	EUROPEAN COMMISSION RESEARCH AND INNOVATION DG	Final Report

Project No: 603885

Project Acronym: ELICiT

Project Full Name: Environmentally Low Impact Cooling Technology

Final Report

Period covered: from 01/01/2014 **to** 31/12/2016

Start Date of project: 01/01/2014

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This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under the Grant Agreement n°603885

1. *Executive Summary*

The aim of the project was to help efficient gas free magnetic cooling technology move from the laboratory scale towards being a high volume marketable product. Magnetic cooling technology exploits temperature changes of solid "magnetocaloric" refrigerants, in the presence of a changing with the eventual aim of replacing gas compressors with magnetic cooling engines.

A high volume marketable product results from the assembly of components, which comprise heat exchangers, pumps, magnetocaloric material components and permanent magnets, into systems, which include the magnetic cooling engine; each must be designed for manufacturability. During the project the design optimization of components and systems were driven both by the analysis of benchmarking validation activities and the results of a Life Cycle Assessment tools developed specifically for this project. The latter tools enable optimisation against both cost and environmental impact. The compliance of the technology to current Regulations and Standards was also considered and studied at the appliance level.

The cabinet of the final appliance prototype is an already high-volume product manufactured at one of the partners' plant. The project consortium includes components manufacturers and designers (Regen/T, S.C.I.R.E., TCS Micropumps Ltd., Camfridge Ltd.), system manufacturer and designer (Camfridge Ltd), domestic refrigerator manufacturer and designer (Whirlpool R&D), researchers active in Life Cycle Assessment (Polimi) and experts in refrigeration industry standards (Cemafroid, IIR). The project considered the magnetic cooling in its entirety and the project activities were organised along six Work Packages (WP):

WP1: System Optimization
WP2: Benchmark Validation
WP3: Life Cycle Optimization
WP4: Regulations and Standards
WP5: Dissemination
WP6: Management

Each WP is structured to support the overall project goal of moving magnetic cooling technology from laboratory scale to a high volume marketable product.

2. *Description of the project Context and Objectives in details*

2.1 Context

The domestic fridge consumes globally 5% of all generated electricity and, as a result, current regulatory regimes are structured to drive domestic fridge manufacturers to bring to market the most energy efficient appliances possible. Magnetic cooling exploits the reversible change of temperature that certain magnetocaloric materials experience when subjected to a changing magnetic field.

Magnetic cooling technology is gas free because it uses solid refrigerants. In the European Union this means the elimination of isobutane which has a Global Warming Potential (GWP) of 3.3 (and is also highly flammable). Outside Europe, magnetic cooling technology will enable the elimination of HFCs with a GWP of 1000 or more. Furthermore, magnetic refrigeration is expected to improve the energy efficiency of appliances over conventional gas compressor technology, helping to reduce indirect CO_2 emissions.

The main objective of the ELICiT Project is to consider the magnetic cooling solution in its entirety, and to optimize the magnetic cooling solution as part of an integrated appliance.

The project focuses on 4 key aspects:

1) System Optimization — to evolve a solution that is production scalable, efficient, cost effective and environmentally friendly. Two distinct steps were conceived - performance followed by cost optimization.
2) Benchmarked Validation — to establish the energy efficient credentials for the technology
3) Life Cycle Optimization — to provide production, cost and environmental data to aid system optimization and inform decision making
4) Regulations and Standards — to ensure the technology complies with existing regulations, and to establish how the new technology will fit into standards.

The aim of the project was to propel the technology along the technology readiness scale, and by so doing enable the accretion of more resources, capital and momentum for the technology. In this regard the project has achieved significant steps forward:

- Camfridge has raised additional private investor funds for the further development, production and commercialisation of the technology
- Cemafroid has become a world leader in testing magnetic cooling systems
- An active standards group, with global reach, has emerging through the IIR Magnetic technology Sub-Working Group
- Increased the interest in global appliance manufacturers to evaluating and assessing compact magnetic refrigeration technology.

Project Objectives in details

(a) WP1: System Optimization

WP1 follows two distinct steps - performance optimisation followed by cost optimisation. Each step has four component strands - pump, heat exchangers, magnetic cooling engine and appliance.

Heat exchangers. The objective of the heat exchanger optimization work is to exploit the particular properties of the magnetic cooling solution to create heat exchanger design that improve overall appliance efficiency, whilst working within the constraints of using a production appliance cabinet.

Pump. Pump optimization is about improving the design of exchange fluid pumps performance. To optimize pump designs against both efficiency and cost criteria for use in a magnetic cooling engine.

Magnetic Cooling Engine. The magnetic cooling engine is a system. The optimisation is focused on improving the components that compose the system - magnetocaloric material, regenerators, magnet. *Magnetocaloric material components*. Improvement of the heat transfer from liquid to solid. *Magnet*. removal of significant portion of expensive materials from the baseline system. *System*. High volume manufacturability ensured by components manufactured according to highly scalable industrial processes and easy to assemble into the system.

Application. Use of a cabinet already in production (Whirlpool Model RE155A) with no structural changes of the same cabinet. Development of enhanced control system based on benchmark results.

(b) WP2: Component/system/application Benchmarked Validation

Heat exchangers. Test of different design and materials hitting the operational specifications and the lowest costs and environmental impacts.

Pump. Test of efficiency and longevity.

Magnetocaloric material components. Test of single regenerators made of a cascade of suitable magnetocaloric material components with the design and construction of specific test-benches. *System.* Test of integrated component designs, specifically their reliability and behaviour.

Application. Test of complete appliance in operational environments compatible with the available magnetocaloric materials that responded to specifications. With the aim to reduce the gap between the research and the production phases

(c) WP3: Life Cycle Optimization

Implementation of a Decision tool implementing the latest literature methodologies including the ISO14040 on Life cycle Optimization and Costing with the aim that partners of the project could use it for evaluating different possible technical solutions of components and system. Evaluation of environmental impacts of the pre-production and production phases of a domestic refrigerator with a cabinet from current industrial production using the gas compressor and the same cabinet using the system designed during the project.

(d) WP4: Compliance to Regulations and Standards at application level
Assessment of the compliance to current regulation and standards at application level, and act as an input to the work of International Institute of Refrigeration (IIR) sub-committee on Magnetic refrigeration at room temperature.

3. *Main S&T Results and Foregrounds*

Below the main Activities and Results subdivided by Work packages are shown.

3.1 WP1
WP1: Component/system/application Optimization
WP1 consisted of two iterative steps - one focused on performance optimisation, the other on cost. Each iteration had 4 strands of technology optimisation:

- Heat Exchangers that work efficiently with both the magnetic cooling engine and the appliance cabinet.
- Pump that efficiently moves the exchange fluid around the magnetic cooling engine and through the heat exchangers.
- Magnetic Cooling Engine to efficiently cool the exchange fluid pumped through the appliance heat exchangers.
- Appliance cabinet adapted to integrate the magnetic cooling engine, pump and heat exchangers.

Heat Exchangers
For each optimisation both a hot and cold exchanger designs were developed.

Across each optimization, aluminium roll-bond plate exchangers were developed for both the hot and cold exchangers - and these were ultimately used in both the second and third appliance benchmarking activities. The target specification was achieved using aluminium roll-bond technology.

However two other designs were also developed and evaluated - metal foam and plastic.

Plastic heat exchangers are not ideal for vapour compression systems, as the pressures that need to be contained are rather high (over 10 bar). However, in magnetic cooling the system is simply pumping a water based exchange fluid at flow rate of under 1 litre per minute so the pressure drop across the entire system is under 1 bar. The LCA and LCC from WP3, indicated that plastic exchangers are in theory both cost and environmentally optimal, compared to the alternatives considered. Both hot and cold exchangers in plastic were developed and both achieved the target specification. The strong performance of the solution, and the low cost (in principle) to manufacture, makes this solution an interesting option for magnetic cooling.

Metal foam exchangers were developed for the hot exchanger. The core of the idea is to use the huge surface areas offered by metal foams to create a compact heat exchanger. An advanced finite element model was developed for optimisation activities, and a version of the exchanger was developed. Unfortunately the specification were not met, but in a subsequent design iteration a new design was developed and the numerical simulation showed that it exceeded the targets. The new design is lighter and with its higher performance promises to be an interesting development path.

Pump

Two different pumps were developed over the course of the project.

For the first optimization, an MG1000 gear pump, was selected for optimisation. Initial efficiency was around 9%. By redesigning the pump, particularly the drive motor and controller, and optimising the types of material used, 20.3% efficiency was achieved - more than double the starting point, and over the target specification (20%) . Furthermore peak efficiency of the pump can be tuned for a range of possible operating conditions - making the pump ideally suited for a number of different magnetic cooling engine optimised for different types of appliances and operating conditions.

During the second optimization a completely new pump was developed - the conical revolution pump (for which a patent has been applied for). Although this pump did not quite achieve the target efficiency (18% was reached), it has a number of important merits:

- Significantly lower cost to manufacture
- Less wearing parts (so longer mean-time to failure)
- Highly compact

During the benchmarking activities of the magnetic cooling engine and the integrated appliance, the MG1000 gear pump was used, the conical pump not quite achieving the target efficiency. Nevertheless, with the huge cost savings and the improved reliability offered by the conical revolution pump, it is likely this pump will be preferable for use in domestic cooling appliance with magnetic technology.

Magnetic Cooling Engine

The magnetic cooling engine was developed in WP1 through two iterations - performance optimisation and cost optimisation, each step taking input from the benchmarking activities undertaken in WP2. The starting point being the magnetic cooling engine used in the first benchmarking.

The first benchmarking encountered some challenges. The main cause was corrosion which destroyed some key components (with long lead times) that need replacing, but also a general lack of reliability and robustness meant extracting informative experimental data was a challenge.

The priority in the first optimization was to address these specific issues, improve the performance of the system, and to be in position to extract useful output data from the cooling engine to guide future development.

Considerable effort was devoted to replacing the regenerator parts.

- A new refrigerant processing method was used to produce 40% thinner components for the replacement regenerator components. Achieving this small scale is a major step change, and is leading in the field of magnetic cooling. Furthermore, the production method is highly scalable and that is key to the cost optimization required for the cooling engine.
- New regenerators were fabricated successfully with those new components, using an enhanced (and high-yield) assembly process. This is critical to achieving an operating frequency of up to 3Hz which increases the power density of the solution, enabling the use of smaller and less expensive magnets; again a feature essential for cost optimization.

Other components

- A new regenerator casing approach was implemented that was completely leak tight and compatible with the new regenerator components.
- The entire fluid handling system was also all improved.
- An interim corrosion solution capable of sustaining the refrigerant for duration of tests was implemented.

The outcomes of these changes to the magnetic cooling engine were highly satisfactory:

- New regenerators were fabricated and implemented at sufficient quantity.
- Reliability and robustness of components were vastly improved.
- The system showed only limited corrosion.
- The system was robust and reliable enough to investigate in detail during benchmarking to help inform the next optimization.

A detailed analysis of the second benchmarking results revealed that the main component for further optimization was the valve - although the switching was much improved, the valve was not consistent across all 7 regenerators and created flow imbalances in the regenerator network. This needed to be addressed. In particular during the second optimization:

- A new valve was designed that worked in a new way in order to avoid back-pressures during switching that could cause flow imbalance.

In the second optimization major progress was made in a number of other areas:

- By assessing multiple anti-corrosion solutions, corrosion was completely eliminated - a major improvement.
- The regenerator assembly method was further developed - simplifying the process and eliminating the need for certain precision machined parts. This being a key step to automating assembly for low cost production (which is now in fact being developed).
- Further simplified refrigerant processing steps by eliminating several (very) time-consuming heat treatment steps.
- Demagnetization effects were shown to be effectively negligible in the cooling engine.

The outcomes were highly satisfactory:

- The magnetic cooling engine was functionally integrated with a Whirlpool production appliance and optimized heat exchangers and a pump.
- No component failures were encountered during testing.
- The valves exhibit good behavior, ensuring that the regenerator cascades operated consistently.
- Key data was extracted from the third benchmarking that will help inform further system improvements.
- A total system benchmark was completed.

Cooling Appliance

A production cooling appliance selected for this project was an under-counter appliance. This particular product has an internal Volume of 155 litres and originally mounted an ON/OFF compressor , which uses a 22g of the refrigerant R600a. During the project three appliances have been built. Two were selected and integrated with a magnetic cooling engine for benchmark testing in WP2. An additional Product has been modified and used for technology exhibition during Thermag VII workshop.

3.1.1 Highlights of WP1

- A magnetic cooling engine, about the same size as a gas compressor (making it the smallest such engine in the world) was successfully integrated into a Whirlpool production appliance.
- The newest version of the magnetic cooling engine incorporates the next generation of magnetic cooling components (and has achieved a unique level of specification).

- Advanced, highly- flexible fluid handling system and a new pressure containment solution able to survive the highest operational pressures.
- A pump has been developed for the magnetic cooling engine that meets the target efficiency, and more than doubled the efficiency value compared with the start of the project.
- A production appliance has been modified to incorporate performance optimised heat exchangers.
- Cost optimisation.
    - Pump. Possibility of reusing high-efficiency parts in much simpler and less expensive designs.
    - Magnetic cooling engine. Industrial scale technologies have been deployed to make and shape refrigerants and a new streamlined process have been introduced that removes three costly processing steps. Furthermore, the optimized regenerator parts ensure good frequency response, increasing power density so lowering magnet costs.
    - Magnet. A new design was identified, that will remove a significant portion of expensive materials from the baseline system.
- Design versions of cold side heat exchangers in aluminium and plastic and of warm side in aluminium, plastic and metal foam were evaluated. A numerical model of a metal foam HEX was realized and validated against the prototype.
- The use of plastic heat exchangers is a major achievement, is both a cost and environmentally optimal solution, that works well with the low pressure fluid system of magnetic cooling.
- A new pump was developed with significant advantages in both ease of manufacture and cost (patent applied for).
- Magnetocaloric material components passed successfully longevity tests; corrosion problem was resolved.
- Design of a full control tool, able to acquire data on the specific field of application and control the new actuators.

3.1.2 Conclusions of WP1

Pump and heat exchangers achieved the specifications desired at the commencement of the project.

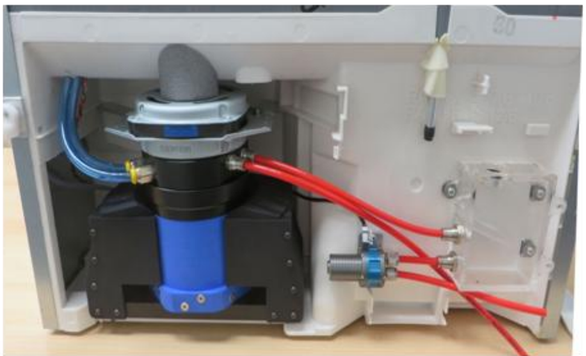
The magnetic cooling engine did not fully meet the complete operational requirements, but numerous cost optimisation activities were successfully implemented, the system achieved a new level of robustness and reliability never previously achieved, and one more iteration of the technology should be sufficient to achieve the specification.

Magnetic cooling can integrate with production appliances with minimal impact on the platform design.

Picture of the Metallic foam passive heat exchanger used to validate the model that is used now to design high performance, low cost and compact heat exchangers. Photo Courtesy of S.C.I.R.E.

Warm side Plastic Channel plate
Photo Courtesy of Re/genT

TCS Micropumps Ltd. new high efficient pump and its measured efficiency. The efficiency of the pump is defined as (Pressure X volumetric flow)/energy consumption. Picture courtesy of TCS Micropumps



Picture of the Camfridge cooling machine sitting in the back of the fridge – photo courtesy of Camfridge Ltd.

3.2 WP2

WP2 consisted of three benchmark events - one at the beginning to set the baseline, another after the first WP1 technology optimisation and a final benchmarking after the second WP1 optimisation. The aim was to track the progress of the optimisation activities and assessed the absolute performance of the technology.

The four strands under development in WP1 - pump, heat exchangers, magnetic cooling engine and appliance - were individually benchmarked.

Pump

Benchmarking of the pump was undertaken by TCS Micropumps on a specifically designed test apparatus that measured output flow rate, resulting pressure and the corresponding input current and voltage to the pump.

First Benchmarking-The MG1000 had an initial efficiency, at the pressure-flow rate specified, of 9%.

Second Benchmarking-The performance optimised MG1000 emerging from the first optimisation, at the pressure-flow rate specified, had an efficiency of 20.3%, exceeding the 20% target by a small margin.

Third Benchmarking-For the cost optimisation, a new conical revolution pump was developed, which removes numerous high precision parts, and simplifies the pumping mechanism. At the pressure-flow rate specified the pump achieved an efficiency of 18%.

Heat Exchangers

Heat Exchanger benchmarking was undertaken by Regent in their dedicated test facility.

First Benchmarking-The Standard tube and fin heat exchangers used in the first benchmarking appliance were assessed, identifying a number of areas for improvement.

Second Benchmarking-Aluminium roll-bond heat exchangers, for both the hot and cold exchange process, were assessed. Both achieved the required level of performance.

An innovative metal foam hot exchanger was also assessed.

Third Benchmarking-Cost optimised plastic heat exchangers were benchmarked, and both the hot and cold exchanger versions achieved the target specification.

Magnetic Cooling Engine

Camfridge undertook the magnetic cooling engine benchmarking, both in its own test facilities and at Whirlpool R&D.

First Benchmarking-During the first benchmark an unexpected corrosion process, which destroyed some key components that need replacing (with long replacement lead times), meant extracting informative experimental data within the time period available was a challenge. This limited the quantity of useful output data available to guide the 1st optimization.

- The presence of the corrosion caused the system pressure to rise revealing a need to improve the pressure containment aspect of the system design.

Second Benchmarking-During the second benchmarking a reduced, but still finite, level of corrosion was observed so benchmarking activities were specifically limited to essential tests. This nevertheless was sufficient to extract critical data from the system to guide the second optimisation activities in WP1.

- With an improved inhibitor formulation system corrosion was reduced (although not to zero).
- New high performance (and cost optimized) regenerators were used, that exploited the advanced material processing methods deployed and tested in WP1.
- All regenerators worked, flow control components all operated with improved performance, and the system cooled.
- The overall reliability of the system and its components were vastly improved; no leaks were observed.
- The new system was sufficiently robust to support extensive investigation of both the individual component and integrated system operational performance delivering valuable data to help inform the second optimization.

Third Benchmarking A new anti-corrosion approach removed all corrosion in the system, enabling a more complete benchmarking of both the magnetic cooling engine and the integrated appliance. Furthermore, components were once again reliable, delivering a robust system, with no failures, and delivered enhance performance over the second benchmarking.

The target system specification was not quite achieved, although the system operated close to the expected parameters given the specifics of the system being tested.

Critically, this benchmark provided sufficiently detailed data to enable to clear path for achieving the system goals in the next optimisation iteration

Appliance
The Appliance benchmarking activities were led by Whirlpool, focused on Performance as well as (laterally) power consumption and efficiency tests.

First Benchmarking-No useful appliance level data was obtained during the first benchmarking following the corrosion of key components in the magnetic cooling engine.

Second Benchmarking-Some data was obtained from the second benchmarking, primarily focused on Performance data, in particular cooling temperatures, cool down times and the response of the appliance to different ambient conditions. An extended testing period was deemed too high a risk, as corrosion had not been fully resolved.

Third Benchmarking-With corrosion finally addressed, the complete system achieved a level of robustness and reliability never previously achieved that allowed a more complete benchmark to be completed. Temperature, power and efficiency data were all obtained as planned, under operational conditions defined by the final system configuration.

With the operational data, an evaluation of appliance controllability was feasible. A flexible tool, based on a data acquisition system, was designed, and a dedicated controller using the LabView tool was implemented to collect all the signals from the temperature and pressure sensors to control the appliance in a simple and intuitive mode. This enabled a further design evaluation of appliance control beyond the traditional ON/OFF approach. A couple of PI(D) control strategies were configured, with different complexity and robustness/safety capabilities, and were analysed for possible future application deployment. The HW part, composed of a Microcontroller and Drivers was also envisioned. It was verified that the already in production Main Control Board has the capability to drive the two additional analogue/digital ports to be connected to the Magnetic Engine and to the Pump respectively.

WP2 Highlights

- Refined MG1000 gear pump exceeded the efficiency target that was defined for the project.
- The cost optimized conical revolution pump did not quite achieve the absolute efficiency target, but on efficiency per unit cost basis was shown to be far superior to the MG100 gear pump.
- Heat exchanger benchmarking demonstrated that the design targets for each were achieved both for plastic plate and aluminium roll-bond plate exchangers.
- The metal foam exchanger was tested and validated
- After difficulties during the first bench marking, the magnetic cooling engine was properly benchmarked twice; the second benchmarking showed a significant improvement over the first, achieved the expected operating span (based on design) and delivered meaningful cooling power.
- Reliability of the magnetic engine (including corrosion) has been much improved.
- The third generation (and cost optimised) regenerator components demonstrated in benchmarking a strong linear frequency response in line with design expectations.

- A complete appliance equipped with improved heat exchangers, optimized pump and magnetic cooling engine tested successfully and the results were compared with the gas compressor based appliance.
- A rigorous series of benchmarking tests had been planned but only a subset could be executed because the magnetic cooling engine could not operate (by design) over the entire parameter space.
- Control strategies have been evaluated and the conclusion was that existing in-production boards were sufficient for this purpose.

WP2 Conclusion

A fully integrated appliance was completed and tested. It incorporated a pump and set of heat exchangers that met the operational requirement for a high efficiency appliance, and a highly compact magnetic cooling engine. Although the magnetic cooling engine reached a new level of robustness and reliability, enabling systematic testing to be undertaken, a couple of areas were identified where further improvement is required to achieve the target design specification. Nevertheless, reliability was sufficiently high for control strategies for the new system to be considered, and it was concluded that current controller technologies already deployed for the compressor based cooling could be re-used.

Neil Wilson, CEO of Camfridge is presenting to Wanda Gaj, Research Programme Officer, DG Research & Innovation of the European Commission and Project officer of the ELICiT project the magnetic cooling engine working on the back of the fridge (Picture on the right). Photos courtesy of Camfridge Ltd.

3.3 WP3

WP3 aimed to implement a Simulation Toolbox to help the engineers develop a new prototype of a magnetic refrigerator respecting the criteria of sustainability. In particular, the Toolbox evaluates the economic and environmental implication both at component level and at system level. At a component level, the three main components analyzed are: the heat exchanger, the pump and the magnetic system. At system level the Simulation Toolbox aims to compare the new prototype with the conventional gas compressor one.

An analysis of the state of the art in the magnetic refrigeration industry was carried out, trying to assess current lifecycle optimization practices proposed by the experts, both in environmental and economic terms. The data obtained was used to define a reference dataset of potential variables to consider in the study.

The innovative Simulation Toolbox designed by Polimi was defined both in terms of functional and structural requirements. A document was produced to present the requirements of the system alongside the main results achieved. This document was progressively refined after the first implementation of the Simulation Toolbox was delivered.

The Simulation Toolbox was applied to magnetic cooling, to assess several components of a magnetically cooled domestic refrigerator. The system developers were directly involved to assess the validity of the Simulation Toolbox in practice during their development activities. The assessment was done on the three main sub-components of a magnetic refrigerator: the pumps, the heat exchangers and the magnetic cooling system. A specific report with the results at component level for the heat exchanger, the pump and the magnetic system, has been presented both to the partners during the project meetings and at scientific conferences.

Finally, the assessment of the whole next-gen refrigerator and its comparison with other similar products were produced. A final report summarizing all the results both at component and system level, in order to have a full picture of the whole work of WP3 were shared with the partners of the project. Moreover, the industrial partners had the possibility to use and test the algorithm implemented in the Simulation Toolbox thanks to the specifically developed web-based version of the Tool.

3.3.1 Highlights of WP3

The Simulation Toolbox has been optimized in order to be useful for the designers and engineers during the prototype product development phase. The idea was to include product lifecycle environmental indicators into the technical decision making process. The Simulation Toolbox comprises the full product lifecycle, with the following five phases: materials extraction and transportation, production process, assembly, usage and end-of-life. The functional modeling methodology - IDEF - has been used to describe the Simulation Toolbox conceptualization through the following four steps: 1) functional group analysis; 2) on-site data acquisition; 3) environmental and economic assessment; 4) data elaboration.

The Decision Support of Simulation Toolbox has been divided in two main levels: 1) a first level, which aims to evaluate the optimal machine solution in terms of single components; 2) a second level which aims to evaluate the optimal machine relative to the conventional refrigerator.

The Life Cycle Assessment methodology has been chosen to quantify the environmental aspects of the magnetically cooled refrigerator prototype, where the Life Cycle Costing approach has been chosen for the economic one.

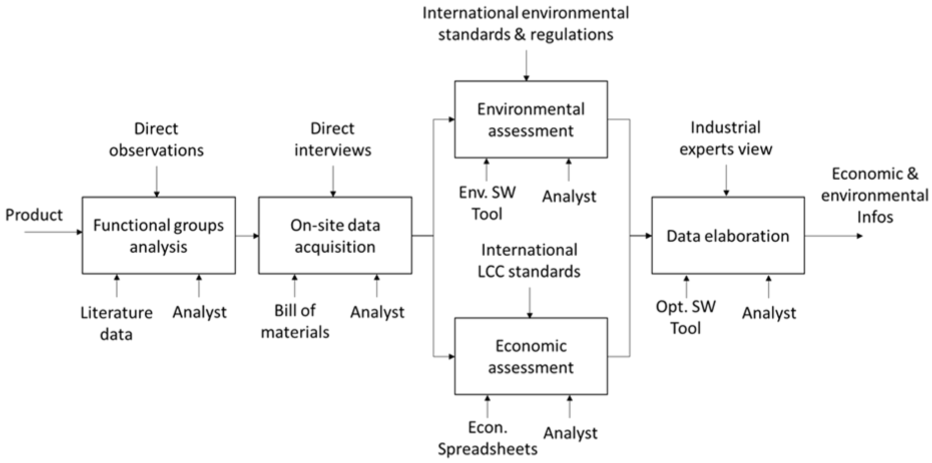
3.3.2 Conclusions of WP3

The Simulation Toolbox developed over the period can be used with each of the main components of the magnetic refrigerator. This methodological choice implied that the same background logic of LCA and LCC standards had to be maintained through-out the project. The main advantage being that all the ELICiT technical partners used the same Simulation Toolbox and cooperated through it during the development of innovative components and/or system with a real time comparison of economic and environmental indexes and diagrams. In order to better facilitate this co-operation, a web-based version of the Tool was developed in the last months of the ELICiT project. To this aim, the Virtual Obeya software – already developed by POLIMI during other European projects – was used as fundamental tool supporting the product definition process. The final results of the Tool showed how the future magnetic system equipment presents a very high potential to become "greener" and more attractive cost-wise than the conventional gas compressor based technology.

At system level, from the environmental point of view, the optimal magnetic machine can ideally be composed by the following components: permanent magnet with cerium doped NdFeB magnets, regenerators using hydrogenated $LaFe_{13}Si$ alloys, plastic heat exchangers and the new conical revolution pump. The prototype modeled by the indicators reported in the Simulation Toolbox can be then compared with the conventional gas compressor-based refrigerator. Preliminary results indicated clearly that the magnetic cooling technology represents a viable alternative to gas compressor technology for domestic refrigeration. Indeed the prototype magnetic cooling system scores 18.400 mPt vs 15.500 mPt of the gas compressor based cooling system. Moreover, the dominant permanent magnet contribution to the score could be further reduced using recycled permanent magnet material and automatic assembly of components improving dramatically the score of the magnetically cooled refrigerator to well below that of the gas compressor based one.

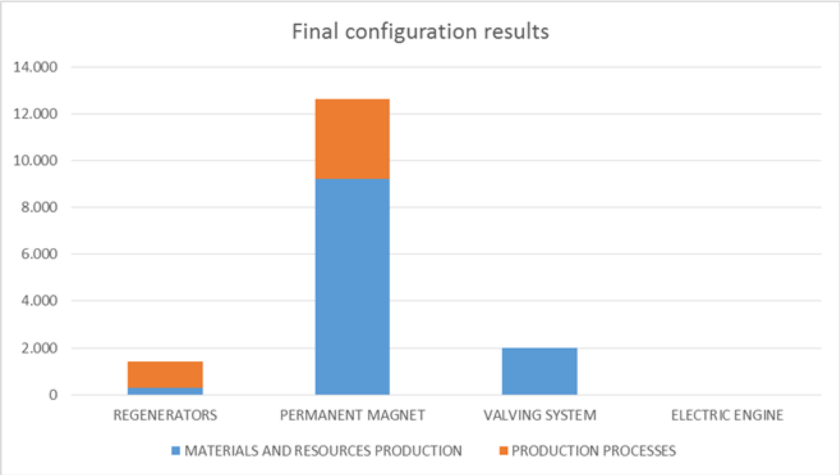
As far as the cost analysis is concerned, the optimal magnetic machine should be composed by: permanent magnet with cerium doped NdFeB, regenerators using cobalt doped $LaFe_{13}Si$ alloys, plastic heat exchangers for both cold and warm sides and a gear pump.

The Toolbox results clearly showed too that material reusability and remanufacturing will have big positive impacts in particular when permanent magnets are considered. Future research will evaluate the benefits of end of life recycling of the permanent magnet components.



Decision Support Toolbox process description through IDEF Diagram [1]

Example of Toolbox results in the case of magnetic cooling system



Toolbox results of the optimal solution of magnetic cooling system

3.4 WP4:

- Eleven (11) standards in four (4) categories - safety, health, performance and environment have been identified. The performance standards for vapour compression based refrigeration systems - ISO-EN 15502:2007 - examined, and an adapted test protocol has been developed specifically to ensure that the performance of magnetic cooling can be evaluated in a manner as compliant as possible with the current ISO standard.
- Release of a working paper on standards compatibility to the International Institute of Refrigeration (IIR) sub-committee on Magnetic refrigeration at room temperature.
- Release of Reference Templates of tests performed with a magnetically cooled appliance
- Performance analysis of the prototype which has been tested in regards to Energy labelling scheme

3.4.1 Highlights of WP4

A deep analysis, related to WP1 activities, has been conducted on the prototype developed within the project in order to understand the relationship between components and their attributes within the magnetic cooling solution, mainly focusing on magnetic source and regenerators.

According to the study performed, the Elicit prototype offers the best trade-off between various performance criteria.

A permanent dialogue was established between the ELICiT members and in particular CEMAFROID and the members of the IIR Sub Working Group involved in standardization work. The general opinion is now to focus the standardization activities first on the intrinsic Magnetocaloric material performance standards to allow companies like Camfridge which uses those materials into devices to fully respond to industrial production demand within the specifications.

At the appliance level, the current standard is (in principle) directly applicable to appliances cooled using either magnetic technology or the current gas compression technology.

3.4.2 Conclusions of WP4

Analysis performed within WP4 showed that there are clearly no regulatory barriers to magnetic cooling technology for being adopted by the refrigerated home appliances global market, although a significant number of existing standards will need to be complied with.

4. Potential impact and main dissemination activities and exploitation results

Potential Impact

The aim of the call in which the Elicit project was funded, was to support the effective demonstration of existing cutting edge eco-innovative technologies, processes and services, which in spite of their high environmental and market potential have not yet succeeded in reaching the market. Specifically targeted were technologies that can enable radically stricter, smarter and more ambitious environmental standards than those currently in place.

The Elicit project demonstrated that magnetic cooling technology can have a significantly improved environmental footprint compared to the conventional gas compressor, In particular, the three key environmental impacts of the technology – being both gas and oil free as well as energy efficient (or at least as energy efficient as the best gas compressor solution, but delivered at a lower cost) can drive significant CO_2 emissions savings both in Europe and elsewhere:

- In Europe 3.7 million tonnes of CO_2 equivalent emissions can be removed by enabling the A+++ market (through reduced prices for the technology) and migrating the efficiency of the mean installed appliance from A++ to A+++.
- In the US 50 million tonnes of CO_2 equivalent emissions can be removed by replace HFC gases used in domestic cooling appliances.
- Globally 130,000 tonnes of CO_2 equivalent emissions can be removed by eliminating compressor oil

These high-level impacts can only be achieved if the technology is turned into a marketable product. In Europe this means demonstrating that magnetic cooling is one of the technologies that can enable a cost-effective A+++ appliance – something desired by consumers, policy makers and the appliance industry. The Simulation Toolbox developed during the PW3 activities shows that at the current development stage of a magnetically cooled domestic refrigerator (Technology Readiness Level), the environmental impacts of the cooling system of the magnetic cooling technology has been estimated of the same order of magnitude of the conventional cooling system, which uses the gas compressors. Moreover, the permanent magnet score could be reduced using recycled permanent magnet material and automatic assembly process making the magnetically cooled refrigerator better than a conventional refrigerator.

This project covered several activities intended to realise a more rapid market uptake of magnetic cooling technology by reducing the barriers for market acceptance of magnetic cooling – through optimising of a mainstream commercial appliance, benchmarking, development of cost, production and life-cycle models and the examination and extension of relevant standards. A strong communication of the key results to the right audiences is also essential to creating market need and acceptance.

Although these activities are sufficient to demonstrate that there are no barriers for the technology, and that it meets a market need cost competitively, they in themselves are not sufficient to propel magnetic cooling into the mainstream. The results generated from this project will however be sufficient to enable the next steps:

- Attract further investment capital for production scale-up
- Attract large European manufacturers to commit to making magnetic cooling engines
- Attract appliance manufactures to use the technology
- Attract consumers to buy the technology
- Convince policy makers of the social and environmental advantage of the technology

As a matter of fact, the results of the project had already allowed the achievement of the following exploitation steps:

- At the end of the project Camfridge successfully attracted more capital from investors to fund its activities for further developing magnetic cooling technology solutions.
- A major European Manufacturing Research Centre was attracted to commit new resources to design and build automatic assembly line for magnetic cooling engines on behalf of Camfridge.
- Other two appliance manufacturers committed resources to use the technology developed during the project.
- At the end of the project Cemafroid was able to position itself as world leader in certifying and testing of magnetic cooling pre-production prototype engines starting to work also with other magnetic cooling system developers.
- Several articles appeared on mainstream press describing the project and the potential benefits to consumers.
- A permanent dialogue was established between the ELICiT members - especially Cemafroid - and the members of the IIR Sub Working Group involved in the standardization work.

The magnetic cooling technology solutions developed within ELICiT demonstrated that those solutions are capable of driving a mainstream appliance competitively and that there are no barriers to industrial production.

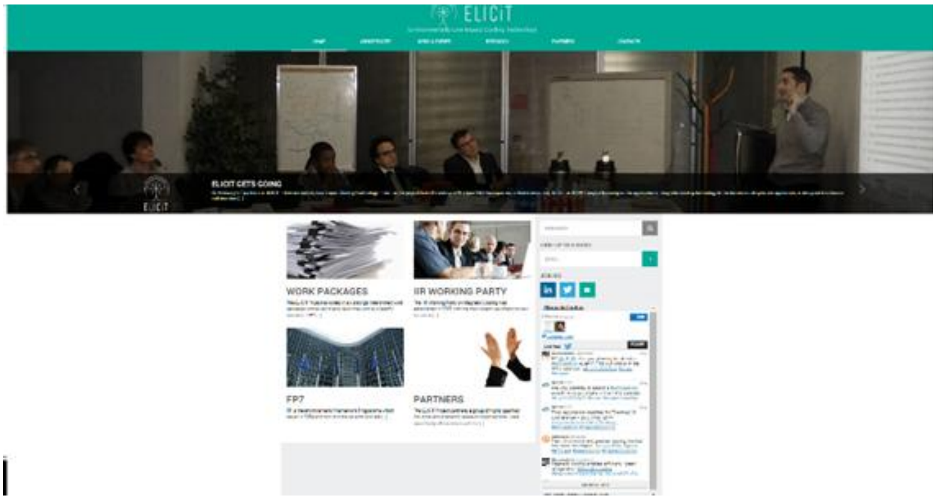
Main Dissemination Activities

The main objective of the work package 5 was the dissemination of the results obtained within the framework of this project. More generally, the objective is also to help raise awareness of magnetic refrigeration technology and its potential benefits in terms of performance, energy efficiency and environmental protection. Several communication channels were used: Web site, electronic communication, flyers, brochures, conferences and congresses, workshops, exhibitions etc. The aim was to disseminate as widely as possible information concerning the outcomes of this project to decision-makers, researchers, developers, marketing and distribution companies, industrial stakeholders and the general public.
The following six tasks have been undertaken during the Work Package 5:

- Development and updating of a dedicated ELICiT Web site.
- Publication of a periodical newsletter.
- Publication of scientific articles in peer-reviewed in leading journals dealing with magnetic refrigeration.
- Publication of news items in technical journals and newspapers dealing with refrigeration or covering broader fields.
- Organisation of workshops during IIR conferences and congresses.
- Exhibiting at trade exhibitions.

A summary of progresses towards the objectives of the above task is presented as follows:

- The ELICiT website was developed to provide project partners with communication tools to allow them to ensure exploitation of project results and reach a larger public audience. The partners provided the contents for the website. All partners promoted the ELICiT project using the social media set-up such the ELICiT Twitter, LinkedIn and #tag. The IIR regularly updated the website. The ELICiT website was officially launched the 1st April 2014 and the web address is http://elicit- project.eu/.

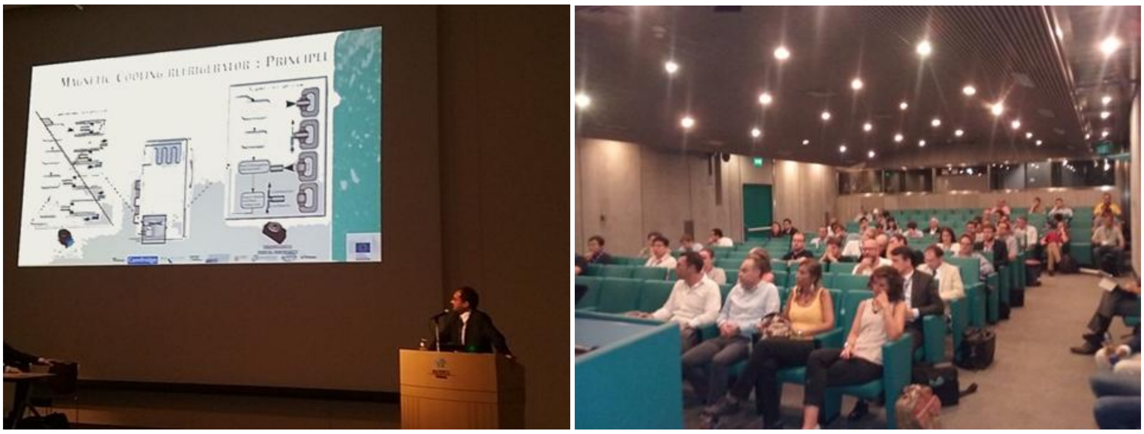


The ELICiT website http://elicit- project.eu/

- The first two newsletters summarised the work achievements of the different ELICiT partners during Years 1 and Year 2, and the last newsletter presented the final results from the different partners of the project which officially terminated on December 31, 2016. All the ELICiT newsletters were in hard copy and electronic formats. The hard copies were distributed at events and conferences to promote the ELICiT project. The electronic formats were disseminated throughout social media: #MagneticCooling, ELICiT e-News and IIR NewsFlash, IIFIIR twitter account reaching directly the 5,839 ELICiT followers and the IIR network and contributors across the globe.

Publication of Newsletter 2016

- Two ELICiT scientific articles were accepted for publication and will be published in the International Journal of Refrigeration during the 2017. Another article submitted by Polimi has been accepted to the Procedia CIRP Open Access peer-reviewed journal. Also, 7 academic papers have been presented in international conferences and 13 presentations in dedicated ELICiT workshops in IIR conferences.
- Four articles in technical refrigeration journals have been written by Whirlpool, Cemafroid and Camfridge. Still in review process, their publications is forecasted to be in the first half of 2017.
- The IIR organised 3 workshops in the two last IIR Thermag conferences and IIR Congress 2015. The workshops were successful with in total 200 attendees worldwide.



ELICiT Workshop at Thermag VII, September 2016 in Turin

- The ELICiT project has been promoted in 12 trade exhibitions, 11 IIR conferences and 8 IIR co-sponsored conferences worldwide. When possible, the IIR promoted the ELICiT project through the IIFIIR Twitter account their attendance and participation in these events. When the ELICiT project was promoted the #MagneticCooling hashtag and the ELICiT Twitter (@ElicitProject) were used at the occasion to increase worldwide visibility. Also, the IIR created communications supports to be distributed during trade exhibitions such as brochures and kakemono.

In overall, about 150 dissemination activities have been undertaken reaching globally an estimated audience of more than 60000 people.

Exploitation results:

Refrigeration and cooling equipment industry is pushed by legislation and pulled by market demand to develop environmentally safe and sustainable, energy efficient and recyclable solutions. Only magnetic refrigeration technology is able to solve these 4 problems simultaneously, overcoming the major challenges that current gas compressor based technology is facing.

Within this framework the exploitation of results of the project must be considered taking into account the different business model of the partners.

The Camfridge technology world leadership in developing magnetic cooling *compact* solutions was strengthened by the results of the project. The exploitation of those result will be coherent with the company revenue mode, which is split into two parts, a services component (based around specify, design and validate instantiations of Camfridge Intellectual Property – IP –) and subsequent licensing of that IP to appliance manufacturers worldwide. Furthermore the results of the LCA and LCC models helped to focus new researches and developments on how to improve recyclability and reuse of material. Those activities will have a positive impact on the cost of magnetic refrigeration technology versus the current high efficient gas compressor based solutions ensuring the sustainable market uptake. With the goal of reaching the same mass production level and economies scale of gas compressors (several hundred million components per year), new financial resources will be committed to design and eventually build industrial automatic assembly lines for the production of the magnetic cooling engines.

The IIR working group on magnetic refrigeration will continue to exploit the results of the project and facilitate further research developments by creating synergy between EU projects with the same target and increasing the awareness of the benefits of the magnetic cooling technology to decision-makers, researchers, developers, marketing and distribution companies, industrial stakeholders and the general public.

Re/genT plans to exploit the additional knowledge obtained in particular in the design and construction of low cost high performance plastic heat exchangers in future appliance and heat exchanger development projects for its customers into domestic as well as commercial cold appliances. Moreover, when magnetic cooling will start to be available Re/genT foresees a large role in delivering to its customers technical assistance and guidance in the integration of magnetic cooling systems into both domestic and commercial cold appliances as a well as an accredited testing partner for energy and performance measurement of cold appliances and manufacturer of test rigs for magnetically cooled appliance components.

TCS Micropumps plans to exploit both concepts and potential product ranges derived from the pumps developed during the project. The unique benefits of these new pumps will help TCS customers to enrich and improve their own offerings to a wide range of market sectors also beyond the magnetic cooling market sector.

The POLIMI exploitation plan can be split into two main stages, an academic phase and a commercial phase. The first one consists in the exploitation of the ELICiT results for the publication of several articles in top scientific journals and conference proceedings. The second phase will start when the Simulation Toolbox methodological approach, validated during the project, will be also extended as a web-based application to other industrial manufacturing sectors and sold on a per access basis. The future routinely use of the Simulation Toolbox will allow:

1. An overall support to designers and engineers during the development phase of new products when sustainability assessment and comparison of different solutions, both in environmental and economic terms are key aspects;
2. A sensible improvement of sustainability performances of new manufactured products, with related reduction of non-renewable resources consumption and CO2 emissions reduction;
3. Development of more environmental-friendly products, easier to dismantle and recover when retired from the market.

Coherently with the SCIRE's mission, which is to enable, facilitate and promote industrial applied research the project results will be exploited in the field of the optimization of Heat Exchanger using innovative high surface-to-volume ratio shapes (metal foams) also to other fields of application such as automotive, as well as the publication of scientific papers.

Cemafroid will exploit the results of this project being an active member of standardization working group as a well as positioning as the world leader in certified testing on magnetic cooling systems.

Whirlpool Home Appliance will continue to monitor the magneto caloric technology in order to take and expand all the potential benefits demonstrated during the Elicit Project. Key component specifications and control parameters were identified: the acquired knowledge during the three years spent on the ELICiT project is extremely important as it reduces the gap between the research and the production phases. The technology can be applicable to many products with minimum impact to the plant and so providing the benefits of low investment cost.

5. Address of the Project Public website

http://elicit-project.eu/