A SURVEY OF FAILURE EXPERIENCE IN EXISTING SUPERCONDUCTING
MAGNET SYSTEMS AND ITS RELEVANCE TO FUSION POWER REACTORS*

S.Y. Hsieh, J. Allinger, G. Danby, J. Keane, J. Powell, A. Prodell †

ABSTRACT

Details of existing superconducting magnet failures are collected and evaluated with regard to future CTR superconducting magnet safety and reliability. Fourteen magnet systems with sixteen failures are presented. These failures are analyzed and categorized as to causative factors (eg. hot spots, arcing, lead failures, and conductor movement). Responses of the instrumentation and protection systems during these accident situations are also presented. Repairs and present status of the magnets are described. Preliminary conclusions are: the failure rate of existing magnet systems is too high to be tolerable for CTR magnets; although failure analyses of present systems can be used as a reference for future CTR magnet safety design, the prediction of successful operation of CTR magnet systems represents a significant extrapolation from the experiences accumulated so far; much development work and repeated testing of magnet system components and sub-systems are required.

I. INTRODUCTION

In an earlier paper¹ a summary of the compiled data on existing superconducting magnet systems was given. This report describes the details of the existing superconducting magnet failures and discusses their relevance to future fusion reactor magnets. Among the twenty magnets studied, fourteen systems have had failure experiences. The cause of failure, the protection system, and the present status of each magnet system are presented. A brief description of the magnet is also added for clarity. Related information such as structure, mechanical support, method of electrical insulation, heat transfer and cooling, etc. will not be discussed because of lack of space. The reader is referred to a BNL Fusion Magnet Safety Studies Annual Report² for more detail. This report is part of the Fusion Magnet Safety Studies Program at Brookhaven National Laboratory which is being supported by the Energy Research and Development Administration.

II. HOT SPOTS AND ARCING

Most magnet failures involve hot spots and arcing as an end result which are induced either by various abnormalities or by design errors. In this section failures caused by conductor breakage, inadequate cooling, poor heat transfer, electrical insulation breakdown, local energy dumping, etc. will be described. Arcing produced by power lead failure and conductor movement will be discussed in following sections.

FNAL Prototype Energy Doubler C10-3

This accelerator magnet is a 40 kG cosine θ dipole designed for pulsed operation. It is ten feet long and contains ~ 0.15 MJ of stored energy. Figure 1 shows hot spots and arced areas caused by local energy dumping during a quench. This magnet had a quench detection and automatic energy removal mechanism to remove $\sim$ half of the stored energy to an external parallel shunt. The powering circuit failed and short circuited the shunt, dissipating all the energy internally, and creating hot spots of $T > 400^\circ\text{K}$. The dielectric strength of the helium then deteriorated, and arcing resulted from a voltage excursion during quench. The coil could not be repaired.

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†Brookhaven National Laboratory, Upton, N.Y. 11973

LBL Beam Transport Magnet System

The system consists of one 42 kG cosine θ dipole and two quadrupoles designed for particle accelerator DC operations. The dipole is one meter long and contains ~ 0.7 MJ of stored energy. Failure occurred during dipole coil testing and the quadrupoles were not involved. Figure 2 shows the burns due to arcing believed to have been caused by a short between windings. This system did not have any external protection, and the energy was dissipated internally in the coil. The magnet was repaired with additional mylar insulation and it is now on loan to FNAL.

NASA Bumpy Torus Magnet System

This system consists of twelve 30 kG circular coils connected in series. The coils are arranged in a similar fashion to a Tokamak magnet system for plasma confinement. The OD of each coil is 0.31 meter and the system contains ~ 0.6 MJ of stored energy. This device was designed to investigate the applications of fusion to space propulsion. The accident occurred after approximately 2000 hours of operation which included about 170 quenches. Figure 3 shows the melted lead wires and damaged areas caused by arcing between shunt and ground. This failure was caused primarily by the internal shunt which was designed on the assumption, based on a two-coil pilot system, that a quench of one coil will trigger a quench of the entire system. A quench of the entire system will occur only when the system is operated at 35 kG. At 30 kG, half of the coils will go normal. At 25 kG only the quenched coil stays in the normal state while the stored energy of the entire system is dumped into the shunt of this single coil. It is believed that both the shunt design (with safety factor of 2) and the shunt insulation deterioration which in turn blocked the cooling passage, are the causes of this accident. The system is also equipped with a power lead over-temperature monitoring system and two pressure relief valves. The twelve dewars are monitored by a set of 48 probes which will alarm for low liquid helium levels. Quench detection is provided for record and warning only. The stored energy has to be dumped manually. The damaged shunt and leads were repaired. The original coil was replaced by a spare wound with the modern twisted NbTi wire. The system's performance is now as good as before the accident.

NASA SUMMA Magnet System

This system consists of four solenoids assembled to form a magnetic mirror device for confining plasma. Each solenoid consists of three concentric circular coils. Nb₃Sn is used in the innermost coil to achieve a higher field of 88 kG. The coil's OD is 0.9 meter and the stored energy is ~ 18 MJ. This device is designed to investigate the application of fusion research to the space propulsion systems. The failure occurred during coil testing. Insulation and packing strips were blown out of the outer NbTi coil of the fourth solenoid. The coil arced at many places. Shorts were also created among pancakes of the inner Nb₃Sn coil due to slippage of Nb₃Sn ribbons under pancake separator strips. These failures are all believed to be caused by insufficient mechanical support and electrical insulation. Photos of these failures were not available. This system was provided with both auto and manual energy dump mechanisms and a quench detection unit. External shunts were provided for the NbTi coils and internal shunts across pancakes were provided for the Nb₃Sn coils. The damaged coils were repaired and the system is back in operation. In a separate incident involving this system, a power lead overheated due to insufficient cooling. A chart recorder had been used to scan the temperature of 16 leads with a scan period of 5

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minutes. Damage from overheating, however, can occur within one minute and consequently the alarm was too late. The damaged lead was replaced and the system is operational except that the performance of one coil was degraded.

Princeton University 3-Section Solenoid

This system is shown in Fig. 4 and was designed as a conductor testing facility. This failure occurred during a quench after a power lead failure during which the lead connected to the center section of the coil overheated because of insufficient cooling flow. The middle section solenoid was damaged. The actual extent of the damage is not known since the system was not opened for investigation. However, it is believed that hot spots and arcing were produced. Part of the coil is shorted resulting in a lower total coil resistance at 300K. Quench detection, and an automatic energy dump mechanism were provided, however, the temperature and cooling flow of the power leads were not monitored automatically and manual adjustments were required. At the present time, this magnet is not in use since the IGC Solenoid insert could generate a high enough field for conductor testing purposes at Princeton.

Princeton University IGC Solenoid Insert

This 55 kG magnet was designed by IGC as an insert for the Princeton 3-section solenoid. It is an epoxy impregnated solenoid with a 16.5 cm bore. The stored energy is ~0.1 MJ. A built-in Nichrome ribbon shunt is provided for coil protection. Figure 4 shows the location of the failure. The lead wire connecting the ribbon shunt to the coil terminal melted open during a quench. Fortunately, an external shunt had been provided which helped to prevent the coils from being damaged. It was assumed that this failure was caused by poor cooling of the lead wire which had been well-covered by electrical insulation. It was then found that the remaining portion of the melted lead wire had high resistance leading to the assumption that a piece of Nichrome wire had been inadvertently used as tinned copper wire for the connection between the shunt and terminal during factory coil fabrication. The protection system is the same as described above.

Rutherford Laboratory Prototype Synchrotron Magnet AC3

This 40 kG magnet is one of the prototypes of pulsed cosine θ dipoles designed for particle accelerators. It is 0.4 meter long and contains ~60 kJ of stored energy. Figure 5 shows the damaged region caused by arcing. The arcing occurred under liquid helium when one of the current feeds broke off at full current. At the time of this incident, quench detection and an automatic energy removal mechanism were provided. The external circuit breaker of the energy removal system opened. The over-pressure valve on the cryostat also opened to relieve the rising helium pressure. The arcing vaporized a few c.c. of copper of the current feed which needed to be replaced. The magnet coil itself seemed to be intact. This magnet was provided with a balanced potentiometer type quench detection circuit, an external circuit breaker and a 33 m Ω dump resistor. The energy removal is triggered automatically by a quench signal. Voltage trips on vapor cooled current leads were also provided as additional lead and coil protection. A new current feed was soldered into place and the magnet appears to be no worse for the experience.

SLAC RCBC Magnet

This 20 kG system consists of two solenoids connected in series designed to be used in a rapid cycling bubble chamber (RCBC). The coil's OD is 0.88 meter and the stored energy is ~1.2 MJ. Figure 6 shows the area of arcing in one of the coils. This accident occurred when plugging in the cooling passage resulted in insufficient cooling along one of the connecting wires between the

coils. The wire melted open and the coil arced to ground. Approximately six inches of doubled conductor vaporized. Quench detection and energy removal mechanism were provided. Energy dump is automatic based upon logic sequential alarms and interlocks, but manual over-ride is provided. Additional system protection includes liquid helium level, vacuum monitoring, dewar pressure and power lead alarms and interlocks. The magnet coil was repaired after this accident and is back in operation.

III. POWER LEAD FAILURE

The power lead failures reported to date are all of gas-cooled leads. For this type of lead the cooling flow required is a strong function of the operating current. When the cooling flow becomes insufficient, a temperature excursion great enough to cause permanent lead damage can occur very rapidly, generally in less than a minute. Insufficient cooling flow is the primary cause of failures described in the following cases.

BNL 8° Beam Transport Magnet System

This 40 kG system consists of two window frame dipole magnets designed for DC operations at the particle accelerator. Each magnet is ~1.8 meter long and the total stored energy of the system is ~0.3 MJ. Figure 7 shows the area of arcing in the magnet. The arcing was caused by an overheated gas-cooled power lead. The heat generated along the lead melted the magnet coil lead wire connected to the end of this lead. The magnet coil was open circuited at full current and arcing resulted between coil and ground as shown. The photo of the damaged lead was not available. The cause of this failure was attributed to a faulty lead and inadequate instrumentation. At the time of this accident, the magnet was in its first test run and no active protection instrumentation had been provided. However, voltage measurements across the power lead, liquid helium levels, and lead cooling flow rates were monitored manually. A fixed external parallel shunt was also provided. During repair, four layers of conductor wire were replaced and a splice connection was made. The unit is back in operation with no loss of performance.

BNL 7-foot Bubble Chamber Magnet

The 30 kG magnet is a split solenoid with the gap provided to allow particle beam passage. The stored energy is about 61 MJ. The power leads for this system are cooled by cold hydrogen gas using an independent cooling system. Insufficient cooling flow resulted in high temperatures which produced the burns shown in Fig. 8. Inadequate instrumentation was another factor in this accident since the overheating of the lead was not detected until a solder joint began to melt and hydrogen leaked into the vacuum space triggering a vacuum alarm. This occurred early enough so that no other components of the system were damaged except the G10 clamp. The damage to the lead was immediately repaired, additional instrumentation was installed, and the system is operational.

MIT Alternator Magnet

This 25 kG magnet is a 1.0 meter long saddle coil pair designed to demonstrate the feasibility of large superconducting AC machines. The stored energy is ~90 kJ. Figure 9 shows the damaged lead schematically. Two inches of lead conductor were evaporated. The magnet coil arced to ground causing some damage to both the coil and the helium dewar wall. Insufficient lead cooling and inadequate copper stabilization of the lead wire were the major factors in this accident. A pick-up coil was provided for quench detection but was not used because armature noise caused false triggering. The magnet coil was protected by a current inverter, a voltage limiter, a Thyrite resistor and spark gaps. A power lead over-heat alarm and a helium vapor flow alarm were also provided. To repair the coil, six turns of damaged conductors were

stripped and the coil was left with an asymmetric winding. The stainless steel dewar wall was also replaced. The system is operational.

IV. CONDUCTOR MOVEMENT

Conductor Movement is a problem which occurs to almost all superconducting magnets built to date and it is the major cause of "training". The conductor movement depends very much on the magnet design and the method of confining the conductor. The degree of conductor movement also differs greatly from magnet to magnet. Most magnets have to be trained to achieve their final design field. Some magnets cannot attain their design field value because of this problem. Generally, there are two types of conductor movement.

(1) After the training process the magnet coil performance is not affected by thermal cycling. DC magnets usually train in this way.

(2) The magnet has to be retrained after each thermal cycle. Some pulsed magnets require retraining. The following two cases are examples of failures caused by conductor movement.

McGill University High-Field Solenoid

This 150 kG system consists of two concentric solenoids. The inner coil has a 19 cm bore and was wound with Nb₃Sn tape. The outer coil has a 41 cm bore and was wound with filamentary NbTi conductor in a copper matrix. Each coil is powered separately and the entire system contains about 4 MJ of stored energy. Figure 10 shows the distorted inner coil caused by inadequate mechanical support of the diamagnetic forces.³ Conductor movement, and minor electrical damage due to arcing also occurred in the outer coil. The conductor movement deformed the 1.27 cm thick stainless steel end plate. This magnet is provided with external parallel shunts for coil protection. The damaged coils were re-wound and potted with epoxy resin. The magnet is operational but its performance has not reached expected values.

Princeton University 60" Levitated Ring

This 28 kG (at the conductor) device was designed for plasma research. The ring was wound with Nb₃Sn tape. The stored energy is ~0.3 MJ. Figure 11 shows the conductor movement which so degraded the performance of the coil that it was replaced by another spare ring. The cause of this failure is believed to be inadequate mechanical confinement. There was no coil protection since the ring is levitated during operation. The damaged ring was repaired.

V. QUALITY CONTROL

Although most commercial components for superconducting applications, such as superconducting wires, power leads, etc. are not under any specified quality control standards, there is one case which is believed to have been caused by the quality of the superconducting wire. This case is the MIT hybrid magnet coil which has a water-cooled coil insert to generate a field of more than 200 kG. The superconducting coil has an OD of 0.67 meter and contains ~2 MJ of stored energy.

Each time this magnet was operated it quenched at a lower current level than the previous time but did not show any detectable damage or evidence of conductor movement. It was therefore assumed that the degradation of performance was caused by the poor quality of the conductor.

This magnet was provided with voltage taps and helium pressure transducers for quench detection. An external parallel shunt resistor was provided with manual power supply disconnect for coil protection. Modern twisted filamentary NbTi composite conductor will be used to rewind the magnet.

VI. RELEVANCE TO FUSION POWER REACTORS

In contrast to present magnet systems, future fusion reactor magnets are much larger and more complex. Stored energies are generally several orders of magnitude higher, and the magnet structures are much more complex due to the higher stresses and different modes of force loadings and torques. The operating current and current density requirements, and the high pulse rate of the ohmic heating coil are also very different from existing systems. In addition to its large size, the entire system has to be operated continuously in a neutron flux environment as a power plant for much longer times than has been the case for existing superconducting magnets. Yet more than 50% of the existing superconducting magnet systems, which are simpler and technologically less demanding than CTR reactor magnets, have had failure experiences. Of the failures described in this paper, none were fundamental in nature and all could have probably been avoided by design and assembly improvements, better monitoring systems and quality control, etc. It should be appreciated, however, that the superconducting magnet systems described here had a great deal of careful design engineering and construction effort put into them, and that very often all problems cannot be foreseen. Similarly, failures of the kind described in this paper and other potential failure modes described in an earlier paper¹ can happen to new CTR magnet systems. Therefore, the continuous documentation of the existing magnet system failures and operational experiences should provide the preliminary CTR magnet design background for magnet safety and reliability. The following can be concluded from this survey.

The present superconducting technology and magnet construction experience are as yet inadequate to form definitive assessments as to whether or not a safe and reliable CTR magnet system can be constructed.

Although failure analyses of present systems can be used as a reference for future CTR magnet safety design to reduce the chance of potential failures, the prediction of successful operation of future CTR magnet systems represents a significant extrapolation from the experiences accumulated so far.

It is also evident that much development work and testing will be needed to evaluate definitively the safety and reliability of CTR magnet systems. Among the present superconducting magnet systems, none has provided continuous long term operational experience of the kind required by power plants. To ensure a safe and successful operation of the future CTR magnet system, repeated long term testing of magnet components, sub-systems, scaled down models and the assessment of engineering and assembly problems are very much needed for the immediate future in order to provide sufficient data for CTR magnet design and construction.

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Although none of us likes to admit our own failings, we must take advantage of what others are learning from actual operational failures and try to design future systems safely and reliably. We therefore would like to sincerely thank those who furnished us with information and helped us to make this study possible. The names and institutions were tabulated in our Annual Report² and could not be included here because of space limits.

REFERENCES

1. S.Y. Hsieh et al., "Summary of Existing Superconducting Magnet Experiences and Its Relevance to the Safety of Fusion Magnets", 6th Symposium on Engineering Problems of Fusion Research (1975)
2. Fusion Magnet Safety Studies Annual Report, BNL.
3. R. Stevenson et al., "Diamagnetic Forces in Superconducting Magnets", IEEE Transactions on Magnetics, Vol. Mag-11, No. 2 (1975)

Fig. 1 Courtesy of D.F. Sutter, FNAL

Fig. 2 Courtesy of R.B. Meuser and W.S. Gilbert, LBL

Fig. 3 Courtesy of J.R. Roth, NASA

Fig. 4 Courtesy of J. Kaugerts, Princeton University

Fig. 5 Courtesy of M.N. Wilson, Rutherford Lab., UK

Fig. 6 Courtesy of S.J. St. Lorant, SLAC

Fig. 7 BNL Photograph

Fig. 8 BNL Photograph

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Fig. 10 Courtesy of R. Stevenson, McGill University

Fig. 11 Courtesy of J. File, Princeton University