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ARMOUR RESEARCH FOUNDATION

of

Illinois Institute of Technology

Technology Center

Chicago 16, Illinois

ARF Project No. A-106

on

IRRADIATION TESTING OF OPERATING ELECTRONIC EQUIPMENT

BY FAST NEUTRONS AND GAMMAS

Contract No. N62269-253

by

R. J. Arndt and C. W. Terrell

to

Receiving Officer

U. S. Naval Air Development Center

Johnsville, Pennsylvania

Attention: Aeronautical Instrument Laboratory

Mr. E. J. Rickner

Final Report

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April 30, 1958

This is the final report on the program "Irradiation Testing of Operating Electronic Equipment by Fast Neutrons and Gammas." The program was conducted under Contract No. N62269-253 and was designated ARF project A-106.

Respectfully submitted,

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ABSTRACT

The work reported herein consists of a study of the radiation effects of fast neutrons (0.5 ev to about 15 mev) and gamma rays (fission spectrum) on various pieces of aircraft instrumentation. Components studied were:

1. Fuel Gage Vacuum-tube Amplifier and Indicator
2. Transistorized (germanium and silicon) Servo Amplifier System
3. 4 inch Diameter Gyro.

The Fuel Gage was subjected to a total neutron flux of about 6×10^5 nvt and about 5×10^8R gamma with no adverse electrical effect. Physical damage was evident.

Four Transistorized Amplifiers were irradiated in a fast flux of about 1.0×10^{10} n/cm^2/sec. Rapid loss in gain, rapid increase in d.c. current drain, and complete failure occurred when the integrated flux reached about 10^{13} n/cm^2. The silicon diodes were unaffected by the same flux.

Studies on the gyro were inconclusive due to equipment failure.

LIST OF ILLUSTRATIONS

IRRADIATION TESTING OF OPERATING ELECTRONIC EQUIPMENT BY FAST NEUTRONS AND GAMMAS

I. INTRODUCTION

The purpose of the study was to determine the effects of a fast neutron flux accompanied by a gamma flux, on three types of aircraft instruments. The work was divided into three parts:

A. Pre-irradiation Operation

B. In-Pile Operation

C. Post Irradiation Operation.

The pre-irradiation phase allowed project personnel to become familiar with each piece of equipment and to ascertain that the instruments were operating within specifications established by NADC.

In-piles studies consisted of exposing each instrument to an integrated fast flux of just under 10^{16} neutrons per square centimeter. Throughout the exposure the equipment was operated by test stations provided by NADC and located at the face of the pile. As the instruments were inserted to within approximately six inches from the surface of the reactor's core, the neutron flux was accompanied by a prompt and delayed gamma flux arising from fission and the gross fission products.

Post irradiation operation was performed to observe any delayed failures which might appear after the termination of irradiation. Those units which failed during irradiation were likewise operated to determine any recovery from radiation induced failure.

II. DESCRIPTION OF THE TEST FACILITY

The Armour Research Reactor is of the aqueous homogeneous-water boiler type and is fueled with Uranyl Sulfate in light water. The fuel solution is contained in a 12-1/2 inch stainless steel spherical core surrounded by a graphite reflector. The reflector, in turn is shielded by five feet of high density concrete.

Control of the reactor is accomplished by four boron carbide rods lifted by electromagnets. The usual complement, with some special features, of instrumentation allows the reactor operator to monitor and control the neutron level and hence, the reactor's power level.

Because of the aqueous moderator (light water), radiolytic decomposition results in the liberation of a large quantity of hydrogen during full power operation. An oxygen sweep gas dilutes and transports this hydrogen to a platinum catalyst bed where recombination of the hydrogen and oxygen occurs. The water vapor formed is transported to the core region where condensation returns the moisture to the fuel solution. Thus, the fuel solution is maintained at a constant volume. The entire gas recombination system described above is located in a gas tight room beneath the reactor proper. This steel lined gas tight room serves as a secondary containment should the primary containment rupture for any reason.

The large quantity of hydrogen released from the core solution removes a significant fraction of certain gaseous fission products, such as Bromine, Iodine, Krypton and Xenon. These gases have a number of gamma emitting isotopes and hence represent a significant source of gamma rays. Advantage of this is taken by passing exposure tubes through the shielding into the gas tight room containing the recombination system. Known as the Armour Gamma Facility, this feature offers irradiation and experimental opportunities for those areas where neutrons are undesirable.

The reactor is centered in a large room (66 ft x 42 ft)(Figure 1) which is maintained at a pressure slightly less than atmospheric. In the event of a release of radioactivity (must penetrate the primary and secondary containments first) the reactor room can be quickly sealed and maintained at a pressure below atmospheric. Thus, with the inherent safety of the aqueous fuel plus the triple containment, the reactor and adjacent areas are entirely protected against an accidental release of radioactivity.

Table I lists the various nuclear parameters of the reactor which may be of interest.

Twenty-six exposure ports penetrate the biological shield and approach the reactor's core. (See Table II.) Most ports are fitted with a removable graphite stringer and two concrete shielding plugs.

The south end of the biological shield opens to expose (Figure 2) the face of the graphite thermal column. The north end has a similar arrangement but has been left open to allow either another graphite thermal column or a large water tank to be positioned against the face of the reflector.

Figure 3 shows project personnel preparing to load one of the instruments into exposure port E.

The in-pile studies were performed with instruments located in either ports A or E or full into the thermal column against the 6 inch bismuth shield. (Fig. 4).

Each instrument was enclosed in a 1/8 inch wall cadmium box to reduce thermal activation. Electrical leads were wrapped in long sheets of 1/16 inch thick cadmium for the same reason. Shield plugs were prepared to reduce the radiation streaming from the port in use.

To insure the that the temperature inside the cadmium box remained at the desired value, a thermocouple was attached to the instrument and read at the

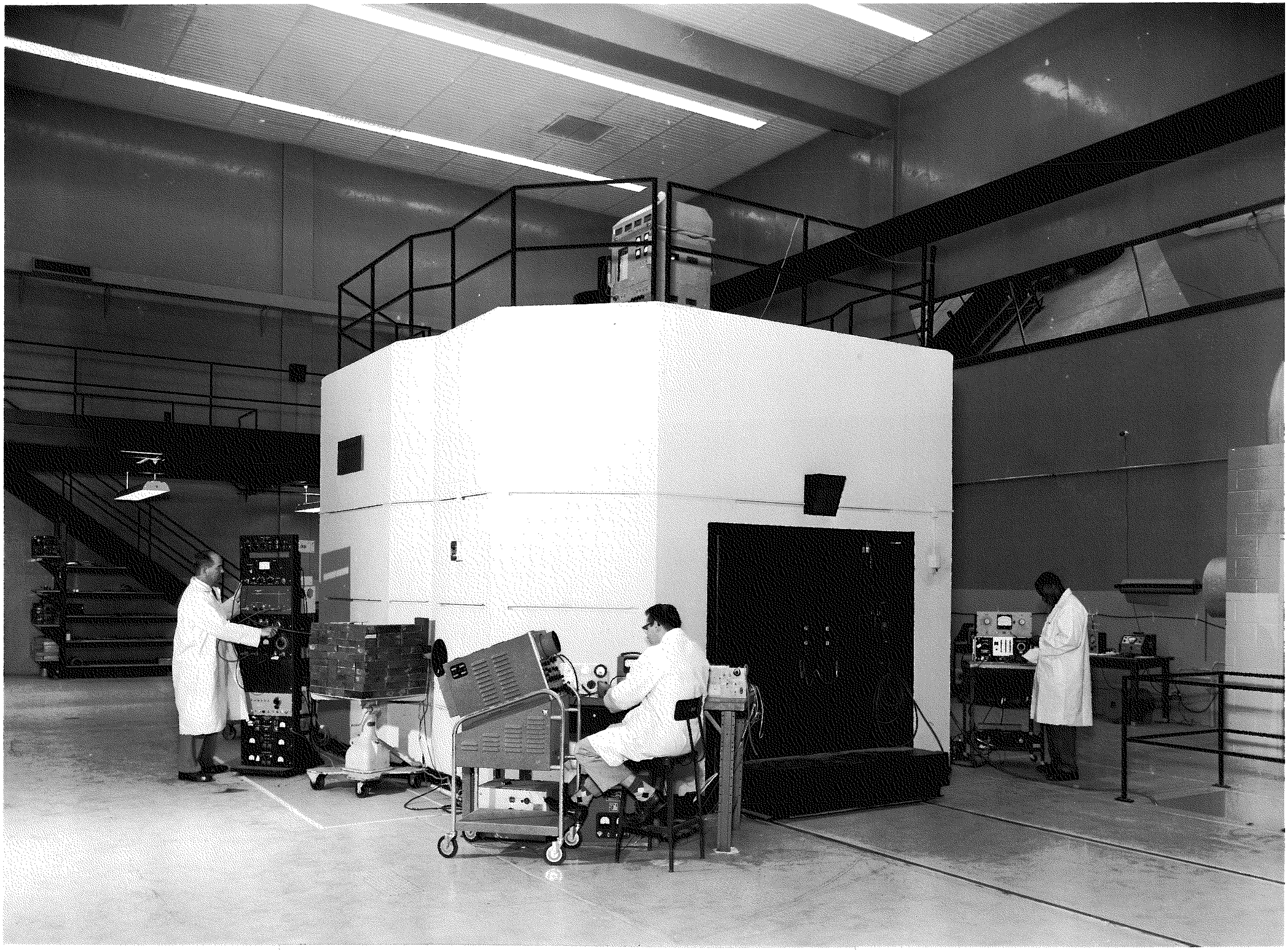

Fig. 1 Experimental Area of the Armour Reactor

TABLE I

NUCLEAR CHARACTERISTICS OF THE ARMOUR RESEARCH REACTOR

(10 KW Operation)

1.	Nuclear fuel	Uranium (88.14 per cent enriched in U-235)
2.	Fuel Arrangement	Homogeneous - Uranyl Sulfate (UO_2SO_4)
3.	Fuel Volume	12.5 liters
4.	Critical Mass	1170 g U-235
5.	Operating Mass	1250 g U-235
6.	Core Size	12-1/2" dia stainless steel - 321 sphere
7.	Reflector	6' x 6' x 7' graphite cube
8.	Moderator	H_2O
9.	Excess Reactivity	1.6 per cent
10.	Mass Coefficient	.010 per cent per gram U-235
11.	Water Coefficient	0.11 per cent per 100 ml of H_2O at 12.5 liter loading
12.	Power Coefficient	0.1 per cent at 10 KW
13.	Average Fuel Temperature	100°F
14.	Core Coolant Flow Rate	4.0 gpm (variable)
15.	Recombiner Coolant Flow Rate	4.5 gpm (variable)
16.	Maximum Thermal Flux Central Exposure Tube	2.6×10^{11} n/cm^2/sec
17.	Maximum Fast Flux Central Exposure Tube	5.6×10^{10} n/cm^2/sec
18.	Maximum Thermal Flux in Other Neutron Irradiation Experimental Ports	1.5×10^{11} n/cm^2/sec
19.	Maximum Thermal Flux at the Face of the Thermal Column	5×10^9 n/cm^2/ sec
20.	Worth of Four Control Rods	7.0 per cent reactivity
21.	Gas Effluent from Reactor	None

The table below lists the exposure facilities and indicates the maximum radiation levels in each location.

TABLE II

REACTOR FACILITY

No. of Ports	ID (inches)	Length (inches)	Maximum Flux n/cm^2-sec-KW	Description
3	2.9	53	1×10^{10}	To surface of core
2	3.9	60	4×10^{10}	To surface of core
1	1.4	120	4×10^{10}	Central exposure tube through core
1	1.9	120	5×10^{9}	Rabbit tube
1	1.4	120	5×10^{9}	Rabbit tube
4	3.9	84	1×10^{9}	Vertical ports
2	6.0	24	1×10^{7}	Tangential to thermal column face
9	4x4 (rectangular)	48	1×10^{10}	Axial thermal column rectangular ports. May all be removed to form a 1 square foot opening up to surface of core.

1 thermal column face 60 x 60 (maximum flux 10^{10}).

GAMMA FACILITY

Port	ID (inches)	Length (inches)	Estimated Maximum Dose in KR/hr at 50 KW
TT	3.5	37	150
UU	3.5	37	150
VV	3.5	57	150
WW	6x18	43	150
XX	3.5	43	120
YY	5.0	43	50
ZZ	5.0	43	50

Fig. 2 Face of Graphite Thermal Column

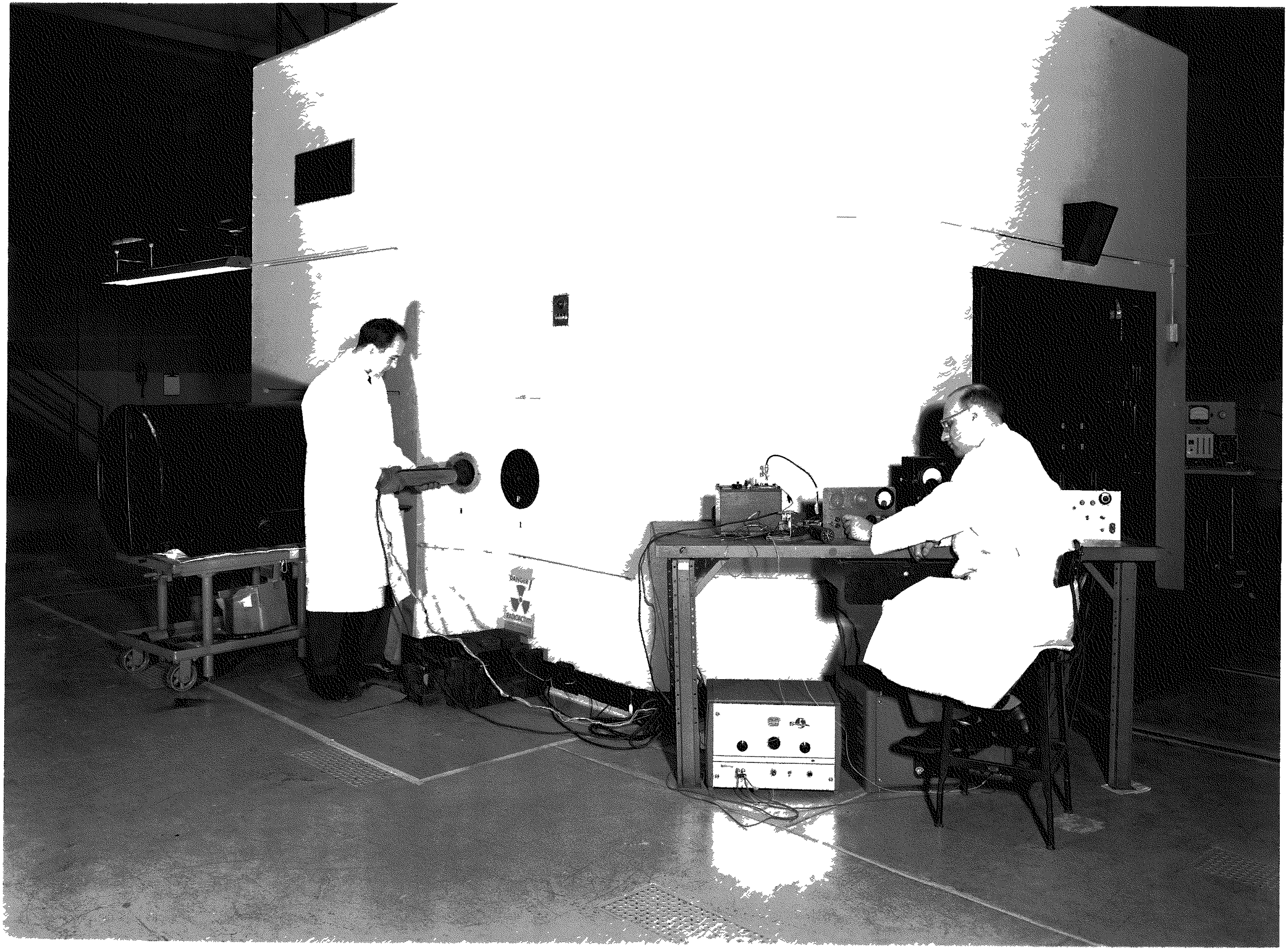

Fig. 3 Loading Fuel Gage Amplifier

THE IRRADIATION AND EXPERIMENTAL FACILITIES OF ARMOUR RESEARCH REACTOR

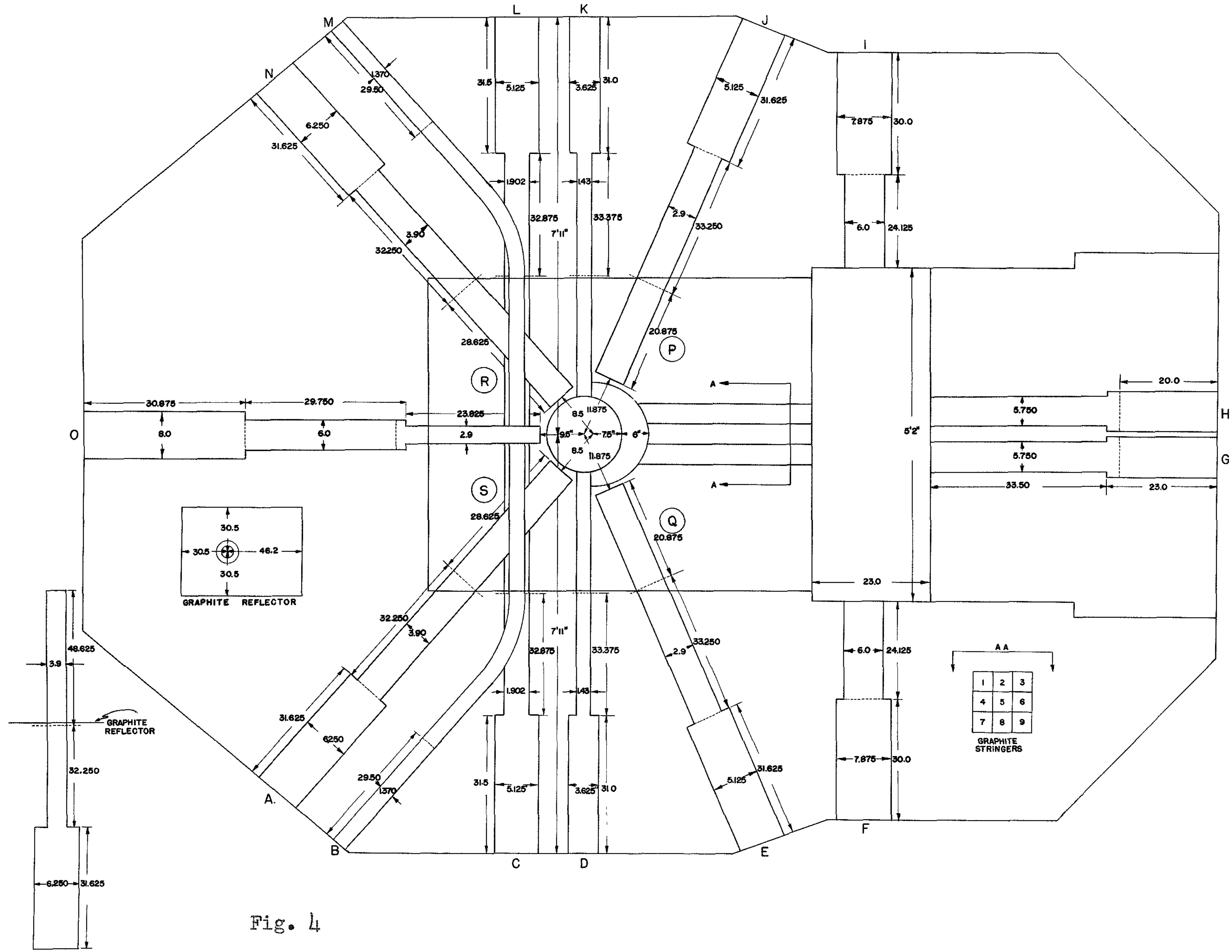

Fig. 4

test station.

The neutron flux was determined by placing two indemum-aluminum foils inside the cadmium exposure box. The value found was about 1.0 x 10^{10} neutrons per square centimeter per second and represents that flux above the cadmium cutoff energy, about 0.5 ev.

III. PRE-IRRADIATION OPERATIONS

Prior to its irradiation, each piece of equipment was operated outside of the reactor for a period of at least one week. This pre-test operation served to insure that the equipment was functioning within specifications. It also permitted the project personnel to become thoroughly familiar with the characteristics of the equipment.

During the pre-test operation of the equipment, performance was measured and recorded in the same manner as was done during the irradiation testing. The resulting data provided a standard with which subsequent measurements could be compared.

IV. IN-PILE OPERATION

A. Fuel Quantity Gage

The first item to be irradiated was the fuel quantity gage. At the completion of pre-irradiation testing, this unit was enclosed in a cadmium box (1/8 inch wall) and placed in the reactor adjacent to the core. With the reactor at 10 KW the fuel gage was irradiated for a total of 132 hours. This exposure was not continuous, but consisted of daily runs whose duration ranged from five to ten hours. The fuel gage was exposed to an integrated neutron flux of about 6 x 10^{15} nvt., accompanied by a total gamma dose of about 5 x 10^{8}R.

The performance of the fuel quantity gage was indicated by the a.c.

voltage appearing at the output of the re-balance potentiometer. This voltage was measured at each of four settings of an input capacitor. Data were recorded at intervals of approximately one hour during the initial week of irradiation, and at intervals of about three hours during the remainder of the runs. A summary of the data is presented in Table III.

TABLE III

FUEL QUANTITY GAGE (PER CENT HEAD)

Ranges of Output Voltages at Specified Capacitor Settings

INPUT CAPACITOR MMF.	DATA SUPPLIED BY NADC	PRE-IRRADIATION TESTS	IN-PILE OPERATION	POST-IRRADIATION TESTS
50	1.60	1.50-1.55	1.38-1.60	1.42-1.49
70	13.3	13.0-13.3	12.7-13.1	12.3-12.8
90	25.5	24.0-24.5	24.1-24.9	23.5-24.5
110	37.8	35.5-36.0	35.5-36.0	35.0-36.5

It will be noted that, except possibly in the case of the lowest setting, there was no significant change in the characteristics of the unit. Indeed, the total change in characteristics, which might be attributed to radiation effects, was generally smaller than the drift which normally occurred during a day of operation.

Even in the case of the lowest setting, the change in output during irradiation does not appear to be significant. The sensitivity of the unit to variation of input capacity is approximately 0.6 volts per micromicrofarad. Accordingly, the largest deviation which occurred during irradiation corresponds to a change of only 0.2 mmf. at the input. The capacitance of the input cable could easily have changed by this amount as a result of irradiation. Since the total capacitance of the cable is very much greater than the change required to account for the difference in readings, it is not possible to determine by measurement whether this effect was really responsible for the discrepancy (total length of leads about 20 feet). In any event, the maximum change in output under these conditions was only 0.3 per cent of the full-scale signal. Its apparent importance is exaggerated by the fact that, at this input setting, the normal output level is quite small.

The somewhat larger spread in output values encountered in the post-irradiation tests may be partly explained by the difficulties encountered with the 400 cycle a.c. power supply. During the tests, this supply failed and was sent out for repairs. When it was returned, the a.c. output voltage was found to exceed the values marked on the dial by about six volts. Since it was not known whether all of this discrepancy occurred as a result of the repairs, or whether a part of this error existed previously, it was not possible to reset the supply voltage to the exact value used in previous tests. Accordingly, a compromise setting was used. Since a change of excitation of a few volts can cause the output voltage of the fuel gage to vary by several per cent, the uncertainty of the correct value of supply voltage could cause a variation in output readings which was at least as great as that which was actually encountered.

In view of these considerations, it appears that the fuel quantity gage was not affected by exposure to the radiation levels indicated above.

Nine days after the completion of irradiation of the fuel quantity gage, its residual activation level was measured. At a distance of six inches from the body of the unit, the radiation flux was found to be approximately 50 mr./hour. This radiation consisted almost entirely of gamma rays.

While the operation of the fuel gage was not affected by irradiation, the finish peeled off of a large area of the case. In addition, the radiation exposure caused a severe discoloration of the glass which covers the dial face. Although it was still possible to read the dial, its legibility was significantly impaired.

B. Floated Gyro

While the fuel quantity gage was still being irradiated, pre-testing was begun on the loated gyro. Two types of tests were performed on this unit. In the first, a measurement was made of the period required for the gyro to drift from one of its stops to the midpoint of its range of free travel. In the second test, the gyro was moved to the midpoint of its free travel and the current through the torque generators was adjusted to hold it in this position. The current required to maintain this position was recorded as an indication of the drift rate of the unit.

After a week of pre-test operation, the gyro was placed in the thermal column of the reactor and irradiation was begun. During this test, the behavior of the unit was quite erratic. Two reasons for this difficulty were later discovered.

One factor which impaired the validity of the test is that the orientation of the gyro, while in the reactor, was not certain. However, it is unlikely that the gyro was level during the test. Consequently, the improper orientation of the unit would modify its drift characteristics to such an extent that the resultant data would probably be meaningless.

The second difficulty which occurred was the failure of the bias battery which was used to control the torque generator current during proportional operation. This battery was also used to energize the torque generators when the unit was being moved between its limits. The current drain occurring during this latter use resulted in the battery becoming discharged to the extent that it failed during the irradiation of the gyro.

While these difficulties were being analyzed, the gyro was removed from the reactor. Before the troubles could be corrected and testing resumed, an accident occurred which prevented the completion of this phase of the testing. The plug of the 400 cycle a.c. power supply was inadvertently disconnected from its receptacle. The condition went unnoticed for a period of several minutes. Since the 400 cycle supply provided power to the heater controller, its failure permitted the heaters in the gyro to remain on continuously. Consequently, the gyro overheated to the extent that the casing ruptured, allowing some of the oil to leak out. Because of the seriousness of the damage, it was felt that further testing of this unit would be useless. Since a replacement gyro was not available, this phase of the program could not be completed.

After the accident in which the gyro was damaged, it was observed that, as the spilled oil cooled to room temperature, it solidified. Since this is not the normal condition of the oil, it may have suffered some change of characteristics as a result of the treatment to which it was subjected. Such a change may have been caused by the severe overheating which occurred. On the other hand, it may have resulted from the radiation damage during the exposure. The actual cause of this change can be determined only by further testing of this fluid.

C. Transistorized Servo Amplifier

The performance of the transistorized servo amplifier, together with that of the associated rotary components, was measured by two different methods. Closed-loop performance of the unit was indicated by the accuracy with which the servo output followed the setting of the input control. This measurement was performed at each of eight input settings. Open-loop performance was determined by measuring the input level which was necessary to produce a given voltage at the amplifier output. The amplifier current and the rotational speed of the motor were also measured at each value of output voltage.

After a week of pre-irradiation testing, the first transistorized servo amplifier (No. 400) was inserted in the reactor and irradiated with the reactor at 10 KW. The behavior of the amplifier during irradiation is shown in Figs. 5a and 6a. Failure began to occur as soon as the reactor reached full power. The amplifier gain diminished steadily throughout the irradiation. The maximum obtainable output voltage also decreased, although this was probably due to the reduction in amplifier gain. Since the voltage available at the input transistor is limited by the silicon diodes, a loss of gain would cause a corresponding decrease in the maximum output voltage. The d.c. current drawn by the amplifier decreased slightly during the early stages of irradiation and then began to increase. For a given output voltage, the period of revolution diminished somewhat from its normal value.

The irradiation of this amplifier was continued for a period of 24 minutes at full reactor power. The total irradiation of the amplifier was 1.4×10^{13} nvt. accompanied by a gamma exposure of 1.6×10^{5}R. At the end of 24 minutes the reactor was shut down and the amplifier removed. Tests were conducted over the next several days to determine the extent of any recovery which might occur. The amplifier performance during this period is shown in Figs. 5b and 6b. Immediately after irradiation, the gain began to recover. Recovery continued over the next several days, although the rate diminished. After about eight days, the amplifier gain reached a level from which little

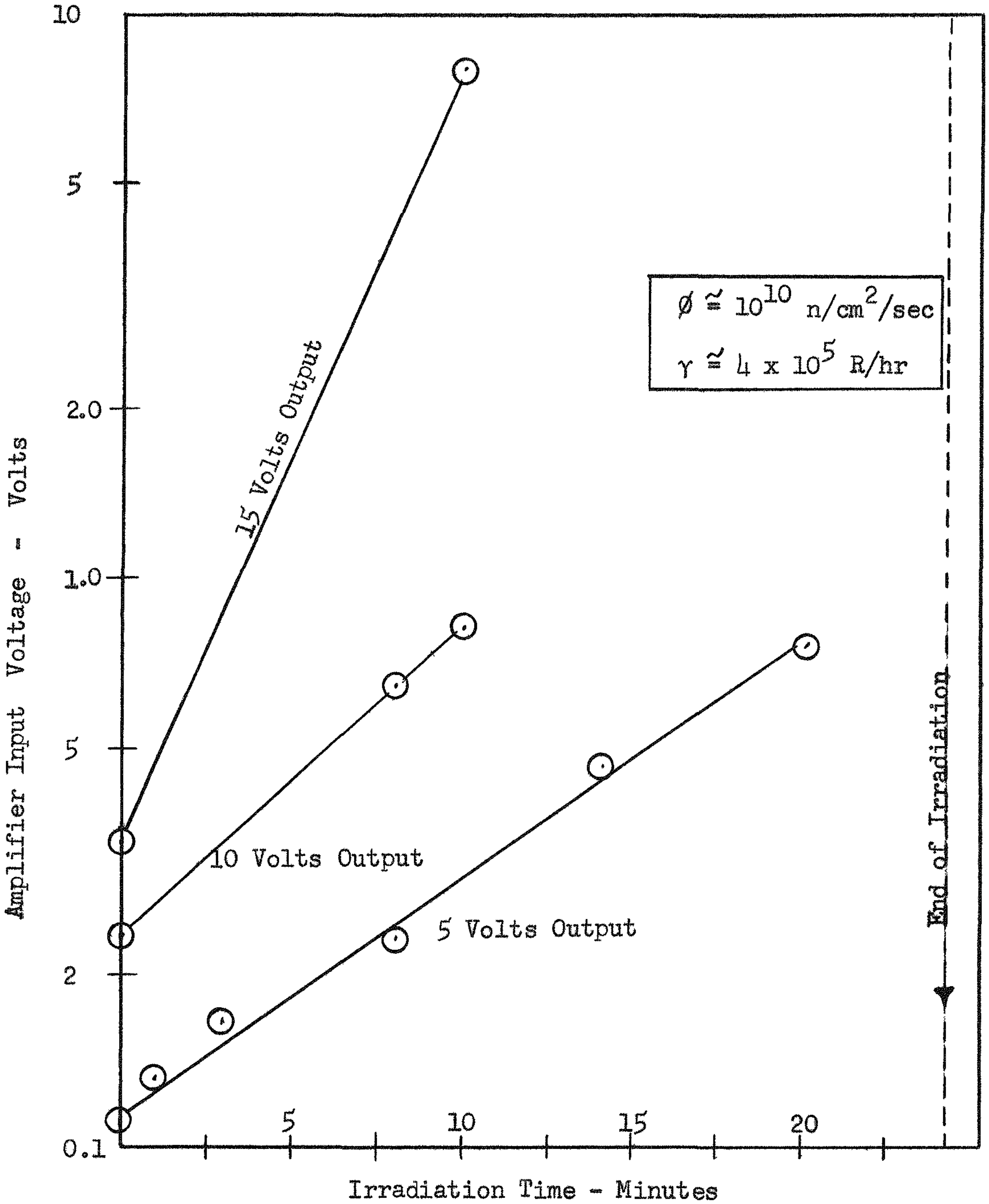

Fig. 5a.- SERVO AMPLIFIER NO. 400

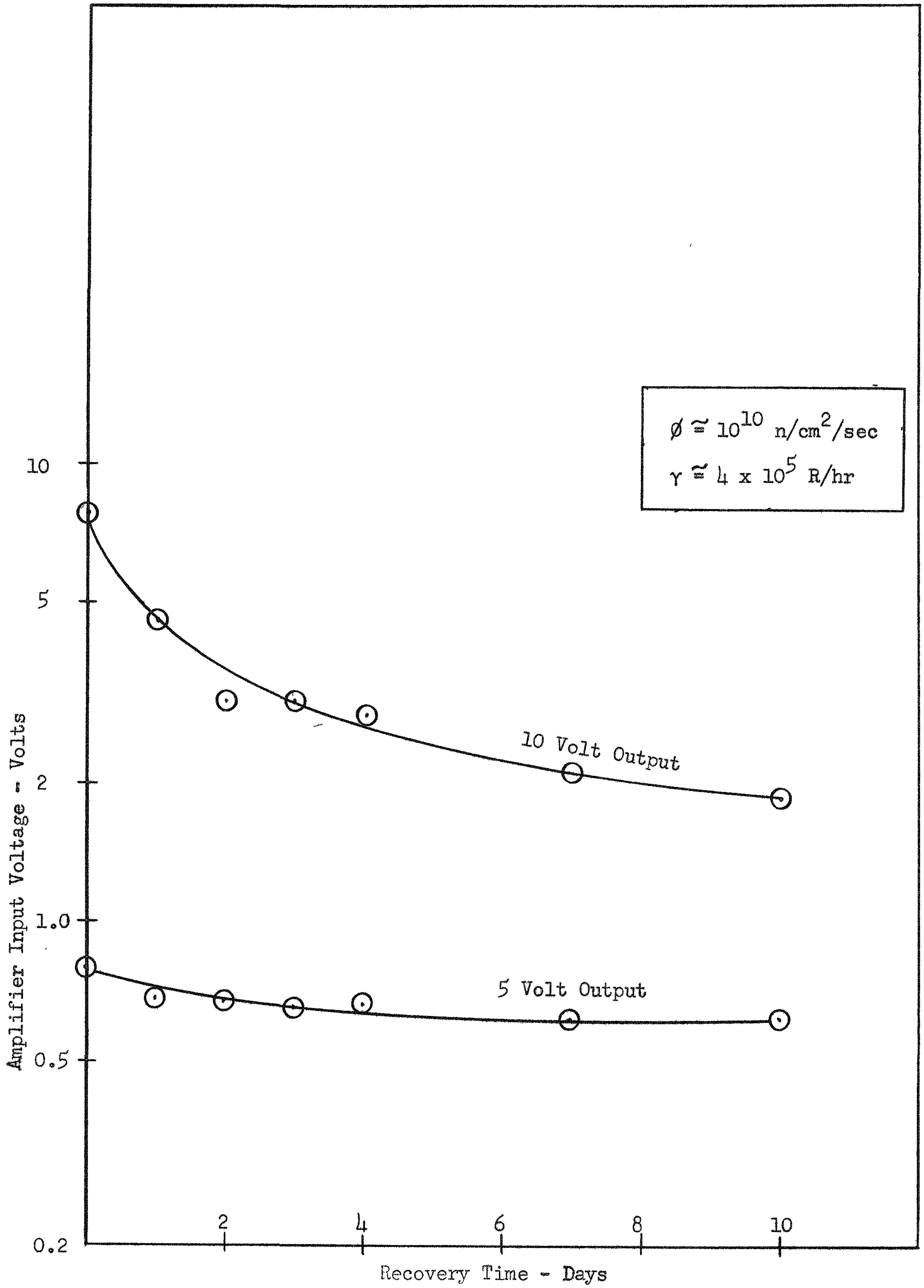

Fig. 5b - SERVO AMPLIFIER - No. 400

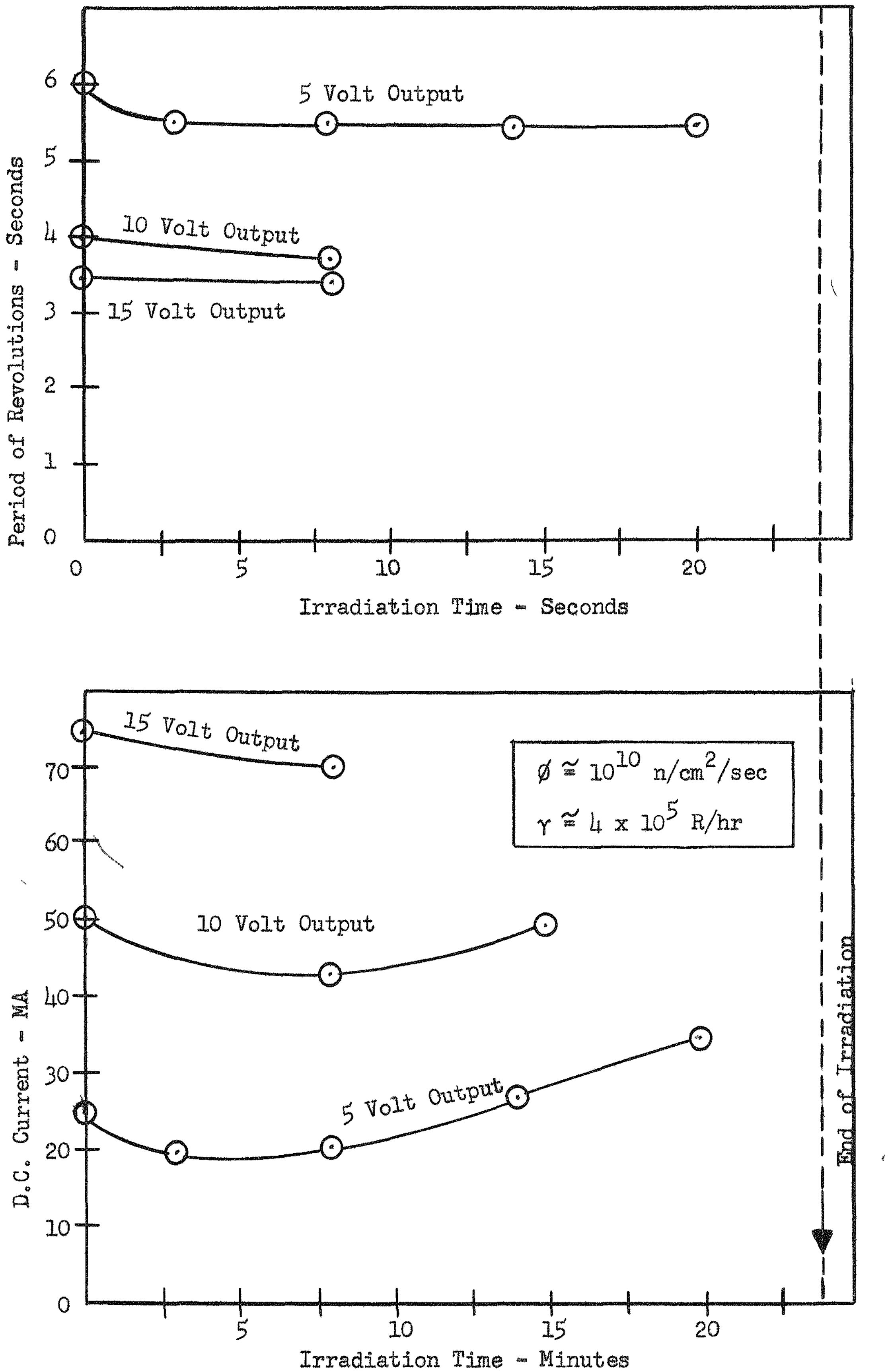

Fig. 6a - SERVO AMPLIFIER - No. 400

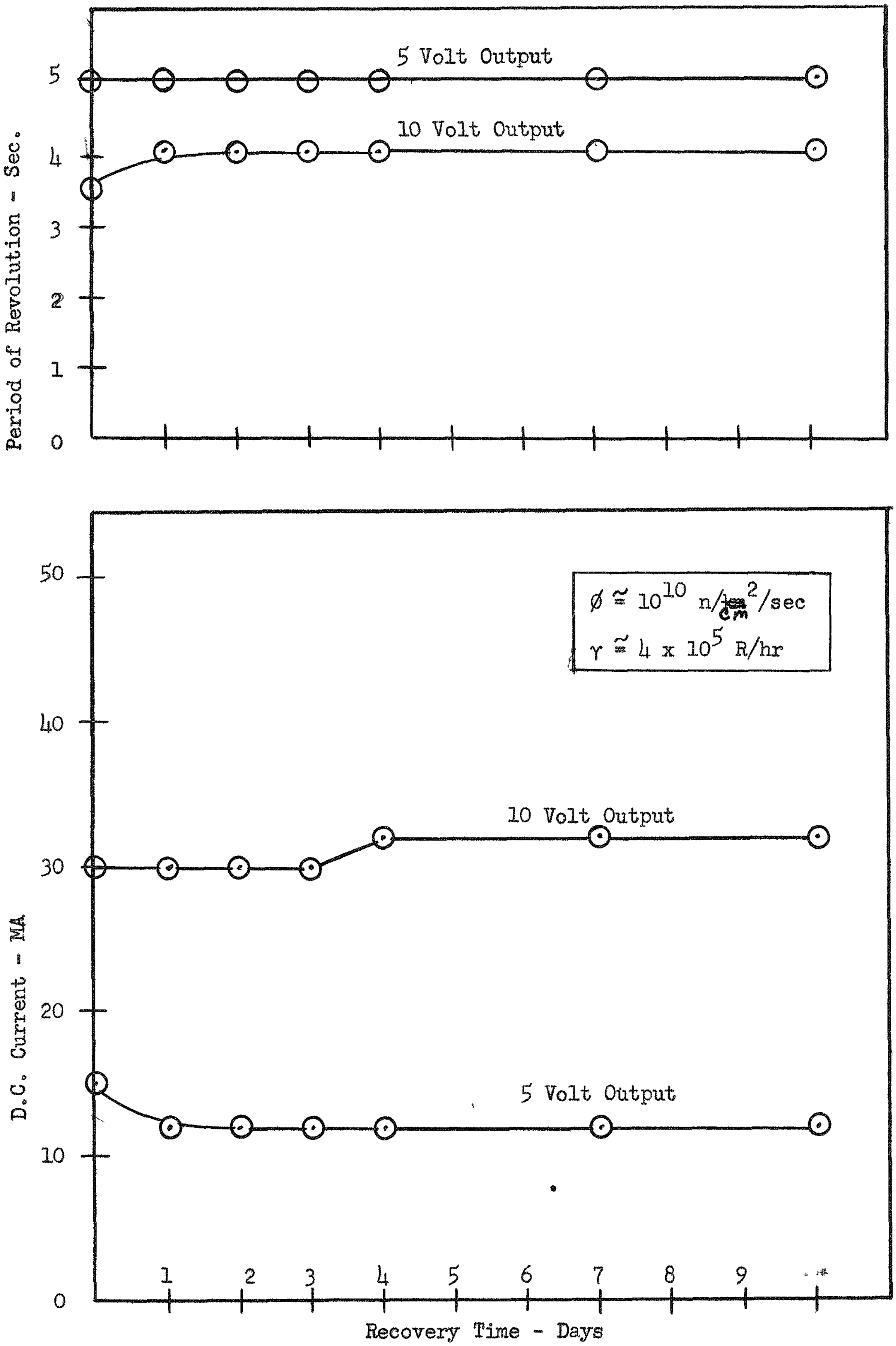

Fig. 6b - SERVO AMPLIFIER - No. 400

further improvement was likely. The final amplifier gain was only about 20 per cent of the initial value.

For the higher values of output voltage, the recovery appeared more pronounced than at low voltages. Moreover, the input characteristic did not level off as rapidly as did that for the lower voltage. These effects are due to the limiting action of the silicon diodes at the amplifier input. Because of the nonlinearity introduced by these diodes, a given change in amplifier gain requires a far greater input change at high output levels than is necessary at lower values of output voltage. Accordingly, the amount of recovery is exaggerated by those measurements which were made at levels in excess of that at which limiting occurred.

During and after the irradiation of the amplifier, it was found that the period of revolution was reduced slightly below its normal value while the d.c. current declined by almost 50 per cent. The reason for these changes is not evident. However, they may have resulted, at least in part, for the reduction of extraneous signals, such as noise and quadrature voltage components, which appeared in the amplifier output. As the amplifier gain decreased, as a result of radiation damage to the transistors the level of these extraneous signals would diminish. Since the original output level was restored by increasing the driving voltage, the extraneous signals would represent a smaller portion of the total output than had formerly been true. Inasmuch as these extraneous signals contribute to the voltage and current readings, but not to the motor rotation, their elimination would require that, for a given total output voltage, the useful portion of the motor drive signal be increased. This, in turn, would result in a somewhat higher speed of rotation.

The closed loop performance of the servo amplifier was also tested during and after irradiation. Throughout the test, the output continued to follow the input position. However, toward the end of the irradiation period, the static error of the system was found to be as large as three degrees, in contrast to a maximum error of one degree which had been observed before irradiation. Furthermore, the closed loop operation of the system was found to be quite sluggish in comparison with response which had been observed previously. In addition, the unit was observed to overshoot the correct position, undergoing several oscillations before coming to rest. This behavior persisted even after the recovery period. However, after ten days of recovery, the static error had decreased to a maximum of two degrees.

During and after the irradiation of this amplifier, frequent checks were made by substituting a second amplifer for the one under test. In all cases, this caused the performance of the unit to revert to normal. Thus, it may be stated that the effects of radiation damage were confined to the transistorized amplifier and that the rotary components had not been affected to any significant extent.

After a period of approximately two months, during which little additional recovery occurred, the semiconductor components were removed from the amplifier and tested. The results of these tests are presented in Table IV.

It may be seen that the performance of the silicon diodes was relatively unaffected by the level of radiation to which they had been exposed. While the forward resistance of the second diode was somewhat higher than normal, this change would probably not affect its functioning in the amplifier circuit.

The performance of the transistors, on the other hand, was found to have been severely degraded. The current gain of each unit had been reduced by a factor of ten or more below its normal value. The leakage currents of the output transistors also had risen significantly. However, this latter change

TABLE IV

CHARACTERISTICS OF AMPLIFIER SEMICONDUCTOR COMPONENTS AFTER IRRADIATION

RADIATION EXPOSURE:

FAST NEUTRONS	1.4×10^{13} nvt.
GAMMA	1.6×10^{5}R.

A. Silicon Diodes

	Reverse Leakage Current at 30 V.	Forward Drop at 2 MA.	Average Forward Resistance Between 2 and 5 Ma.
Normal Diode	0μa.	0.72V.	30 Ohms
Diode No. 1 from Amplifier	0μa.	0.68V.	27 Ohms
Diode No. 2 from Amplifier	0μa.	0.82V.	80 Ohms

B. Transistors

Type	Collector Leakage Current	Grounded-Emitter Current Gain
904 (Normal)	1 μa at 30 V.	27
904 (From Amplifier)	1 μa at 30 V.	2.7
951 (Normal)	0 at 30 V.	16
951 (From Amplifier)	0 at 30 V.	0.8
H-2 (Normal)	0.09 MA at 30 V.	54
H-2 (From Amplifier)	1.2 MA at 30 V.	5.7
H-2 (From Amplifier)	1.5 MA at 30 V.	6.3

alone would not have caused serious impairment of the amplifier performance.

In order to determine whether any other components had failed during irradiation, the transistors were replaced with units which were known to be good. Since the diodes still seemed to be operating properly, the original ones were used. The amplifier was then tested. Its performance was found to be identical with that observed before irradiation. Accordingly, it may be concluded that no other components were affected by the radiation.

As was pointed out previously, the presence of the diode limiters at the amplifier input causes a distortion of the amplifier characteristics as measured under conditions of constant output voltage. When a reduction of gain occurs, restoration of the output to its original values requires that the level of the input signal be raised. However, because of the nonlinearity of the limiting circuit, only a part of the increased input voltage is actually delivered to the base of the first transistor. Consequently, the input voltage must be increased by a larger percentage than that by which the gain was reduced. Thus, when measurements are made on a constant-output basis, the data tends to exaggerate the extent of any change in amplifier gain.

In order to obtain a true picture of the change of amplifier gain under irradiation, it would be necessary to measure the change in output voltage which occurred while the input voltage was held constant. Under conditions of constant input, the limiting circuit would not distort the data, since the amount of limiting would not change as long as the diodes remained unaffected.

In order to separate the effects of irradiation on amplifier gain from those effects which occur only because of the presence of the diode limiter, it was decided that one amplifier should be irradiated while being operated on a constant-input basis. This mode of operation also permits the acquisition of a greater amount of data in the relatively short time available. This results from the fact that constant-input operation does not require frequent readjustment of the input level to compensate for the changing amplifier gain. In addition, this mode provides more information during the latter stages of deterioration than does constant-output operation. In the latter case, several of the selected output voltages were no longer obtainable after a few minutes of irradiation.

The amplifier (Serial No. 220) was placed in the reactor and irradiated in the same manner as was the previous one. The results of this test are plotted in Figs. 7 and 8.

The timing of the amplifier failure was approximately the same as that observed in the preceding test. Failure began as soon as the reactor reached full power. The gain dropped sharply throughout the test. The current, on the other hand, fell off at first, but then began to rise rather sharply. During the latter portion of the irradiation, the d.c. current was not dependent upon the signal level but appeared to indicate that the amplifier was undergoing some type of runaway phenomenon.

Irradiation of the amplifier was continued until the d.c. current reached a value of 200 milliamperes. This occurred after a period of 36 minutes. At that point the amplifier had been subjected to an integrated neutron flux of 2.2×10^{13} nvt. and a gamma flux of 2.4×10^{5}R.

Immediately after the reactor was shut down, the d.c. current began to drop. Within a few minutes, it had dropped to 50 milliamperes.

The amplifier was operated for a period of several days during which its characteristics were measured frequently. As in the case of the previous unit, some recovery did occur. This recovery represented only a small portion of the loss suffered during irradiation.

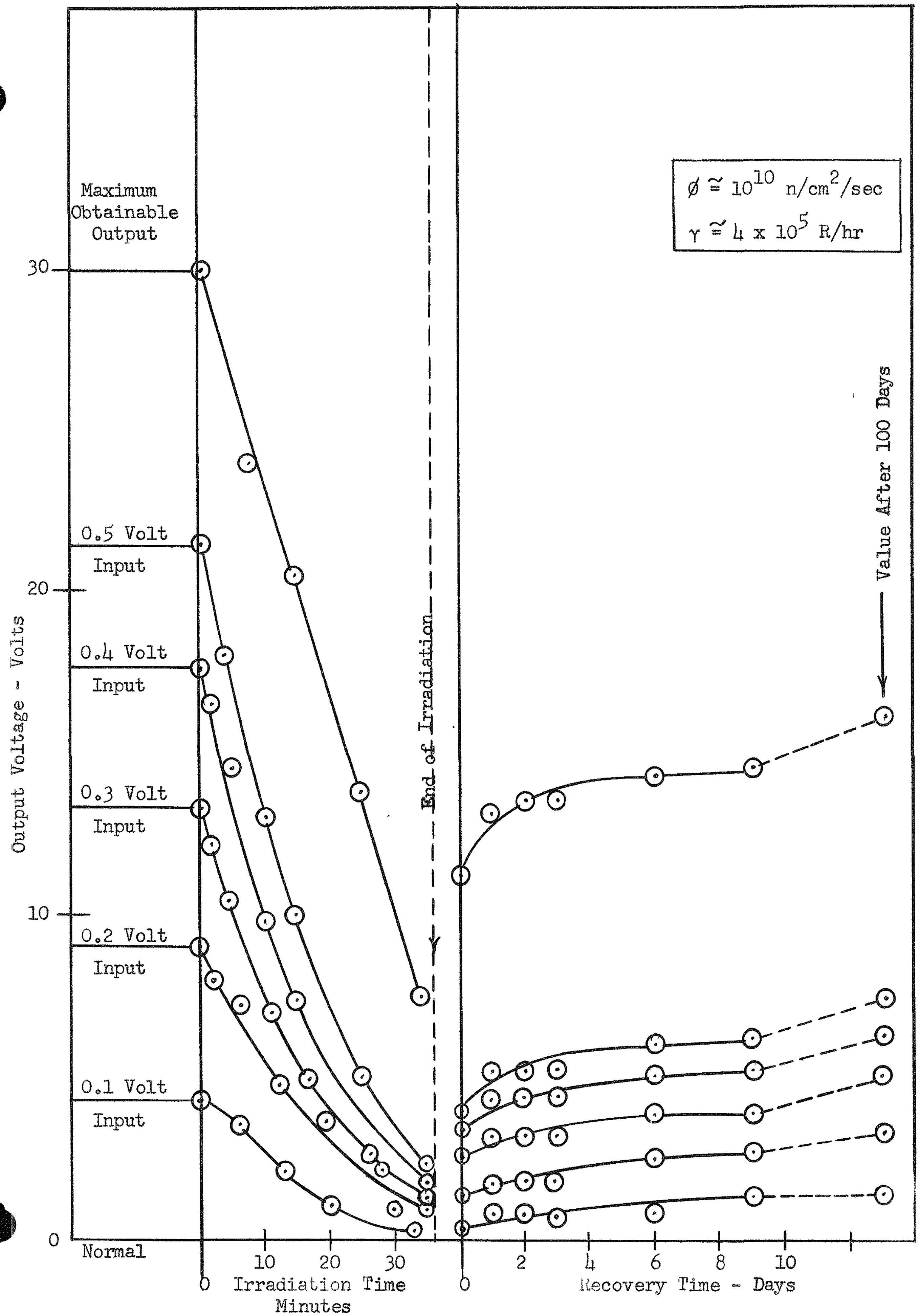

Fig. 7 - SERVO AMPLIFIER - No. 220

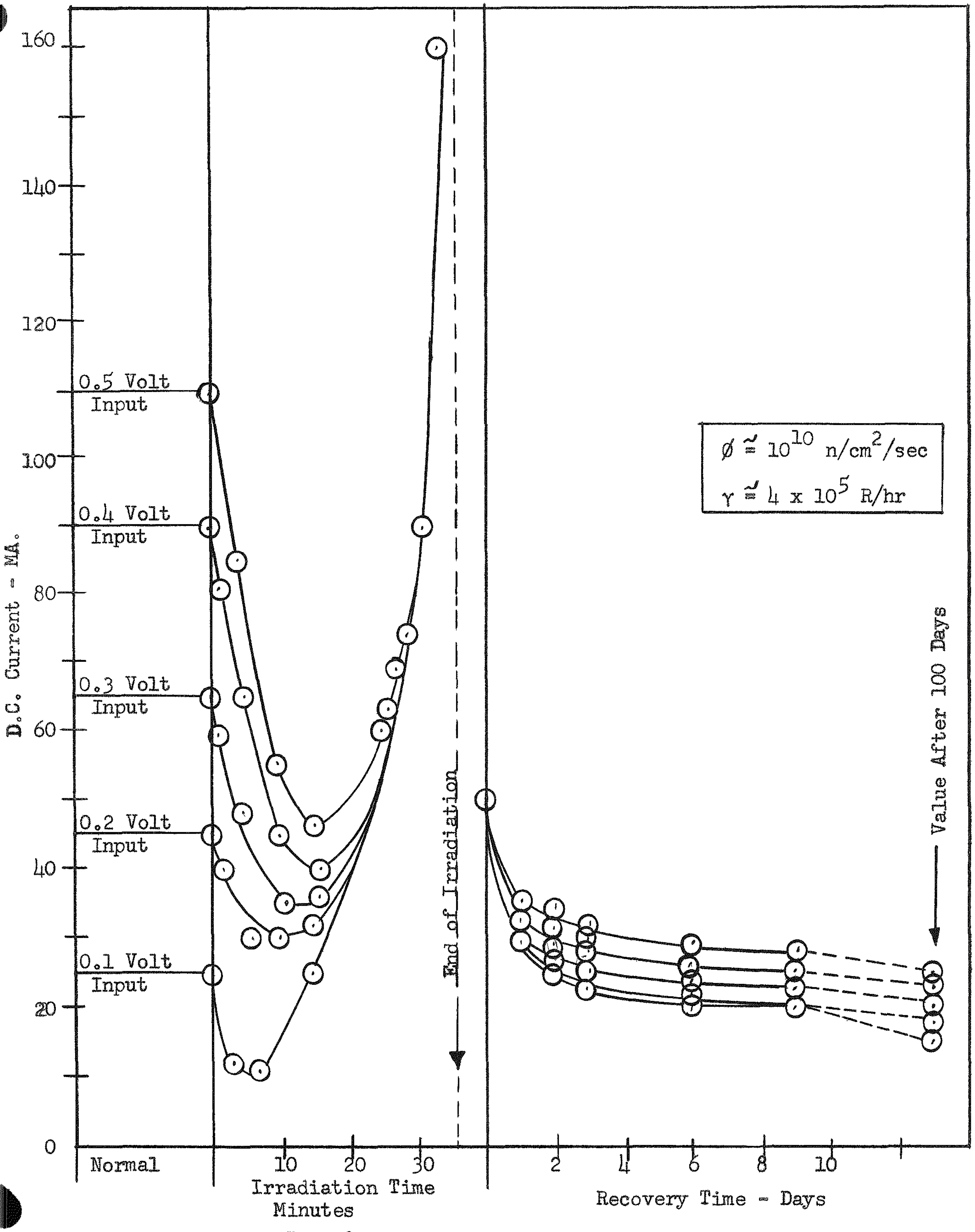

Fig. 8 - SERVO AMPLIFIER - NO. 220

After the amplifier had been allowed to recover for a period of 100 days, its characteristics were again measured. It was found that little additional recovery had occurred. All transistors in the amplifier were then replaced with units which were known to be good. A test of the amplifier indicated that its characteristics were completely restored to normal by this substitution. Thus, no components, other than the transistors, appear to have been damaged.

Because of the rapidity with which the transistorized amplifiers failed, it was felt that much useful information could be obtained from a test in which an amplifier was irradiated at much lower flux levels. Such a test would indicate whether failure occurred as a result of the total irradiation received, or whether the degradation resulted primarily from the high rate at which the dose was administered.

In order to evaluate the effects of dose rate upon the rate of failure, a third amplifier (serial no. 215) was irradiated with the reactor operating at power levels of 50 and 100 watts. After a period of 15 hours, during which the amplifier received an integrated dose of 4.3×10^{12} nvt., the amplifier gain had decreased to approximately 60 per cent of its initial value. See Figs. 9 and 10.

In the case of the first amplifier, the gain decreased to a corresponding value after approximately six minutes of irradiation at full power. The integrated neutron flux affecting the amplifer during this period was 3.6×10^{12} nvt. Allowing for the inaccuracies which might be present in the data, it appears that failure results almost entirely from the total neutron irradiation, and that, within this range, the rate of irradiation has little effect upon the level at which failure occurs. However, it is probable that the runaway

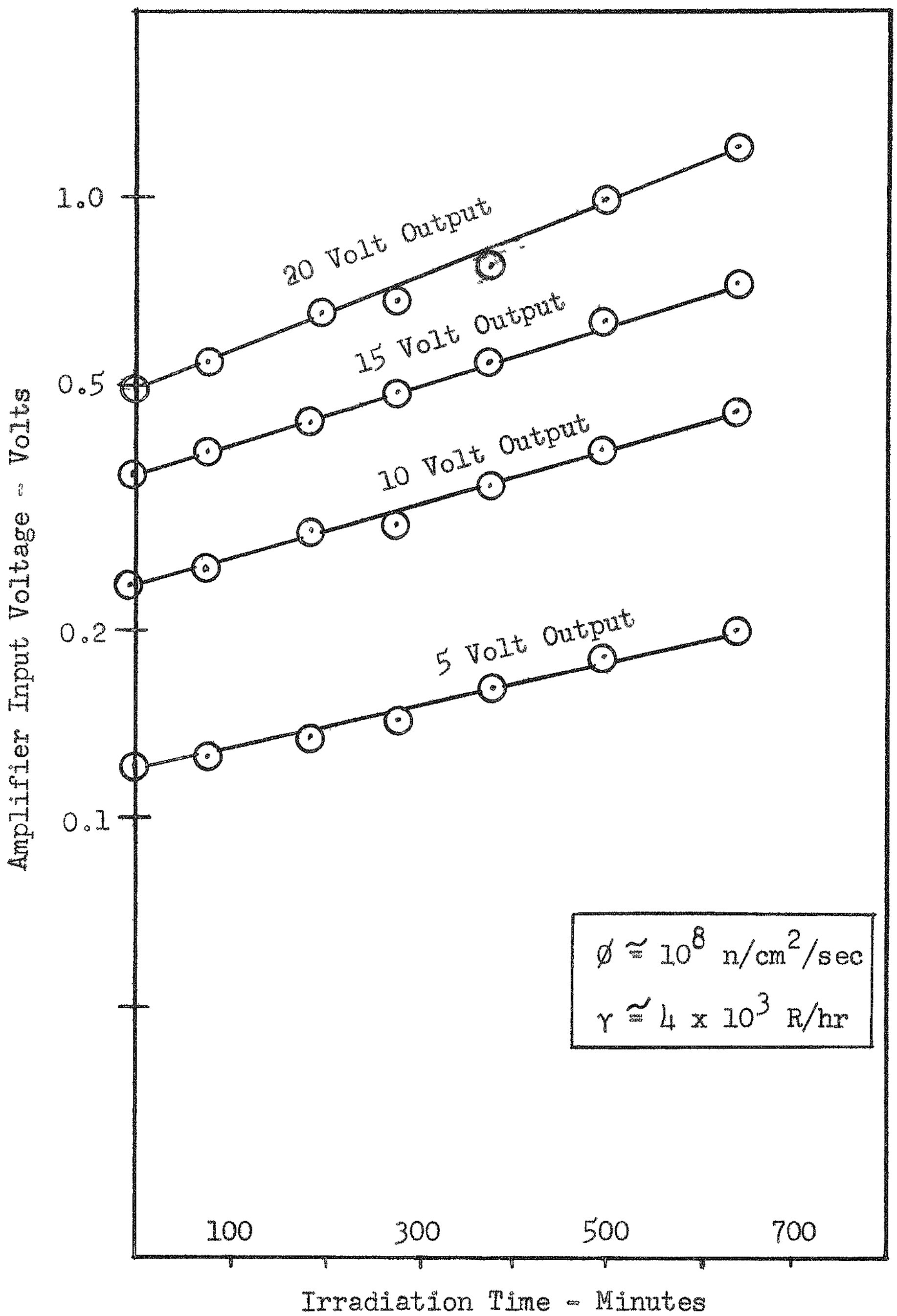

Fig. 9 - SERVO AMPLIFIER - No. 400

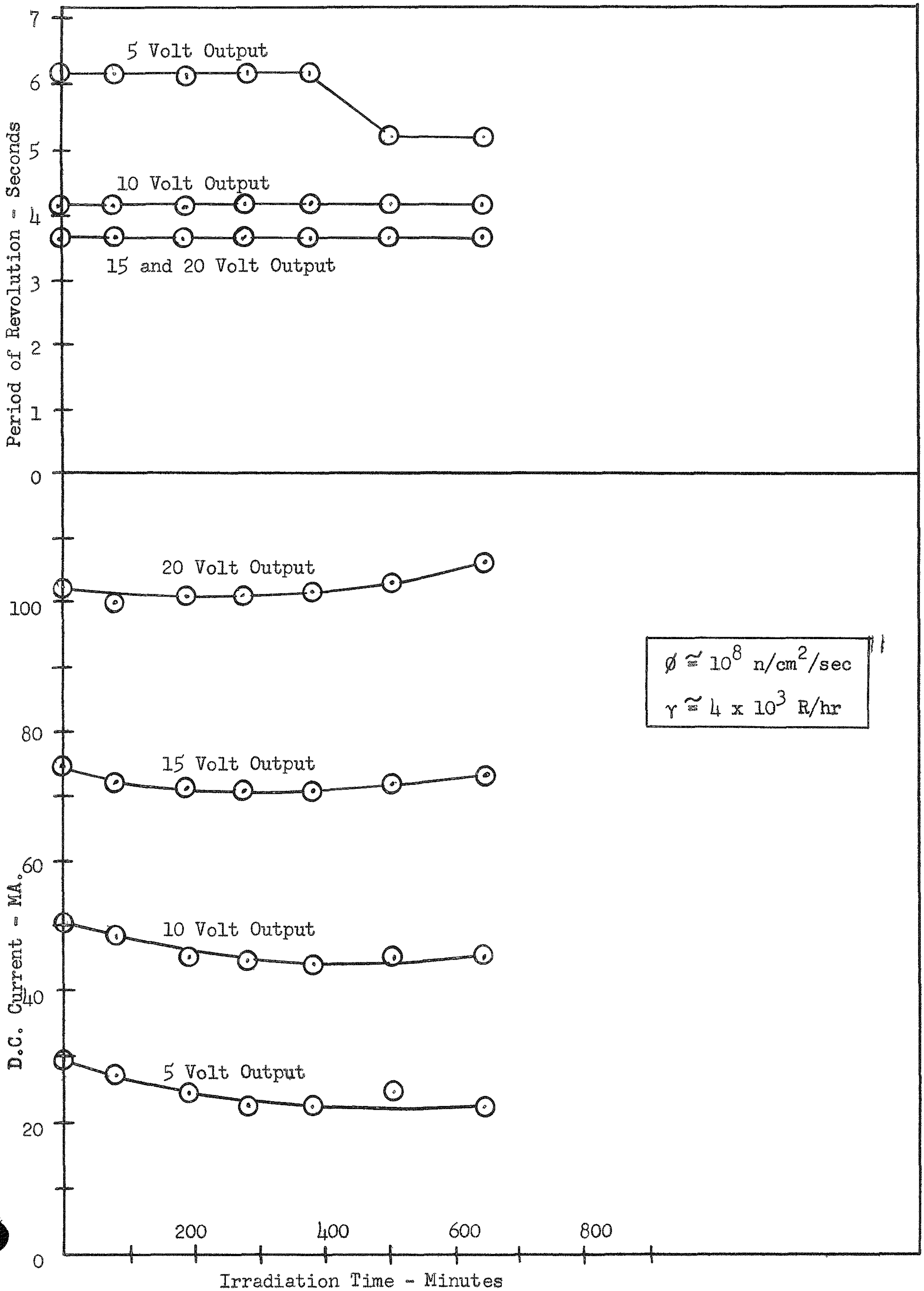

Fig. 10 - SERVO AMPLIFIER - NO. 215

phenomenon which occurred during the later stages of the high-level irradiation tests, was entirely the result of the high rate.

In all of the tests described above, the amplifier was subjected not only to a fast neutron flux, but also to the gamma radiation which accompanied it. Consequently, it was not known which of these components was responsible for the failure of the unit. In order to separate the effects of the two, another amplifier was tested. Irradiation of this unit was performed in the gamma facility of the reactor. Since the gamma flux in this facility contains a very low neutron flux (about 10^4) the only changes which would occur would be those resulting from the gamma radiation alone.

The amplifier was irradiated in the gamma facility for a total of 33 hours with the reactor at full power. During this time, the accumulated gamma exposure was 3.3×10^5R, far more than that to which the previous amplifier had been subjected. Throughout the irradiation, the amplifier characteristics were measured in the same manner as had been done in the previous tests.

The gamma irradiation of the transistorized servo amplifier did not produce any perceptible change in its characteristics. Consequently, it appears that most, if not all, of the deterioration observed in previous tests was result of the neutron irradiation alone. However, since the rate of gamma irradiation used in this test was considerably lower than that encountered in the previous ones, it is not certain that the gamma flux did not contribute to the runaway which occurred near the end of the high-level neutron irradiation tests, though unlikely.

D. Servo Rotary Components

During the irradiation of the several transistorized amplifiers, these units were mounted on the chassis containing the rotary components of the servo system. Consequently, the rotary components were subjected to irradiation equal to the total received by all the transistorized amplifiers. However, because of the rapid failure of the transistorized amplifiers, the total irradiation received by the rotary components during the amplifier tests was far less than the desired value. Accordingly, it was necessary that the irradiation of the rotary components be continued.

Before irradiation of the rotary components was resumed, a new transistorized amplifier (serial no. 047) was placed in the reactor along with them. The reactor was then brought to full power and testing was resumed. The performance of the amplifier during the early part of the irradiation is shown in Figs. 11 and 12. This amplifier failed in the same manner as had the previous units. Complete failure occurred after 22 minutes of irradiation. Within that time the amplifier had been exposed to a neutron irradiation of 2.2×10^{13} nvt. and a gamma flux of 1.8×10^{6}R. After failure of the amplifier occurred, operation of the rotary components was continued using the standby amplifier. However, the damaged amplifier was allowed to remain in the reactor throughout the remainder of the test.

Several attempts were made to operate the damaged amplifier, both during its irradiation and after it had been allowed to stand for a week after the completion of the test. In all cases the amplifier was found to be completely inoperative. Furthermore, the d.c. current drawn by the unit was far in excess of the 250 milliampere range of the meter in the test unit. Thus, it appears that this amplifier has been permanently destroyed by the irradiation.

Irradiation of the rotary components was continued for a period of 70 hours, during which time they received a neutron exposure of 5×10^{15} nvt. and a gamma dose of 4×10^{8}R.

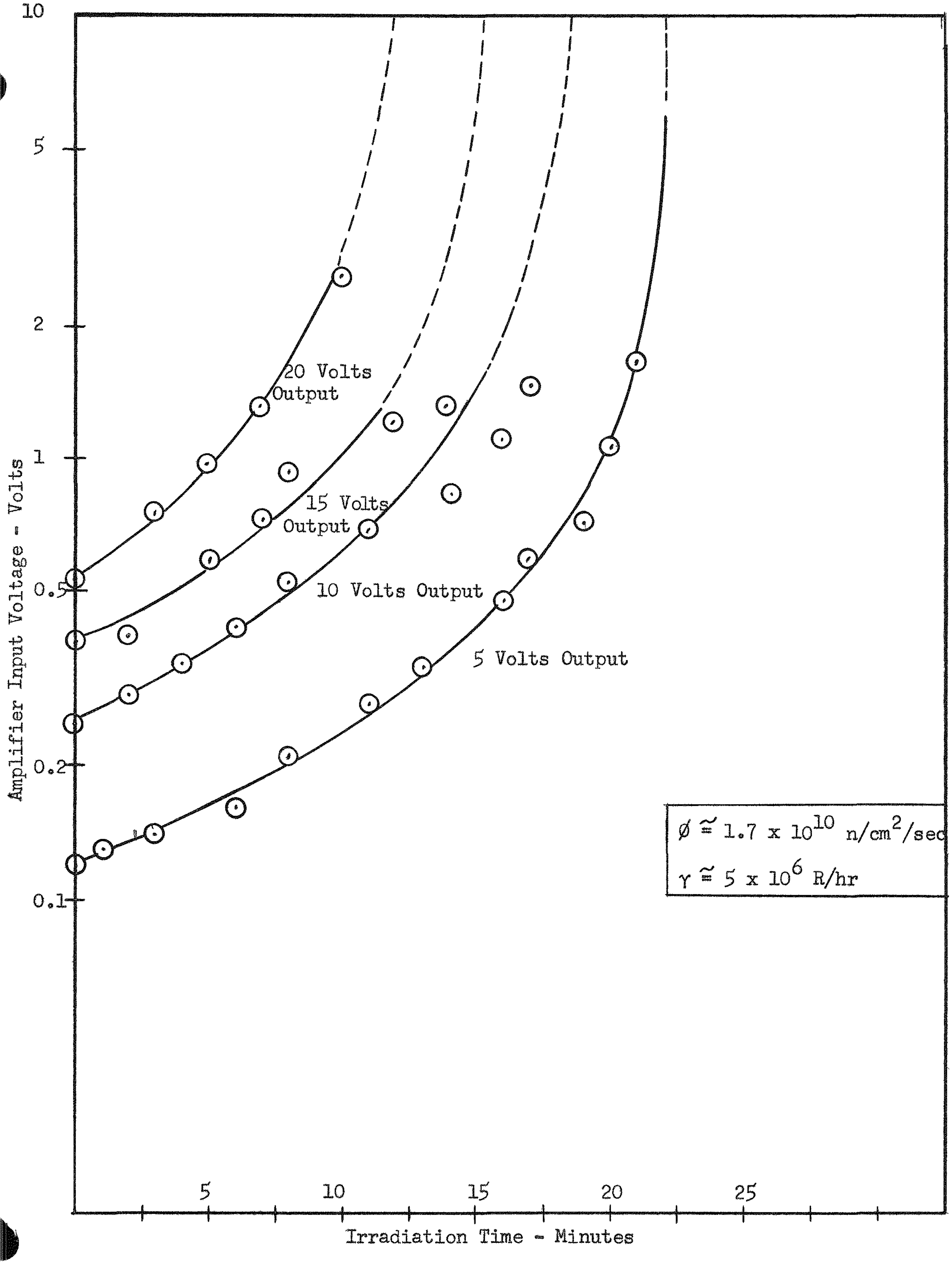

Fig. 11 - SERVO AMPLIFIER NO. 047

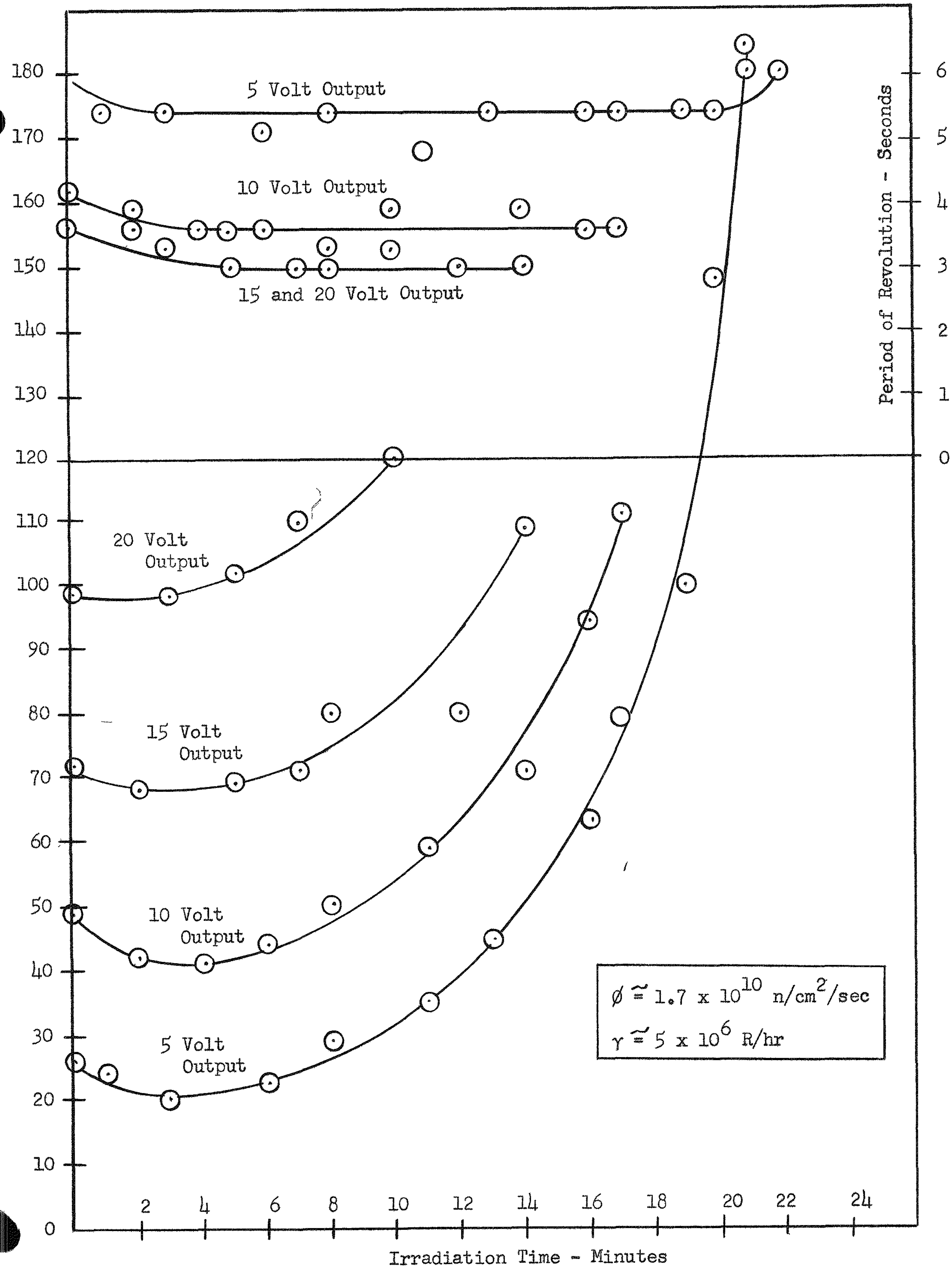

Fig. 12 - SERVO AMPLIFIER - NO. .047

During the last eight hours of irradiation and throughout the period of post-irradiation testing, the behavior of the servo system appeared to be somewhat erratic. In the open-loop mode of operation, the rotation of the output indicator was quite jerky. Furthermore, the accuracy of closed-loop operation decreased to the extent that the error in indicated output often exceeded five degrees.

The above behavior would indicate that the performance of the system was being degraded by the presence of static friction in one or more of the mechanical components. It was feared that irradiation might have affected the lubricants which were used in the rotary components or in the associated gear train. Alternatively, particles of dirt or other foreign matter might have entered the bearings and caused them to bind. However, subsequent examination showed that the entire assembly of motor, synchros, and gears could be rotated quite freely. Further examination showed the presence of an irregular drag in the Autosyn receiver which was mounted in the test panel. Because of its relatively low torque, this unit was unable to overcome static friction until its displacement from the correct position was much larger than normal. This conclusion was reinforced by the fact that, if a large static error did occur, its correction could be effected by tapping the Autosyn receiver or the panel upon which it was mounted. Since this procedure could not have affected the position of the other rotary components, it must be concluded that they already occupied the proper position, and that the measured error was entirely the result of the drag in the receiver unit.

Further tests of the rotary components were conducted, employing tapping of the receiver to eliminate the errors which resulted from the drag in the indicating link. Under these conditions, the performance of the entire system returned to normal. Thus, it may be concluded that the rotary components were not affected by the amount of radiation to which they had been subjected.

Nine days after the irradiation of the rotary components had been completed, the residual activation of the units was measured. It was found that, at a distance of six inches from the unit, the radiation level was approximately 300 mr/hour. The transistorized amplifier, which had been irradiated along with rotary components, was found to have been activated to approximately the same level.

The residual activation of these units was somewhat higher than that measured on other units which had previously been exposed to similar levels of radiation. This increase was a consequence of the fact that, in order to fit these components into a reactor port in which high flux levels were available, it was necessary to omit the cadmium shielding which had been used in previous irradiations. Consequently, these units were exposed to an appreciable thermal neutron flux which would have been eliminated by a cadmium shield. However, they were able to be handled after about one week of decay time.

V. CONCLUSIONS

Studies on the fuel quantity gage indicated no neutron or gamma sensitivity when irradiated to 6×10^{15} nvt. and about 5×10^{8}R respectively. It is quite probable that the unit would stand considerably more radiation before suffering any failure. It may be concluded that unit could operate in a high radiation background without danger of radiation induced failure.

As indicated earlier, studies on the gyro unit were not completed. The possibility of radiation sensitivity may be considerably greater due to the fluid environment. Radiation has been shown to produce radical changes in viscosity. The degree and type of change is highly dependent on the type of oil. It is recommended that the study on the gyro be made if time and funds are available.

A considerable amount of effort has been expended on the study of radiation effects in semiconductor materials. These materials, in general, show a hyper-sensitivity to neutrons and this was borne out in the studies just completed. Table IV indicates a significant difference between the Silicon and Germanium transistors. Germanium transistors are generally more susceptible to gamma induced damage than their silicon counterparts. Measurable gain changes are noticeable at about 10^{11} nvt. and complete destruction occurrs at around 5×10^{13} nvt. It is felt that the goals of the project were successfull attained, with the exception of the gyro unit. Operational performance was investigated to determine the effects of pile neutrons (epi cadmium) and gammas on the units while under normal operation. The only components found to suffer radiation damage were the transistors. These were replaced and all units operated normally.

Project personnel who participated in the work were: A. Brauner, D. Krebes, C. W. Terrell and E. Conti from the Physics Research Department; R. Bull, R. Arndt and G. Brennan from the Electrical Engineering Research Department.

Data pertaining to the project may be found in ARF Logbooks C-7476 and C-7481 and the Reactor Operations Logbook.

The Foundation is pleased to have participated in the study and would have considerable interest in pursuing additional studies.