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Abstract. This paper describes the development and manufacture of a 1.7MW, 5.25kV, 28pole, 214rpm hydroelectric power generator consisting of superconducting HTS field coils and a conventional stator. The generator is to be installed at a hydro power station in Hirschaid, Germany and is intended to be a technology demonstrator for the practical application of superconducting technology for sustainable and renewable power generation. The generator is intended to replace and uprate an existing conventional generator and will be connected directly to the German grid. The HTS field winding uses Bi-2223 tape conductor cooled to about 30K using high pressure helium gas which is transferred from static cryocoolers to the rotor via a bespoke rotating coupling. The coils are insulated with multi-layer insulation and positioned over laminated iron rotor poles which are at room temperature. The rotor is enclosed within a vacuum chamber and the complete assembly rotates at 214rpm. The challenges have been significant but have allowed Converteam to develop key technology building blocks which can be applied to future HTS related projects. The design challenges, electromagnetic, mechanical and thermal tests and results are presented and discussed together with applied solutions.

1. Introduction

The Advanced Technology Group at Converteam, Rugby is currently involved in a European Union part-funded project to design, develop and manufacture a superconducting hydroelectric generator. Although this machine is primarily a technology demonstrator, it is intended to replace and uprate one of three conventional generators at a power station in Southern Bavaria, Germany - to generate and supply electricity to the German grid.

The machine is rated at 1.79MVA, 5.25kV, 0.95pf (over excited), 28 poles, 214rpm, with an over speed of 320rpm and a runaway speed of 450rpm. It is a horizontal shaft machine driven by a Francis double turbine with integral thrust bearing and is part of a run-of-the-river hydroelectric power scheme. The generator has a back-of-core diameter of 3m and an axial length of 1m.

1.1. Why Superconducting Machines

HTS wire is presently very expensive but forecasts from the major wire manufacturers indicate that in time these novel materials could cost less than copper! For example, the cost to carry 1000A over 1m using copper (at the current densities used in conventional high power density motors) is about US$15/kAm (with copper prices at US$6.5/kg), whereas present HTS (1G) wire has only just fallen to below US$100/kAm.

HTS machines can be 30% of the size of conventional machines leading to potential savings in weight, volume and material costs. The most attractive markets are those where high power density and particularly high torque is required – achieved by utilising higher magnetic flux densities and reduced iron in the magnetic circuit – both achievable with HTS materials. Ship propulsion motors and wind turbine generators are potential candidates for such technology.

Electrical efficiency improvements of several per cent are possible leading to substantial operational cost savings over the lifetime of the machine. A rotor with an HTS field winding has almost zero ohmic losses – the power consumed by the cryogenics is a small fraction of the normal losses in a conventional rotor – about 25kW compared to 300kW in a 25MW machine. These higher efficiencies are available even with the machine operating under partial load conditions.

Higher steady state system stability is also attainable due to the inherently low reactances associated with certain designs of HTS machine which employ large magnetic air gaps. A lower synchronous reactance permits operation of these HTS machines at smaller load angles compared to conventional machines. Another consequence of a low synchronous reactance is a high short circuit ratio, which might be beneficial if the machine operates within 'weak' electrical power grids with low short circuit power. An additional benefit of an HTS machine with decreased armature reaction is its somewhat 'stiff' behaviour within an electrical power network, producing only small voltage changes with changing electrical loads. Certain designs of HTS machines can supply both leading and lagging reactive power up to their full rating.

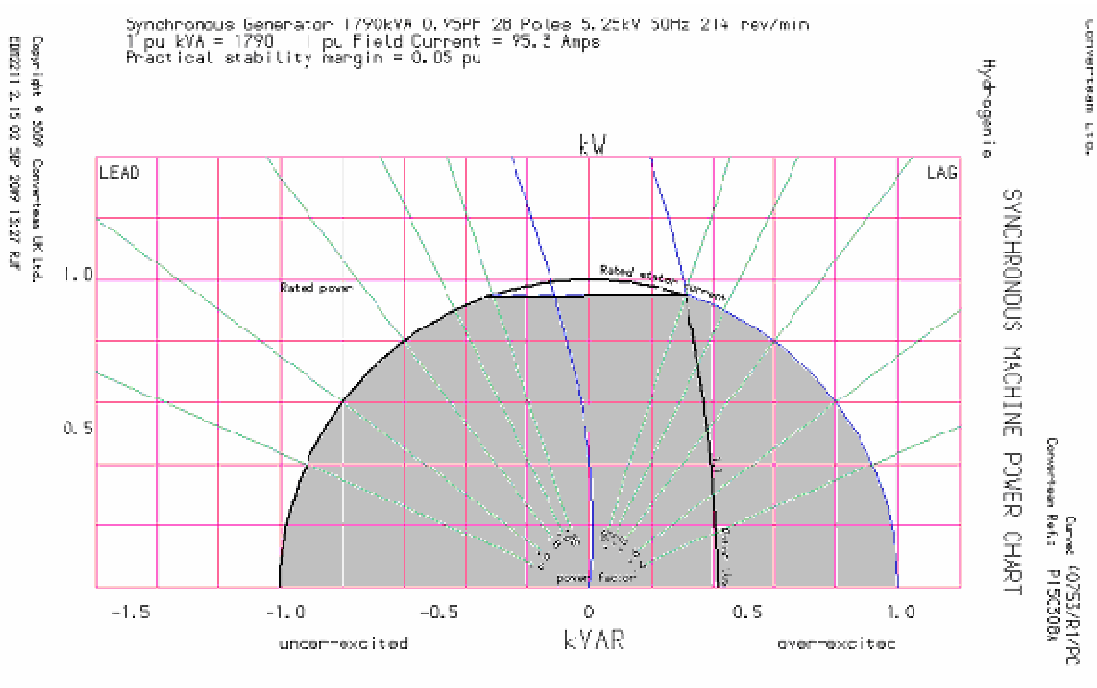

Fig.1 Hydrogenie HTS generator operating chart (safe operating region shown shaded)

Thermal cycling of conventional copper rotor field windings can cause winding failures in large power generators as the ground and turn insulation deteriorates due to mechanical wear. A rotor using HTS field coils will undergo fewer thermal cycling events as the winding will always be at the same cryogenic temperature. All thermal contraction and expansion of the winding and its suspension system will only occur during cool down and warm up of the rotor.

2. Selection of Machine Design Concept

The high current density of HTS materials allows the use of designs without iron or with a partial iron magnetic circuit.

A. Conventional stator with iron teeth + rotor with magnetic pole bodies (warm or cold)

B. Conventional stator + rotor with non magnetic pole bodies – more HTS wire needed, but lower cold mass – otherwise similar to A.

C. Airgap stator winding + rotor with magnetic pole bodies – rotor iron can be operated highly saturated – allows significant reduction in size and mass.

D Airgap stator winding + rotor with non-magnetic pole bodies – uses more HTS wire than C (depending on flux density) - significant reduction in size and mass.

Hydroelectric generators require high inertia; hence reduction of mass was not a key driver in this case.

Design Type A was selected primarily to satisfy the requirement to be able to synchronise the machine directly to the electrical grid (an air-gap winding at 28 poles, 50Hz would have resulted in most of the HTS Ampere-Turns being wasted as leakage). The machine construction was therefore fairly conventional i.e. iron stator and copper winding with 1G HTS (Bi-2223) field coils on a more-or-less conventional rotor using magnetic iron at room temperature.

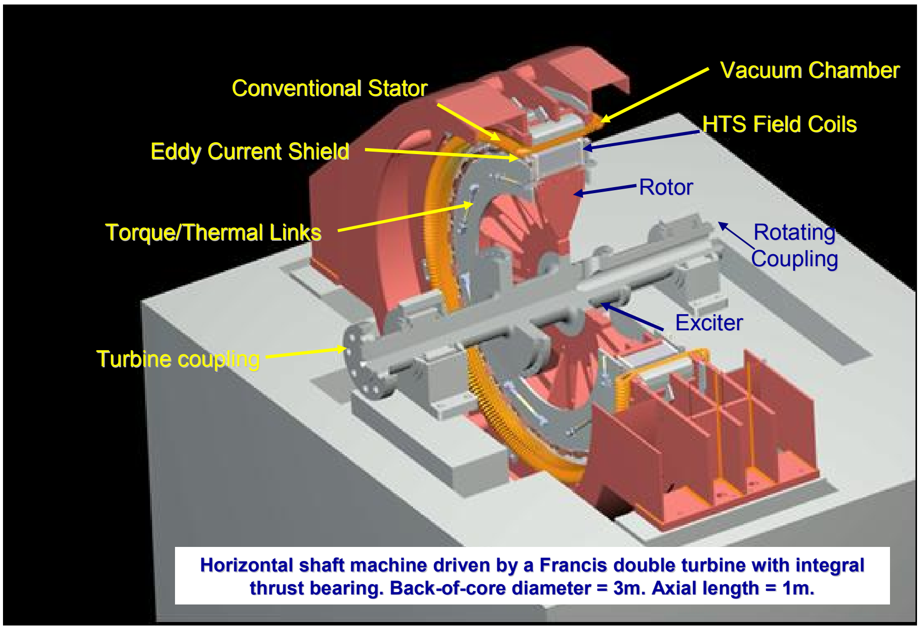

Fig.2 The HYDROGENIE superconducting generator

Keeping the rotor iron at room temperature reduces the overall cold mass of the superconducting rotor. This reduces the required cryogenic cooling power and allows faster cool down and warm up times. Special steel suitable for operation at cryogenic temperatures, although available, was thus not necessary for this generator.

The majority of the load torque is transferred from the rotor shaft and magnetic iron poles directly to the stator teeth and then to the stator core frame with minimal torque acting on the superconducting coils, resulting in a more simplified suspension system.

The complete rotor is housed within a vacuum chamber which is sealed to and rotates with the shaft. The HTS coils are cooled using gaseous helium at about 30 to 40K, from a Stirling-type cryocooler, which is pumped up the shaft and radially outwards to the coils. As the rotor iron is at room temperature, the individual HTS field coils 'float' over the iron poles and are wrapped in multi-layer insulation as are all the other cryogenically cold components. The suspension system consists of radially and axially located glass fibre rods linking 'cold' and 'warm' components.

Field excitation for the HTS coils is provided via electronic circuitry located on the outside wall of the vacuum chamber. The temperature and voltage of each HTS coil is monitored continuously and is fed into the control and protection circuitry also located on the outside of the vacuum chamber. Communication between the HTS machine and the Automatic Voltage Regulator (A.V.R.) is provided via a wireless link. A rotating brushless interface, instead of slip rings, was selected to provide a robust and reliable means of providing electrical power for the electronics mounted on the vacuum chamber.

3. HTS Winding Design and Construction

The maximum current carrying capacity (I_c, critical current) of HTS wire is normally quoted with its self-field at a temperature of 77K i.e. with no externally applied magnetic field. If an external field is applied the critical current reduces. HTS flat conductor is more sensitive to fields in the direction perpendicular to the broad face compared to the narrow face. Minimising exposure to this particular magnetic field vector is therefore a key part of our HTS coil design.

The critical current density decreases as the stress or strain in the wire increases - this can be very difficult to quantify in practice. Recommendations from HTS wire manufacturers with respect to minimum bend radii and wire strains were adhered to.

The coil and former design needs to be able to cope with the relatively high rotational 'g' forces which also contribute to the overall stress in the HTS conductors. For this particular design most of the torque is experienced by the field pole iron rather than the coils, however the coil design still needs to allow for worst case short circuit conditions when the field current, and therefore coil forces, can increase significantly.

Coil winding and impregnation processes can influence coil performance significantly, as can soldering temperatures whilst making joints. Differential thermal contraction between the coil winding pack and the coil former can also contribute to the stress within a coil and can lead to delamination of the winding pack.

We only get true superconductivity with direct current. Alternating current and time-varying fields produce losses in the HTS wire necessitating the use of eddy current shields. These shields are only truly effective for a certain range of frequencies – therefore the performance of the coil and the overall system heat budget must make allowance for additional internal coil heating produced during the various phases of operation of the generator.

The a.c. losses within the HTS coils also limit the rate at which the field current is allowed to change.

4. Cooling and Coolant Transfer

Low temperature superconductors require cooling to sub-30K temperatures, normally using liquid helium at 4K. With helium costs ranging from £3 to £6/litre, this can be prohibitively expensive. High temperature superconductors can be cooled by liquid nitrogen at 77K which is much cheaper at about £0.70/litre. However, to get any useful work out of the current range of HTS materials, they still need to be cooled to lower temperatures of about 30 or 40K.

Commercially available cryocoolers can provide about 100W or more of cooling power at 25 to 40K and the relative cooling costs are lower when compared to the cost of liquid helium.

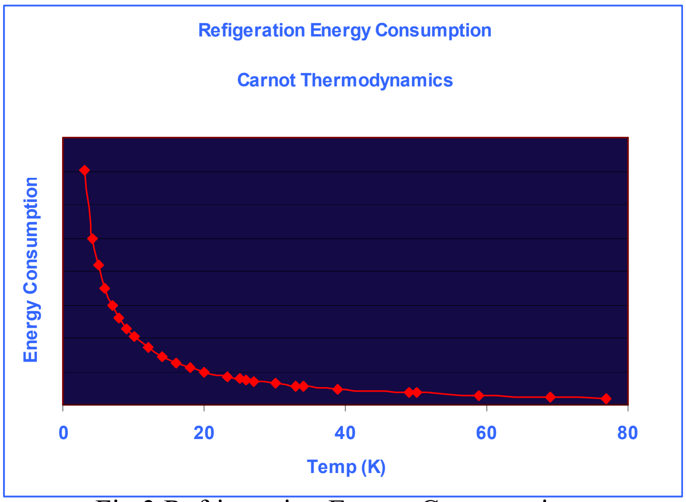

Fig.3 Refrigeration Energy Consumption

Although it is widely accepted that the ideal Carnot efficiency can never be attained in practice, present cryocooler designs are still a very long way off this ideal – a typical work input/output ratio for the temperature range 300K to 30K is approximately 100:1 – i.e. to obtain 100W of cooling power at 30K, an electrical input power of about 10kW is required.

For rotating machinery, one of the significant challenges lies in transferring the cryogenic coolant from a stationary cryocooler to a rotating component. A rotating coupling is usually the solution and in its simplest form uses two concentric thin-walled tubes, one rotating inside the other. Seals used can be either PTFE or ferrofluid or a combination of the two. At high speeds and torques, ferrofluid seals can generate a considerable amount of heating which must be removed. Alignment, robustness and reliability of these transfer couplings remain key concerns.

Transferring the 'cooling' to where it is needed on the HTS coils poses its own challenges and is dependent on the heat transfer mechanism employed – be it via convection or conduction. For conduction cooling methods, choice of high thermal conductivity materials, e.g. annealed high purity copper as well as material surface conditions can be critical for adequate thermal transfer – oxidation of thermal transfer surfaces should be kept to a minimum.

Soldered thermal connections are best but need to be assessed for integrity. Correct choice of solder for operation in vacuum and at cryogenic temperatures is essential to ensure even solder flow between jointed parts (without void formation) and the prevention of cracking when subjected to repeated thermo-mechanical cycling. Bolted connections are also a possible solution but again, thermal differential contraction of materials must be allowed for, usually by employing the use of disc springs with bolts torqued to appropriate values. On a rotating machine, some vibration is always present and can loosen bolts and fixings if not secured appropriately.

Depending on the cooling mechanism employed, different parts of the HTS machine can cool down at different rates which can lead to differential stresses between welded and bolted components, necessitating the use of flexible connections such as braids, bellows and disc springs.

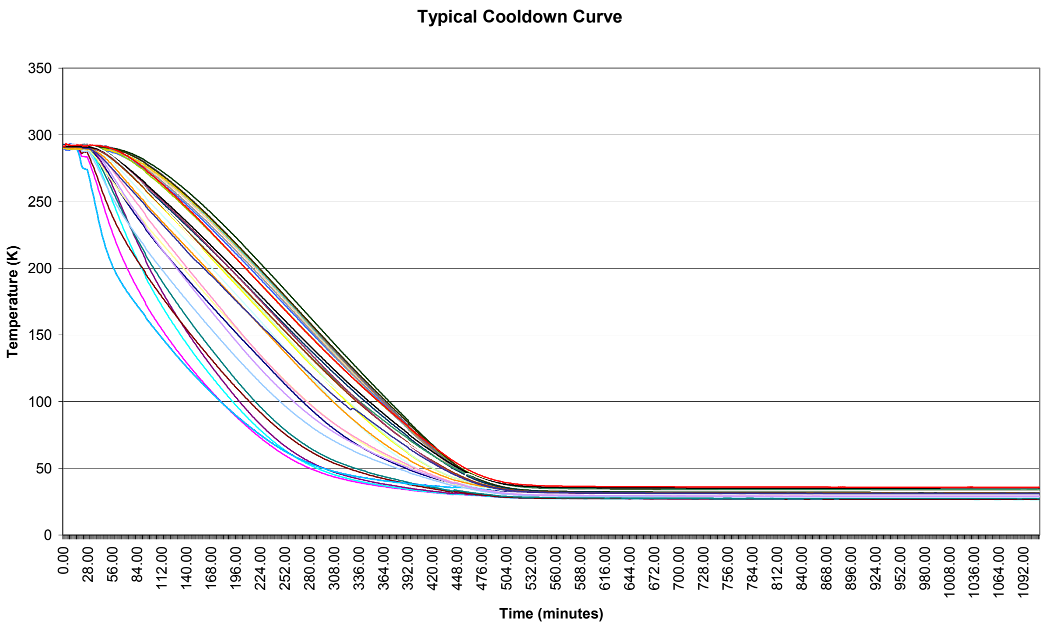

Fig.4 Typical Cool Down Profile

5. Minimisation of Heat Loads

The Hydrogenie machine heat budget is split fairly evenly between conduction and radiation heat loads with a small amount linked to internal coil heat generation during operation.

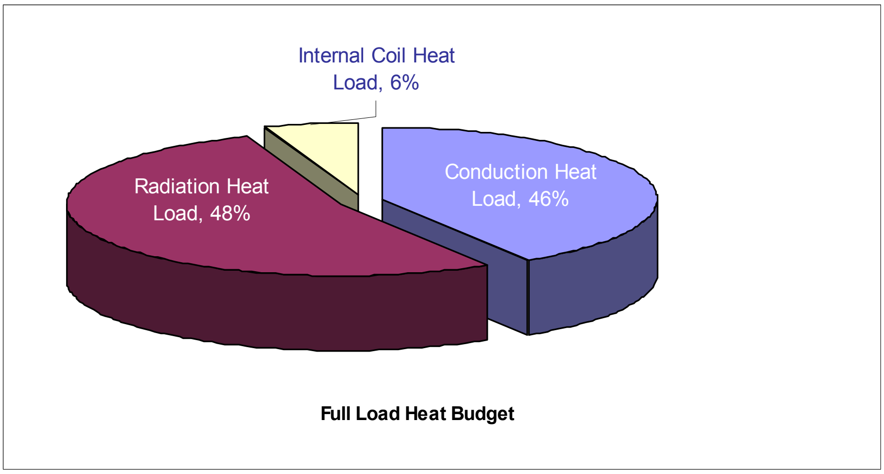

Fig.5 HYDROGENIE Heat Budget

Conduction loads were reduced by the appropriate use of low thermal conductivity materials (e.g. GFRP, CFRP) for the linkages between cryogenic components and components at room temperature. However, as these links are also intended to transmit some torque, a compromise had to be struck between reducing cross sectional area (to reduce heat load) and increasing it for strength. A mechanical test rig was developed to allow tensile testing of these links down to 30K.

A vacuum space was used to minimise conduction and convection heat loads, and it was critical that this space was kept scrupulously clean. A vacuum level of about 1 x 10^{-5} mbar was found to be adequate for our generator. Rotating machinery construction involves the use of many non-vacuum friendly materials like mild steel, plastic and paper insulation materials, impregnation resins, lubricating oils and greases, etc. It was therefore essential that, wherever possible, materials were cleaned to at least high vacuum standards and clean handling methods and manufacturing areas were employed during the machine build.

Rust is extremely hygroscopic and corrosion was therefore kept to a minimum by the plating of large components. Certain key components were also vacuum baked to remove moisture. A controlled pump down and cool down process was also adopted to produce a clean moisture-free system. Differentially pumped vacuum seals greatly reduced the ‘in-leak’ into the vacuum system.

‘Trapped volumes’ were eliminated by the careful design of all vacuum sub-assemblies – otherwise these volumes would have manifested themselves as ‘leaks’ thereby degrading the vacuum level and limiting the operational lifetime of the machine. Appropriate fasteners, for example vented bolts and washers, and vacuum compatible weld preps were used for all sub-assemblies within the vacuum chamber.

Outgassing and residual gas analyses were carried out for each individual material used within the vacuum chamber to enable the proper design of vacuum seals, cryopumping surfaces and getters. Vacuum degassing of the rotor shaft steel was carried out while still in its molten state, primarily to remove hydrogen.

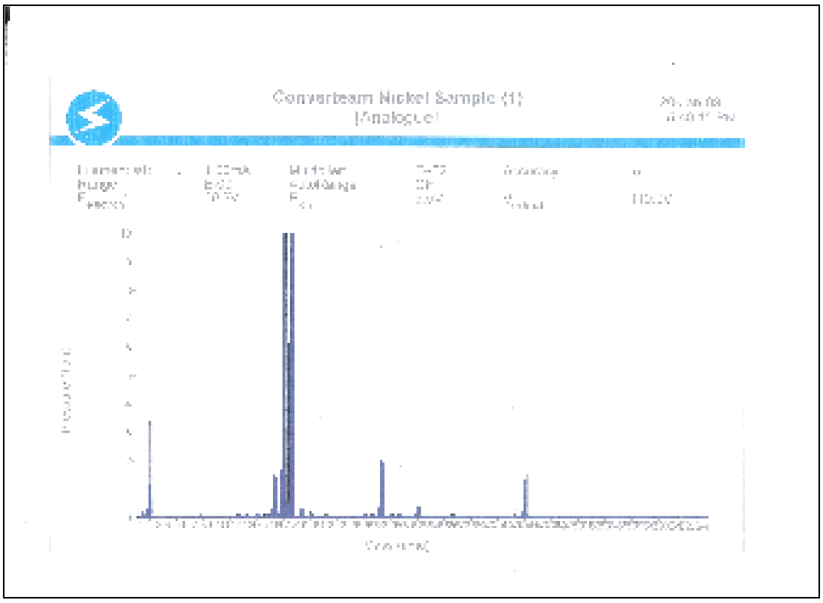

Fig.6 Spectral peaks from outgassing tests

Cryogenically cold surfaces can behave as ‘cryopumps’ and act to ‘remove’ certain contaminants within the vacuum system, thereby improving its overall vacuum level - typically by an order of magnitude.

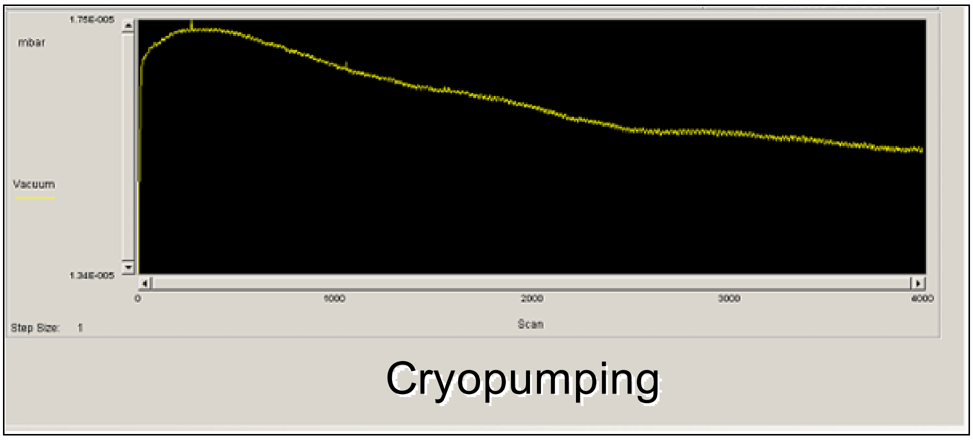

Fig.7 Improvement of vacuum level due to cryopumping (vacuum pumps turned off)

In order to assess the efficacy of any cryopumping surface, the temperature of the said surface and its surrounding vacuum pressure level must be established [1, 2]. For example, if there is a leak from atmosphere into a vacuum chamber operating at 1 x 10^{-5} mbar, in order to successfully cryopump N2, the major constituent of air, the cryopumping surface temperature needs to be lower than 30K.

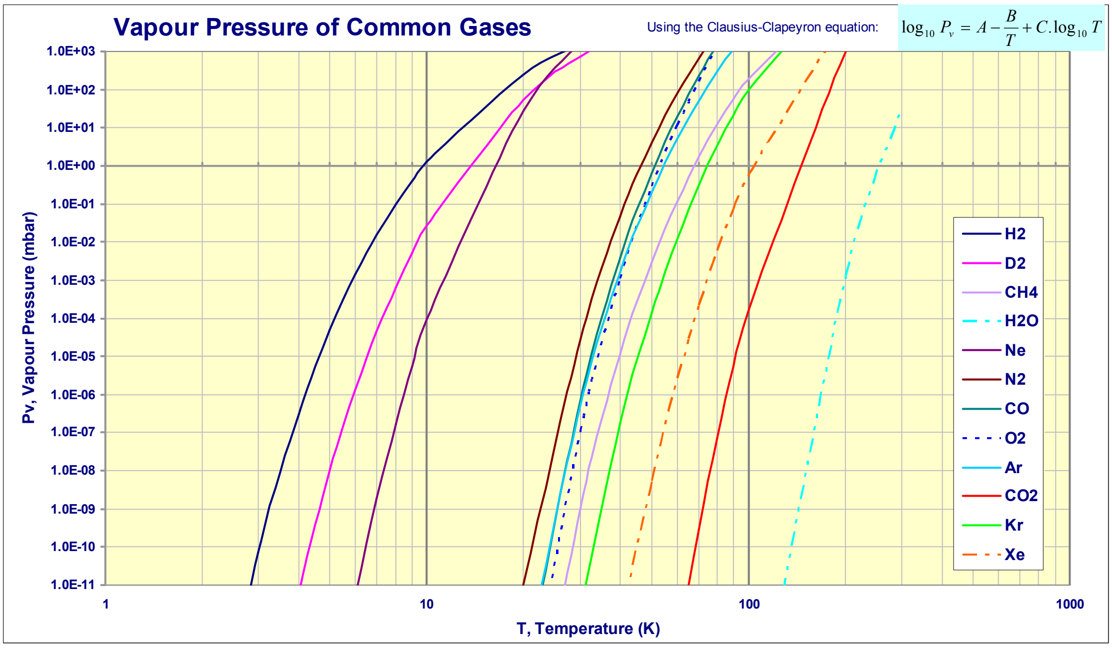

Fig.8 Vapour pressure of some common gases

Multi-layer insulation (superinsulation) was utilised to reduce radiation heat loads onto cryogenically cold components. These pre-cut MLI blankets were appropriately supported against rotational forces. During the application of these blankets care was taken not to thermally short the individual layers of the blanket. Vulnerable areas are the joints between individual blankets and sufficient overlap area was employed.

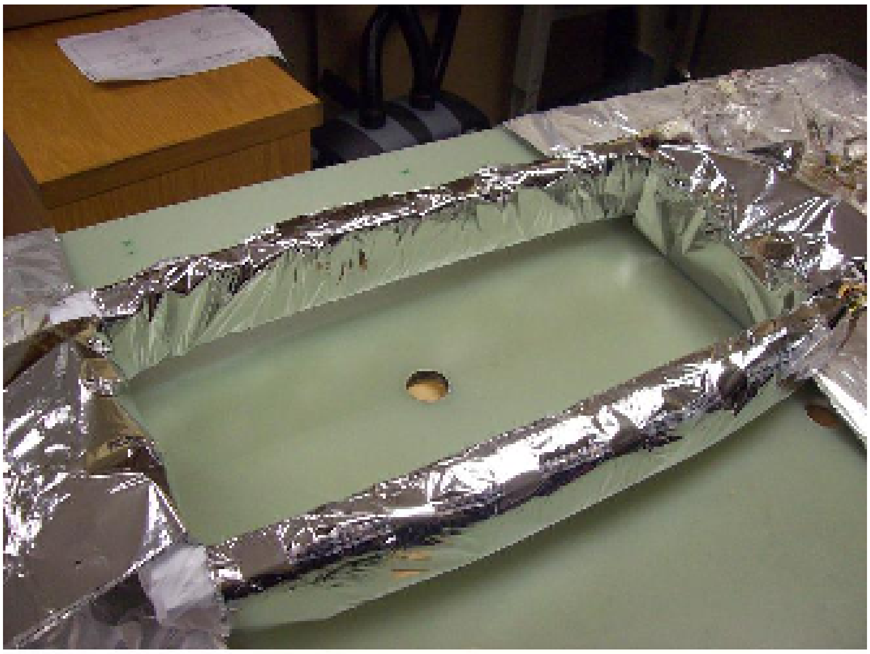

Fig.9 MLI blanket being fitted to an HTS coil

An estimation of the radiation heat load transmitted through a typical (uncompressed) multi-layered superinsulation blanket can be obtained using [3]:

$$\frac{Q}{A} = \frac{\sigma . e . \left(T_2^4 - T_1^4\right)}{n+1}$$

Q/A = Watts transmitted per unit area (W/m^2)
σ = *Stefan-Boltzmann Constant* = 5.67×10^{-8} $W/(m^2K^4)$
e = emissivity
T_2 = *'hot' surface temperature*
T_1 = *'cold' surface temperature*
n = no. of layers of superinsulation

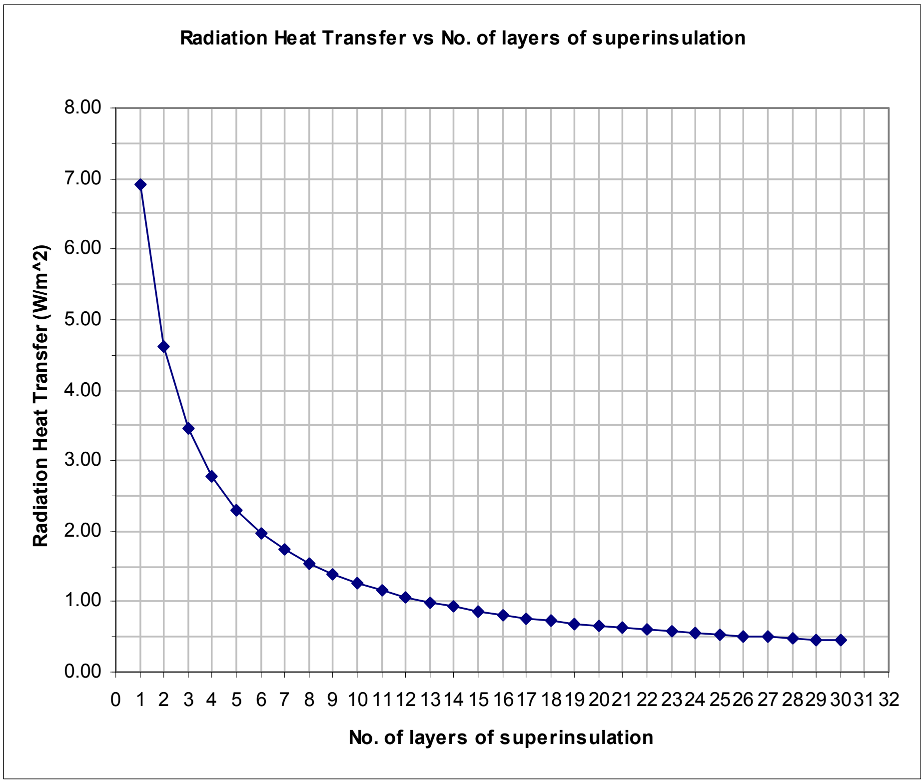

Fig.10 Radiation heat transfer vs no. of layers of superinsulation *(T_2 = 300K, T_1 = 30K, e = 0.03 for aluminised Mylar)*

It is essential that these blankets are not over-compressed or their excellent radiative properties will be compromised by conduction heat loads through the compressed blanket walls. The effect of compression on the performance of these blankets can be assessed using the following chart.

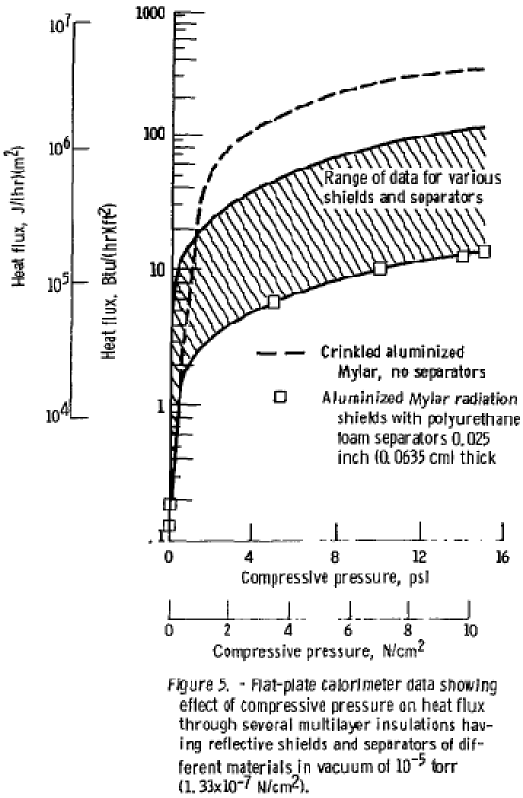

Fig.11 Increase in radiation heat load transmitted through a MLI blanket due to compression of the blanket [4]

Special consideration was also be given to the design of the HTS coil current leads. The leads were profiled in order to minimise the conduction heat load – by varying the cross section of the leads along their length. The leads together with all the diagnostic wiring was also thermally dumped to further reduce conduction heat loads.

6. Key Enablers for HTS Rotating Machinery

As we see it, there are five key areas for further development that are crucial to the successful application of HTS materials to rotating machinery.

1. **Industrialisation of cryocoolers**
   - This equipment needs to be low maintenance or preferably maintenance-free.
   - Have low susceptibility to vibration.
   - Able to withstand the high ‘g’ forces due to rotation (for rotor mounted coolers)
   - Low mass and low profile
   - Higher efficiencies are required

2. **Industrialisation of rotating cryogen transfer couplings**
   - Must not impose high heat loads
   - Need to be robust and have low susceptibility to vibration and misalignment
   - Long term reliability is all important

3. **Industrialisation of instrumentation and vacuum components**
   - e.g. high vacuum pressure gauges, valves, getters etc. capable of withstanding high 'g' forces due to rotation
   - Low mass and low profile

4. **Industrialisation of vacuum pumps**
   - This equipment needs to be low maintenance or preferably maintenance-free. (Note: Turbo pumps with magnetic bearings are available but backing pumps still fall short of these requirements)
   - Capable of withstanding high 'g' forces due to rotation
   - Low mass and low profile

5. **Supplier chain and test facilities**
   - Suppliers with an appreciation of the requirements for good vacuum and cryogenic practice
   - Flexible bespoke test facilities for testing at cryogenic temperatures (outgassing, thermal conductivity, stress and strain etc.)

7. Conclusion

It is clear that the electromagnetic design of an HTS machine cannot be carried out in isolation from the cryogenics and vacuum design. These areas need to be considered as early on in the design process as possible.

In order to be able to apply HTS technology successfully, a company's infrastructure must be able to support it. For example, appropriate testing facilities are crucial as are suitable industrial and academic partners. An understanding of good vacuum and cryogenic practice is essential for the successful production of these machines as is the availability of 'clean' manufacturing facilities.

Fig.12 Test vacuum chamber and associated equipment

Databases of experience and knowledge are essential in order to qualify the materials and processes applied within the dual fields of cryogenics and vacuum technology. National laboratories like the Rutherford Appleton and Daresbury Laboratories have vast amounts of expertise and knowledge databases that can be tapped – usually for a fee. Similarly, certain specialist suppliers to various industries, notably aerospace and motor sport can also be of enormous assistance.

At present, the application of superconductivity to industrial equipment can be extremely costly with low economic returns and limited technical advantage over conventional technology if its application is not handled selectively and appropriately.

Cryogenics and vacuum technologies (like superconductivity itself) are sometimes treated like the 'black arts'. However, that attitude is simply due to the fact that for every HTS related project, the number of variables is high and they are all interlinked - any one of them can compromise a cryogenics or vacuum system if not treated appropriately. It is for this reason that most present HTS machines are over designed. Until we can begin to understand better the limits of this technology, only then will we be able to make more educated design compromises.

Acknowledgments

This work was supported by a partial grant from the European Union Framework 6 Programme. The project involves a consortium of companies led by Converteam U.K. and consists of E.On Wasserkraft GMB, KEMA Nederland BV, Politechnika Slaska (Silesian University of Technology, Poland), Stirling Cryogenics and Refrigeration BV, Cobham Technical Services (Vector Fields) and Zenergy Power GMBH.

E.On Wasserkraft GMB operates the Hirschaid Power Station and will assist with the removal of the existing generator and installation and operation of the HTS generator.

KEMA Nederland BV carried out the electrical network analyses for the HTS generator operating as a stand alone machine and connected to the grid.

Politechnika Slaska advised on the selection of wireless data transmission devices and carried out rotational tests on getter elements and vacuum gauges, performed some electromagnetic finite element analyses and advised on HTS coil testing methodologies at liquid nitrogen temperatures.

Stirling Cryogenics and Refrigeration BV are providing the two cryocoolers and associated equipment and designed the helium transfer rotating coupling. They also advised on Pressure Equipment Directive requirements for the cooling pipe work.

Cobham Technical Services (Vector Fields) provided the finite element tools for the electromagnetic analysis of the HTS generator and advised on modelling techniques for various aspects of the machine.

Zenergy Power GMBH manufactured and tested the individual HTS coils for the HTS generator.

The Hydrogenie team at Converteam would also like to acknowledge the following colleagues Graham Le Flem, Ming Yuan-Rao, Changjiang Zhan, Philip Thomas, Martyn Drogan, Andy Stoker, Andy Clarke, David Peach, Charlie Hockenhull, Karen Burdett, Norman Emery, Phil Kettle and manufacturing staff for their vital contributions to this project.

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