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A REPORT ON THE OPERATIONAL RELIABILITY OF THE FERMILAB MAIN RING MAGNETS

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SUMMARY

Over the past three years the magnets in Fermilabs main ring have failed at a rate of 3.5% per year. As a result of the evolution of fabrication techniques six magnet types can be identified. This report presents the magnet failure statistics for the past seven years and draws conclusions as to what is expected in the future for each fabrication technique. Operational conditions at the time of each failure have been recorded for the past two years, and this information has been used to make hardware changes and procedural changes to reduce the number of failures resulting from causes external to the magnet. A black listing technique is used to find magnets which are close to failure; these magnets are removed during maintenance periods to prevent interruption to the physics program.

INTRODUCTION

Fermilabs' main ring consists of 1014 magnets. Of these 240 are quadrupoles and 774 are dipoles. Four different generations of construction techniques have been used and with these distinctions the dipoles are broken down into the following catagories:

1. Plaster Stick (PS). The coils are insulated with epoxy. The half cores are stuck together with epoxy and the empty places are filled with plaster of paris[1].

2. Epoxy Stick (ES). The same technique as plaster stick are used, but epoxy is used to fill the empty spaces.

3. Original Vacuum Impregnation (OVI). The construction technique in this case is essentially the same as ES, with the additional step of bagging and pumping down the magnet in an attempt to impregnate the magnet with epoxy[2]. This had been developed as a salvage technique for the first two construction types.

4. Integrally Impregnated Butt Joint (IIBJ). This construction type differs greatly from the previous types. The coils are placed into the magnet partially cured, and the entire magnet is impregnated with epoxy under vacuum[3]. As with the earlier construction types[1] these magnets used a butt type joint at 16 locations on the inner coils.

5. Integrally Impregnated Sleeve Joint (SJ). Same as IIBJ but with sleeve joints used on the inner coils.

6. Integrally Impregnated Grooved Sleeve Joint (GSJ). Same as IIBJ but with grooved sleeve joints used on the inner coils. Quadrupoles have also gone through several stages of construction techniques, but no analysis of them has been done.

Table I shows how many of each of these magnets were originally installed, and now many are currently (1/1/79) in the main ring.

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TABLE 1

	Installation period	No. Installed	No. In ring 1/1/79	% Inst. still in ring
PS	before 1972*	317	120	38%
ES	before 1972	458	279	61%
OVI	before 1972	147	110	75%
IIBJ	12/71 - 12/73	158	110	63%
SJ	7/73 - 9/74	49	43	88%
GSJ	6/74-present	129	122	95%
Total		1258	774	62%

*First ramping of main ring magnets began in 1972.

Magnets can be removed from the ring for a variety of reasons. Several of the reasons which have little to do with the magnet itself are buckled vacuum chambers, and vacuum leaks. Both of these problems can be caused by beam. The overwhelming majority of magnets removed from the ring have shorts. Figure 1 shows the precentage/yr of each type of magnet which have failed with shorts since 1972.

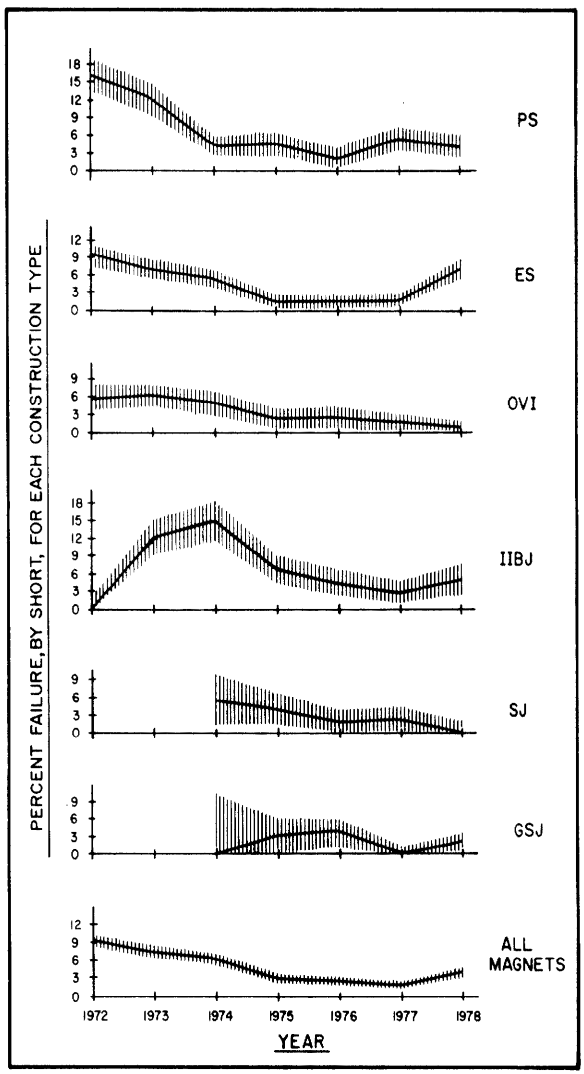

Figure 1

Rigorous conclusions cannot be drawn from this data, but a few observations, can be made. Plaster Stick failures have stayed constant since 1974. To this point there is no sign of them weakening from old age. Epoxy sticks on the other hand, show an increase in shorts in 1978. This may be attributed to factors discussed later. Original Vacuum Impregnation appear to have been a considerable improvement over PS and ES, and also, show no signs of weakening. Integrally Impregnated Butt Joint magnets looked very promising on January 1, 1973. Over 100 of them had been installed without a single failure. However, in 1973, fifteen failed with shorts, and in 1974, twenty. It was felt that the greatest problem with these magnets was that the impregnation technique which holds the coils very tightly in this construction type does not allow the coil package to move with temperature variations. Hence tremendous forces are placed on the butt joints of the inner coils, particularly on cool downs when the forces are acting to pull the joints apart resulting in water leaks and eventual shorts to ground.

In 1975 through 1977, the percentage failures of IIBJ were greatly reduced, possibly indicating that the magnets which survived were built better and had survived the "weeding out" process. In 1978, the percentage failures of IIBJ was up almost a factor of 2 over 1977. This may be only a statistical variation, but a possible explanation is given later.

In 1973 a sleeve joint was introduced on the inner coils in an attempt to prevent the separation of the joints. The resulting magnets have been much better in their resistance to shorts.

The use of a grooved sleeve joint on the inner coils is the most recent stage of magnet development. Because of the long time necessary to build up statistics it is difficult to say much about operational reliability of these magnets. However, 5 of the 129 installed to date have failed with shorts. Because these are the current production type, an autopsey program is being developed in order to thoroughly understand the shorts. Up until this point, the only testing following a failure has determined which coil shorted, and if the short was accompanied by an internal water leak.

REASONS FOR MAGNET FAILURES

Table II has been drawn up for the years 1977 and 1978.

Breakdown of Magnet Failures

	1977	1978
I. Total Magnet Failures	30	43
A. Shorts	21	40
1. short-to-ground	17	38
2. turn to-turn	4	2
B. Structural or Vacuum	9	3
1. Vacuum leak	1	1
2. Collapsed chamber	2	1
3. Blocked coils	6	0
4. Contaminated chamber	0	1
II. Reasons for Failures by Shorts		
1. Soaked by broken insulator	0	6
2. Soaked by ground water or extremely high humidity	0	5
3. Human error	0	1
4. Restricted cooling	0	2
5. Over voltage conditions due to malfunctions in power supply system	5	10
6. Internal water leak (visible in tunnel)	4	4
7. No obvious reason from operational conditions, or visible symptoms.	12	12

The program for documenting operational characteristics at the time of a magnet failure has been expanded. As shown in the table there are five categories of external reasons for magnets shorting. The last two "reasons" listed are not reasons, but are listed because either there was no way of telling from the environment what caused the failure, or water could be seen leaking out of the core. It may be that the reason for failure could have been extreme temperature fluctuations, but until a good history of temperature fluctuations is maintained this will not be known.

The most obvious entries in the table are the large number of shorts which were caused by external factors in 1978. Two factors contributed to the increase over 1977.

1. In November of 1977, Fermilab adopted a day-night pricing scheme for electrical power. This meant a large variation in main ring power, 30 MW during daytime hours and 55 MW at night. The resulting temperature fluctuation proved to be a serious problem. Five transformers for main ring power supplies shorted (primary-secondary) putting very large voltage transients on the magnets. Eight main ring magnets shorted as a result. It also became harder to control the magnet temperatures possibly leading to the failure of more IIBJ magnets.

2. Construction work on the energy doubler and colliding beam areas began in earnest in 1978. Many penetrations were drilled through the tunnel roof, in most cases without problems. However, the worst rainstorm of the year occurred immediately following one day of drilling tunnel penetrations resulting in a tunnel flood. Four plaster stick, and epoxy stick dipoles and one quad shorted to ground.

The construction work also meant more people in the tunnel with more potential for accidents. At least two magnets shorted after getting wet from insulators which were broken by workers.

PREVENTIVE MEASURES

Larger fluctuations in the temperature of the cooling water are very hard on the magnets as well as adding stress to the insulators which are at the ends of long sections of bus. In order to minimize these fluctuations, the control system for the cooling water has been upgraded so that it regulates the temperature better over large power ranges. An interlock technique will be implemented to shut off the pumps as soon as a temperature problem is sensed.

Another long term enemy of the magnets has been the power supply system. The following changes are being made to prevent voltage transients from getting to the magnets:

1. Heaters are being installed in the transformers for use during cold weather, extreme power

variation periods.

2. Transients occur when the vacuum circuit breakers for the power supplies open or close. This problem is severe enough so that if all the VCB's open simultaneously, enough voltage is placed on the magnets to cause shorts. During normal operation the turn-on and turn-off is staggered, but many of the fault conditions have been initiating aggregate off commands to the power supplies. These included shorts-to-ground, loss of firing pulse current for the SCR's,magnet overtemperature and door interlocks, both for the tunnel and the power supplies. Most of these fault conditions now turn the magnet current off by phasing back the SCR's; the VCB's are opened only if the condition persists. The door interlocks continue to open all VCB's, but all the power supply cabinet doors now electronically display the status of that supplies interlocks. This problem alone led to two magnet failures in 1978. When power supplies are removed from the circuit they are in a condition safe for maintenance even while the main ring magnets are energized. The process of removing a supply from the circuit is supposed to also remove the supply from the interlock loop. This has not always happened, and as a result all of the VCB's have opened when the power supply door is opened for service.

3. Zinc oxide varistors are being installed on both sides of all power supplies[4]. These will act as transient suppressors.

In addition to the hardware changes mentioned, tighter control of tunnel construction work will have to be maintained in order to eliminate magnet failures caused by related external factors.

BLACKLIST PROCEDURE

Rougly twice a year a tour is made of the tunnel looking for low resistance magnets. Experience has shown that if the resistance of a magnet to ground becomes less than 10 MΩ, that magnet will fail. These magnets are replaced during shutdowns. During the three year period, 1976-1978, fifteen magnets were found and replaced using this procedure. Of the fifteen, two of the magnets were quads, and of the remaining 13 dipoles, twelve were integrally impregnated. Blacklisting appears to be an effective way of finding magnets with slow internal water leaks before they become hard shorts.

CONCLUSION

Each of the construction types of the main ring dipoles have a most vulnerable point. The earlier magnets are more susceptible to getting wet and overvoltage conditions. The later, integrally impregnated magnets have solved these problems, but are more vulnerable to factors which stress the rigidly held internal joints, presumably temperature fluctuations.

While efforts are underway to solve any remaining problems with current magnet construction, it is clear that the greatest improvements in reliability will be realized if the existing main ring magnets are provided with an environment that doesn't stress their weaknesses.

Eliminating external causes of failure should limit the failure rate of magnet shorts to 1.6%/year.

ACKNOWLEDGEMENT

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