THE HIGH MAGNETIC FIELD LABORATORY, RRE MALVERN

D.H. Parkinson, A.G. Harris and J.W. Stearn
Ministry of Defence (Procurement Executive)
Royal Radar Establishment, Malvern, Worcestershire, England.

Abstract

Recent developments in the RRE High Field Laboratory are described. A comprehensive range of Bitter Solenoids has been designed and is working with high reliability. Examples of standard fields are 155 kG in a 33 mm clear bore at 3.81 MW, and 86 kG in a 140 mm clear bore at 4.16 MW. A series transistor magnet current stabiliser, designed to handle 3.5 MW at 14,000 A from a transformer/rectifier set, has been devised. Established permanent facilities for magneto-optical studies are outlined as are those for short-sample hard-superconductor tests.

The evaluation of conduction and constructional materials for RHEL's superconducting bubble chamber has been a recent item of work. A Niobium-Titanium solenoid for working at 84 kG has been successfully tested and proved. Stainless steel AISI 316 (LN) has been shown to be a first choice for 'Cryo-Magnetic' enclosures.

I Introduction

An outline of the RRE High Magnetic Field Laboratory was given at the Nottingham Conference in 1969.[(1)] Since that time a number of new features which merit description have been introduced. The power supplies consist of a 3 MW rectifier transformer set and 3 batteries each of 168 lead-acid cells (7,420 Ah capacity per cell), which are capable of delivering 5 MW at 280 V. In this paper the innovations dealt with concern the solenoids, a 14,000 ampere magnet-current stabiliser, a magneto-optical system which is at present used for examining Zeeman splitting of lines in the photo-luminescent spectra of III-V semiconductors, and the hard-superconductor test facility which can deal with very large specimens and specimen currents up to 13,500 amperes. Extensive tests have been carried out to evaluate the conductors and materials used in the RHEL's superconducting Bubble chamber.

II Solenoids

A comprehensive range of Bitter solenoids has been designed and built at RRE. Standard cooling hole layouts, constructional techniques and interchangeable components are utilised wherever possible. Fibreglass cases and manifolds are used. It has been necessary to reinforce the high-pressure-end manifold with radial strands of carbon fibre. Table I shows the main characteristics of the standard designs which are available for the achievement of maximum field (HF) irrespective of uniformity, or high fields with good uniformity (UNF), or for providing radial access at the median plane (RA).

To ensure a long solenoid working life (1,000 hours) the heat flux into the cooling water is restricted to a maximum of 800 W/cm^2, and great care is taken to ensure clean assembly. A 27.5 mm working bore variant of the axial (HF) type has been built by the International Research and Development Co. Ltd., Newcastle-upon-Tyne for the Technical University of Braunschweig, West Germany and has achieved 180 kG at a power of 4.75 MW.

TABLE I

		HF	HF	HF	HF	UNF	UNF	RA	RA
Clear working bore	mm	33	52	106	140	33	52	33	106
Radial access bore	mm	-	-	-	-	-	-	33	52
Depth to magnet centre from manifold top	mm	290	310	340	360	310	325	315	335
Typical field for 3 MW	kG	135	120	85	70	125	110	85	60
Example of measured field	kG	155	117	106	86	125	110	80	73
at power	MW	3.81	3.13	4.16	4.16	2.42	3.05	2.43	4.48
and inlet temperature	^{o}C	24	15	20	18	22	20	18	12
Approximate field variation over 20 mm diameter sphere	%	0.9	0.7	0.4	0.3	<0.1	<0.1	6	1.5

A large bore stripwound solenoid has also been constructed and operated. It is designed with an i.d of 441 mm so as to nest round the standard axial Bitter magnets of table I. Used in this duplex manner it can give 'backing fields' of up to 50 kG.

The standard 50 kG (441 mm clear i.d) stripwound solenoid consists of eight double pancakes of 43 mm x 8 mm copper strip, double wound face together, with 15 turns per layer (Fig. 1). The

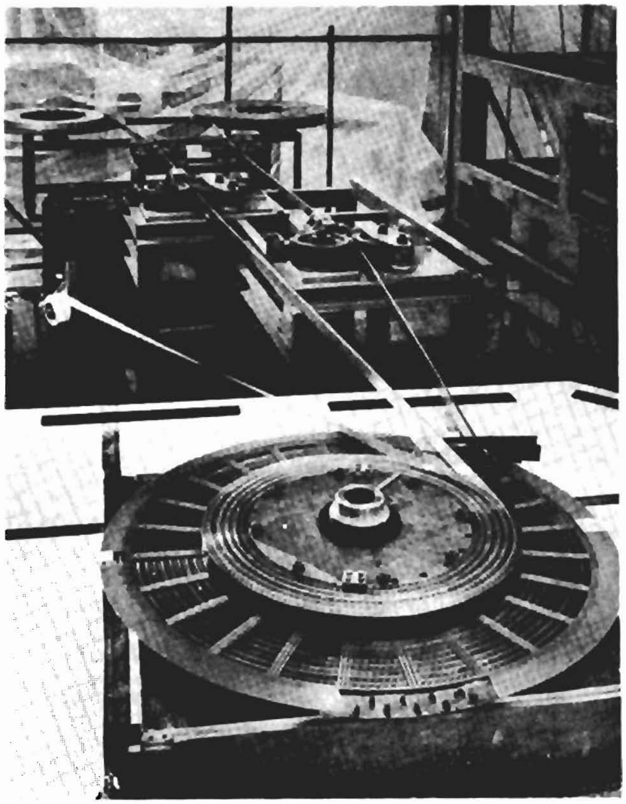

Fig. 1. Winding one of the double pancakes for the 50 kG 441 mm bore solenoid.

mating face of one of the two paralleled strips is castellated, 7 mm wide x 1 mm deep, to provide water cooling passages. Insulation between turns is provided by 0.017 mm thick Nomex, a high temperature resistant nylon paper tape. 50 kG is produced at the centre of the coil when energised at 280 V x 17,275 A.

III. Magnet Current Stabiliser

General

During the last 18 months design and constructional work has been undertaken to improve the performance of the 3 MW 12 pulse rectifier set.[2] Initial measurements showed peak to peak ripple voltage approaching 10% of the DC output level and diode commutating transients in excess of 50% of this level spread over a wide range of frequencies.

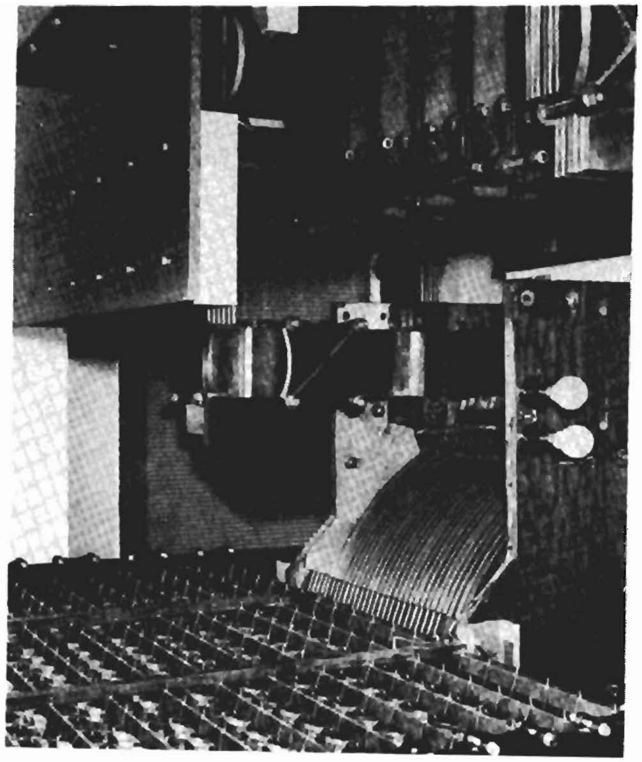

Fig. 2. Passive filters for the magnet current Stabiliser.

Passive filters (Fig. 2) have been used to limit the voltage excursion at the output of the rectifier set to a level at which a transistor controller is a practical proposition. Bridge circuits of 1.5 Ω in series with 55 μF across the rectifier transformer secondaries have reduced the transient voltages to less than 1 V at full power and a simple 32 Hz tuned LC filter in the main DC bus bar has reduced the ripple level to 3.0% with the main component frequencies at 50 Hz and 600 Hz.

Series Element

The series regulating element consists of 1,242 MJ 3771 transistors mounted in groups of 54 on 23 water cooled heat sinks together with a similar heat sink carrying 50 MJ 3771 transistors and 3 2N 3447s which form the driving stage (Fig. 3). The thermal impedance of the heat sinks from transistor case to the cooling water is $0.3^{\circ}C/W$ which enables a continuous power level of 130 kW to be maintained up to a coolant temperature of $28^{\circ}C$. The heat generated is dissipated in a forced draught evaporative cooling tower with a water circulation of 14,000 gal/h at 10 $lb/in.^2$ gauge. The simplified circuit is that of two cascaded emitter followers feeding the output stage which has the magnet as its collector load. In order that the output stage can be run almost into saturation, the driver is fed via a 4 V 600 A booster supply derived from a 3 phase full wave bridge. This arrangement eliminates the unusable

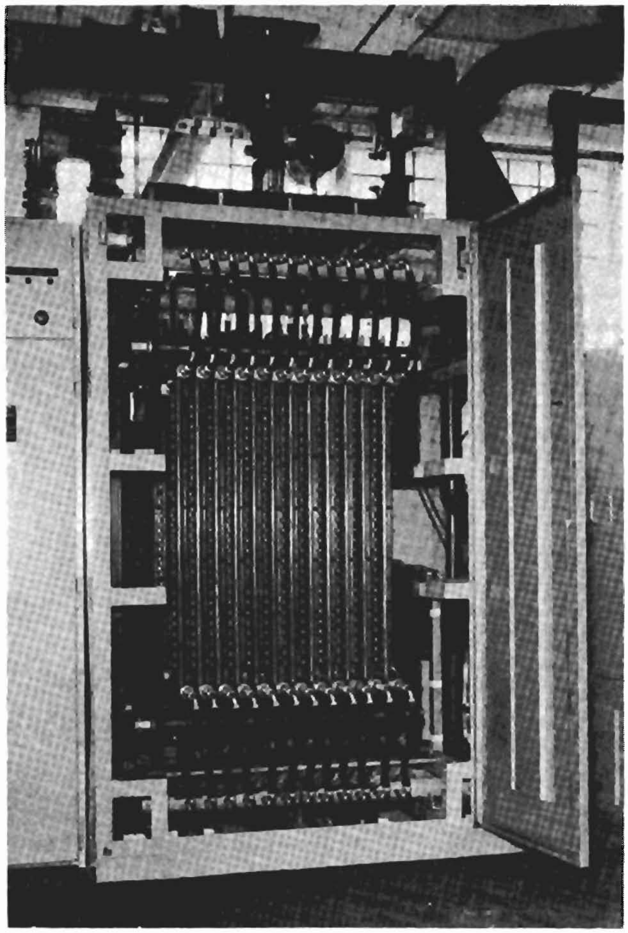

Fig. 3. Transistor series element assembly.

power dissipation incurred due to the combined base emitter voltage drops, about 4 V at full output, of the basic configuration (Fig. 4). Normal full output is 14,000 A at a mean collector voltage of 9 volts but the circuit can safely pass 37,500 A with the transistors "bottomed".

Shunt Resistor

The current monitor is a 100 μ Ω manganin resistor with a surface area of 1.25 m^2 totally immersed in paraffin which is circulated at 2,400 gal/h through a combined heating/cooling temperature control system (Fig. 5). The control temperature is 30°C ± 1°C, the zero temperature coefficient of resistance point for the manganin used, and control is readily maintained up to a power level of 21 kW. The secondary coolant is mains supply water which enters the system at 10°C with a total loss flow of 430 gal/h necessary at full power. When operated under these conditions the short term stability of the resistor will be better than 1 part in 10^5.

Protection

The complete equipment is continuously monitored at all critical points and any fault condition initiates a standard shut down sequence. The output stage is "bottomed" by means of a high power thyristor connected from base to collector and at the same time a compressed air actuated "crow bar" is triggered together with the 11 kV mains circuit breaker.

The short circuit is applied within 12 msec and complete disconnection occurs at 100 msec a time scale which will accommodate all but the most disastrous magnet failure. A novel feature is the incorporation of an automatic system for locating and indicating faulty transistors in the output stage. In essence this system samples the voltage developed across the 0.1 Ω emitter resistors associated with each transistor and compares it with the voltage that should be present at any particular current demand. In the event that a voltage sample is more than ± 100 mV from the demand level a fault is registered. In normal operation the sampling frequency is 1 kHz and the only display is a static fault count which is updated every 1.24 sec. At a predetermined fault an audible alarm sounds and the equipment operator can then obtain a numerical print out of the fault locations. Failure to replace faulty transistors leading to a second higher predetermined count results in the automatic shut down sequence operating.

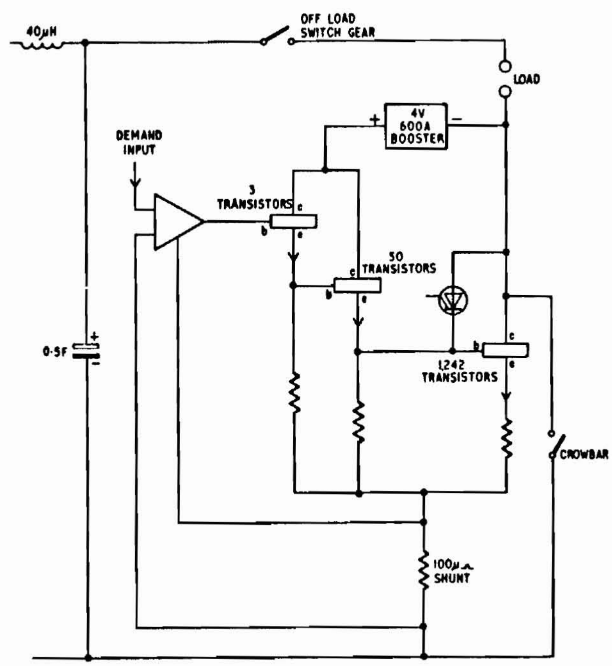

Fig. 4. Schematic circuit diagram.

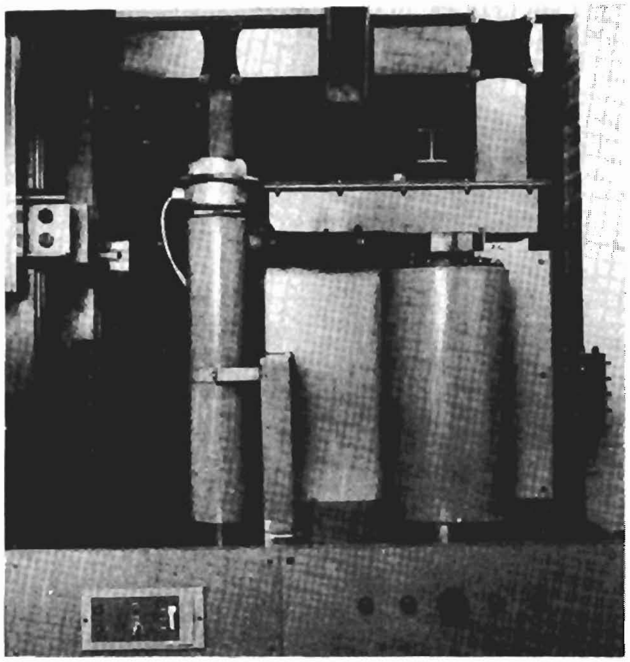

Fig. 5. Temperature controlled shunt resistor.

Performance

Closed loop performance figures are not yet available due to the failure of one of the epoxy bushings carrying the main current bus bar into the shunt resistor but full load current stability of a few parts in 10^5 is anticipated.

All the separate systems have been individually operated up to their design levels with complete success.

IV. Laboratory

The principal function of this laboratory is to provide high fields for solid state research. Two main lines have been followed. The first concerned with magneto-optical studies in semiconductors and the second with characterising hard-superconductors to be used for solenoid production. Most emphasis in the paper is given to the second of these topics and the testing of RACOON II in particular.

Magneto-Optical System

A typical magneto-optical system is shown in Fig. 6.

The specimens under observation are suspended in a glass-tailed, metal-bodied liquid He dewar off-set in the bore of a 52 mm, 120 kG solenoid. Appropriate wavelength radiation is applied to the specimens in the magnet bore by means of a system of remotely adjustable mirrors and the resulting photo-luminescence collected by further mirrors and analysed photographically in a 3.4 m focal-length Jarrell Ash spectrograph.

Superconductor Test Facility

Since 1956, this laboratory has handled almost the entire testing of UK produced superconductors both of development and production type.

Critical current characteristics are obtained from measurements on short sample specimens at approximately 10 kG intervals using the standard Bitter solenoids and cryostats. Specimen currents up to 13,200 A have been furnished and are controlled through a transistor bank with control circuits for current ramping and rapid turn-off when the desired specimen voltage is detected. A range of cryostat current leads has been designed,[3] (Fig. 7) and built with facility for mounting the specimens in any desired attitude to the magnetic field.

V. Evaluation of Conductors and Materials for RHEL's Superconducting Bubble Chamber Design

The Testing of RACOON II

RACOON II is a superconducting magnet built to provide final acceptance tests for the 70 kG magnet of RHEL's High Field Bubble Chamber design. It was manufactured from approximately 100 m of stabilised superconducting strip wound into six double pancakes of approximately 25 turns per layer. The conductor is formed from 361 Niobium-Titanium filaments 0.3 mm diam embedded in a copper matrix 25 mm x 6 mm with a filament twist about the longitudinal axis at a pitch of 0.5 m to

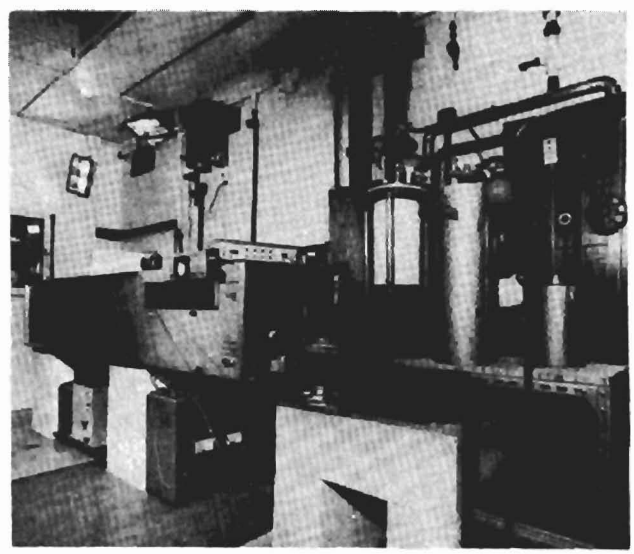

Fig. 6. Standard Magneto-Optical Studies Laboratory.

Fig. 7. Some of the Cryostat Current Leads in use in the Superconductor Test Facility.

eliminate virtually persistent magnetisation currents which would otherwise produce significant time dependent distortions of a magnetic field in the bore of the magnet. The overall dimensions of the coil are 302 mm o.d, 130 mm i.d and 355 mm length.

The cryostat for RACOON II was built to enable it to be mounted within RRE's 441 mm bore conventionally powered 50 kG stripwound solenoid. (Fig. 8). Radial misalignment forces were taken care of by the use of remotely controlled wedges between the coil's supporting framework and the cryostat followed by pads to the RRE coil inner tube walls, while axial forces were transmitted via the cryostat top plate.

The first stage of the tests was made at RHEL with RACOON II energised with currents up to 14,800 A reaching a peak magnetic field of 66 kG.

The second stage of the tests, carried out inside RRE's stripwound solenoid, proved that the selected superconducting strip could carry its rated current of 7,500 A in a total magnetic field of 84 kG. The two magnets were run up several times together at various combinations of background magnetic field and superconductor current. The maximum current achieved on RACOON II when at the required total magnetic field of 84 kG was 9,800 A, (Fig. 9), well above the conductor current rating of 7,500 A. RACOON II showed characteristics of high stability and its performance agreed closely with that predicted by the short sample tests on the superconducting strip made at RRE prior to magnet winding.

Investigation of Non-Magnetic Stainless Steels[4]

Austenitic stainless steels are widely used as structural components at low temperatures. They have highly suitable metallurgical, mechanical, thermal and other properties. In particular they are non-magnetic, causing minimum perturbation of the adjacent magnetic fields. In practice, the last factor is not entirely true, due to decomposition into ferro-magnetic martensite by cooling or deformation at low temperatures. An important design restriction of the RHEL superconducting bubble chamber was that variations in the intensity of the magnetic field

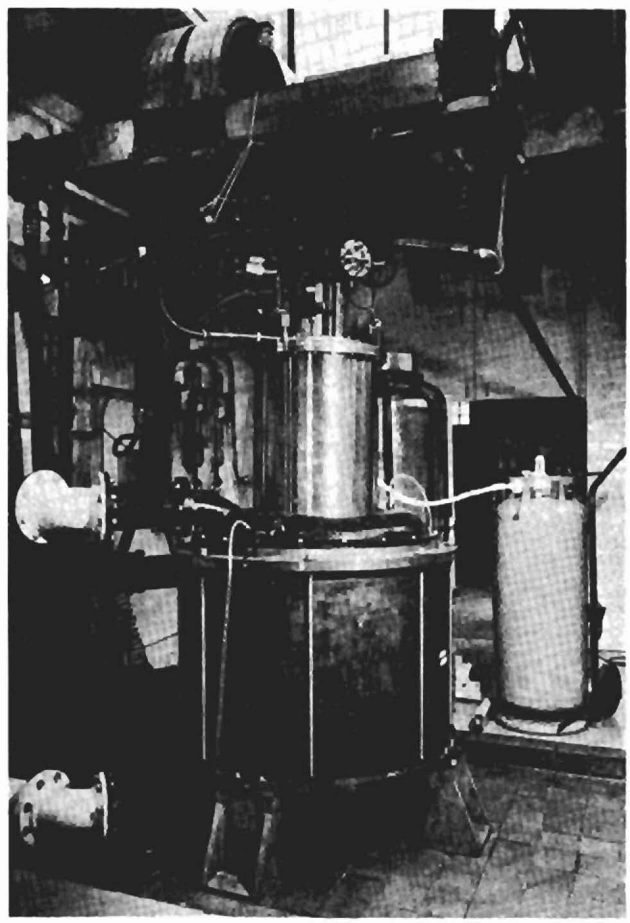

Fig. 8. RACOON II Test Assembly Mounted within the 50 kG 441 mm Bore Stripwound Solenoid.

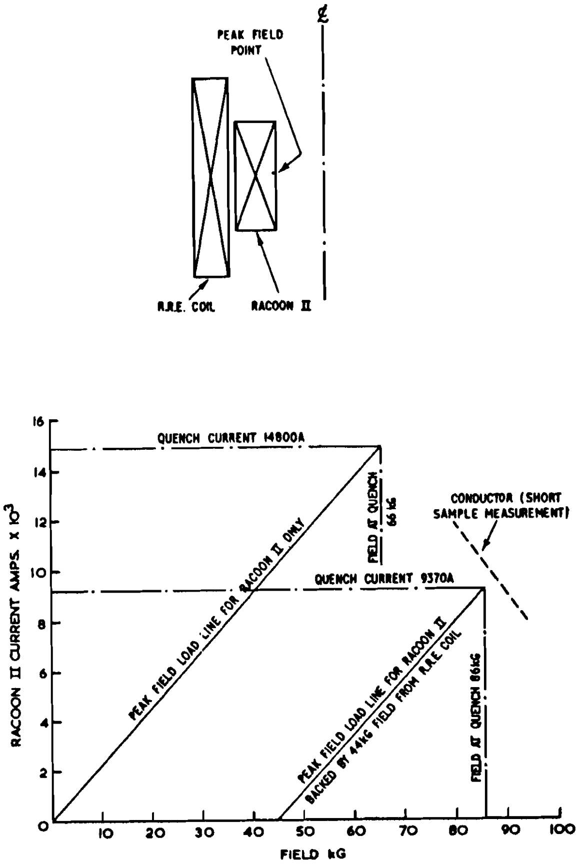

Fig. 9. Example of Performance of RACOON II With and Without RRE Backing Coil.

should be less than 0.1%, thereby limiting the maximum permeability to 1.03 at the design field of 80 kG. An investigation into the magnetic properties of stainless steels was therefore necessary[4].

Magnetisation measurements were made on 4 mm diam x 30 mm long samples with a DC integrating magnetometer capable of working between 2°K and room temperature. Fields up to 50 kG were generated at Imperial College, London, while higher magnetic field measurements up to 120 kG were made at RRE.

Standard grade austenitic Fe-Cr-Ni steels were studied, also some commercial casting alloys and, in addition, 40 Fe-Cr-Ni alloys were arc-melted in the laboratory. Some special steel alloys were supplied by the British Steel Corporation laboratories. To complete the range of observations on suitable materials for use at liquid He temperatures, a range of about a dozen copper and aluminium alloys were also investigated.

From the measurements, the results obtained showed that the standard 18/10 steels are on the borderline of suitability for cryogenic magnetic purposes and the suggested descending order of merit is, AISI 316, 316(L), 304, 347, 304(L) and 321. The high proof (N) or high Nitrogen, (minimum content 0.18 wt % N) versions of these steels, (316 to 347) showed no instability and the Eichelman and Hull equation suggests that they remain stably austenitic down to 0°C.

It was of some concern that the least suitable steel, 321 (or En 58B (M), by its obsolete British classification) appeared to be the most widely available grade of bar and tube in the UK so that a shift from its use for cryo-magnetic applications is highly desirable. Since the 0.2% proof stresses of the high nitrogen grades are more than 100% higher than the standard grades, the use of 316 (LN) as first choice for the construction of the chamber is recommended, followed by 304 (LN).

References

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(2) A.G. Harris and B.E. Mulhall, Les Champs Magnétiques Intenses, Grenoble 1966, p. 113.

(3) J.M. Lock, Cryogenics, Vol. 9, No. 6, 438 (1969).

(4) D.C. Larbalestier and H.W. King, Non-Magnetic Steels for Cryogenic Purposes, Rutherford Laboratory Report RHEL/R217, (1971).