Fermi National Accelerator Laboratory

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Magnet Power Supply Regulation Comments
240 kW and 500 kW Magnet Power Supplies

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1. Introduction

This note is written for users who need better than about 100 ppm regulated magnet fields in electromagnets. A magnet excitation current regulation of 100 ppm is generally specified to obtain this field regulation, but there are many other variables, in addition to magnet excitation that can change the magnet field. The effects of these other variables are often overlooked or underestimated. If things do not work out, the power supply often gets blamed. A field regulation of 100 ppm requires that the power supply regulates substantially better than 100 ppm and that the effects of other variables are limited.

Before we can talk about regulation we must define what regulation is. Power supplies can be regulated for current or voltage. We will only talk about current regulation, since that is the regulation mode used to establish precisely regulated magnetic fields in electromagnets. It is assumed that the same current value will always produce the same corresponding magnetic field value. Later on we will discuss that this assumption is not correct.

An ideal current regulated power supply will produce a perfectly scaled current from the impressed reference. If the reference changes, the output current changes. In other words, the output current of an ideal power supply tracks the reference precisely.

In the real world we do not have ideal power supplies and the power supply will try to do as good as it can to regulate the required current. The amount of deviation from the required current value is called regulation. Regulation is mostly expressed in percent or ppm (0.01% is 100 ppm) random deviation from a set value. A specified power supply regulation of 0.01% allows the output current to roam around in an error band with a peak to peak value of +0.01% to -0.01% of set value. The difference between maximum and minimum current can therefore be 0.02% of set value. Experimenters often use the "width of the error band" as a percentage of set value as a definition of regulation. There is a factor of two difference in these definitions. Power supply specifications are therefore mostly twice as liberal than what users think. It must be clearly spelled out what the users definition of regulation is. Power supplies are specified to regulate continuously within the error band over a wide range of conditions as specified below for a typical 240 kW power supply used at Fermilab. The specifications for a 500 kW power supply are similar.

2. Typical Power Supply Regulation Specification for a 240 kW Power Supply

"The power supply flattop current after warm-up shall be regulated for any programmed current value between 20% and 100% of rated output for each connection. The regulation shall be as specified hereafter:

The current regulate "Envelope of Uncertainty" shall be within:

$$\pm 0.01\%$$

of the programmed flattop current value, with the "Envelope of Uncertainty" containing the sum of the absolute values of the deviations caused by:

a) ±10% Static Line Variation
b) 25% Static Load Variation
c) 30°C Thermal Variation
d) partial PARD, Only 60 Hz and 360 Hz components caused by power supply unbalances

e) ±0.2 Hz Line Frequency Variation
f) 5% Line Voltage Unbalance
g) Line Harmonics
h) Drift

3. Definitions

Warm-Up

Unless stated to the contrary, all specifications apply after a minimum warm-up period of 30 minutes at 50% of maximum rated load and nominal power line input.

Static Line Regulation

The unprogrammed variation in output current (voltage) that occurs when the input line voltage is varied slowly from nominal value to either minimum or maximum specified values, while all other operating parameters are held constant.

Thermal Regulation

The variation in output current (voltage), after rated warm-up period, with the input held at nominal value and constant operating parameters, while the temperature in the vicinity of the unit is varied within the specified ambient temperature range.

Stability (Drift)

The variation in output current (voltage) over a 24-hour period after rated warm-up period, measured at any selected load point, during steady state conditions of all external operational and environmental parameters.

Dynamic Line Regulation

The variation of the current (voltage) that ultimately disappears after an abrupt increase or decrease of the nominal line voltage, while the external operational conditions are held constant.

PARD (Periodic and Random Deviation)

The variation of the output current (voltage) which is the sum of unprogrammed current (voltage) deviations harmonically related to the input power frequency, hum, noise and spikes, while all external operational and environmental parameters are held constant.

Envelope of Uncertainly

The "Envelope of Uncertainty" is the sum of the absolute values of static load regulation, static line regulation, thermal regulation, stability, PARD, the effects of power line frequency variations, harmonics, and ac line voltage unbalance.

The repeatability of a current setting value shall be typically <50 ppm."

4. Power Supply Regulation Performance

Power supply performance has been extensively tested at the manufacturer's plant. Testing of the first production units is by far the most extensive. These tests are not easy to make because voltage changes in the order of 10 μV out of about 10 V need to be indisputably detected around heavy power equipment. The regulation test results for a typical 240 kW are listed below.

5. 240 kW Current Regulation at About 50% Load, Test Results 1974

Static line regulation	-	1 ppm/±10% line change
Static load regulation	-	20 ppm/25% load change
Thermal regulation	-	40 ppm/28°C temperature change
PARD	-	0.5 V_{pp} at 60 Hz 1 V_{pp} at 360 Hz
Frequency variation	-	not tested
Line harmonics	-	No observable effect
Drift	-	< 1 ppm
Total power supply regulation	-	≤ 70 ppm

The load and ambient temperature will usually remain fairly constant and the power supply output current may therefore not change more than 20 ppm during 24 hours of operation. The performance of a 500 kW power supply is expected to be similar, but I have no test data on hand.

6. Magnet Field Errors Beyond the Control of the Power Supply

Even an ideal power supply does not guarantee an ideal magnetic field regulation. No matter how well a power supply regulates the current, there will still be differences in the magnetic field caused by:

1. Magnet variations.
    - 1.1 Remnant field
    - 1.2 Temperature
    - 1.3 Saturation
    - 1.4 Leakage
    - 1.5 Magnetostriction
2. Reference variations.
3. Reference noise pollution.

Other points affecting the quality of power supply current regulation are:

4. Power supply operating point as a percentage of its rating.
5. Deterioration of regulation when two or more power supplies are connected in series.

6. Power supply voltage ripple.
7. Power supply aging.
8. Humidity, dirt, electrolysis and cooling water leakage resistance.
9. Structural movement, earth movement and vibration may look like regulation problems.

7. Magnet Field Variation

The magnet field vs. excitation current ratio is not perfectly constant. Differences in magnetic field for the same current are caused by:

7.1 Effects of remnant field (hysteresis).
7.2 Temperature changes.
7.3 Saturation of the steel, causes different $\Delta I/\Delta B$ ratios.
7.4 Leakage resistance of the cooling water connections, dirt, humidity and electrolysis.

7.1 Estimate of the Remnant Field Effects

All magnets, under this discussion are made from ordinary hot rolled low carbon steel plates, such as 1030 or other electrical grade steels. The amount of hysteresis depends on the previous excitation history, and H_c can be as high as about 5 Oersteds (400 Ampturns/meter) coming from 10 kG to 0 Oersted for virgin steel. The hysteresis can aide or oppose the excitation current depending on whether the excitation current was reversed. The field contribution caused by hysteresis diminishes when the steel saturates. Magnets are mostly operated at the same point, but after an overcurrent fault or current overshoot things will be different. What can we expect? It depends on the magnet construction and the type of steel (H_c) used. The remnant field (hysteresis) effect is larger in small gap magnets than in magnets with a large gap. Suppose we have a magnet as follows:

Gap	1 meter
Field	1 Wb/m^2 (10 kGauss)
Excitation for 10 kGm	800,000 AT
Magnet Steel Length	5 meters
Assume: H_c difference	1 Oersted (80 AT/m)
Difference of excitation contribution of 1 Oersted hysteresis over 5 m steel length	400 AT
Field change	500 ppm caused by hysteresis.

We can also look at hysteresis another way. For many electrical grade steels H_c is slightly less than 1 Oersted. Most commonly used beamline magnets have a gap height h_g (h_g is the opening between the pole faces) and iron length l_i (l_i is the average distance between the pole faces when traveling through the magnet steel) ratio of about 5. It can be proven, using an Hc of about 1 Oersted, that the remnant field in a magnet equals l_i/l_g Gauss after reasonable excitation. Thus, most magnets have, after use, a remnant field of about 5 Gauss. Spoilers that have no gaps, can have remnant fields of 2000 to 10,000 Gauss. A remnant field difference of 1 Gauss out of 10,000 Gauss would yield 100 ppm field change for the same excitation.

The effect of hysteresis should not be underestimated.

7.2 Magnet Temperature Change

The magnet steel temperature may rise 20°C after startup, which expands the magnet gap. The gap length, l, should also increase the same amount, so that Bl remains constant. I am not sure whether this is true for short magnets with a large aperture, because of the large contribution to Bl caused by the leakage field. Gradual warm-up of the steel may take 6 hours to several times that long.

The temperature coefficient of expansion of steel is 13 ppm/°C. A 20°C magnet steel temperature rise will make the magnet field drop 260 ppm.

7.3 Saturation of the Magnet Steel

Magnets that operate with saturated steel require a larger current change than an unsaturated magnet, for the same amount of field change. Saturated magnets can, therefore, improve field regulation. It is not cost effective or practical to operate the steel of a magnet in the saturation region.

7.4 Leakage Resistance of the Cooling Water Connections, Dirt, Humidity and Electrolysis

Changes in cooling water conductivity and humidity change the amount of leakage current that bypasses the coil windings. This varying leakage current is in reality subtracted from the magnet excitation current. Dirt accumulates gradually on the magnet insulation and insulators. A combination of high humidity and dirt will increase leakage currents. Highly regulated magnets must be kept clean. Electrolysis gradually deposits a conductive layer on the inside of the cooling water hoses and insulators, which deteriorates their insulation quality over the years. A typical magnet leakage resistance to ground may vary from 10 kΩ to 50 kΩ during a day. Leakage currents also flow from coil winding to coil winding at different potentials. Making a simplified model, we could say that the magnet coil is shunted with a variable resistor from 10 kΩ to 50 kΩ. A magnet running at 1000 A and 100 V may have a shunted leakage current, which varies from 10 mA to 2 mA. In that case the excitation and thus the magnetic field changes about 10 ppm. It is best to use fairly long cooling water hoses.

7.5 Magnetostriction

When steel is magnetized, it changes its dimensions. For silicon steel this change is in the order of 2 ppm for a field change from 0 to 15 kG. Magnetostriction will not change the magnet field since the shrinkage is always in the same direction and of the same magnitude for the same field. However, the alignment of items referenced to a magnet pole location will be different for a de-energized cold magnet, compared to an energized warm magnet. Steel has a temperature coefficient of 13 ppm/°C.

8. Reference Variations

If the reference to the power supply is not stable, then the excitation current will not be stable.

8.1 Temperature

The remote reference voltage to the power supply is generated via the beamline control system (EPICURE) and uses a 16 bit DAC followed by a buffer. Drift in the reference will cause the power supply current to drift. The typical specified total drift of the remote reference may be estimated at 37 ppm/oC (1) of full scale rating. Operating at about 75% of full scale yields an estimated typical reference drift of 50 ppm/oC, and a maximum possible reference drift of 100 ppm/oC. It is possible to make some simple modifications (1) to the electronics to reduce the reference drift about a factor of two.

8.2 Resolution

The digital reference will regulate ± 1 LSB. An ideal 16 bit reference will change 65536±1. Assuming 75% of full scale, the resolution is 49152 ± 1 or ± 20 ppm.

8.3 Humidity

High humidity and dirt will impair the remote reference performance.

8.4 Thermal emf's

Typically we like to operate the reference (power supply) close to the full output of 10 V or 10,000,000 μV. The wiring between the reference and the power supply regulator contains several junctions. Dissimilar metals do exist and this could be aggravated by body salt deposits when the connections are made. The connection emf's should cancel, because they are at the same temperature and opposite in the reference loop. Is it reasonable to estimate a thermal emf change of 5μV/°C and a temperature variation of 10°C? In that case the reference could vary 50 μV or 5 ppm. This effect has a greater impact at lower reference values.

9. Reference Noise Pollution

The distance between the external reference and the magnet power supply is typically 25 feet. Common mode voltage differences between the reference and power supply location, and EMI (electromagnetic interference) pickup in the reference cables to the power supply, can pollute the reference signal. Good installation practices must be followed to minimize reference noise pollution.

General Reference Comment

Power supplies that are run DC could be run from the built-in internal reference. The internal reference has a temperature stability of 0.05 ppm/°C and better resolution than the external reference. Noise pollution should not be a problem. A drawback is that the local reference cannot be set from remote. Another drawback is that the magnets cannot be pulsed. Pulsing is often needed to reduce the average d.c. losses. A motor driver, to set the reference potentiometer, could be made.

10. Power Supply Operating Point

Power supplies work the best when operated close to their rated output, but they meet specifications in the operating range from 20% to 100% of rating. Better performance at rated output may be expected, because error voltages in the regulator loop at full output may be 5 times larger than at 20% output for the same percentage value of error regulation. There are no specified regulation requirements below 20% of rated output. Continuous operation at low output requires the selection of a different power supply. Power supplies operated at low values of their voltage ratings have a very poor power factor.

11. Power Supplies in Series

Some loads require two or more power supplies in series to supply the needed load current and voltage. In most cases, one power supply is connected in "Current Regulate" and the other(s) in "Voltage Regulate". The overall current regulation of such a setup is usually a factor 2 (2 power supplies) or a factor 3 (3 power supplies) worse than the regulation of one power supply.

Controlling series connected power supplies in a master/slave configuration does not impair regulation much. A practical limitation is, that the series connected power supplies have to have the same AC phasing (come from the same substation). The current regulated master power supply fires the slave SCR's in a master/slave setup. The slave power supply has no regulator at all.

12. Power Supply Voltage Ripple

The 12 phase power supply peak to peak output voltage ripple increases from about 10% to about 18% of the maximum design output, when the power supply voltage is reduced from 100% of rating to about 60% of it's voltage rating. The design output voltage is about 1.1 times the power supply voltage rating. Suppose we have the following power supply and load matches.

Case	Magnet	Power Supply	Power Supply Ripple 720 Hz	*Power Supply Current 720 Hz	*Ripple Current ppm	Comment PS/Load	AC Power Factor
A	100 V 1000A 5 mH	100 V 1200 A	11 V	0.49 A	490	Good Match	Good
B	60 V 1000 A 5 mH	100 V 1200 A	19 V	0.84 A	840	Poor Match	Poor

*Real case load ripple currents will be higher because of magnet iron losses, but the effect in the magnet field will be diminished due to eddy currents in solid iron magnets or magnets with thick laminations, or thick wall vacuum chambers. The power supply output voltage ripple can be reduced by installing a ripple filter. The magnet field ripple can also be reduced by installing a 1/8 thick (estimate) copper or aluminum plate at each magnet pole. Eddy currents in the plates will cancel magnetic field variations. The pole plates are not practical for pulsed magnets. As can be seen, it is best to match the magnet power supply and the load.

13. Power Supply Aging

Most of our supplies are 15 to 20 years old. Many components have been changed in the regulators, firing circuits and transductors. Many of those changes were required because the old parts were not serviceable anymore or improved circuits became available. Excellent maintenance is performed on the equipment. We do not expect that power supply regulation has deteriorated over the years, but it may be wise to check the power supply performance at critical installations. The internal reference should be used for this.

14. Humidity, Dirt, Electrolysis, Cooling Water Leakage Resistance

All the above conditions can change the power supply regulation the same way as they cause changes at a magnet (7.4), but there are additional effects caused by humidity and dirt in the regulator electronics. Additional or changing leakage resistances in sensitive regulator electronics areas can affect power supply regulation. This effect was observed during testing and the regulator layout was slightly changed to cancel or reduce this effect. All equipment must be kept clean and dry.

15. Stuctural Movement, Earth Movement and Vibration

Heavy magnets and shielding may cause an area to gradually sink. Minor earth movements may also be caused by climate changes (summer, winter) rain, earthquakes, etc. This effect, however, will be small over 24 hours except for earthquakes. Temperature changes will cause structural members to expand and contract, and this could have an impact when precise swics are used to measure magnet field regulation from beam position stability. Suppose that in a long beamline, a beam spot move of 250×10^{-6} m could be caused by an upstream magnet current change of 250 ppm. Imagine that the swic is mounted on a 1 meter long steel post, that changes 20°C in temperature. This temperature change will cause the swic to move 260×10^{-6}m. If we do not think about this, we would conclude that the current changed 250 ppm. Vibration can also move a swic. Slight changes in extracted beam location on a swic might wrongly be interpreted as magnet current changes.

Changes in extracted beam stability will have a similar affect and may create the illusion of power supply regulation problems.

16. Conclusions

When a user requires a regulation of 100 ppm he is most likely thinking of a total error band width of 100 ppm of set value, or ± 50 ppm deviation of set value. He is probably also agreeing that this regulation is only needed for a 24 hour period after a fairly long (6 hours?) system warm up time.

During the 24 hours period we will assume that cooling water temperatures, cooling water resistivity, ambient temperature, line voltage, and hysteresis, etc. remain fairly constant. With these assumptions we can make an estimate of the magnet field regulation for the total error band as summarized below:

Item / Cause	Estimate of magnet field changes with one power supply at 80% load during 24 hours, after warm-up.			
	Power Supply ppm	Internal Power Supply Reference ppm	External Power Supply Reference ppm	Magnet Field ppm
5°C Ambient Change	8	2	250	---
5°C Load Temperature Change	2	--	--	70
Cooling Water Resistivity Change	2	--	--	5
Magnet Hysteresis	--	--	--	20?
Power Supply Ripple	--	--	--	20?
Resolution	--	5?	40	--
Other	5	2	5?	--
TOTAL	**17**	**9**	**295**	**115**

From this table we find an expected total magnet field error band of 140 ppm with the internal power supply reference and 436 ppm with the external power supply reference. From this estimate it becomes clear that the largest expected error contribution is caused by the remote reference. The temperature regulation of the remote reference needs to be improved to < 2 ppm/°C and the resolution also needs to be improved by at least a factor of two when a field regulation of 100 ppm error band is specified.

Changes in the magnet are probably less than 115 ppm over 24 hours of operation. With a proper reference it appears possible to current regulate a power supply within ± 50 ppm in a reasonable constant environment. Beam spot location movement does not indisputably mean that a power supply drifts. The magnet field ripple must be checked. The existing power supply current readback system is not good enough (14 bit, drift, noise) to read 50 ppm regulation in a range from 20% to 100% of full scale rating.

17. Operating Recommendation for Installations Needing a Regulation of Better than 100ppm (±50ppm)

a) Use one power supply, or a master/slave connection if needed.
b) Operate close to the power supply rating.
c) Use an NMR to read the magnet field and set the current to match the needed field, after 6 hours of warm up.
d) Use the internal power supply reference, or improved external reference.
e) Control the ambient temperature.
f) Control the cooling water temperature.

g) Control the magnet hysteresis (not important when method 3 is used).
h) A power supply ripple filter, or pole face plates may be needed for low inductance magnets, or magnets with thin laminations.
i) System regulation should be thoroughly checked using the power supply internal reference, an external transductor and a NMR Gaussmeter. Use the external reference for this test if it will be used.
j) Make sure all equipment is clean.
k) Check the magnet field ripple.
l) Operate equipment at least 6 hours at operating levels before beamtime. This will reduce thermal effects.

18. Historical Experience

There is not much recorded historical data describing our experience with highly regulated loads. The experimental area (about 200 - 240 kW and 500kW) power supplies have caused very few regulation complaints, but they operate probably in areas where ±300 ppm regulation of the current is adequate.

A regulation problem occurred at CDF, where a space heater blew hot air at the external power supply reference area. Although this heater was about 25 feet away, it was enough to cause about 200 ppm field (current) change in the load. This was a different style external reference than the unit described previously.

Experiment 690 did check the power supply (actually the magnet field) regulation total error band at three places in their experimental area beamlines (2). All three places used more than one power supply in series and the magnet string currents were pulsed in synchronism with the main accelerator pulse (pulse period 60 sec and flattop 23 sec) from the standard (1) beamline control system reference. The results of these tests are tabulated below:

Installation E690	NE9E	NEBE	NEFE
Number of power supplies in series	2-500 kW 1 current regulator 1 voltage regulator each 100 V/5000 A	2-500 kW 1 current regulator 1 voltage regulator each 200 V/2500 A	3-500 kW 1 current regulator 2 voltage regulators each 100 V/5000 A
Load	5 magnets B1 35 mΩ 33 mH	13 magnets, EPB 240 mΩ 390 mH	1 magnet B2 & 4 magnets B2 (opened) 50 mΩ 32 mH
Flattop current	3300 A	1100 A	4800 A
Power supply current operating point vs. rating	66%	22% (of 5000 A XDTR)	96%
Power supply voltage operating point vs. rating	58%	66%	83%
Estimated current regulation with 5°C change after warm up	Power supply - 35ppm load - 10 ppm reference - 280 ppm **TOTAL = 325 ppm**	Power supply - 35ppm load - 10 ppm reference - 840 ppm **TOTAL = 885 ppm**	Power supply- 50 ppm load - 10 ppm reference - 250 ppm **TOTAL = 310 ppm**
Measured field flattop regulation (2)	≤ 150 ppm NOTE A	≤ 400 ppm NOTE A	≤ 100 ppm NOTE B

(A) A beam spot movement, traced back to the total Bl change caused by the sum of NE9E and NEBE was used to get a measure of the summed regulation of NE9E and NEBE. The beam position was monitored for 3 days at SWIC NECPWC (2). This regulation is about a factor of 2 better than estimated.

(B) The magnet field was measured with a precision Gaussmeter for several days. Initially (~10 minutes) the field drops 210 ppm and drops thereafter exponentially another 210 ppm during five hours. After about 5 hours the field stays within 80 ppm. at the same flattop point. The field also droops 40 ppm during flattop. The measured performance is about a factor of three better than estimated.

The initial observed drop after startup of 210 ppm is probably caused by temperature changes in electronics, since it has a short time constant. The second exponentially decaying field drop of 210 ppm is very interesting. It has a time constant of several hours, which is about the thermal time constant of a magnet, because a magnet has a lot of mass. The average magnet coil temperature will rapidly increase about 20°C after startup based on cooling flow and loss estimates. This elevated coil temperature will gradually heat the magnet steel an additional 20°C causing the magnet gap to expand (7.2). The gap expansion would be 260 ppm for 20°C steel temperature rise and cause the field to drop 260 ppm. The exponentially decaying observed field drop of 210 ppm can be explained by this gradual magnet gap increase. Figure 1 shows plots of field measurements at NEFE during the gradual warm up period.

19. References

(1) EED internal note, 2/12/92, to T.M. Watts from P. Kasley, subject: C1151 power supply controller reference output.

(2) Private conversation with Gaston Gutierrez, 2/16/93. E690, Gaston Gutierrez personal file about NE9E, NEBE, and NEFE regulation checks.

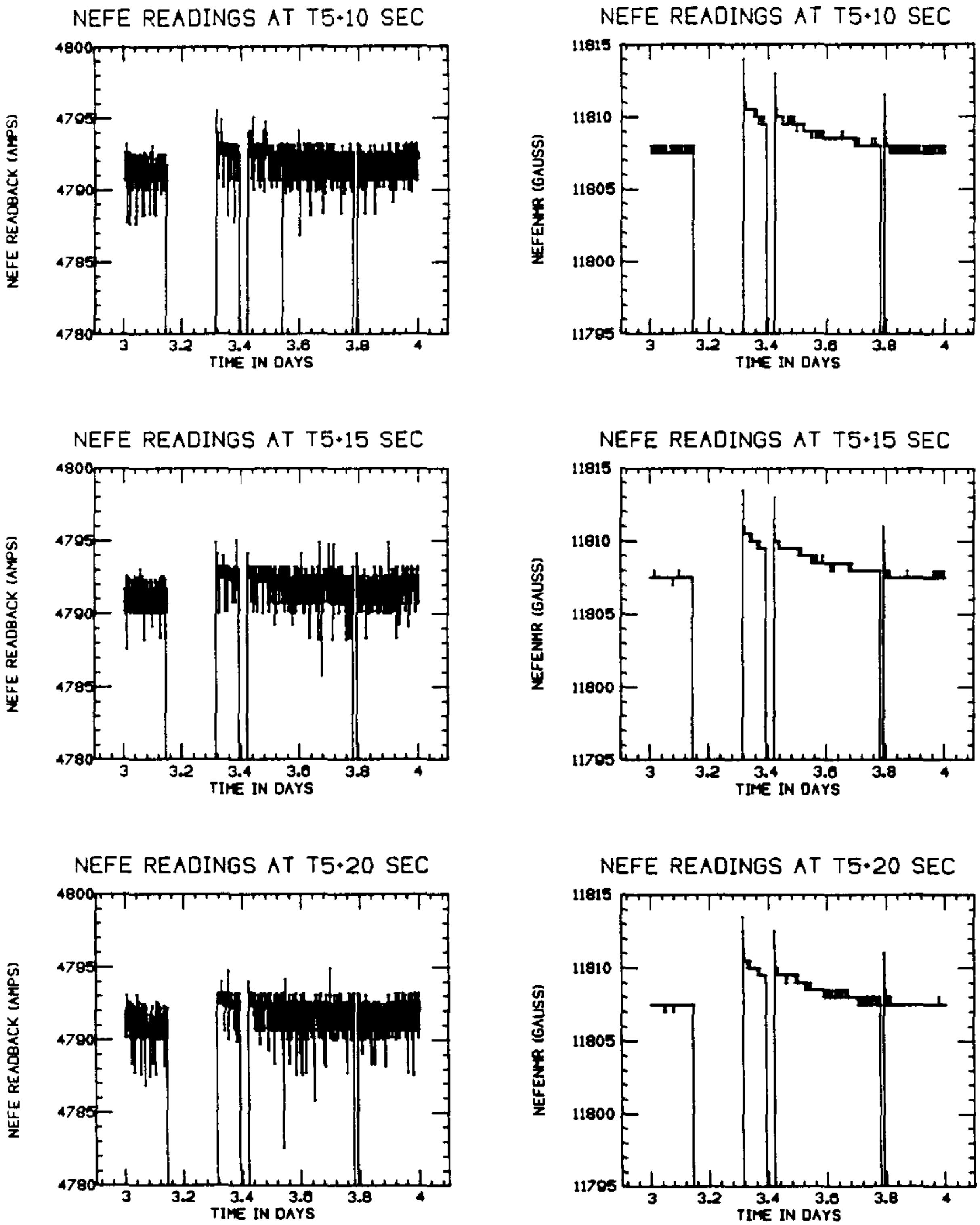

FIGURE 1

Magnet NEFE Field Readings During Flattop

E690 Gaston Gutierrez
file - 1991