ALUHEAT

NMP2-CT-2005-013683

ALUHEAT

High Efficiency Aluminium Billet Heater

Specific Targeted Research Project

Nanotechnologies and nano-sciences, knowledge-based multifunctional materials and new production processes and devices

Publishable final report, February 2010

Period covered: from 1 June, 2005 to 30 November, 2008 Date of preparation: 12 February, 2010

Start date of project: 1 June, 2005 Duration: 3.5 years

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Revision 1

Publishable final report, June 2005 - November 2008

1 Project execution

1.1 Aluheat objectives

The objectives of the project ALUHEAT was to develop new technologies based on new materials and novel electromagnetic design. The technology was based on the ability of superconductors to carry DC currents loss-free and the aim of ALUHEAT was to show how this ability can be combined with novel electromagnetic concepts to fully utilise the potential of the superconductor materials.

More specifically the major technical and scientific objectives of ALUHEAT are:

- To develop technology to dramatically reduce energy consumption and thereby the life-cycle costs in one of the large-scale electrotechnical components with absolutely poorest energy efficiency and at the same time improve the production quality.
- To validate the technical and economical feasibility of the new concept by building a 200-300 kW aluminium billet electromagnetic induction heater and test it in an industrial aluminium extrusion plant.

1.2 Contractors

The table below lists the partners of the project.

Partner name	**Country**
SINTEF Energy research (*SINTEF)*, co-ordinator	Norway
Fraunhofer Gesellschaft (*FhG)*	Germany
Tampere University of Technology (*TUT)*	Finland
Institute of Non-Ferrous Metals (*IMN-OML)*	Poland
Columbus Superconductors (*Columbus)*	Italy
GK Kety (*Kety)*	Poland
SMS Elotherm (*ELO)*	Germany
University of Hannover (*UHann)*	Germany
Skoda Vyzkum (*SKODA)*	Czech Republic

1.3 Work performed and end results

1.3.1 Life cycle analyses

Initially evaluating work of different concepts for billet heating was performed considering both environmental and economical aspects. Environmental life cycle assessments (LCA) of the process of heating aluminium billets show that the new superconducting dc induction heater gives a lower environmental impact than both conventional gas burners and ac induction heaters. The table below shows environmental impact factors obtained using three different LCA methods for one year of operation where 5,600 tons of aluminium is heated. (A high value indicates a large impact.)

Table 1:

	Gas burner	***Ac induction***	***Dc induction***
Annual electricity consumption [MWh]	151	1,230	670
Annual gas consumption [MWh]	1,230	0	0
Ecopoints 97 [points]	$119 \cdot 10^6$	$221 \cdot 10^6$	$120 \cdot 10^6$
Eco-indicator 99 [points]	21,200	8,700	4,740
EPS 2000 [points]	162,000	107,000	58,500

In a simple economical present value analysis where no premium is put on the quality of the heating process (i.e., obtaining an accurate and predetermined temperature profile), gas burners come out with the lowest life time cost, see the table below.

Table 2:

	Gas burner	***Ac induction***	***Dc induction***
Investment cost [€]	*550,000*	*550,000*	*660.000*
Gas cost [€/year]	20,300	0	0
Electricity cost [€/year]	8,300	67,700	36,900
Repair and maintenance [€/year]	9,250	3,000	6,000
Emission tax [€/year]	200	0	0
Total operation costs [€/year]	38,050	70,700	42,900
Present value of operation costs [€]	*523,000*	*973,000*	*590,000*
Total present value [€]	***1,073,000***	***1,523,000***	***1,250,000***

When comparing ac and dc induction heaters, which are assumed to provide comparable heating quality, the dc heater is estimated to have the lowest cost.

1.3.2 Superconductor development

<u>MgB2 superconducting wire manufacturing</u>

Amongst the advantages of MgB2 with respect to other superconductors is the very high flexibility in the selection of the wire configuration, that can be quite drastically adjusted between the flat tape shape to the round/square geometry. For our new induction heater demonstrator, the flat tape shape has been selected, because it maximizes the flexibility and handling properties of the conductor, although this partly occurs at the expenses of the transport critical current density. The selected flat tape configuration presents the following transverse cross section:

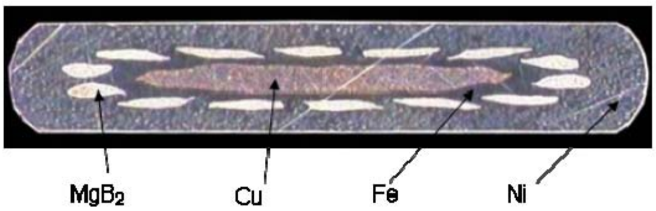

Figure 1: Transverse cross section of the conductor supplied for Aluheat

A reproducible process to manufacture this conductor in very long lengths has been studied and optimized. A regular production of this conductor in unit length of 1.7 Km has been established. Because of the specific requirements of Aluheat in terms of required conductor (32 lengths of 550-600 meters each), 11 lengths of 1.7 km have been produced for this purpose. In the following picture, one of such 1.7 km lengths is shown.

Figure 2: Picture of a 1.7 km conductor on its spool after completion of the production phase 5

Superconducting wire test & delivery

Each length of MgB2 superconducting tape produced for Aluheat, has been obtained by a highly reproducible route, and individually tested at both ends of the conductor by critical current measurements as a function of temperature and magnetic field. A typical conductor performance test is reported in the figure 3 below:

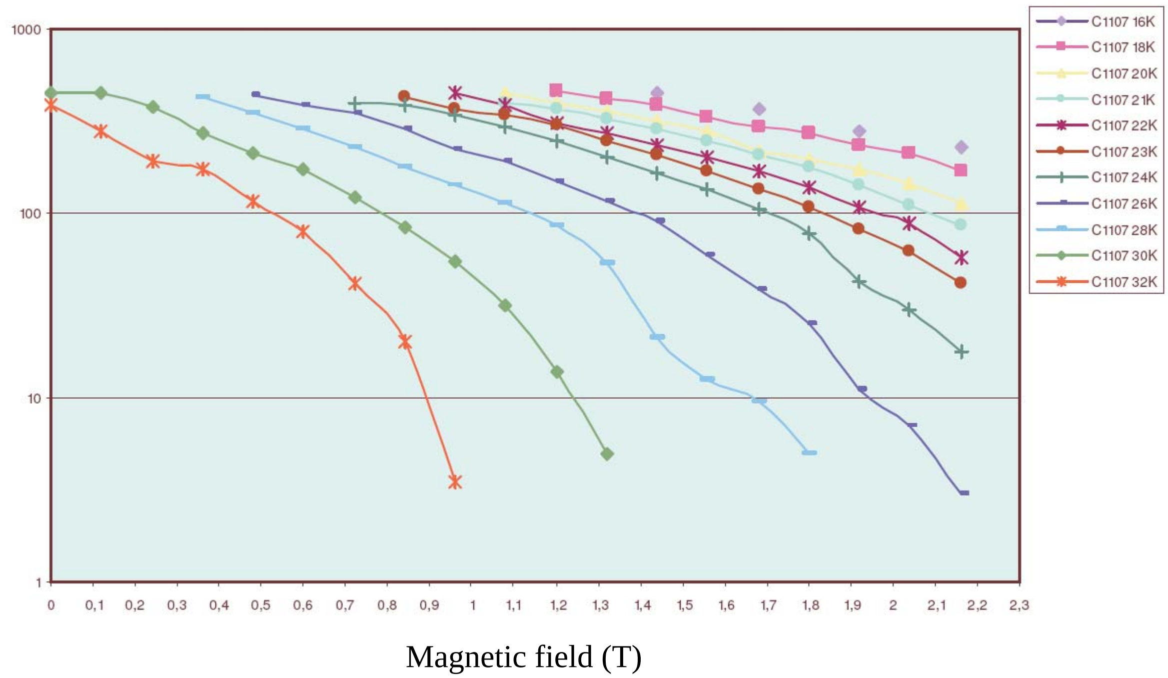

Figure 3: Critical current data as a function of temperature and magnetic field for one of the supplied conductors

The targeted critical current value was of the order of 200 A at 20K, 1.5 Tesla, which corresponds to the average value measured on each length of the produced conductor. The repeatability and homogeneity of the produced conductor is reported in the following figure. Conductor unit (1.7 km each)

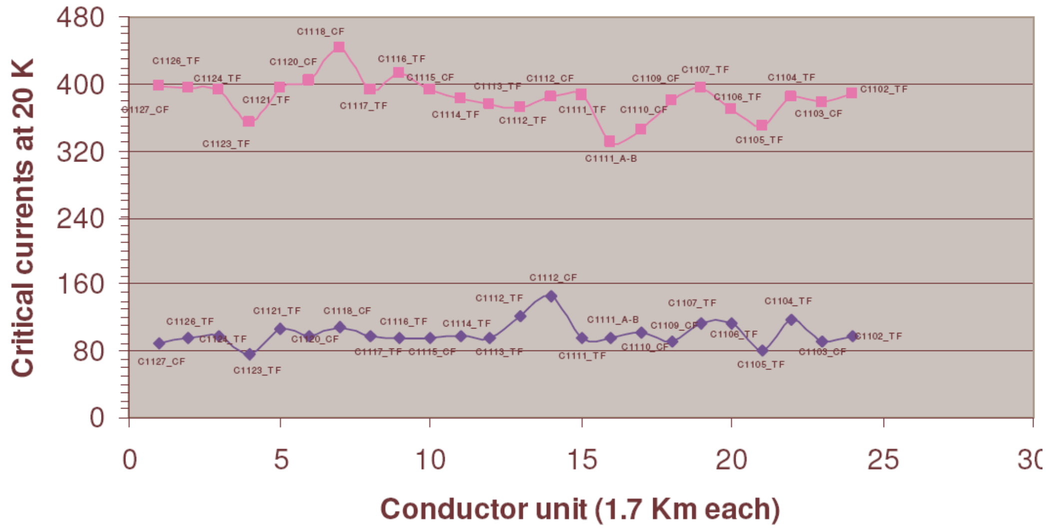

Figure 4: critical current at 20K and fields of 1 and 2 Tesla as a function of conductor batch number 6

The fluctuations of the critical current from batch to batch are limited to +/- 10%, which is acceptable for our application. In order to test the homogeneity of an entire length of 550 m, the only option has been to directly measure the quench critical current of an individual double pancake. For such purpose, a dedicated measuring system has been operated on a double pancake manufactured at Sintef and shipped to Columbus. The test results are shown in Table 3 below:

Table 3: Test results of first coil wound.

Temperature (K)	Critical current (A)	Max. magnetic field (T)
24	334	0.5
28	200	0.3
33	97	0.15

Quench currents of the double pancake wound at Sintef as a function of temperature and peak magnetic field on the winding. Comparing these results with the short sample critical current results, it appears that there is no major degradation of the superconductor due to the winding procedure.

Conclusions

The objective of producing a large amount (>18Km) of MgB_2 based superconducting tapes has been achieved. Aluheat has become so far the largest device ever developed using MgB_2 superconducting material. The homogeneity of the produced material has been verified both by sampling the conductors at their ends, as well as by testing an entire double pancake, both leading to successful results.

1.3.3 Cooling technology

The cryosystem includs components such as thermal interface, radiation shield, superinsulation structure, mechanical support, current leads, vacuum vessel and cryocooleers. The system is shown in figure 5. A stability analysis of the coil was performed. It was simulated that a safe quench can be performed. With the use of a dump resistor the coil can be cooled down faster to the operation temperature after a fault situation.

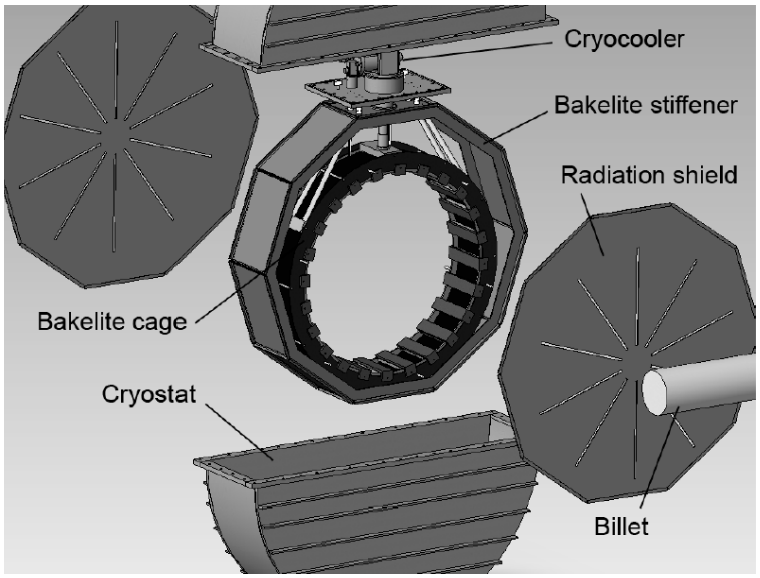

Figure 5: Overview of cryosystem

1.3.4 Current source

The overall layout of the dc power supply is shown in figure 6.

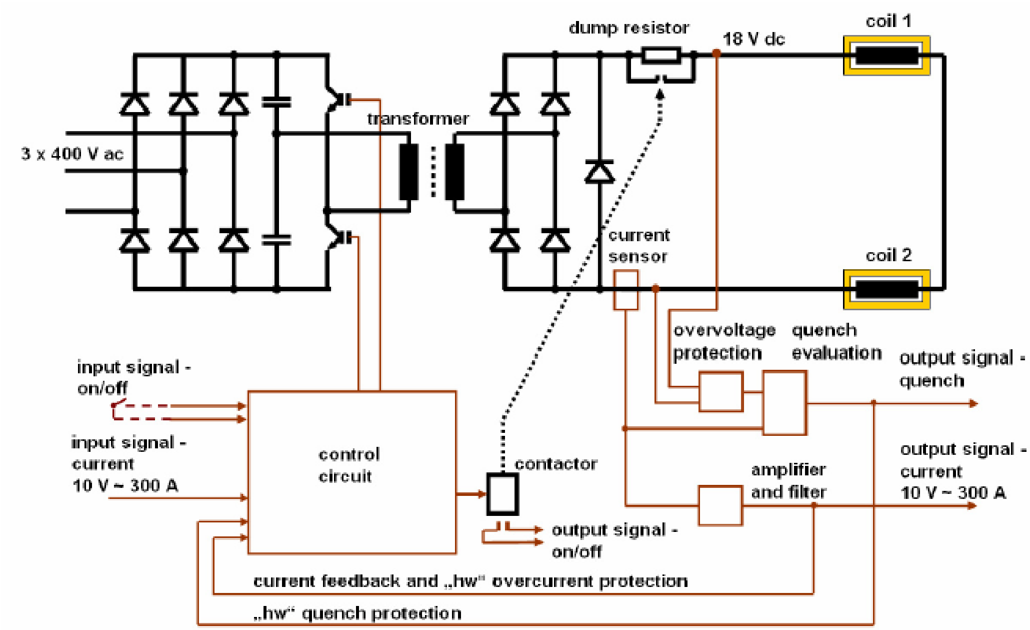

Figure 6: Overall layout of dc power supply.

The current rating has been upgraded to 300 A in order to be able to handle a superconductor with greater current carrying ability than previously expected. Moreover, a number of features for coil protection during a quench are included.

1.3.5 Mechanical design

The entire system consists of the following components:

1 - Machine-bed with axial pressure unit
2 - Turning spindle unit
3 - Opposed spindle unit
4 - Protection tunnel
5 - Workpiece transfer
6 - Workpiece magazine
7 - Machine frame - Cryostat storage
8 - Main drive
9 - Cooling unit

The manufacturing of the mechanical system was not finalized within the project period.

1.3.6 Superconducting coil winding

The winding of the superconducting coils are performed in three steps: 1. Insulating the tape. 2. Winding of double pan-cakes (coils consisting of two layers). 3. Assembly of the double pan-cakes to two coils.

<u>Step 1</u>: A machine for putting on electric insulation tapes (8 mm wide Kapton) on the MgB_2 superconductor was designed, built and successfully tested. The machine is depicted below to the left and a detail showing MgB_2 conductor with yellow Kapton foil wrapped around is shown to the right. With this machine 17 km of superconducting tape were insulated.

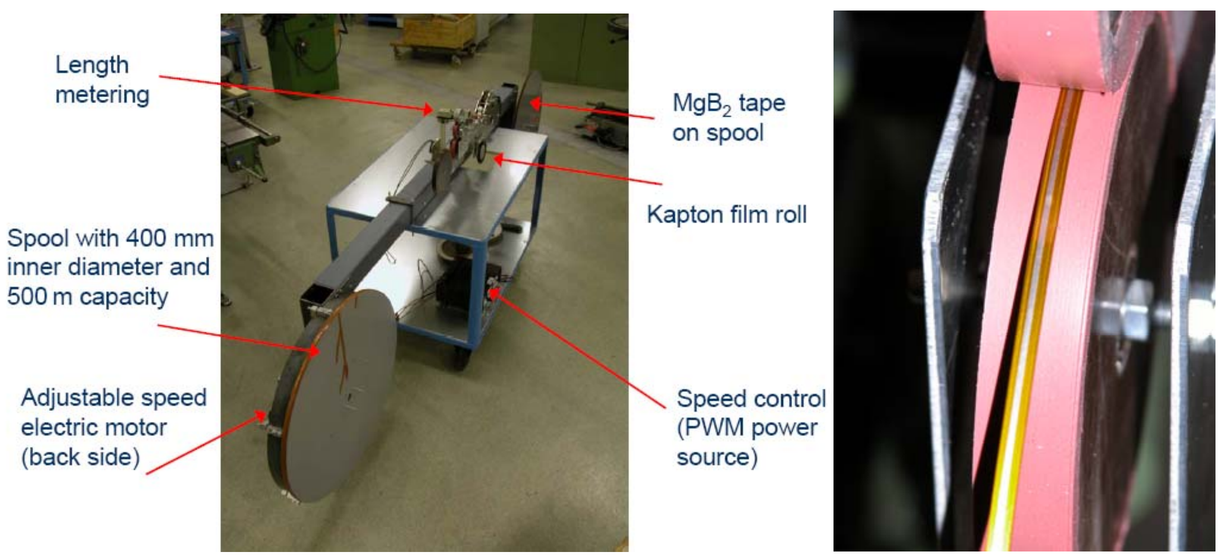

Figure 7: Insulation machine (left) and the insulated MgB_2 superconductor coming out from the machine (right).

<u>Step 2</u>: After insulating the tape, the winding of the double pancakes was initiated. A wet winding process was chosen. In this process a layer of epoxy is continuously applied to both sides of the tape just before the tape is wound into pancakes. Hence, between every turn of the coil there will be epoxy and there is no need for vacuum impregnation after winding. From experience with dry winding processes it is well-known that it may be very difficult to have epoxy penetrate everywhere in between the conductor layers.

Stycast 2850 epoxy with Catalyst 24LV as hardener agent was used. Stycast 2850 has a high content of alumina filler, and this improves the thermal conductivity and reduces the thermal contraction close to that of metals. The pot life at room temperature is about 1 h.

To wind the pancakes, a turning table with an adjustable speed motor drive was used (figure 8). The surface of the table and the inner structure were equipped with Teflon sheaths, greased with a release agent to facilitate the release of the coil after curing of the epoxy. At the other end, about 3 m away, the reel with the superconductor to be wound was placed.

The winding speed was about 8 m/min. The wet wound pancakes cured in room temperature on the winding table over night. However, by increasing the temperature to 65 °C the epoxy could be cured in only 2 hours. The increased temperature was obtained by passing a DC current of 2.5 A (generating about 100 W) through the tape. It was then possible to electrically insulate and wind two double pancakes in one working day.

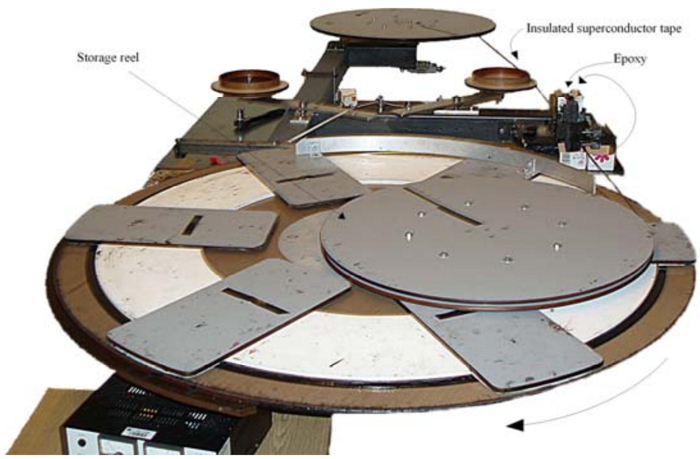

Figure 8: Winding table.

Step 3: This part of the winding process was performed after the project end (see chapter 1.4 below).

1.4 Post project results

After the project certain activities have continued. One important such activity is the step 3 in the winding process of the coil. Another is testing of the coil.
Step 3 of the winding process: The 16 double pan-cakes were stacked on top of each other. Stycast 2850 was used to fix the double pan-cakes to each other and to the cooling interface. The double pan-cakes were then connected in series by soldering the conductor end of one pan-cake to the end of the next.

Good joints between the double pan-cakes are crucial to avoid heating. Tests were performed in advance to secure a reliable soldering technique. A modified soldering iron which applied both heat and pressure to the joint was used. A high enough pressure was essential to squeeze out all the excessive soldering tin at the soldering temperature of 250 – 300 °C. Figure 9 shows a good and a bad joint with the resistance of the bad joint being about 2 times higher than the good one.

For the coil, 100 mm overlap joints were used. The soldering tin was regular Sn50Pb49Cu1 and this tin was applied to both contact surfaces before melting them together. Voltage taps were soldered to each end of the pan-cakes for measurements of the voltages over the joints and over the pan-cakes.

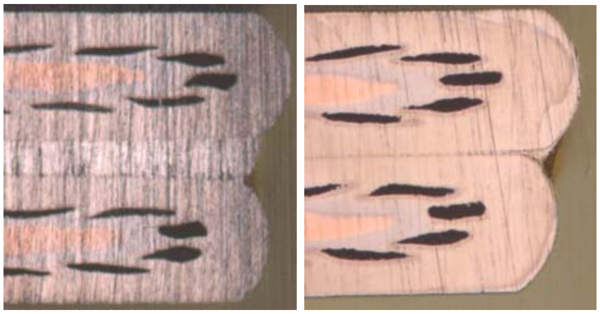

Figure 9: Worthy joint to the right and bad joint to the left, due to too low contact force applied during soldering.

Cool down: The system was successfully cooled down and the coil energized.

1.5 Project information

The project website has been www.aluheatproject.com.

Information can also be obtained by contacting the co-ordinator at niklas.magnusson@sintef.no

2. Dissemination and use

2.1 Exploitable knowledge and its use

Overview table

Exploitable Knowledge (description)	**Exploitable product(s) or measure(s)**	**Sector(s)** of application	Timetable for commercial use	Patents or other IPR protection	**Owner** & Other Partner(s) involved
1. Superconducting MgB_2 tape manufacturing technology	*High field dc magnets*	*1. Medical NMR 2. Dc billet heater coils*	*2007 2011*		*Columbus*
2. Superconducting coil winding technique	*Superconducting coils*	*1.Industrial 2.Electrical utilities 3. Medical*	*2011*		*SINTEF*
3. Superconductor tape insulation	*Insulation machine*	*1.Industrial 2.Electrical utilities 3. Medical*	*2009*		*SINTEF*
4. Cooling technology	*Large magnets*	*1.Industrial 2.Electrical utilities 3. Medical*	*2010*		*TUT*

1. *Superconducting MgB_2 tape manufacturing technology*: Columbus Superconductors has developed a superconductor to a commercial performance level. The superconductor is available to the market.
2. *Superconducting coil winding technique*: The wet winding technique developed at SINTEF can be used in further research projects. With this technique at hand and the knowledge of its important steps, any project involving an MgB_2 coil can more easily be realized. SINTEF intend to use this knowledge in its marketing.
3. *Superconductor tape insulation*: A fast and reliable method for insulation of superconducting tapes is available at SINTEF. The availability of the machine will be discussed with possible project partners in future projects.
4. *Cooling technology*: The cooling system developed at Tampere University of Technology can form a basis for several different kinds of superconducting coils. TUT has gained the knowledge to build such coils for prototype superconductor applications.

2.2 Disseminations of knowledge

Planned /actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible /involved
2005-2010	*Project web-site*	*General public*	*All*		*All*
2006	*Publications*	*Research*	*All*		*All*
2007	*Conference presentations*	*Research*	*All*		*All*
2007	*Conference session at Aluminium 2007, Kliczkòw, Poland*	*Mainly industrial*	*Mainly European*	*Approx. 100*	*IMN-OML*
2007	*One day seminar at University of Bologna*	*University students and faculty*	*Italy*		*SINTEF*
2008-2009	*Journalist contacts*	*General public*	*All*		*SINTEF*
2009	*Radio appearance*	*General public*	*Norway*		*SINTEF*
2008-2009	*Popular science articles*	*General public*	*Norway/all*		*SINTEF*

Publications

The following scientific papers have been published:

A. Stenvall, A. Korpela, R. Mikkonen and P. Kovac, "A Critical current of an MgB2 coil with a ferromagnetic matrix", Supercond. Sci. Technol., vol. 19, pp. 32 - 38, 2006.

A. Stenvall, A. Korpela, R. Mikkonen and G. Grasso, "Stability considerations of multifilamentary MgB_2 tape", Supercond. Sci. Technol., vol. 19, pp. 184 - 189, 2006.

A. Stenvall, A. Korpela, R. Mikkonen and G. Grasso, "Quench analysis of MgB_2 coils with a ferromagnetic matrix", Supercond. Sci. Technol., vol. 19, pp. 581 - 588, 2006.

N. Magnusson and M. Runde, "A 200 kW MgB2 Induction Heater Project", J. Phys: Conf. Ser., vol. 43, pp. 1019-1022, 2006

N. Magnusson, "Prospects for Rotating Billet Superconducting Induction Heating", Proceedings of the Heating by Electromagnetic Sources Symposium, pp. 479-486, Padua, Italy, June 19-22, 2007

A. Stenvall, N. Magnusson, Z. Jelinek, G. Grasso, I. Hiltunen, A. Korpela, J. Lehtonen, R. Mikkonen, and M. Runde, "Electromagnetic viewpoints on a 200 kW MgB2 induction heater", Physica C vol. 468, pp. 487-491, 2008

M. Runde, A. Stenvall, N. Magnusson, G. Grasso and R. Mikkonen, “MgB2 coils for a DC superconducting induction heater“, J. Phys.: Conf. Ser. Vol. 97, 012159, 2008

B. Nacke and N. Magnusson, “Heating of Aluminium Billet by Rotation in DC Field Using Superconducting Coil”, Proceedings of Aluminium 2007, Referat 12, Kliczkow, Poland, 24-26 October, 2007

A. Ulferts and B. Nacke, “Contact-less temperature measurements of aluminium surfaces”, Proceedings of Aluminium 2007, Referat 13, Kliczkow, Poland, 24-26 October, 2007

B. Plonka, A. Milenin, J. Senderski and T. Stuczynski, “Numerical simulation of temperature distribution in billet and in the extruded bar during the process of quasi-isothermal extrusion”, Proceedings of Aluminium 2007, Referat 14, Kliczkow, Poland, 24-26 October, 2007

N. Magnusson, M. Runde, S. Dappen, A. Dobosz, P. Blau, G. Kalkowski, G. Grasso. R. Mikkonen, Z. Jelinek, B. Nacke and T. Stuczynski, “Building a 200 kW Rotating Billet Superconducting Induction Heater”, Proceedings of the 9th International Aluminum Extrusion Technology Seminar & Exposition, Orlando, USA, 13-16 May, 2008

I. Hiltunen, A. Stenvall, A. Korpela, J. Lehtonen, R. Mikkonen, M. Runde, N. Magnusson and G. Kalkowski, “Cryogenic Design of the Aluheat Project”, ADVANCES IN CRYOGENIC ENGINEERING: Transactions of the Cryogenic Engineering Conference, CEC, Vol. 53, Chattanooga, 16-20 July, 2007

M. Zlobina, B. Nacke, A. Nikanorov and G. Galunin, ”Numerical Modelling of an Innovative Induction Heater Technique for Aluminium Extrusion Process”, Proceedings of IFOST-2008 - 3rd International Forum on Strategic Technologies, p 487-491, 2008

I. Hiltunen, J. Jarvela, J. Lehtonen, R. Mikkonen, A. Stenvall and J. Viljamaa, “Transverse Thermal Conductivity in an Epoxy Impregnated MgB_2 Coil“, IEEE Trans. Appl. Supercond. Volume 19, Issue 3, Part: 2, Pages: 2407 – 2410, 2009

A. Stenvall, I. Hiltunen, A. Korpela, J. Lehtonen, R. Mikkonen, J. Viljamaa and G. Grasso, “A checklist for designers of cryogen-free MgB2 coils“ Supercond. Sci. Technol., vol. 20, no. 4, p 386-391, 2007

A. Ulferts and B. Nacke, “ALUHEAT - A superconducting approach of an aluminium billet heater”, International Scientific Colloquium: Modelling for Electromagnetic Processing, Hannover, October 27-29, 2008