs from Advent (see Figure 55), the "proof of concept" could be considered as demonstrated. However, better results are expected following electrode-electrolyte interphase optimization due to the nananostructured membrane roughness (see Figure 52).

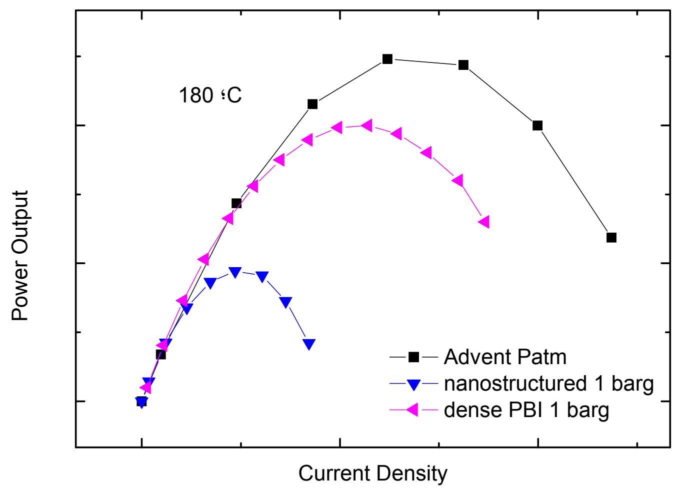


Figure 55. Power output curve at 180ºC in H2/O2 single cell for MEA based on nanostructured electrolyte membrane and electrodes prepared by CIDETEC.

A preparation procedure for 3-layer integrated MEA by CCM (Catalyst Coated Membrane) relying on the catalytic properties of zeolite coatings has been established. The nanostructured electrolyte membrane preparation procedure already described has been slightly modified for catalytic activation purposes. In particular, the second covalent linkage step has been carried out with Vulcan/amine/Pt/amine/ETS-10 instead of amine/ETS-10 crystals to incorporate the Pt and also de Vulcan required for electron transport at the three boundary layer. The final preparation scheme for 3-layer integrated MEA is shown in Figure 56. In this scenario, the zeolitic layers play the two following roles: i) catalyst support due to the well-known properties of zeolites as platinum support to provide with higher metal dispersion; and ii) microporous barrier to diminish fuel crossover and proton conductor leakage during operation. The preparation method developed here, involves Vulcan-Pt-zeolite electrocatalysts. Accounting from the gained knowledge, the catalysts here prepared are also amenable to deploy in other catalytic chemical reactions.

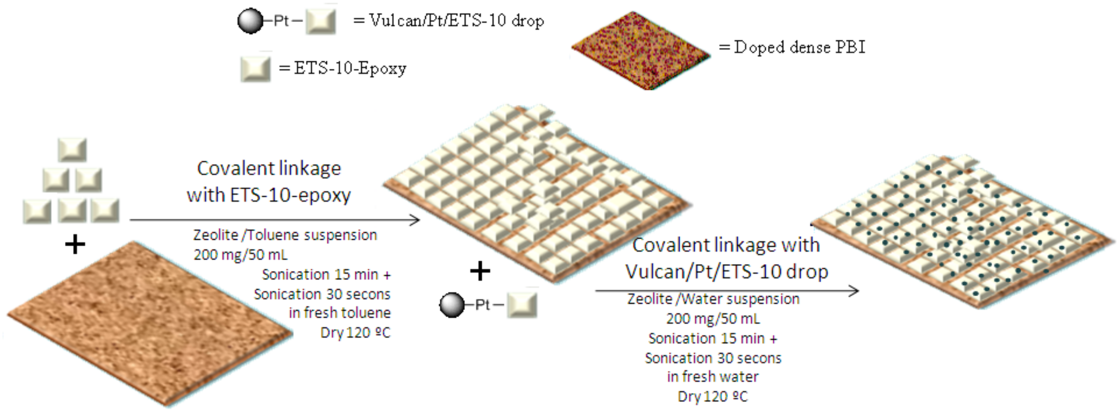


Figure 56. General scheme for the preparation of catalytically activated nanostructured electrolyte membranes based on zeolites, ionic liquids and PBI developed in this project.

- **Potential impact and main dissemination activities and exploitation results**

  - **POTENTIAL IMPACT OF S&T RESULTS AND EXPLOITATION**

The main ST outcome from ZEOCELL is the development of three novel electrolyte membranes fulfilling all the ST requirements originally claimed for high temperature PEM fuel cells in stationary applications with the exception of durability issues which are briefly described below:

1) **Hybrid randomly porous PBI membranes doped with phosphoric acid** (PCT/EP2010/064857; priority date 05/10/2010). The endurance properties of this family are under investigation.
2) **Nanostructured Electrolyte Membranes** based on randomly porous acid doped PBI membranes with tortuous pores filled up with protic ionic liquid and two microporous ETS10 coatings on top surfaces. The endurance properties a 150º and 200ºC reveals severe performance decay after 150 h operation in presence of 5% H2O
3) **Reinfonced Polymeric Ionic Liquid Membranes on Porous PBI supports** (also being considered for intellectual protection). A continuous stepwise loss in performance is observed during the first 500 h at 200ºC, but thereafter conductivity values remain constant at around 275 mS/cm.

The manufacture requirements have been present throughout the project as a criterion to guide the research and development to obtain a PEM able to be mass manufactured in market competitive conditions. The preliminary industrial evaluation of the basic materials proposed in the project (i.e. PBI, protic ionic liquids and zeolites/zeotypes) reveals that neither raw material and energy costs, not chemicals availability are limiting factors for the commercialization of membranes significantly cheaper than the commercially available membranes for HT applications. Furthermore, the principles of Green Chemistry have been followed to synthesize selected ionic liquids in good agreement with the requirements for a safe and efficient large scale production. Finally, our assessment of intellectual property on the basic materials used indicates that they shouldn't be an obstacle for a potential implementation at industrial level.

CEGASA INTERNACIONAL, leader of work-packages related to industrial manufacturing and exploitation issues, has contributed with knowledge and experience in the field of manufacturing electrodes for PEM fuel cells and lithium ion batteries to establish how the manufacturing process of the new membranes could be performed in a pilot line. The general procedure for membrane manufacturing by casting is illustrated in Figure 57. As an example, Figure 58 shows an updated version of standard pilot line for PEM electrodes suitable for the manufacturing of hybrid porous PBI membranes. Before the coating unit, a mixing unit is required for the preparation of a homogeneous casting solution. The main issue in this process is the reproducibility of the rheological characteristics of the solution in each batch of mixing. At the end of the mixing process, a homogeneous membrane solution will be available. Once the mixing is done, the membrane solution goes to an intermediate vessel from where it will be pumped to the slot die. The second step is the casting of membranes onto an inert material (i.e. Teflon substrate). Once the membrane solution is cast onto the substrate, a conditioning procedure must be applied. A thermal cycle in the oven (I) will be used to eliminate the solvent. The next step is porogen leaching from the casted membrane by Immersion Bath (I) + Oven (II). The membrane manufacturing method also includes coating an electrolyte in the carrier film by Immersion Bath II (Phosphoric acid solution) and final Oven (III) (Evaporation of free water). The last step in the membrane manufacturing consists on the membrane lamination by winding device.

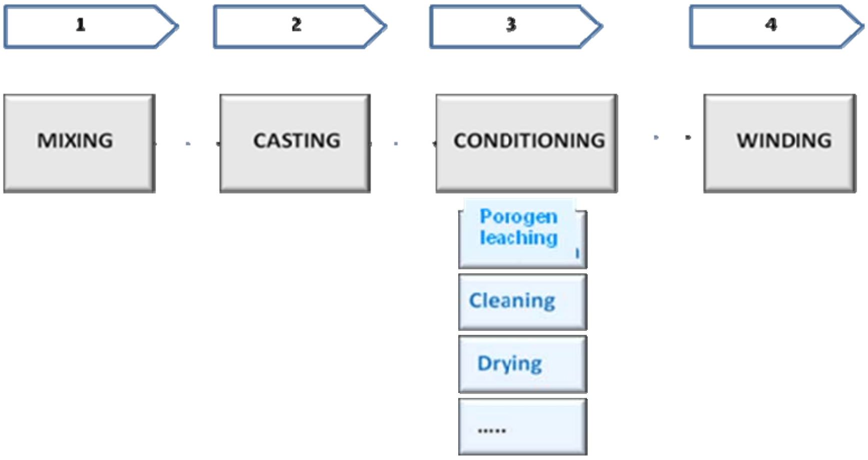


Figure 57. General Procedure for electrolyte membrane manufacturing by casting/coating method.

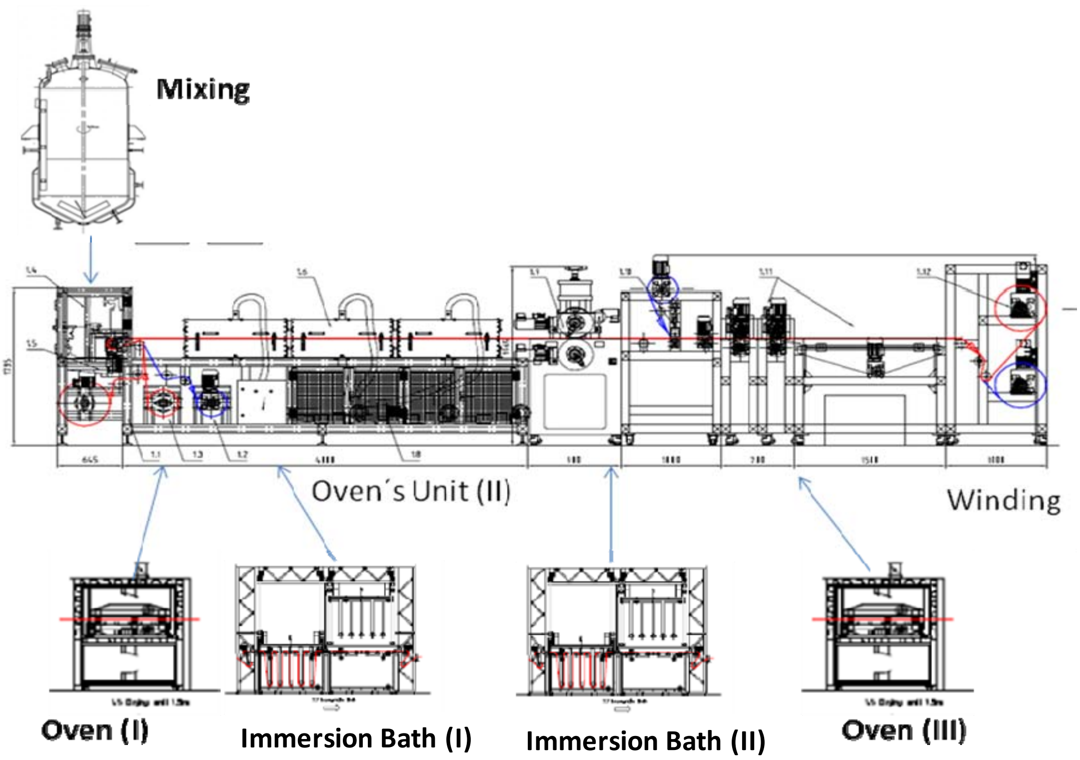


Figure 58. Pilot line for hybrid porous PBI membrane manufacturing.

Furthermore, the cost analyses of the aforementioned membranes have been carried out considering two main aspects: materials cost and manufacturing cost. Table 7, Table 8 and

Table 9 show the calculated materials cost for manual production of the finally Zeocell membranes selected for exploitation studies. It is estimated that the materials cost, especially the PBI ionomer cost would drop by roughly 90% when production scales up from laboratory to industrial production. This estimation is applied in the calculation of both membranes cost from 1 m^2 of membrane surface to 2.000.000 m^2. Moreover, price evaluation for ionic liquids has been reconsidered using continuous process as a function of annual production rate (see Table 10). On the other hand, there is a reduction in losses associated with the manufacturing process which directly affect the membrane material cost. In the case of porous hybrid PBI membranes, and considering the membrane fabrication process, the simplified membrane cost analysis assumption is shown in Table 11 for three different production rates.

Table 7. Calculated materials cost for manual production of hybrid porous PBI membranes (100 microns in thickness).

Component	1 m^2
PBI	167.5
DMAc (solvent)	16
POROGEN (75%)	40
METHANOL	1
Phosphoric acid	0.5
ZEOLITE	0,02
TOTAL	**225.1** €/m^2

Table 8. Calculated materials cost for manual production of nanostructured electrolyte membranes (75% in porosity and 100 microns in thickness).

Component	1 m^2
PBI	167.5
DMAc (solvent)	16
POROGEN (75%)	40
METHANOL	1
Phosphoric acid	0.2
Protic ionic liquid Im0008b	2.12
ZEOLITE	0,2
TOTAL	**227** €/m^2

Table 9. Calculated materials cost for manual production of reinforced polymer ionic liquid membranes on porous PBI (75% in porosity and 100 microns in thickness).

Component	1 m^2
PBI	134
NMP (solvent)	12
Additives (PEG)	0.2
Monomeric Ionic liquid (ImSF0108b)	13.5
TOTAL	**159.7** €/m^2

Table 10. Production cost of 1-H-3-methylimidazolium bis(trifluoromethanesulfonyl)imide (Im0008b) using two different processes (batch or continuous production) and as a function of annual rate.

Volume of production of Im0008 (T/year)	0,1	0,1	1	1	100	100
Type of process	batch reactor of 100kg	continuous production	batch reactor of 100kg	continuous production	batch reactor of 7500kg	continuous production
Equipment Cost: Reactor (k€)	100,00	25,00	100,00	25,00	700,00	75,00
Equipment cost: Dryer (k€)	15,00	75,00	15,00	75,00	200,00	150,00
Damping of equipment over 5 years (k€)	23,00	20,00	23,00	20,00	180,00	45,00
Equipment cost €/kg/year	230,00	200,00	23,00	20,00	1,80	0,45
Manpower cost (€/kg)	6,00	6,00	12,00	0,80	4,00	0,10
Raw materials cost (€/kg)	430,00	430,00	310,00	310,00	90,00	90,00
Total cost (€/kg)	**666,00**	**636,00**	**345,00**	**330,80**	**95,80**	**90,55**

Table 11. Simplified membrane cost analysis assumption for large scale manufacturing of hybrid porous PBI membranes.

Membrane Prod. (m2/year)	**10.000 m2**	**500.000 m2**	**2.000.000 m2**
Capital amortization			
Capital cost (€)	962000	5.000.000	10.000.000
Machine lifetime (years)	10	10	10
Capital Recovery factor (%)	10	10	10
Labor costs			
Labor staff	3	15	30
Labor rate (€/MM)	6000	6000	6000
Machine cost			
Maintainance (%)	2	2	2
Total Power consumtion (kW)	97	200	250
Electrical utility cost (€/Kwh)	0.08	0.08	0.08
Membrane production parameters			
Speed (m/min)	0.5	15	35
Coating width (m)	0.25	0.5	0.5
Net production (m2/year)	10.000	500.000	2.000.000
Work hours per year	1300	1300	1300
Work hours per day	5	5	5
Effective Pilot Plan Utilization (%)	35	70	80
Annual cost Summation			
Labor cost (€/year)	180000	900000	1800000
Capital recovery cost (€/year)	96209	500000	1000000
Maintenance (€)	19240	100000	200000
Utility cost (€)	11000	20800	26000)
Manufacturing cost (Pre-Markup) (€/m2)	92	3.6	2.74
Manufacturing Cost Markup (%)	100	100	50
Total manufacturing (€/m2)	**184**	**7.2**	**4.1**

Total Cost estimations for the Zeocell membranes are comparatively shown in Figure 59 as a function of annual production rate. Dense PBI membranes and the study from Direct Technology Inc are also depicted for a proper market value assessment. The results of this cost assessment clearly indicate that the membranes developed in the ZEOCELL project would be competitive in the high temperature PEMFC stationary applications market. Due to the favourable cost evaluation, the analysis for a 2 kW PEMFC stack manufacturing based on MEAs prepared by CCS method from hybrid porous PBI membranes doped with phosphoric acid has been carried out (see Table 12) and compared with state of the art PBI membranes and DOE-EU targets from 1000 to 500000 stack units/year (see Table 13). A power of 2 kW for the stack has been considered as particularly attractive for micro-scale residential applications, such as ‘‘single-family’’ households, for which the average net electric power requirement is, generally well below 5kW.

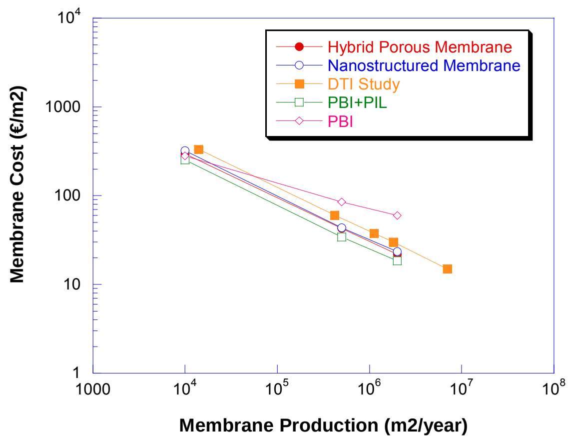


Figure 59. Membrane cost (materials+ manufacturing) for Zeocell membranes in comparison with the Direct Technology Inc. Estimations (DTI Study).

Table 12. Total system cost (in €/kW) for Zeocell Hybrid Porous PBI based HT-PEMFC stacks.

Annual Production rate	1 (Manual)	1000	80000	130000	500000
Stack Power (kW)	2	2	2	2	2
Membranes	300	237	120	92	34
Catalyst	2900	410	232	188	145
GDLs	350	274	64	57	28
MEA	3550	921	416	337	207
STACK	3510	410	132	117	86
Total stack cost (€)	7060	1331	548	454	293
Total stack cost (€/kW)	**3530**	**665**	**274**	**227**	**146**
BOP	2765	495	215	195	160
Total system cost (€)	9825	1826	763	649	453
Total system cost (€/kW)	**4912**	**913**	**381**	**324**	**226**

Table 13. Comparison of estimated costs for 2 kW high temperature PEMFC stack.

Stack units/year	1000	80000	130000	500000
Dense PBI membranes	**1026** €/kW	**397** €/kW	**343** €/kW	**240** €/kW
ZEOCELL Hybrid Porous PBI membranes	**913** €/kW	**381** €/kW	**324** €/kW	**226** €/kW
DoE 2010 target	**1500 $/kW (demonstrated for Plug Power[5] PBI based stacks from Celanese membranes in 2007)**			
2020 EU target	500 €/kW			

In general, the manufacturing process of fuel cell components is still in the development stage and fits into the category of low volumes of high quality production with high production costs. For this, there are several approaches to manufacturing processes, depending on the solutions adopted by each manufacturer, without a generally applicable standardized process. The mass manufacturing scale associated to an automated process reduces the price of 1kW stack (manually assembled) by 95% approximately. In particular, a cost reduction of 4.1 to 1 with manufacturing rates (i.e. from 1000 to 500.000 units) has been estimated. Considering the automated versus manual processing, the manufacturing time is reduced by approximately a 60%. According to our estimations based on the components cost and the automated manufacturing process on 500.0000 units/year basis; the high temperature stack cost (214 €/kW) based on Zeocell Hybrid Porous PBI membranes would fulfil the European and USA targets, provided that the durability requirements (which are still under investigation) can be met.

The project exploitation plan has provided business analysis of those stacks in the two following markets: i) Micro-Combined Heat and Power Systems and ii) Backup/supplemental power for Telecom Applications. The analysis is based on HT PEMFCs penetration in the market of 10% for micro-CHP and 20% in the case of backups (see Table 14). For a hypothetical scenario in which Zeocell membranes would achieve a 20% and 30% share of the market for CHP's units and back-up systems respectively, the surface requirements (see Table 15) and the foreseen benefits (see Table 16) are quite encouraging. Annual benefits from 9 M€ to 64 M€ for 2015 and 2025 have been estimated.

Table 14. Estimation of total units sold globally for each of the applications.

Application	Units (2015)	Units (2020)	Units (2025)
Micro-CHP	3,600,000	7,200,000	24,000,000
Back-up Telecom	215,000	350,000	500,000

Table 15. Estimations of membrane worldwide sales for the selected applications.

	2015	2020	2025
Micro-CHP (5Kw)			
HT-PEMFC units (accumulated)	360,000	720,000	2,400,000
Units with ZEOCELL membranes	72,000	144,000	480,000
Total Power of HTPEMFC units (KW)	360,000	720,000	2,400,000
Membrane needed (m2)	***144,000***	***288,000***	***960,000***
Back-up Telecom (5Kw)			
HT-PEMFC units	43,000	70,000	100,000
Units with ZEOCELL membranes	12,900	21,000	30,000
Total Power of HTPEMFC units	12,900	21,000	30.000
Membrane needed (m^2)	***25,800***	***42,000***	***60.000***
Total membrane surface (m^2)	***169,800***	***330,000***	***1.020.000***

Table 16. Economic Analyses of Zeocell Membrane Business for the selected applications.

Year	2015	2020	2025
m^2 MEMBRANE			
Membrane (m^2)	***169,800***	***330,000***	***1,020,000***
COSTS			
€/m^2	75	50	30
Other costs (indirect,R+D,(15%)	11	8	5
Benefits (%)	60	50	37
INVESTMENT			
Investment	2,000,000	8,000,000	16,000,000
AMORTIZATION			
Amortization (10 years)	200,000	1,000,000	2,400,000
amortization/m^2	***1***	***3***	***2***
TOTAL COSTS			
Cost/m^2 (€)	***87***	***61***	***37***
Total cost *(€)*	14,845,250	19,975,000	37,590,000
SALES			
Cost/m^2 (€)	***145***	***120***	***100***
Total incomes*(€)*	24,612,000	39,600,000	102,000,000
RESULTS			
Annual result *(€)*	**9,775,750**	**19,625,000**	**64,410,000**

- **OTHER EXPLOITABLE RESULTS**

Apart from the power generation sector, exploitable foregrounds and potential new applications in different fields for the individual and composite materials and membranes studied in the project have been also identified. Thus, from the properties found for ZEOCELL materials, the potential markets and new research lines not directly related to FC technologies are the following:

- ☑ Applications of porous and Dense PBI membranes in the field of gas separations at high temperature and pressure conditions (H2 Separation/ CO2 Precombustion Capture; Natural gas sweetening)
- ☑ Porous PBI membranes for Liquid Phase Separations (Solvent stable nanofiltration)
- ☑ Straight Porous PBI Membranes prepared by Ion-Track Technology as Separators for Lithium Ion Batteries & Inert Containers for Proton Conductors
- ☑ Micropatterned PBI films by Microtransfer Moulding Techniques for micro Fuel Cells and Smart Microsystems (reaction, separation and detection purposes)
- ☑ Ionic Liquids as Ion Conductors for PEMFC and Energy Storage Applications
- ☑ Ionic Liquids as Solvents/Carriers in Supported Liquid Membranes for Gas and Liquid Separations
- ☑ Monomeric and Polymeric Ionic Liquids: Development of Polymer Ionic Liquid Based Membranes for Fuel Cells and Energy Storage
- ☑ Polymer Ionic Liquid Based Membranes for Gas Separation Applications
- ☑ Functionalized Microporous Materials for Adsorption and Catalytic Applications
- ☑ Development of Flexible SU8 and PBI microstructures with advanced functionalities for micro Fuel Cells and Lab on Chip Applications

- **DIFFUSION OF PROJECT RESULTS, DISSEMINATION AND IMPACT (SOCIETAL, SOCIO-ECONOMIC, ETC.)**

The diffusion of project results started with ZEOCELL web site (http://ina.unizar.es/zeocell/), which has been continuously updated with relevant information related to any action of dissemination carried out by any of the partners: attendance to conferences, participation in exhibition fairs, presentations made in some of these events, internal events where ZEOCELL have been presented, meeting communications (abstracts, proceedings, papers). Moreover, some publications directly related to the work within ZEOCELL have been / are being obtained and have been / are being published the main scientific journals of the field. Additional dissemination of the consortium activities is granted due to the fact that some of partners are members of important networks in the field of fuel cells and hydrogen.

All Partners have contributed, along the project, to maximising the potential impact of the knowledge (see Figure 60) both in terms of the dissemination of results of academic interest to scientific community (nanomaterials, polymer membranes, ionic liquids, microporous materials, and PEMFCs) and of exploitable to potential end-users (materials provider and PEMFC manufacturers). The most outstanding dissemination activities carried out are cited below.

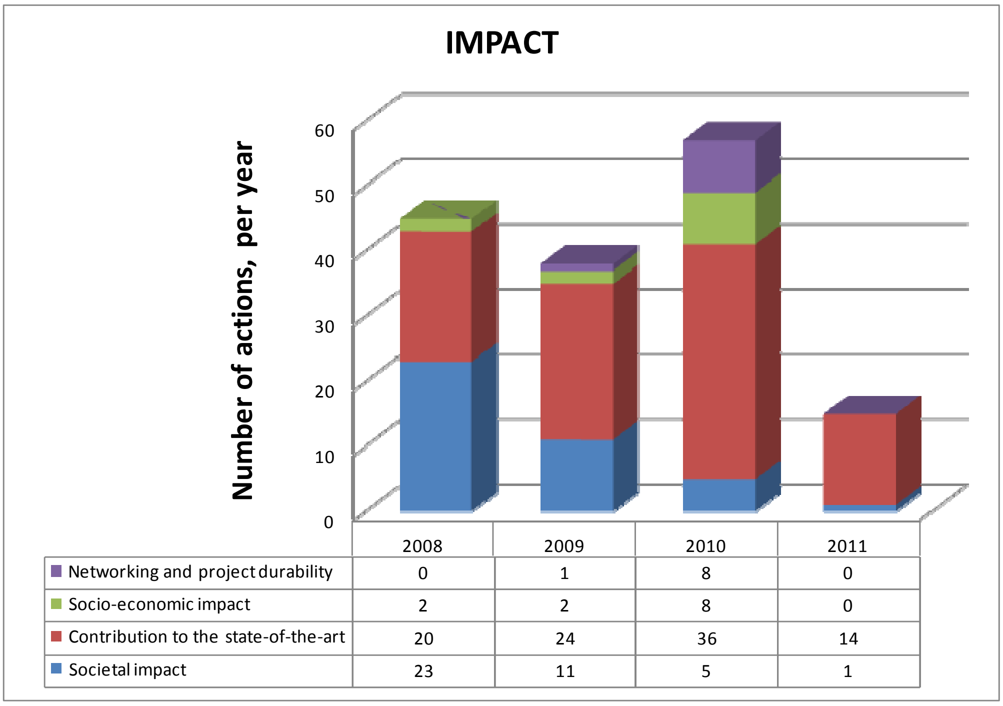


Figure 60. Impact of the different activities carried out along the project.

➢ **SCIENTIFIC PUBLICATIONS**

SCIENTIFIC PAPER. Title: "Novel hybrid membranes based on polybenzimidazole and ETS-10 titanosilicate type material for High Temperature PEMFCs: a comprehensive study on dense and porous systems".
Order of Authors: María Pilar Pina Iritia, Ph.D.; Adela Eguizábal, Engineer; Javier Lemus Godoy, Engineer; Miguel Urbiztondo Castro, Ph.D.; Oihane Garrido; Jaime Soler Herrero, Ph.D.; Alberto Blázquez, Ph.D.
Publisher: Elsevier.
Submitted to Journal Power Sources Special Issue FUCE 2010.
http://dx.doi.org/10.1016/j.jpowsour.2011.03.006

SCIENTIFIC PAPER. Title: "Preparation and ion transport properties of NaY zeolite–ionic liquid composites". SESAM.
Authors: S. Ntais (a), A.M.Moschovi (b), F.Paloukis (a), S.Neophytides (a), V.N.Burganos (a), V. Dracopoulos (a), V.Nikolakis (a, *).
Main Author: V. Nikolakis.
Title of the periodical or the series: Journal of Power Sources.
Publisher: Elsevier.
DOI: 10.1016/j.jpowsour.2010.09.061.

SCIENTIFIC PAPER. Title: "Zeolite films and membranes. Emerging applications". SESAM.
Authors: M. P. Pina, R. Mallada, M. Arruebo, M. Urbiztondo, N. Navascués, Ó. de la Iglesia and J. Santamaría.
Publisher: Elsevier Science BV.
Microporous and Mesoporous Materials. Impact factor: 2.652.
DOI: doi:10.1016/j.micromeso.2010.12.003.

SCIENTIFIC PAPER. Title: "Ammonium based ionic liquids immobilized in large pore zeolites: encapsulation procedures and proton conduction performance". SESAM.
Article type: Special Issue - CONAPPICE 2010. Congreso Nacional de Pilas de Combustible (Seville, Spain). 16th to 18th of June, 2010).
Title of the periodical or the series: Journal of Power Sources. Impact: 3.792.
Publisher: Elsevier.
First Author: Adela Eguizábal Alguacil, Engineer.
Order of Authors: Adela Eguizábal Alguacil, Engineer; Javier Lemus Godoy, Engineer; Anastasia M. Moschovi, Engineer; Spyridon Ntais, Ph.D.; Vladimiros Nikolakis, Ph.D.; Jaime Soler Herrero, Ph.D.; María Pilar Pina Iritia, Ph.D.
Submitted to Journal Power Sources Special Issue CONAPPICE 2010.
Journal of Power Sources. Volume 196, Issue 9, 1 May 2011, Pages 4314-4323.
DOI 10.1016/j.jpowsour.2010.12.019.

SCIENTIFIC PAPER. Title: "Ionic liquid/zeolite composites: Synthesis and characterization using vibrational spectroscopy techniques". SESAM.
ECS Transactions, 33 (7) 41-47 (2010).
The Electrochemical Society.
Authors: S. Ntais, A. M. Moschovi, V. Dracopoulos, and V. Nikolakis.
Main Author: V. Nikolakis.
Title of the periodical or the series: ECS Transactions.
DOI: http://dx.doi.org/10.1149/1.3484760.
Publisher: The Electrochemical Society.

➢ **PUBLICITY ACTIONS**

- February 2011. Mr Jonathan Smith informed us that Cordis has selected our technology for special promotion it their Technology Marketplace. Title: "Nano-structured membrane for boosts fuel cell technology" (12/02/2011). He informed us also about the possibility of being selected for publication in the colour magazine "research*eu results supplement".
- March 2009. The prestigious researcher Prof. Chintamani Nagesa Ramachandra Rao came to the University of Zaragoza (24/03/2009) and visited the Institute of Nanoscience. This visit was followed in local media outlets. This piece of news (in Spanish) was published in the web site Aragón Investiga (30/03/2009): "El grafeno: nuevo material imprescindible en la electrónica del futuro". The last paragraph is referred to ZEOCELL.
- March 2009. A piece of news related to our project, published in the Spanish newspaper El Periódico (05/03/2009): "Pilas de hidrógeno, menos CO2".
- February 2009. There were some pieces of news in the local and regional press, thanks to the Department of Communication and Image, University of Zaragoza:
    - ADN (23/02/2009): "Investigadores buscan reducir la emisión de CO2 un 20% con pilas de hidrógeno".
    - Aragón Digital (23/02/2009): "La Universidad de Zaragoza diseña un dispositivo para reducir en un 20% la emisión de CO2 a la atmósfera".
    - Europa Press (23/02/2009): "La Universidad de Zaragoza diseña un dispositivo para reducir en un 20% la emisión de CO2 a la atmósfera".
    - 20 Minutos (24/02/2009): "Impulsan estudios para reducir el CO2".
- October 2008. There was a dissemination action in the Trade Fair of Zaragoza next week (07 -13/10/2008). A PhD student of the INA, Ismael Pellejero, was present in-situ to provide information about ZEOCELL (Science Pavilion 2008).
- October 2008. Dissemination of a job offer (post-doc position) through different web pages, e-mail lists, etc.

- July 2008. Review in the web site Euskadi+innova: "CIDETEC y CEGASA participan en un proyecto europeo para elaborar pilas con polímeros" (24/07/2008).
- May 2008. Review in the web page of IST World (Information Society Technologies): "Nanostructured electrolyte membranes based on polymer-ionic liquids-zeolite composites for high temperature pem fuel cell (ZEOCELL)".
- April 2008. Information about ZEOCELL in the bulletin No 19 of CIDETEC: "Lanzamiento del proyecto europeo ZEOCELL, "Nanostructured electrolyte membranes based on polymer / ionic liquids /zeolite composites for high temperature PEMFC fuel cells"".
- April 2008. Brochures handed to some members of the enterprise Solutex, the Supercritical Fluid Technology Company, who visited the INA.
- April 2008. Review in the web page Aragonéame: "El Instituto de Nanociencia de Aragón coordinará el proyecto europeo ZEOCELL" (08/04/2008).
- April 2008. Review in the web page Fuel Cell Today: "INA coordinates ZEOCELL project" (02/04/2008).
- April 2008. Massive e-mails (general information about the project and the web page - press summary in Spanish) sent to some e-mail lists of the University of Zaragoza. http://webmail.unizar.es/mailman/listinfo.
- April 2008. Review in the web page Cordis (project's data).
- March 2008. Brochures were handed to evaluators (Aragonese Government) of the Institute of Nanoscience of Aragon.
- March 2008. Available web page: http://ina.unizar.es/zeocell.
- February and March 2008. Design of our web page.
- February 2008. A piece of news about ZEOCELL (the English version of our press summary) was published in the web site of the Plataforma Tecnológica Española del Hidrógeno y las Pilas de Combustible (PTE-HPC), Spanish Hydrogen and Fuel Cells Technology Platform: "El INA coordina el proyecto ZEOCELL".
- Information about ZEOCELL provided by Hugues van Honacker and Patrice Millet, from the European Commission, the Directorate General for Research. See the presentation: "FP7 projects: European research opportunities on fuel cells & hydrogen (current activities, EU calls and future prospects)". Year 2007.

Two additional tools that have been used frequently along the project when partners attended conferences, workshops, etc.: poster were in the form of (to be displayed) and brochures (to be handed).

➢ ATTENDANCE TO SCIENTIFIC CONFERENCES

- July 2011. Adela Eguizábal and Javier Lemus will attend the Network Young Membraines, within the International Congress on Membranes and Membrane Processes, ICOM (Amsterdam, 23 - 29/07/2011). Accepted as oral presentations: "Preparation of 3-layer integrated MEA from in-situ catalytically activated nanostructured electrolyte membranes" (Adela) and "Crosslinking polymer ionic liquids based on protic imidazolium salts by ultraviolet radiation-induced polymerization for fuel cell applications".
- July 2011. UTWENTE is organising the International Congress on Membranes and Membrane Processes, ICOM (Amsterdam, 23 - 29/07/2011). INA and FORTH-ICE/HT Teams will attend this conference. Accepted as oral presentations: "Preparation and characterization of ionic liquid doped polybenzimidazole (PBI) membranes for high temperature PEMFC applications" (UTWENTE), "Nanostructured electrolyte membranes based on microporous materials, protic ionic liquids and porous PBI films for HT PEMFCs" (INA), "Conduction in fuel cell membranes impregnated with ionic liquids and zeolite crystals" (FORTH/ICE-HT). ICOM 2011 is organized by the Membrane Technology Group of the University of Twente, Enschede, The Netherlands (http://www.utwente.nl/tnw/mtg/).

The conference is chaired by Dr. Kitty Nijmeijer, Dr. Antoine Kemperman and Prof. Matthias Wessling.

- June 2011. INA Team will attend the III Iberian Symposium on Hydrogen, Fuel Cells and Advanced Batteries, HYCELTEC 2011 (Zaragoza, 27 - 30/06/2011). Accepted as oral presentation: "Nanostructured electrolyte membranes based on zeotypes, protic ionic liquids and porous PBI membranes: preparation, characterization and MEA testing".
- November 2010. INA Team attended the 4ª Jornada de Jóvenes Investigadores (Química y Física) de Aragón (Zaragoza, 18/11/2010). 2 poster presentations:
  - "Estudio de la influencia de la funcionalización de la superficie inorgánica para la mejora de la interfase polímero-zeolita en membranas para PEMFC"
  - "Desarrollo de membranas híbridas para su uso en PEMFCs: Comparación entre sistemas densos y porosos".
- November 2010. FORTH/ICE-HT Team attended the AIChE Annual Meeting (Salt Lake City, 07 - 12/11/2010), where they made a presentation based on this paper: "Preparation and ion transport properties of NaY zeolite–ionic liquid composites". The title of the oral presentation made was: "Zeolite - protic ionic liquid composites: Preparation, characterization and evaluation of ion conduction properties".
- October 2010. Spyros Ntais (FORTH/ICE-HT) attended the 218th ECS Meeting (Las Vegas, 10 - 15/10/2010). Scientific paper: "Ionic liquid/zeolite composites: Synthesis and characterization using vibrational spectroscopy techniques", he made a presentation.
- October 2010. Pilar Pina (INA) attended the Fuel Cells Science & Technology 2010, FUCE 2010 (Zaragoza, 06 - 07/10/2010). She made an oral presentation: "Development of new conducting membranes based on microporous materials/PBI composites for high temperature PEMFCs".
- July 2010. Jesús Santamaría and Miguel Urbiztondo attended the 16th International Zeolite Conference & the 7th International Mesostructured Materials Symposium (IZC-IMMS 2010) (Sorrento, Italy, 04 - 09/07/2010). Programme. Jesús was invited to give a keynote lecture: "Membranes and films based on zeolites". Related to this lecture, scientific paper published: "Zeolites films and membranes. Emerging applications".
- June - July 2010. Stay of Javier Lemus (INA) at the University of Twente (Membrane Technology Group). 01/06 - 15/07/2010. "Report on results of stay at Twente University", uploaded to SESAM as Deliverable Report (not foreseen in the Annex I).
- June 2010. Mauro Sgroi made an oral presentation during the Italian Nanoforum (Politecnico di Torino, Turin, 17/06/2010): "Stoccaggio di energia a bordo veicolo: applicazioni della nanotecnologia".
- June 2010. INA, CIDETEC and CEGASA Teams attended the IV Congreso Nacional de Pilas de Combustible, IV National Congress on Fuel Cells, CONAPPICE 2010 (Seville, 16 - 18/06/2010). 4 oral presentations and 1 scientific paper were published in the Book of Abstracts:
  - "Comportamiento de las membranas híbridas Nafion/sepiolita en aplicaciones PEMFC".
  - "Optimización de procesos de inmovilización de líquidos iónicos en zeolitas para su uso en membranas para pilas PEM de alta temperatura".
  - "Efectos del ciclado térmico sobre las prestaciones de las pilas PEM".
  - "Oxidación de metanol sobre catalizadores de PdPt en una pila de combustible de metanol".
  - "Ammonium based ionic liquids immobilized in large pore zeolites: encapsulation procedures and proton conduction performance".
- June 2010. Sébastien Fantini (SOLVIONIC) attended the Ionic Liquids for Electrochemical Devices, ILED-2 (Rome, 09 - 11/06/2010). He made an oral presentation: "Ionic liquids for electrochemical applications".

- June 2010. Mauro Sgroi (CRF) made an oral presentation during a PhD school at the University of Turin: "Prima Scuola Residente della SAT Pracatinat (To)", 02/06/2010, "Energia e sostenibilità: scienza e tecnologia per il pianeta". Title: "Fuel cells e batterie per applicazioni automotive. Stato attuale e prospettive future".
- May 2010. Miguel Urbiztondo (INA) used the CNM facilities through the 7th call (GICSERV) at Barcelone (05/05/2010). Discussion during this meeting: the fabrication processes of the straight-pore PBI membranes by micro-moulding techniques to reach a new membrane approach where ionic liquid could be load in pores.
- May 2010. Vladimiros Nikolakis and Vasilis Burganos (FORTH/ICE-HT) were part of the Organizing Committee of the 5th International Zeolite Membrane Meeting, IZMM 2010 (Loutraki, Greece, 23 - 26/05/2010). Vladimiros made a poster presentation: "Investigating the potential of using ionic liquid – zeolite composites in high temperature fuel cell membranes: A vibrational spectroscopy and electrochemical study". Miguel Urbiztondo and Ismael Pellejero (INA) attended this meeting as well. They made an oral presentation: "Zeolite films as catalytic coatings for micro-reactors with ultra-high surface/volumen ratio".
- April 2010. Distribution of bound documents related to ZEOCELL (months 12 to 24) among the partners.
- March 2010. Pilar travelled to Barcelone in order to prepare the SUDOE proposal: 'Microtechnologies for high added value PEMs: Cooperation to innovate in SUDOE' (MHAE) (project proposal related to ZEOCELL).
- March 2010. FORTH/ICE-HT Team attended the Conference on Molten Salts and Ionic Liquids, EUCHEM (Bamberg, Germany, 14 - 19/03/2010). V. Dracopoulos made a poster presentation: "A vibrational spectroscopic and electrochemical study of using ionic liquid - zeolite composites in high temperature fuel cell membranes"
- March 2010. FORTH/ICE-HT Team attended the 4th International Workshop on Dynamics in Confinement, CONFIT 2010 (Grenoble, France, 03 - 05/03/2010). They made a poster presentation: “Encapsulation of H-3-methylimidazolium bis(trifluoromethanesulfonyl)imide (HMITFSI), in zeolite NaY : A vibrational spectroscopy and electrochemical study”.
- March 2010. Workshop “Electrochemistry and ionic liquids” (Paris, 25/03/2010). The concept, the objectives and the technical target of ZEOCELL, as well as some advances, were explained by SOLVIONIC: "Nanostructured electrolyte membranes based on polymers / ionic liquids / zeolites for high temperature proton exchange membrane fuel cells".
- December 2009. European Research Institute on Lithium Batteries, ALISTORE (Toulouse, 11/12/2009), biannual meeting (European project, 6FP). Again, ZEOCELL was briefly introduced during a presentation of SOLVIONIC activities: "Ionic liquid based zeolites" (1 slide).
- November 2009. Jesús Santamaría and Miguel Urbiztondo (INA) attended the Encuentro Anual de la Iber-Red en Nanotecnología y Microsistemas (IBERNAM 2009) (Seville, Spain, 26 - 27/11/2009). Miguel made an oral presentation: "Nanostructured zeolite films development: from traditional to technological applications". Proceedings.
- November 2009. Workshop CIC Energigune: “New Perspectives for Advanced Batteries and Supercaps” (Vitoria, Spain, 10/11/2009). ZEOCELL project was briefly introduced during the presentation of SOLVIONIC activities: "Electrochemical energy storage" (1 slide).
- October 2009. FORTH/ICE-HT Team attended the 4th Panhellenic Symposium on Porous Materials (Patras, 22 – 23/10/2009). P. Krokidas, E. D. Skouras, V. Nikolakis and V.N. Burganos made a poster presentation: “Molecular reconstruction of ionic liquids and prediction of sorption and diffusion in zeolites”. A.M. Moschovi, S. Ntais, V. Dracopoulos

V. Nikolakis made the poster presentation: "Investigation of Ionic Liquid encapsulation in zeolites using vibrational spectroscopy".

- October 2009. Alberto Blázquez (CIDETEC) and Jaime Soler (INA) attended the "final event" of AUTOBRANE project (http://www.autobrane.eu/pages/index.php) in Stuttgart, 20 - 21/12/2009). They were invited by the organisers of the meeting (Daimler AG). Jaime and Alberto contacted the Coordinators (Dr Deborah Jones, CNRS, Montpellier) and other partners (Johnson Mattey, FumaTech). The project Coordinator was delighted to share her experiences with them; even she is willing to attend some of our meetings (ZEOCELL) and let us know the main conclusions of AUTOBRANE project.
- September 2009. INA was in its own stand so as to disseminate ZEOCELL and the Institute of Nanoscience of Aragon in the Exhibition Centre of Zaragoza. It is the International Hydrogen and Fuel Cell Show (Zaragoza, 22 - 24/09/2009). You can see a photograph of our little stand. Pilar spoke about ZEOCELL with an oral presentation: "Proyecto ZEOCELL". Ciclo de Conferencias de la AeH2: "Proyectos de Hidrógeno y Pilas de Combustible de España" (PowerExpo).
- September 2009. Javier Lemus and Adela Eguizábal (INA), attended the 11th Grove Fuel Cell Symposium (London, 22th - 24th September 2009). They made two poster presentations: "Proton conduction properties of immobilized ionic liquids in BEA type zeolites" and "Preparation of doped PBI-zeolite membranes for high temperature PEMFC's". Mauro Sgroi (CRF) attended this symposium as well and made a poster presentation. This was the poster he presented, related to ZEOCELL: "Ordered 2D nano-porous polymeric matrices for nano-structured membranes based on polymers, zeolites and ionic liquids".
- September 2009. Erik van de Ven (UTWENTE) attended Euromembrane 2009 (Montpellier, 06 - 10/09/2009). He made an oral presentation speaking about ZEOCELL: "Preparation and characterization of composite membranes using blends of SPEEK/PBI for high temperature PEMFC applications".
- September 2009. Spyros Ntais, A.M. Moschovi, V. Dracopoulos and Vladimiros Nikolakis (FORTH/ICE-HT) attended the 3rd International Symposium on Advanced micro- and mesoporous materials (06 – 09/09/2009, Varna, Bulgaria). They made a poster presentation: "Encapsulation of low temperature ionic liquids in zeolites: A vibrational spectroscopy study".
- June 2009. Distribution of bound documents related to ZEOCELL (months 1 to 17) among the partners. This is the pdf file.
- June 2009. Erik van de Ven (UTWENTE) made an internal presentation of ZEOCELL at his University. 05/06/2009.
- June 2009. The Technology Centre of the Academy of Sciences of the Czech Republic organised EuroNanoForum 2009, with the support of the European Commission and under the auspices of the Ministry of Education, Youth and Sports of the Czech Republic, to be held in Prague, Czech Republic, on 2-5 June 2009, as an official event of the Czech Presidency of the Council of the European Union. The extensive conference programme targeted on Nanotechnology for Sustainable Economy, follows on the successful past EuroNanoForums 2003, 2005 and 2007 held in Trieste, Edinburgh and Düsseldorf. After the recommendation from the European Commission, the Technology Centre AS CR invited Pilar Pina to give an oral presentation at the EuroNanoForum 2009 (Prague, 02 - 05/06/2009), in the Parallel Session A3: 2.2 Nanotechnology for energy –Nanotechnology for H2 Production & Storage; Fuel cells on June 3rd starting at 9:00am. She made an oral presentation: **"**An innovative membrane for PEMFCs: ZEOCELL project". Carlos Saraiva, our Officer, and Vito Lambertini (CRF-Fiat) attended the meeting as well.
- April 2009. Jaime Soler (INA) attended the Jornada de Difusión de la PTE HPC (Puertollano, Spain, 02/04/2009).

- February 2009. Juan I. Gallego (INA) presented our project (current situation, delivery of reports, general problems arisen, anecdotes, etc.) to other University of Zaragoza's Project Managers. Presentation of Juan I. Gallego.
- February 2009. AAAS Annual Meeting (Chicago, 12 - 16/02/2009). Carlos Saraiva (Officer) and Pilar Pina (INA) gave lectures on the 13th of February. Oral presentation of Pilar Pina: "An innovative membrane for polymer electrolyte membrane fuel cell".
- February 2009. Mauro Sgroi (CRF) presented ZEOCELL during the workshop of the project: Marie-Curie Network NANOMATCH - Supramolecular Nanostructured Organic/Inorganic Hybrid Systems (Turin, 12 - 13/02/2009). Title of the presentation: "Nanomaterials for fuel cells".
- December 2008. INA Team attended the 3ª Jornada de Jóvenes Investigadores (Química y Física) de Aragón. Zaragoza, 10/12/2008. 3 poster presentations:
  - "Incorporación de zeolitas a membranas PBI dopado con ácido fosfórico para su uso en pilas de combustible"
  - "Inmovilización de líquidos iónicos en zeolitas para membranas conductoras en pilas de combustible"
  - "Estudio de conductividad de zeolitas: efecto del cation de intercambio y Si/Al".
- December 2008. Mauro Sgroi (CRF) took part to the mid-term meeting of the European Training Network COSY (Barcelone, 10/12/2008), devoted to RHC materials for hydrogen storage. CRF is part of the industrial advisory board of the project, so he was invited to present an industrial viewpoint of the hydrogen storage technologies. The trends in PEMFC research are obviously correlated to hydrogen storage, so he presented to the students also a couple of slides regarding ZEOCELL project (one is the official poster). Title of the presentation: "On-board hydrogen storage: an industrial viewpoint".
- November - December 2008. Javier Lemus (INA) attended the Workshop about "Frontiers of nanocomposite materials" (Düsseldorf, 21/11 - 04/12/2008).
- October 2008. INA Team attended the 4ª Jornadas de Encuentro Hispano-Francés CMC2-IBERNAM en Micro y Nanotecnología (Toulouse, 16 - 17/10/2008). Pilar made an oral presentation: "Microsystems based on zeolites".
- October 2008. During the NMP information day at the Industrial and Business Regional Chamber of Midi-Pyrenees (Toulouse, 14/10/2008), ZEOCELL was briefly introduced during a presentation of SOLVIONIC and its experience in FP7 as an SME (1 slide).
- October 2008. A brief presentation of ZEOCELL was sent to Prof. Cantelli (University of Rome). He presented the project among the activities related to hydrogen and fuel cell during the Scientific Meeting of the Experts & Governments Representatives of Hydrogene Storage, organised by the International Energy Agency (IEA) (Rome, 07 - 10/10/2008).
- September 2008. Igor Cantero (CEGASA) presented our project in the 8th F-Cell Forum 2008 for Producers and Users (Stuttgart, 29 - 30/09/2008).
- September 2008. INA, CIDETEC and CEGASA Teams attended the III Congreso Nacional de Pilas de Combustible (National Congress on Fuel Cells, CONAPPICE 2008) (Zaragoza, 24 - 26/09/2008). Presentation of a poster. 7 oral presentations:
  - "Proyecto DEIMOS: Desarrollo e innovación en pilas de combustible de membrana polimérica y óxido sólido"
  - "Membranas híbridas polímero/zeolita a partir de PBI dopado con acido fosfórico"
  - "Desarrollo de stacks PEMFC CEGASA-CIDETEC"
  - "Minipilas de combustible hidrógeno/aire CEGASA-CIDETEC"
  - "Nuevas membranas nanoporosas de polibencimidazol para su uso como electrolitos sólidos en pilas de combustible PEMFC"
  - "Efecto simultáneo de varios contaminantes en las prestaciones de pilas de combustible PEMFC".

  - "Líquidos iónicos comerciales inmovilizados en zeolita como componentes de membranas de intercambio protónico para PEMFC".
- July 2008. Erik van de Ven (UTWENTE) attended a course on electro-impedance spectroscopy (EIS), used for the proton conductivity measurements. University of Bath, UK, Summer School, 15 - 18/07/2008.
- July 2008. Attendance of Javier Lemus (INA) to the I Iberian Symposium on Hydrogen, Fuel Cells and Advanced Batteries (HYCELTEC) (Bilbao, Spain, 01 - 04/07/2008). He handed some leaflets about ZEOCELL. Two poster presentations were made, and a scientific paper was published.
  - "Influencia del catión de intercambio y de la relación Si/Al en zeolitas como conductores protónicos para su uso en pilas PEMFC de alta temperatura". Poster presentation.
  - "Evaluation of the pyrochlore (H3O) SbTeO6 as a candidate for electolytic membranes in PEM Fuel Cells". Poster presentation and scientific paper with the same name (published in June 2009).
- June 2008. Participation of Mauro Sgroi (CRF) in a technical meeting of Autobrane project, devoted to development of new membranes for automotive PEMFC. He presented some slides about ZEOCELL, based on our poster information.
- March 2008. Pilar Pina (INA) gave some information about ZEOCELL in a her presentation and handed several leaflets when she attended to the Forum "Los Nuevos Retos de la Automoción", "The New Challenges of Automotion" (Zaragoza, 13/03/2008), http://www.forotecnologicoyempresarial.com), organised by:
  - Instituto de Investigación en Ingeniería de Aragón (I3A).
  - Instituto Tecnológico de Aragón (ITA).
  - Cátedra SAMCA (CPS-I3A).
  - Confederación de Empresarios de Aragón (CREA).

- **Address of project public website and relevant contact details**

http://ina.unizar.es/zeocell/

Contacts:

✓ Juan I. Gallego, Project Manager. Institute of Nanoscience of Aragon, University of Zaragoza. Phone: +34.976.10.00, ext. 5363. Fax: +34.976.27.76. E-mail: gallegoj@unizar.es.

✓ Pilar Pina, Main Researcher. Institute of Nanoscience of Aragon, University of Zaragoza. Phone: +34.976.11.55. Fax: +34.976.21.42. E-mail: mapina@unizar.es.

✓ Jesús Santamaría, Coordinator. Institute of Nanoscience of Aragon, University of Zaragoza. Phone: +34.976.11.53. Fax: +34.976.21.42. E-mail: jesus.santamaria@unizar.es.

INSTITUTO DE NANOCIENCIA DE ARAGÓN
Campus Río Ebro, Edificio I+D
Calle Mariano Esquillor, s/n
50018 Zaragoza, Spain.

- **Glossary**

  - APA: anodic porous alumina
  - CCM: catalyst coated membrane
  - CHP: combined heat and power
  - CL: cross linker
  - DBP: dibutylphthalate
  - DD: double deionized
  - DMAC: dimethylacetamide
  - FC: fuel cell
  - FCH JU: Fuel Cells and Hydrogen Joint Undertaking
  - HT: high temperature
  - MEA: membrane electrode assembly
  - NMP: n-methyl pyrrolidone
  - PBI: poly-benzimidazole
  - PEM: Proton Exchange Membrane
  - PEMFC: Proton Exchange Membrane Fuel Cell
  - PIL: polymeric ionic liquid
  - PVP: poly-vinylpyrrolidone
  - SP: stationary power
  - SPEI: sulfonated naphthalenic polyimides
  - ST: scientific and technical
  - TPP: triphenylphosphate

LIST OF FIGURE CAPTIONS:

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