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ENERGY SAVER A-SECTOR POWER TEST RESULTS

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Introduction

The superconducting magnets and associated cryogenic components in A-sector represent the initial phase of installation of the Fermilab superconducting accelerator, designed to accelerate proton beams to energies of 1 TeV. Installation of the magnets, comprising one-eighth of the ring, was completed in December, 1981. Cooldown and power tests took place in the first half of 1982, concurrent with main ring use for 400 GeV high energy physics. The tests described in this paper involved 151 cryogenic components in the tunnel: 94 dipoles, 24 quadrupoles, 25 spool pieces, 3 feed cans, 4 turn-around boxes and 1 bypass. Refrigeration was supplied by three satellite refrigerators, the Central Helium Liquefier, and two compressor buildings. The magnets were powered by a single power supply, located in the A2 service building, (Figure 1).

Quench Protection

An MC68000 microprocessor Quench Protection Monitor (QPM) is located in each service building A1, A2 and A3. Each QPM monitors four quench protection units (QPU), normally containing eight dipoles and two quadrupoles. For monitoring purposes, each QPU is divided into an upper and lower channel (Figure 2). The QPM samples each channel every 60 Hz line period to determine if a quench has occurred. This determination is based upon the resistive voltage, the difference between the measured (applied) voltage and the inductive voltage, L(dI/dt). During the early part of the A-sector tests, as at the B12 test facility, the dI/dt signal was derived by differentiating the signal from a current transductor. This is referred to as the "absolute monitor mode". There are three difficulties that arise in using the absolute monitor mode, however. First, the signal itself is fairly noisy; even with careful design and shielding, the noise signals exceed .3 V, where the quench detection threshold required to protect the magnets[1] is .5 V. Second, the hysteresis in the magnets, which reflects itself as a change in inductance, produces signals on the order of .5 V, which are difficult to correct. Third, and most important, a large noise signal or a failure of the dI/dt electronics leads to a false quench indication for <u>every</u> QPU.

Because of these difficulties, the way in which dI/dt is determined was changed to the "relative monitor mode". In the relative mode, dI/dt is determined independently by each QPM by dividing the sum of the applied voltages by the sum of the inductances, where the sum is taken over all non-quenched channels that the QPM monitors. As an intermediate step, a "mixed monitor mode" was also used, in which some fraction of absolute mode, usually 10%, was combined with the relative mode. While the mixed mode reduced the noise and hysteresis to acceptable levels, the problem of electronic failure of the dI/dt signal remained.

In both the relative and mixed mode, an additional safeguard is necessary, a comparison of the relative dI/dt with the absolute. This threshold may be somewhat higher (Δ(dI/dt)= 15 A/s, or $L \cdot \Delta(dI/dt) \approx 3V$) than the quench threshold, and the response taken is not the same as for a quench. In the determination of the resistive voltage, the subtraction can yield a remainder of either sign. The sign convention used for the A-sector tests implies that a quench is a negative resistive voltage. A positive resistive voltage ("anti-quench") indicates a monitoring problem, and the same response is taken as for a quench. In the absolute mode, the anti-quench tolerance was rather arbitrarily set at 10 V; in the relative mode, however, a positive resistive voltage in one channel is reflected as a negative resistive voltage of roughly one-eighth the magnitude in all the other channels. Therefore, rather than let a monitoring problem in one channel manifest itself as a quench in the other seven, the anti-quench tolerance was reduced to 3 V.

The applied voltage for a channel is measured differentially, utilizing the voltage monitor taps shown in Figure 2. A schematic of the monitoring electronics is given in Figure 3. The isolation resistor R_I, located close to the magnets, serves the dual purpose of personnel protection and preventing any problem in the service building from producing hard ground faults to the bus. Initially, the isolation resistors were one megohm. This size resistance led to two difficulties. First, the RC time constant for charging the 200 m long cables (20 nF) between the isolation resistor and the electronics was 20 ms, comparable to the QPM sampling time. This places stringent requirements upon the accuracy to which cable capacitances must be matched. Second, stray resistances in the gigohm range can lead to resistive voltages exceeding 1 V in the presence of an applied common mode voltage of 500-1000 V. Consequently, the isolation resistors were reduced to 100 kΩ during the power tests.

The isolation resistor introduces another effect into the QPM, related to the fact that one resistor is common to two monitor channels A voltage on one channel has associated with it a current through the isolation resistor. This influences the adjacent channel in a manner which can be calculated, dependent only upon the values of the resistances and capacitances in the circuit.

The presence of the 50 MΩ resistors is not directly related to the monitoring; instead they have the following intent. By placing a test voltage of 100 volts to ground on the bus, one can check the integrity of the monitoring system. A voltage monitor cable which is floating or shorted to ground will give a quench indication to the QPM. Without these resistors it is difficult to check that all connections are intact.

Power for the QPM is supplied by an Uninterruptable Power Supply (UPS), which uses a storage battery as a buffer between the conventional input AC power and the output AC. Loss of input power to the UPS is sensed by the QPM as a fault condition, and the magnet power supply is turned off

When a QPM detects a quench, it initiates the following sequence of events (see Figure 4):

1. The heater firing units in the quenching QPU are activated.

2. The power supply is turned off and the shunt SCR gated on ("fast-bypass").

3. The quench bypass SCRs are gated on.

4. The dump resistor is switched into the circuit by opening the series SCR ("dump").

This action causes the entire QPU to go normal, forcing the current into the bypass circuit, thereby protecting the point where the quench originated. In the following sections, each of the elements in this quench protection system will be discussed.

<u>Heater Firing Units</u>

The heater firing unit is basically a group of 6.6 mF capacitors, each charged to 450 V. Upon receiving a trigger from the QPM, the capacitors are discharged into the stainless steel heater strips (resistance ≈20 Ω) integral to the dipole assemblies. Two heater firing units are required per QPU. Two of the capacitors in each unit are connected to dipoles on the upper bus, and two to dipoles on the lower bus. The capacitors are charged by a current source derived from the conventional AC power; the control logic is powered by the Uninterruptable Power Supply.

The heater firing units are tested periodically to verify that the capacitors discharge promptly. This guarantees continuity of the circuit, but does not protect against short circuits Eventually the QPM will check the discharge time constant, but this is not yet implemented. The QPM does check the charge status of the capacitors. If the voltage on a capacitor drops below the 400 V threshold, the magnet power supply is turned off and the dump resistor switched into the circuit.

Power Supply and Dump Resistor

The power supply was a pair of standard main ring supplies adapted for use in the Tevatron as a ramping power supply. As such, it can ramp to currents in excess of 4 kA, but its transformers are not capable of running 4 kA DC for more than a few hours. When the entire ring is complete, there will be twelve similar supplies, plus one holding supply capable of sustained high currents.

The voltage output of the power supply determines the maximum ramp rate. During the early phases of the A-sector power test, the supply was configured as a 500 V supply. As the ability of the magnets to withstand higher voltages was demonstrated, the supply was reconfigured, first as a 1000 V, and then as a 1500 V supply. In the final configuration, the magnets were ramped at +300 A/s during ramp, -240 A/s during invert. The power supplies in the final ring will be adapted single ring supplies nominally capable of 1000 V.

The size of the dump resistor is determined by two opposing factors. On the one hand, it must be small enough that the IR voltages be within the limits that the cryogenic magnets can withstand during quenches. On the other hand, it must be large enough to reduce the L/R time constant of the current decay. This is necessary to protect the QBS circuit, described in the next section. An L/R time constant of 12 seconds has been selected as the design; for A-sector, the dump resistor was .375 Ω. In the Tevatron, there will be twelve .25 resistors equally spaced around the ring.

The dump resistor is switched into the circuit by opening the series SCR. Since the switching of the resistor is a critical part of the quench protection system, the series SCR is backed up by a DC breaker. The operation of the DC breaker was tested twice under full load during the A-sector tests.

The shunt SCR is capable of carrying 4 kA DC for extended periods. It is used in conjunction with the dump resistor in instances in which current must be quickly removed from the magnets. It is also used alone in the event of a ground fault or excessive voltage-to-ground indication. In that case, the power supply is turned off and the shunt SCR closed, but the dump resistor remains out of the circuit. The current then decays with an L/R time constant determined by the resistance of the bus leading to the magnets, a few milliohms. The resulting time constant is several minutes.

Quench Bypass Switches

The quench bypass circuit is designed to bypass current around a quenching cell. Within a fraction of a second after discharging the heater firing units, the bypass current is essentially equal to the current in the dump resistor, and will decay with the 12 second L/R time constant. Proper operation of the QBS is essential; failure to conduct would certainly damage magnets during a high current quench. Each quench bypass circuit contains three elements, as follows:

1. Safety leads

2. Cable

3. Quench bypass SCRs

The safety lead is designed to carry bypassing current from the superconductor to conductor at 300 K. As a direct path from warm to cold, its cross-sectional area has been minimized, consistent with the current-carrying requirements. It is not intended to carry large currents for extended periods of time, and therefore, safeguards must be taken to avoid overheating. Protection of the safety lead is the primary reason for the redundancy of the series SCR - DC breaker system. The comparison by the QPM of the relative and absolute dI/dt is also intended to protect the safety lead.

The cable connecting the safety lead to the SCR consists of two pieces of 250 MCM wire. It is mentioned here for two reasons. First, it is at the same potential as the superconductor itself, and proper insulation and care in the installation is required. Second, the cable, along with the safety leads, are a resistive element which, together with the SCR voltage, allow one to calculate the bypass current, and, in turn, the $\int I^2 dt$ in the magnets during the quench. This integral determines the peak temperature reached during a quench.

Upon detecting a quench, the QPM sends a signal to each of two QBS controllers, A and B, which in turn send firing pulses to the SCR switches, connected in parallel across each cell. While each SCR alone is capable of carrying the full current, the resistive voltage developed in the cable between the safety lead and the SCR insures that the two SCRs share the current equally. As a matter of convenience, the SCRs for the upper bus and for the lower bus are mounted in a single module and installed in a hole bored in the wall for radiation shielding.

The dump resistor voltage reverse biases the SCR. In order to bypass current, the quenching magnets must develop enough resistive voltage to overcome the reverse bias; at 4 kA, this occurs about .1 sec after discharging the heater firing units.

Since proper operation of the QBSs is essential, they are checked periodically, according to the following procedure.

1. Set up low current, low ramp rate program (50 A/s, roughly 10 V per cell).

2. Desensitize quench limits, ΔdI/dt limits; tell QPM to ignore status of QBS controllers.

3. Send trigger to QBS A controller.

4. Observe that applied voltage in each QPU is clamped at roughly 2 V during the ramp, due to the SCR drop and cable resistance, indicating that all QBS units are conducting.

5. Repeat for QBS B circuit.

The design of the QBS unit includes a snubber and self-firing network, and to protect against large reverse voltages, a 200 V metal-oxide varistor in parallel with each SCR.

<u>Transient Response</u>

From earlier tests at B12, it was known that 1 V transients were induced during the fast bypass/dump/QBS firing sequence; the largest source was determined to be the QBS firing pulses. To prevent these transients from causing the QPM to believe a quench has occurred, a Triggered Compensation Program (TCP) was introduced into the software. The TCP is simply a set of numbers, experimentally determined, added to the resistive voltages prior to comparison to the quench threshold, for twelve sample periods of the QPM following the dump. The length of the TCP was primarily an attempt to correct for hysteresis. Three or four sample periods contained the fast transients.

In A-sector, the power supply-dump configuration is significantly different from B12. The delay between fast bypass and dump is not fixed: it may be 10 ms (if initiated by the QPM), it may be 150 ms (if initiated by the power supply), or it may be very long (if initiated by a ground fault, followed by a quench some time later). The dump resistor is twelve times larger, producing a much larger voltage change, and consequently, larger signals due to V or dV/dt common mode. With the better resolution under the relative mode, it was seen that transients were occurring during fast bypass alone, as well as during a dump. Therefore a retriggerable TCP has been implemented. The nature of this transient, and a comparison of the signals observed in the absolute and relative modes is shown in Figure 5.

Pressure Tests

A major consideration during the early phases of the A-sector power tests was determining the capability of the system, in particular the 8" header, to withstand large scale quenches. During a quench, much of the helium is ejected from the cryostat into the header as liquid; it then vaporizes, with a resulting pressure increase. To study the pressure rise during a quench, a number of pressure transducers were installed in A-sector (Figure 6), and a series of tests were done in which every magnet in A-sector was quenched simultaneously.

The first of these tests came slightly ahead of schedule, following the first two hours of ramping to 2225 A (500 GeV). The plan was merely to do a dump; instead, everything quenched, due to the TCP not being large enough to cover the transients. As a result of the quench, the snow covers bolted on the relief valves for the 8" header were blown off; one was reported to have been as high as the seventh floor of Wilson Hall. Repeating the test at 1500 A gave a second point from which one could extrapolate to higher currents. The extrapolations were not reassuring, and at that point additional valves which relieve from the 8" header directly into the tunnel (set for 47 psi) were made active. Additional tests were performed at 2600 A, 3000 A, and 3350 A, (see Figures 7 and 8). The extrapolations to higher currents now appear reasonable; the header should be able to withstand 100 psi. The pressure rise in the single phase helium system during a quench was, as in earlier tests at B12 and the Magnet Test Facility, fairly insensitive to the pressure rise in the 8" header.

During the 3350 A full sector quench, a single phase bellows on the A1 feedcan failed, destroying insulating vacuum. The squirm protector on the bellows was not installed properly and had fallen away. The repair required about a month, including three days of tunnel access which disrupted the high energy physics program.

The relief valves which open into the tunnel do not open during single cell quenches. During a full house (four cells) quench, as might happen when a QPM fails, a small amount of helium is vented into the tunnel, but no oxygen-deficient hazards are present.

High Voltage Characteristics

During installation, all components of A-sector were demonstrated to withstand 500 V to ground while filled with 1 atm, room temperature helium. Prior to the first power tests, the system (full of liquid helium) was tested to 1 kV. This permitted ramping to 2600 A, using the criterion that the peak current times the dump resistance must be less than the voltage to which the system has been tested. The hipot was repeated at the beginning of each day's tests.

Following the 2600 A full sector quench, a ground fault occurred while trying to hipot to 1.2 kV. The approximate location of the fault was determined. Power tests were halted at this point, and refrigeration studies were done for a ten day period. Since the ground fault was not a hard short, and was located close to the zero-voltage point on the bus, it was decided to continue power tests. Upon hipotting again, the ground fault had disappeared! The string was hipotted to 1.2 kV, the power supply was reconfigured to 1 kV, and currents over 3 kA were permitted. A number of single cell intentional quenches were done, along with a few unintentional ones due to a cable problem, over the course of a week. Following the 3kA full-sector quench, however, the ground fault reappeared in the same location. Power tests continued until the 3350 A full-sector quench during which the bellows failed. While the magnets were warming up in preparation for the repairs, an attempt was made to "burn in" the ground fault by passing current through it. With only 300 V on the bus and 150 ma through the ground fault, the system sparked. Another ground fault had been produced, of even lower impedance, at the A2 feedcan. During the tunnel access, both faults were repaired. The first was a QBS cable (250 MCM) which had been crushed during installation of the A21 double turn-around box. The second was an instrumentation lead (voltage tap) in the A2 feedcan, one not used by the QPM.

After the repairs, the string was cooled down and hipotted to 1.6 kV, the level necessary for 4 kA. Several weeks later, while hipotting to 1750 V, another failure occurred, this time in a voltage tap connector (again unused) on the A29 double turn-around box. the string was partially warmed up and the connector removed, the leads cut off and insulated, and a cap installed in place of the connector. Since the leads were in a tube connected directly to the single phase, insulating vacuum did not have to be broken.

The string was subsequently hipotted to 2 kV with no problems. A series of 4 kA quenches was done with additional high voltage stress applied. These will be described in another section.

A high voltage related problem was mentioned in an earlier section relating to the isolation resistors. Under extremely humid conditions, difficulties were encountered with the QPM system. A frequent signature was adjacent channels having apparent resistive voltages of equal magnitude but opposite sign. The signal would appear during the ramp, disappear during flattop, reverse polarity during invert, and disappear during injection. The problem was clearly associated with the presence of voltage on the bus, in conjunction with a leakage to ground. The signal seen by the QPM is directly related to the excess leakage times the resistance of the isolation resistor. Reducing the isolation resistor from 1 MΩ to 100 kΩ reduced the problem dramatically. In addition, the voltage-to-frequency converter (VFC) cards will be coated to reduce the leakage itself.

<u>Ramping Tests</u>

The magnets in A-sector were ramped to 4 kA (900 GeV) for the first time on April 29, 1982. A single cell, spontaneous quench followed within ten minutes. Such a quench is not entirely unexpected: the transit time of the helium through the magnets imposes a delay in the response of the refrigeration controls to a sudden change in heat load. A second attempt at 4 kA was terminated by a QPM software error which resulted in quenching all of A2, again after only ten minutes of ramping. The following day, the string was ramped for over two hours; a power supply over-temperature problem then caused a dump, which, because the retriggerable TCP was not yet implemented, initiated a quench response by the QPM.

That same evening, the ramp was started again, with the intention of ramping for as much of the time as possible for the next ten days. The goal of this portion of the power tests was, obviously, to demonstrate the capability of the system to operate in a stable manner consistent with the requirements for a high energy physics accelerator. For this period of long-term ramping, the link between the refrigeration controls and QPM was enabled. The refrigeration microprocessors would remove the ramp permit from the QPM whenever any one of several variables went out of tolerance.

The successes and failures of this period of ramping are best described by breaking the period into runs. Each run is characterized by its length and is terminated generally for one of two reasons, refrigerator problems or QPM/power supply problems. Histograms of run duration and down-time duration are given in Figure 9. As a measure of the success of these tests, one can calculate an efficiency for the period April 30 at 1742 hours to May 11 at 0900 hours as follows:

Total Elapsed Time		255 hours
Accelerator M&D (Main Ring)		7 hours
Total Available Time		248 hours
Total Time Ramping		136 hours
Ramping Efficiency	55%	
Time Ramping Lower than 4 kA		20 hours
Ramping Time at 4 kA		116 hours
Ramping Efficiency at 4 kA	47%	
Total Down Time		113 hours
Due to PS/QPM		92 hours
Due to Refrigerators		20 hours

It is left to the reader to form his own judgment on the degree of success of these tests. One should weigh the following in forming that decision, however:

1. The cryogenic operators during this time were accelerator operators, recently trained in the operation of the system; the more experienced personnel were not, for the most part, involved in the daily operations.

2. Many of the QPM-related problems were being encountered for the first time, and as such, required longer periods to diagnose, understand and cure. Problems such as the humidity related leakage, which accounted for most of the 59 hour down-time period, once solved, should not reappear in the final system.

Quenches

The behavior of the A-sector system insofar as quenches are concerned has to be considered very encouraging. Not only are spontaneous quenches infrequent, but also the system has demonstrated its ability to withstand repeated quenching with additional high voltage stress applied.

Spontaneous quenches: The number of spontaneous quenches observed is small. On the first ramp to 3 kA, one cell, A19, quenched. During the 4 kA ramping tests, A38 and A19 each quenched once, both times within the first ten minutes of ramping. A19, which is at the end of the longest cryoloop and has poor vacuum, is the warmest region in the system. It quenched again under the following conditions: first ramp to 4050 A; after two minutes at 4 kA DC; and on the first ramp to 4200 A. One other quench occurred with a puzzling voltage growth which casts doubt as to whether it was a real quench or not. Finally, there were three quenches associated with refrigeration anomalies: the first in A19 again, occurred shortly after the microprocessor was rebooted; the second, after the microprocessor inexplicably closed the helium flow valve; and the third, during refrigeration studies when the flow was throttled back too far.

<u>False Quenches:</u> A number of false quenches, instances in which the QPM believes a quench has happened, occurred during the course of the A-sector power tests. These are symptomatic of hardware or software problems - problems which are bound to occur during the development of a system of this complexity. Some of these affected single cells, but more often an entire house or all houses were affected. Examples of the causes of these problems were:

1. Software errors

2. The non-retriggerable TCP

3. Loss of the dI/dt signal for a single sample during a thunderstorm

4. The humidity problem already described

While these problems can be corrected, the final system will still have occasional full-house quenches when a QPM simply stops functioning.

<u>Intentional Quenches:</u> For the purposes of collecting the pressure data, a number of full-sector quenches were done at currents up to 3350 A. A one-house, 4 kA quench was also done for pressure information. In addition, a large number of single cell quenches, mainly at 4 kA, were induced. Many of these quenches were performed with an additional high voltage bias on the string, such as might occur in the final system when one of the twelve dumps failed. During these quenches, the high voltage stress appears on the system under conditions very different from normal operation: the single phase helium system contains warm helium gas, at pressures of a few atmospheres, instead of liquid helium. The polarity of the additional voltage was chosen so that it added to the dump voltage at the location of the quenching cell. Altogether, 22 quenches were induced, with high voltages up to 1300 V. In several instances, following a quench of one cell, the adjacent cell (upstream with respect to the single phase helium) also quenched, but many seconds later, at which time the current was down to less than 300 A. In one case, an adjacent cell went fairly promptly (3500 A, about one second after the first).

The magnet system did not survive all of this quenching entirely intact. As mentioned previously, a bellows failed during the 3350 A full-sector quench. During that same quench, some damage was done to four of the QBS modules. This damage arose because the dump voltage, which back-biases the QBS units, ends up appearing across the last few cells to quench. This back-bias is serious only insofar as the voltage characteristics of the SCR are concerned. The MOV devices placed in parallel with the SCR to bleed off the excess reverse voltage cannot carry large currents, and it was these MOVs that were damaged. This only happens when a large fraction of the magnets are quenching, and then only at high current.

Another failure occurred during a 4 kA quench. The intention was to quench two cells, A17 and A19, with a +1300 V bias voltage on the bus; the reason for quenching two cells was merely to save time. With the application of the dump voltage at the time of quench, the quenching magnets would see voltages close to 2 kV. The QPM discharged the heater firing units and activated the shunt SCR across the power supply, as expected. However, the dump resistor did not get switched into the circuit! Since the QBS controllers are activated by the dump signal, the QBSs were not gated on, either. The self-firing circuits in the QBS units functioned properly, and current was bypassed around the quenching magnets. After roughly ten seconds, the personnel at the console responded to the failure by manually activating the dump controller, just in time to protect the safety leads and QBS. At this late time, the high pressure helium had been vented out of the magnets. Apparently there was a high voltage breakdown inside the magnets at the time the dump voltage appeared. This breakdown created voltage transients which exceeded the quench threshold in A2 and half of A3. Again, as in the 3350 A full-sector quench, all of the dump voltage appeared across the remaining cells, this time with a slightly higher current, around 3550 A remaining. The remaining four cells quenched shortly thereafter, simply due to the excessive dI/dt. Unlike the intentional full-sector quench, this event was accompanied by a breakdown, within the QBS module, from upper to lower bus, at both A15 and A36, which resulted in substantial damage to the modules.

The failure of the communication link between the QPM and the dump controller is not understood. The system performed appropriately the next day, and during subsequent, high statistics tests. Since the communication link used during the A-sector tests is intended as the back-up system for the Tevatron, there is considerable concern over this failure. The magnets themselves were not damaged; the string was hipotted to 1.6 kV the next day, following replacement of the damaged QBS modules. The cell with the highest probability of damage to the safety leads, A19, was intentionally quenched at currents up to 4 kA following this episode, with no signs of damage.

The problem of the dump voltage redistribution during large scale quenches, with subsequent damage to the MOV, was not anticipated. Clearly, some changes in the design are required to alleviate this difficulty. Eliminating sources of large scale quenches has to be given high priority.

The repeated, single cell quenches provided an opportunity to test the refrigeration quench-recovery software. The procedure for recovery involves opening the single-phase relief valves on the spool pieces upstream, in the middle, and downstream of the quench cell. Each valve is closed as the liquid helium front reaches it. Recovery times of less than thirty minutes were achieved. This and other aspects related to refrigeration are discussed in another paper.

Other Accomplishments

DC Tests: As mentioned in the previous section, an attempt at running 4 kA DC ended in a quench after two minutes. Another try was more successful. The string was run at 3750 A for two hours, then at 3900 A, 3950 A and 4000 A for one-half hour each, with no difficulties encountered.

TECAR: Throughout the power tests, the power supply was controlled by the Tevatron Excitation Control and Regulation microprocessor, which allowed selection of any one of a small number of pre-programmed ramps. During the last days of the tests, this system was changed to allow the operator to simply enter the desired peak current and dI/dt for ramp and invert. The maximum ramp rate achieved without saturating the power supply was 300 A/s (1350 V) during convert, and -240 A/s during invert.

Electronics Stability: Short term electronics drifts were small from the start, but recalibrations were necessary, and were done on a daily basis as part of the start-up procedure. The recalibration is handled by the QPM software. By the end of the power tests, the stability was such that the maximum offset of any channel was less than one scaler count (28 mV) after one week.

Hardware Tests: A substantial number of tests were performed on various portions of the quench protection and power supply hardware, in particular to determine the system response to failures of components to function properly. Examples of the tests included failures of a heater firing unit, a QBS controller, the dI/dt signal, the dump SCR, and an Uninterruptable Power Supply. Other tests included opening the vacuum circuit breaker which supplies the 13.8 kV AC power, and simulation of a ground fault. The results of these tests were considered acceptable in all cases.

Software: A discussion of the details of the software involved in the A-sector power tests is beyond the scope of this paper. Let it suffice to say that the software, both in the QPM and the host computer, underwent a substantial evolution during these tests. In order that the significance of the software not be lost, it should be stressed that the development of the QPM software into its present form can in fact be considered the major achievement of the power tests. It was through that development that the system was able to be run reliably at high currents with the required quench detection threshold.

Acknowledgements

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References

1. Fermilab UPC-155 K. Koepke, P. Martin

2. Fermilab TM-1130 M. Martin, et al.

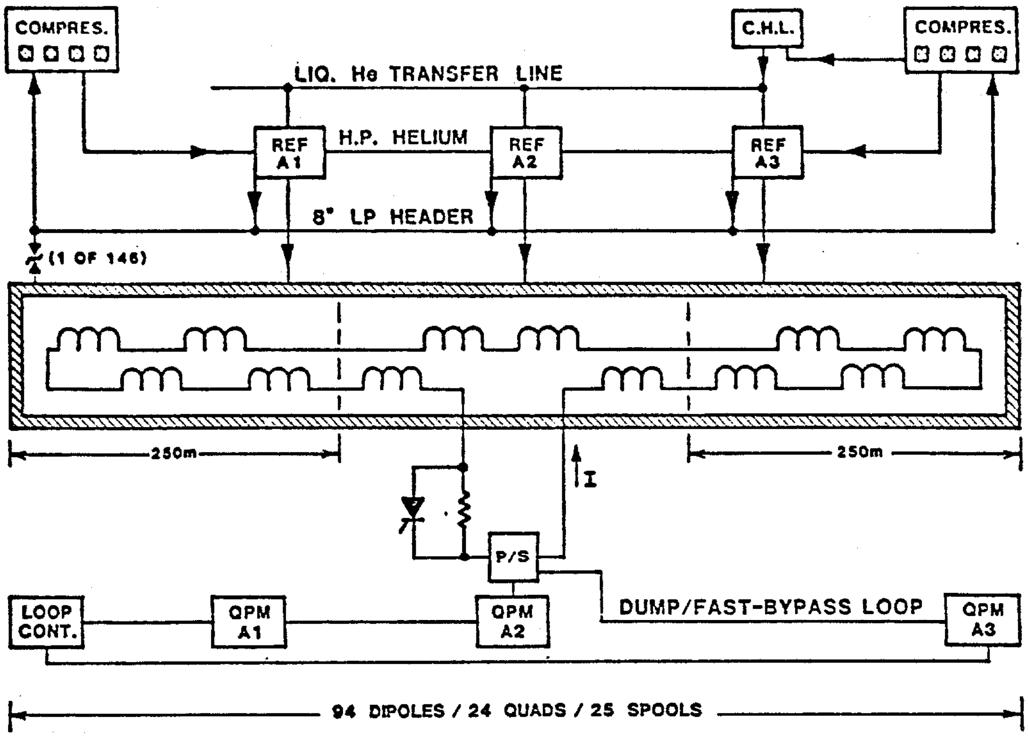
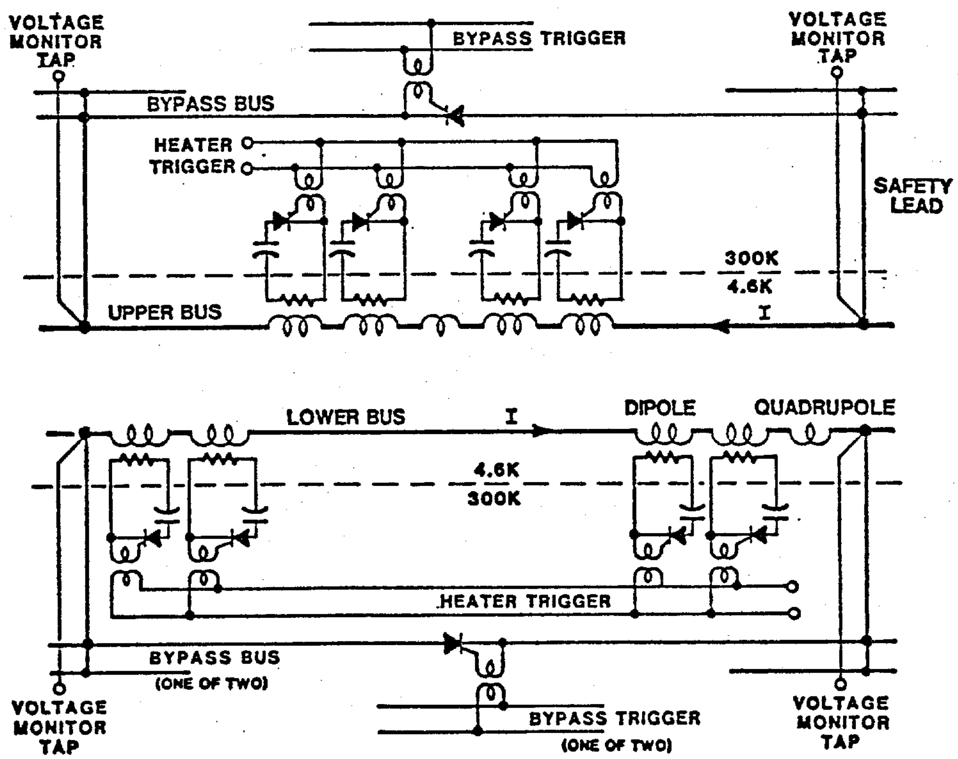


FIGURE 1



QUENCH PROTECTION UNIT

FIGURE 2

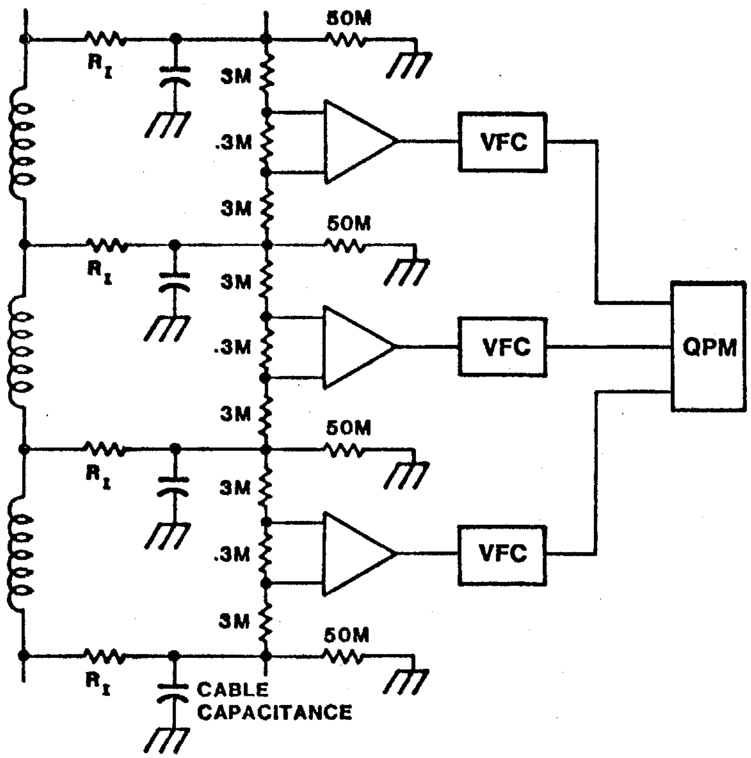
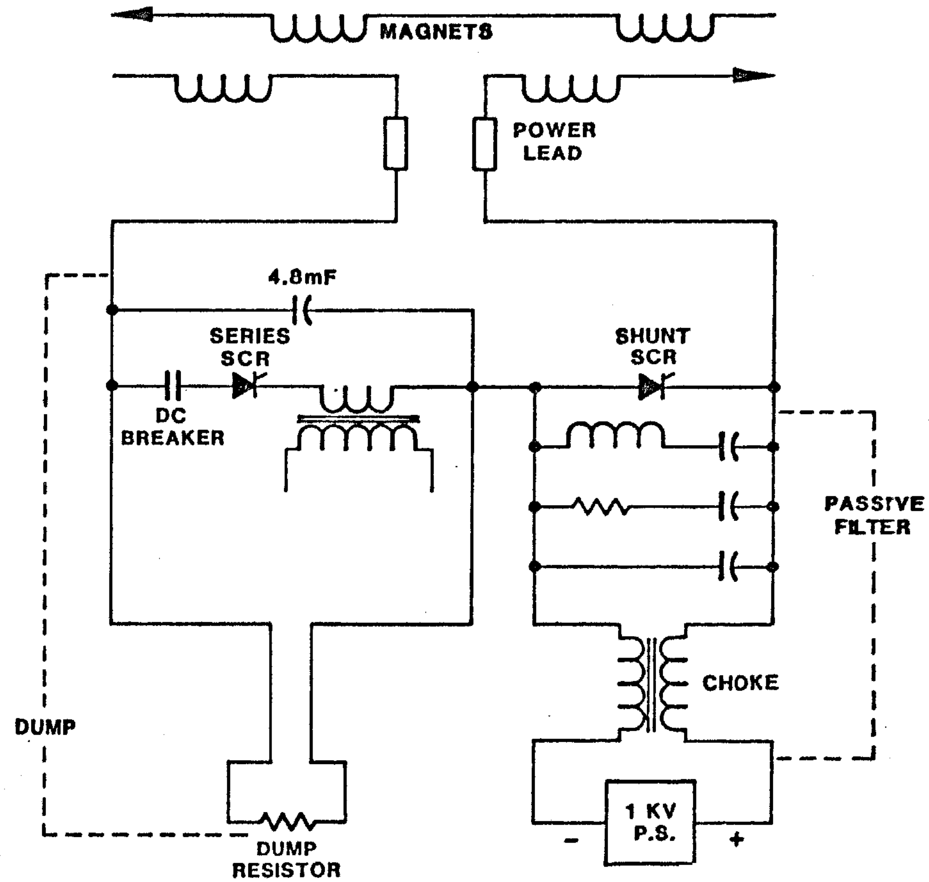
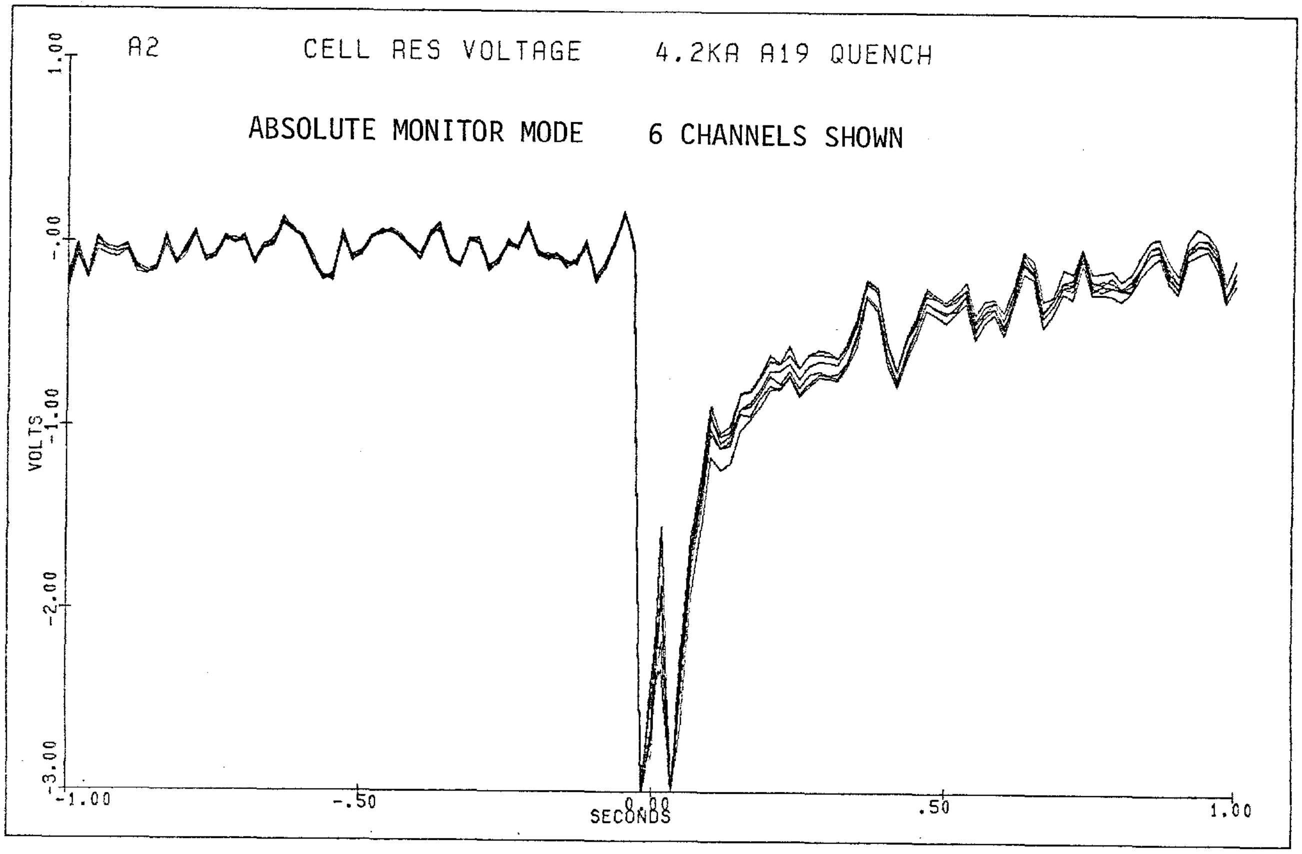


FIGURE 3



TEVATRON POWER SUPPLY SYSTEM POWER CIRCUIT

FIGURE 4


A2
CELL RES VOLTAGE
4.2KA A19 QUENCH
ABSOLUTE MONITOR MODE
6 CHANNELS SHOWN
1.00
-.00
-1.00
-2.00
-3.00
VOLTS
-1.00
-.50
0.00
.50
1.00
SECONDS

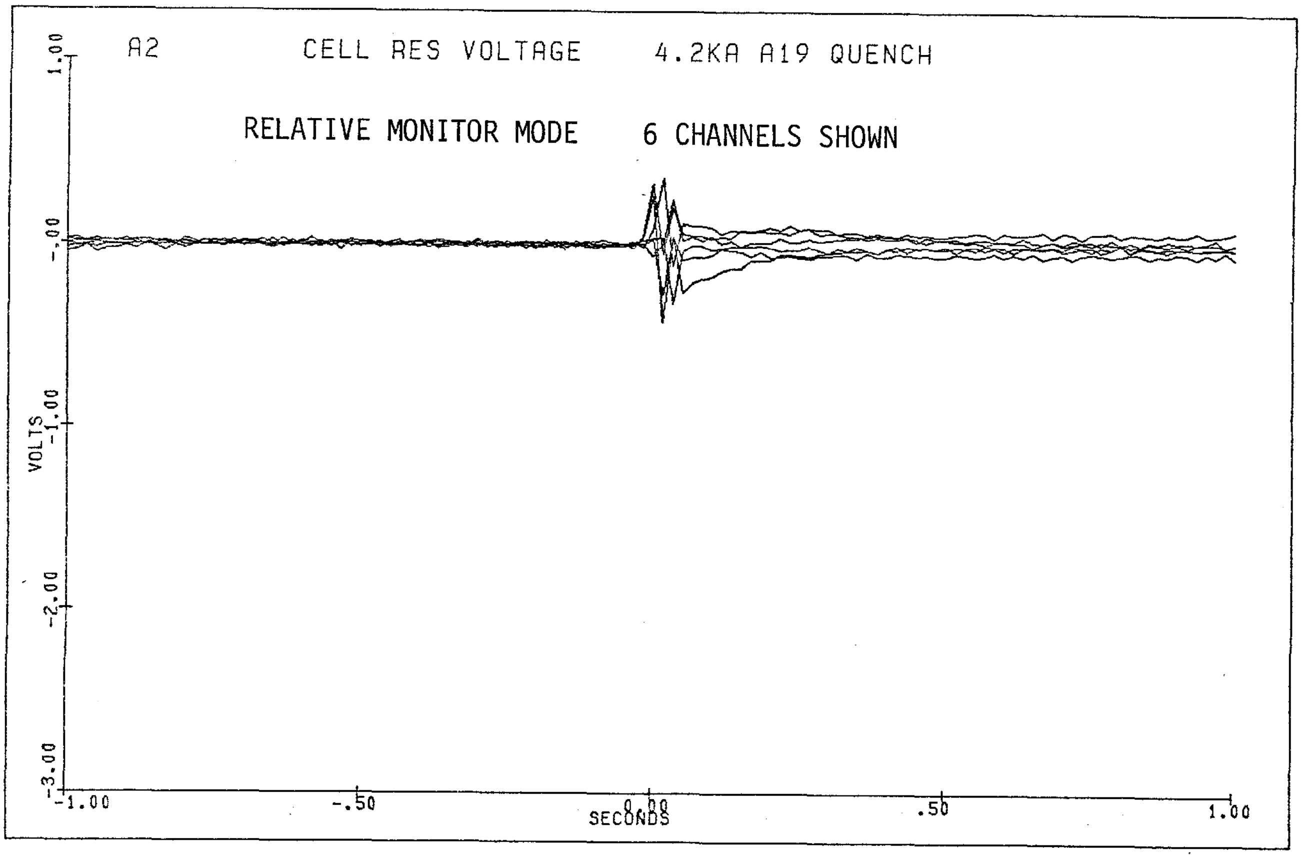

A2
CELL RES VOLTAGE
4.2KA A19 QUENCH
RELATIVE MONITOR MODE
6 CHANNELS SHOWN
1.00
-.00
-1.00
-2.00
-3.00
VOLTS
-1.00
-.50
0.00
.50
1.00
SECONDS

FIGURE 5

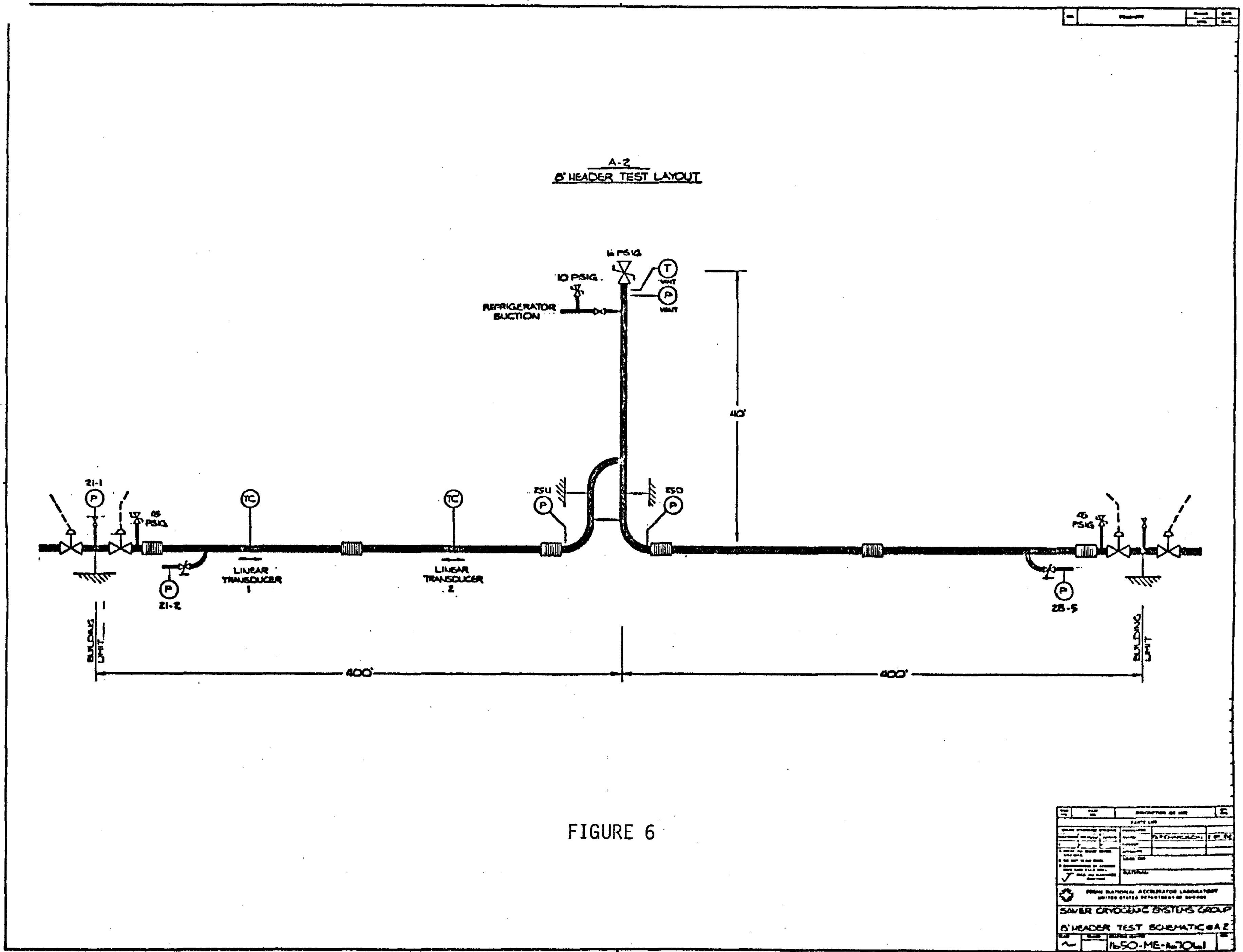

A-2
8" HEADER TEST LAYOUT
6 PSIG
10 PSIG
REFRIGERATOR SUCTION
T
VENT
P
VENT
40'
21-1
P
45 PSIG
TC
TC
25U
P
25D
P
45 PSIG
LINEAR TRANSDUCER 1
LINEAR TRANSDUCER 2
P
21-2
P
25-5
BUILDING LIMIT
400'
400'
BUILDING LIMIT
SAVER CRYOGENIC SYSTEMS GROUP
8" HEADER TEST SCHEMATIC @ A2
1650-ME-167061

FIGURE 6

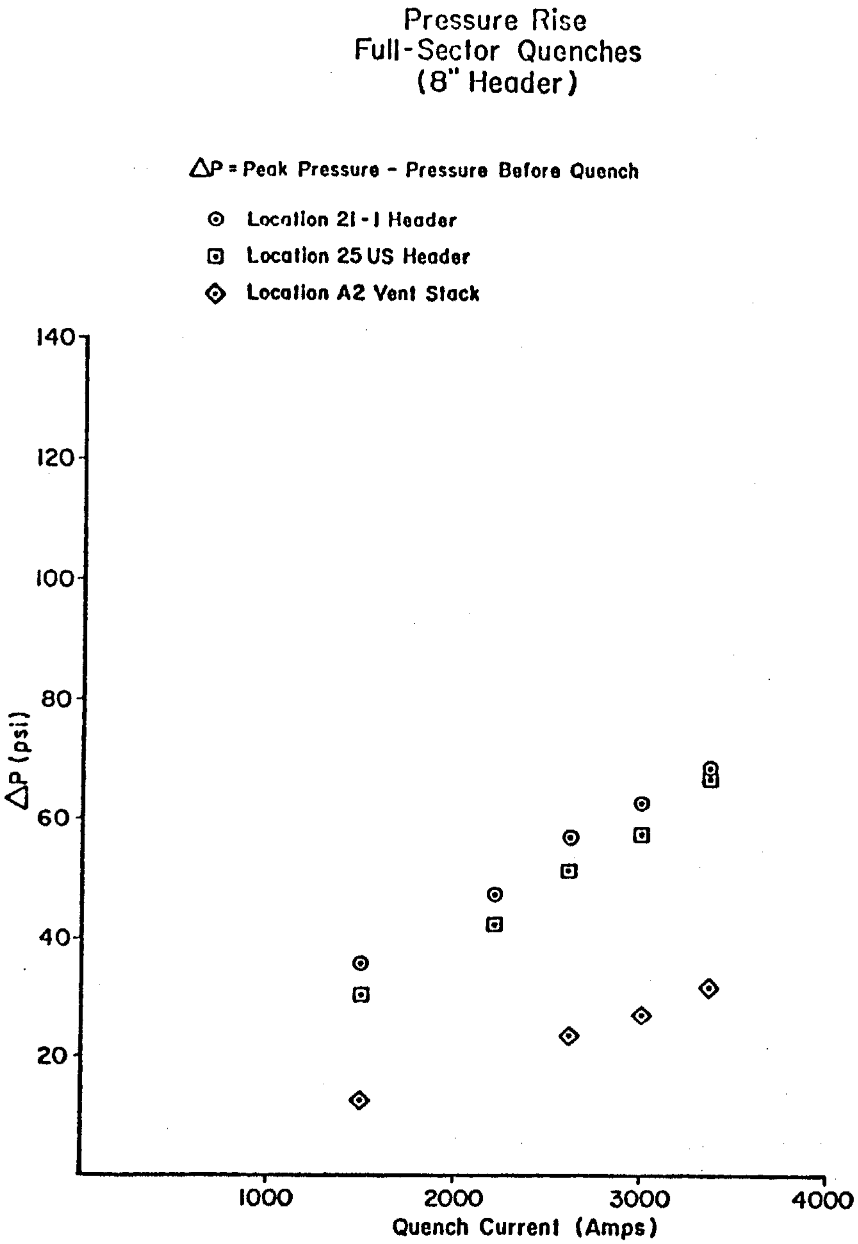


FIGURE 7

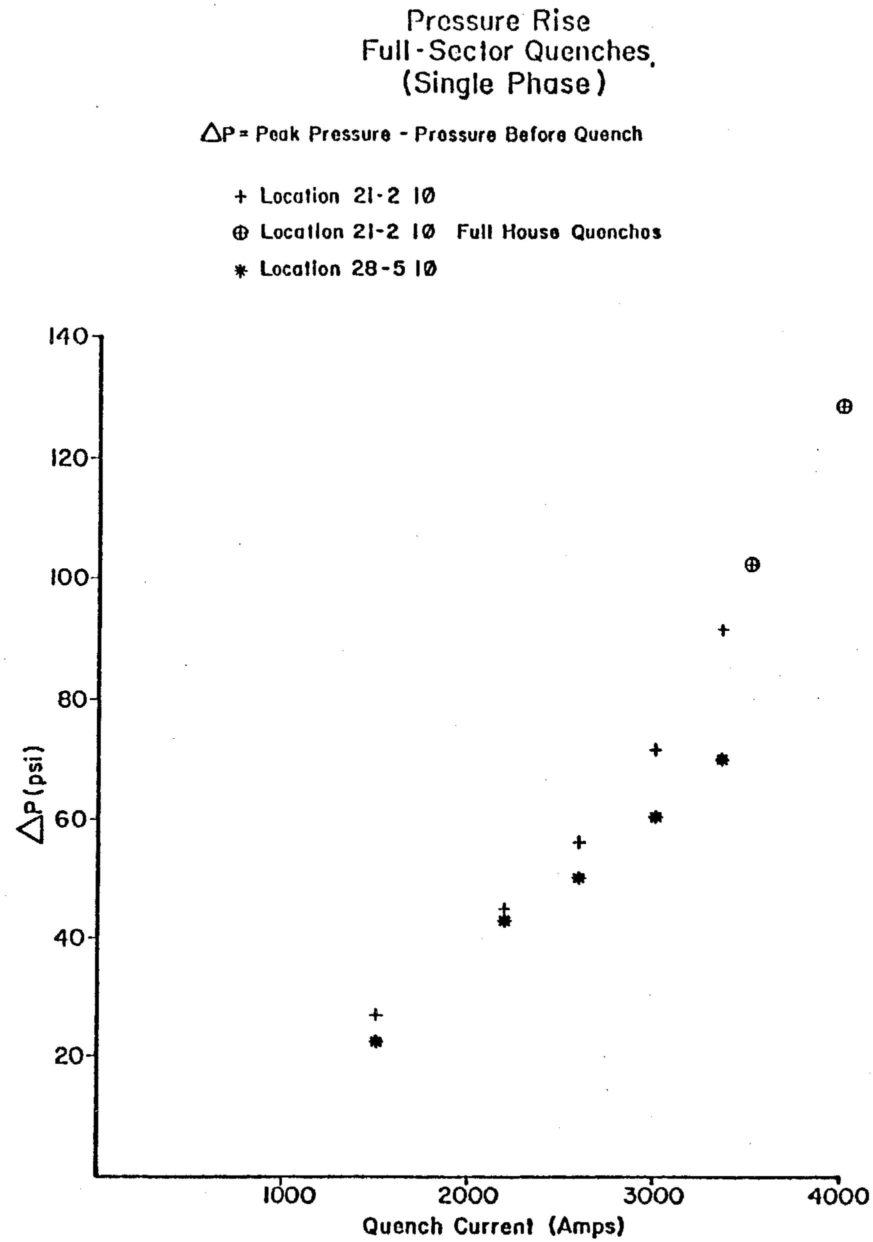


FIGURE 8

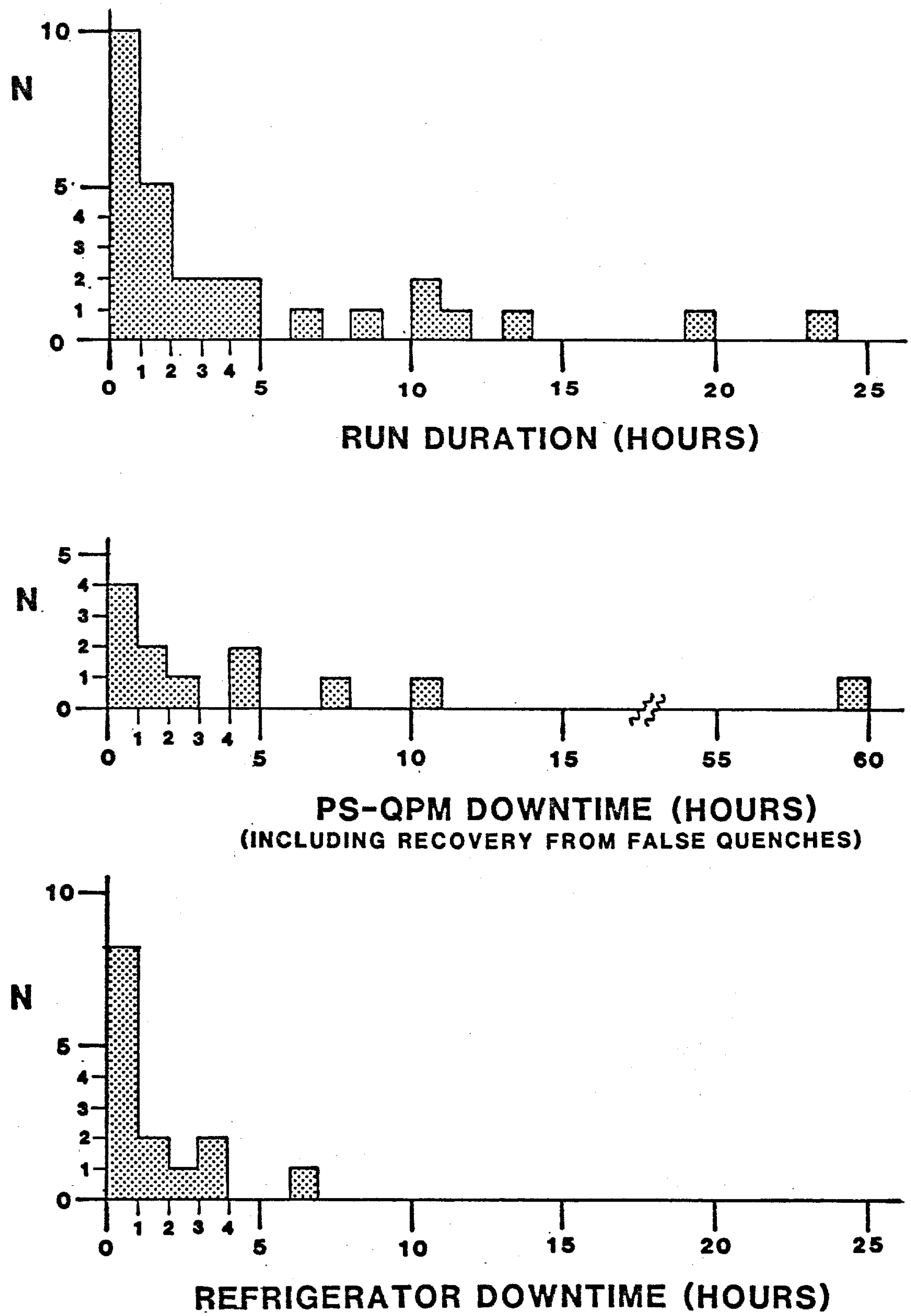

N
10
5
4
3
2
1
0
0
1
2
3
4
5
10
15
20
25
RUN DURATION (HOURS)
N
5
4
3
2
1
0
0
1
2
3
4
5
10
15
55
60
PS-QPM DOWNTIME (HOURS)
(INCLUDING RECOVERY FROM FALSE QUENCHES)
N
10
5
4
3
2
1
0
0
1
2
3
4
5
10
15
20
25
REFRIGERATOR DOWNTIME (HOURS)

FIGURE 9