ENRICO FERMI ATOMIC POWER PLANT NUCLEAR TEST SERIES

NUCLEAR POWER CALIBRATION AND LINEARITY INVESTIGATION OF THE NEUTRON DETECTORS IN THE ENRICO FERMI REACTOR

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ABSTRACT

The power calibration of the Enrico Fermi reactor was obtained at low powers (~ 100 w) by nuclear techniques, using an absolute fission counter in the reactor core. Neutron flux detectors for temporary start-up were calibrated from which permanent plant detectors were later calibrated when they were installed. Disturbances to the detectors were the major cause of increasing the probable error of the calibration from an optimum 4 per cent to the resultant value of 9 per cent.

Extraneous sources of disturbance to the reactor neutron leakage rate with power were investigated. Experiments were performed to investigate nonlinear relationships of leakage detector response and power level up to 100 Mw; none were found.

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FOREWORD

This report is one of a series of reports on the low-power (up to 1 Mwt) and high-power (up to 200 Mwt) nuclear testing of the Enrico Fermi reactor. The Nuclear Test Program is planned, directed and evaluated by Atomic Power Development Associates, Inc. (APDA). The tests are conducted by Power Reactor Development Company (PRDC). The reactor proper is owned and operated by PRDC. The steam generators and electrical generating facilities are owned by The Detroit Edison Company (DECo).

Many individuals have contributed to the nuclear testing of the Enrico Fermi reactor. Listed below are those, exclusive of the authors, who have made significant contributions to the work described in this report.

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SUMMARY

A power calibration by nuclear techniques was performed during the earliest operational tests of the Enrico Fermi reactor. A fission counter of known detection efficiency was positioned at the reactor midplane and near the core center by means of a stainless steel thimble which extended downward from the personnel floor. During reactor operation at ~ 100 w, the responses of temporary start-up neutron detectors in the graphite shield were compared to the fission-counter response. These responses were converted to reactor power through an analytical determination of the sensitivity of the absolute fission counter per unit power, using two-dimensional multigroup calculations. Later, the thimble was removed and, thereafter, start-up detector readings were used to determine power level.

In preparation for high-power experiments, temperature-resistant permanent plant neutron detectors were installed and calibrated by comparison of their response with the start-up detectors at a power level of ~ 800 kw. The final calibration uncertainty was found to be ± 9 per cent. However, it has been estimated that optimum experimental conditions achievable for this reactor would yield an uncertainty of ± 4 per cent for the low-power level nuclear calibration. The major contribution to the increase above this optimum value was caused by at least one removal and replacement of the detectors in their operational locations, to prevent their damage in other tests.

The degree of linearity of permanent detector response to reactor power over the range of 100 w to 100 Mw was determined in the following manner. The intrinsic linearity of the permanent ion chamber was verified by comparing its response at different reactor powers to that of fission counters also located in the graphite shield. Overall linearity of response was investigated at the higher power levels by comparing neutron detector response to that of reactor temperature detectors which measure coolant temperature rise through the core and thus provide a measurement proportional to reactor thermal power. These investigations revealed no nonlinear effects over the power range of 100 w to 100 Mw.

In addition, experiments and calculations were performed to investigate the separate effects of reactor temperature and changes in core configuration on the neutron flux levels at the detector locations. Significant changes in core configuration and isothermal temperature were found to have significant effects on detector response. For example, these two effects can supplement each other, even in normal circumstances, and alter response of some detectors by more than 10 per cent.

I. INTRODUCTION

A nuclear power calibration test was performed in the Enrico Fermi reactor soon after criticality was reached. The nuclear technique was selected since operating powers were at that time restricted to low levels (<1 Mw). The results have been used in many other tests which required power normalization, such as fission and other reaction rate measurements, shielding tests, and the measurement of the reactor power coefficient of reactivity.

The calibration required that an absolute fission chamber be inserted in the reactor core. Partially for that purpose, a temporary thimble was installed in the reactor. The response of temporary start-up neutron-level detectors located in the graphite shielding surrounding the reactor vessel was calibrated to preserve the power calibration for later operations following removal of the thimble.

Response of the detectors is dependent on the magnitude and spectrum of the reactor neutron leakage flux as a function of power. However, the reaction rate in the detectors can be varied by more than power changes. An increase in the system temperature will increase the reaction rate at constant power. Changes in the position of core subassemblies, especially those at the core edge, will also change the detector reaction rate. For a given change, the magnitude and sign of the change in response will vary between detectors, depending on their locations with respect to that of the core changes.

Other effects inherent to the detector are of concern in establishing response to power. Such intrinsic effects as saturation in the detector chamber or nonlinear operation of any gamma-compensation circuits can introduce nonlinear response. The tests reported here were designed to investigate such problems. Power was determined, detector response to power was measured, and variations in neutron leakage and intrinsic response were determined so that the power calibration could be maintained and extrapolated to high-power operating levels.

II. DESCRIPTION OF THE ENRICO FERMI REACTOR

A. GENERAL DESCRIPTION

The Fermi reactor and its associated structures are shown in perspective in Fig. 1. The reactor is contained in a stainless steel reactor vessel sealed at the top by a rotating shield plug which supports the control mechanisms, the fuel subassembly holddown mechanism, and the fuel subassembly handling mechanism. The reactor vessel is surrounded by borated and plain graphite neutron shielding material which is contained inside the primary shield tank. The reactor is of the fast breeder type, cooled by sodium, and it is operated at essentially atmospheric pressure. The maximum reactor power obtainable with the first core loading (Core A) is 200 Mwt.

The core and blanket are located in the lower reactor vessel and consist of 2.65-in.-square subassemblies containing the fuel pins and blanket rods. The core and blanket subassemblies are arranged to approximate a cylinder about 80 in. in diam and 70 in. high. The core, which is contained in the central portion of the core subassemblies, approximates a right cylinder 31 in. in diam and 31 in. high; it is axially and radially surrounded by the breeder blankets. The fuel in the first core loading consists of zirconium-clad pins containing U-10 w/o molybdenum alloy with the uranium enriched to 25.6 w/o U-235. The blanket is depleted U-3 w/o molybdenum alloy.

The reactor cross section, shown in Fig. 2, indicates the placement of individual components within the lower reactor vessel. There is a total of 149 central lattice positions that are occupied by core and inner radial blanket subassemblies, the antimony-beryllium (Sb-Be) neutron source, and the 10 operating control and safety rod channels. These positions are supplied with sodium coolant flowing upward from a high-pressure plenum which is connected to the discharge lines of the three primary sodium pumps. The coolant flows upward through the individual core and inner radial blanket subassemblies into a large upper plenum. From there it flows by gravity to the three intermediate heat exchangers and then to the suction side of the primary pumps.

Sodium is used in the three independent nonradioactive secondary coolant loops. Each loop provides coolant to the tube side of the intermediate heat exchanger and carries it from there out of the reactor building to the steam generator. The sodium enters the shell side of the steam generator for transfer of heat to the feedwater-steam coolant system through single-wall tubes. From there it is returned to the intermediate heat exchanger through lines which pass through the secondary coolant pump.

FIG.1 PERSPECTIVE VIEW OF REACTOR

FIG.2 REACTOR CROSS SECTION

The lattice positions surrounding the inner radial blanket contain the outer radial blanket subassemblies. Beyond the outer radial blanket are lattice positions used for stainless steel-filled thermal shield bar subassemblies. These subassemblies provide thermal and neutron shielding for the reactor vessel. The outer radial blanket and shielding lattice positions are supplied with sodium coolant from a low-pressure plenum.

The reactor is controlled by two operating control rods and seven safety rods which are uniformly spaced around the center of the core. On occasion, only six safety rods are used although provisions have also been included in the design for an eighth rod. The rods are all of the poison type, containing boron carbide (B_4C) in which the boron is enriched in boron-10 ($B-10$). One operating control rod is for regulating purposes and the other is for shimming. Both rods have approximate reactivity worths of 46 cents. The seven safety rods are worth more than 1.00 dollar each and provide shutdown reactivity. During operation of the reactor, they are held above the upper axial blanket section of the core so that they can be rapidly inserted into the core if it becomes necessary to scram the reactor.

An antimony-beryllium (Sb-Be) neutron source is located in the reactor, normally at the core-blanket interface (Fig. 2), to provide a neutron flux at the neutron detectors during reactor startup and to maintain a flux when the reactor is shut down. The radioactive antimony portion of the source is made as a separate piece for easy replacement and is in the form of a cylindrical rod. The radioantimony rod fits inside a beryllium assembly which is in the form of a hollow cylinder and which is placed inside a stainless steel can having the external dimensions of a normal core subassembly fuel can.

Additional information concerning the reactor design may be found in Reference 1.

B. DESCRIPTION OF THE NEUTRON-COUNTER TUBES

The permanent neutron detectors required for monitoring reactor power level are located in six neutron-counter tubes (NCT) installed in the graphite neutron shield surrounding the reactor vessel (Fig. 3). These tubes penetrate the reactor operating floor and primary shield tank at angles of 6 to 8 deg from the vertical and extend downward to below the level of the reactor core. Penetration of the primary shield tank is below the bottom of the operating floor (Fig. 4). Borated graphite is kept away from the region of the counter tubes to minimize interference with the response of the detectors. Neutron-counter tube 4 (NCT 4) is surrounded by lead shielding over a portion of its length to reduce the gamma background from a nearby sodium coolant pipe (Fig. 3). Neutron-counter tubes 3 and 4 have plain graphite "neutron windows" installed opposite them in the inner 6-in.-thick borated graphite shield layer next to the vessel. The bottom edge of each 2-ft-high window is located at the core midplane. Their purpose is to enhance the re-

FIG.3 LOCATION OF NEUTRON — COUNTER TUBES

FIG.4 TYPICAL PENETRATION OF NEUTRON — COUNTER TUBE

sponse of the source range detectors which are located in these two counter tubes.

C. DESCRIPTION OF THE PERMANENT PLANT NEUTRON DETECTION SYSTEM

To adequately cover the entire reactor power range from shut-down source power to full power (200 Mwt), three separate ranges of power detection are employed, using a total of ten permanent plant neutron detectors. The three ranges are designated as source range, intermediate range, and power range. The source range system contains two detection channels; the intermediate range contains three detection channels, and the power range contains five detection channels. Each of the two source range channels is supplied by signals from two Westinghouse two-connector fission chambers located in NCT 3 and 4 are designed to cover the power range from shut-down source power to about 12 kw. The three intermediate range channels are supplied by signals from three B-10-lined compensated ion chambers (Reuter-Stokes, Inc.) located in NCT 2 and NCT 5 and are designed to operate from approximately 1.2 kw to 1200 Mw. Thus, a minimum overlap of one decade with the source range channels is provided. The five power range channels, to be located in NCT 1, NCT 2, and NCT 6, consist of five B-10-lined uncompensated ion chambers (Reuter-Stokes, Inc.) and they cover the power range from approximately 2 Mw to 300 Mw (1 to 150 per cent of full power).

In addition to the ten neutron detectors required for normal operation, five other permanent detectors are mounted in the neutron-counter tubes. There is a spare ion chamber for each of the intermediate and power ranges located in NCT 5 and NCT 6, respectively. The intermediate range spare was connected to a micromicroammeter (Keithley Co. Model 415) for monitoring of power level over as wide a range of powers as is feasible. The detector plays the major role in the accurate monitoring of reactor power. It is designated ND-1. There is an additional power range ion chamber channel located in NCT 6, connected to a monitor which covers the power range from about 14 Mw to 1400 Mw. There are two absolute fission chambers located in NCT 3; one is surrounded by a zirconium hydride moderator. They were provided primarily for these tests to monitor ion chamber linearity. Two fission chambers mounted in NCT 4 also have zirconium hydride moderators and they are used to enhance source range counter response. All of the permanent detector components were selected to withstand the elevated temperatures encountered in reactor operation at high powers. Details of type and location of the permanent detectors are included in Table 1.

During the initial, low level (<1 Mw) tests, temporary start-up detectors were employed to sensitively monitor the low-power levels. They were also more easily inserted and removed, to determine permanent detector locations in the neutron-counter tubes. Their use is detailed elsewhere.² However, two of them were used in these studies and they are described in Table 1.

TABLE 1 - CHARACTERISTICS OF THE FERMI NEUTRON DETECTORS

					Location	
Range	Chamber Type	Manufacturer	Model No.	Channel Designation	NCT	Elevation Above * Core Midplane, ft
PERMANENT PLANT DETECTOR SYSTEM						
Source Range	Fission Chamber	Westinghouse	WX-4516	1	a) 3	-0.4
					b)† 4	
				2	a) 3	-0.4
					b)† 4	
Intermediate Range	B-10-Lined Ion Chamber, Gamma-Compensated	Reuter-Stokes, Inc.	RSN-15A	1	2	-1.1
				2	2	-1.1
				3	5	-1.1
				Spare ‡	5	-1.1
Power Range	B-10-Lined Ion Chamber, Uncompensated	Reuter-Stokes, Inc.	RSN-36A	1	1	-1.3
				2	1	-1.3
				3	6	-1.3
				4	2	2.3
				5	5	2.3
				Spare	6	2.3
	Hi-Range	6	-1.3			
U-235 Loading(mg)						
Absolute Fission Counters		Constructed by Argonne National Laboratory	2.1	1†	3	1.4
			0.097	2	3	5.5
TEMPORARY START-UP DETECTORS REFERENCED IN THIS REPORT						
Start-Up	High-Sensitivity Uncom- sated BF ₃ Ion Chamber	Reuter-Stokes, Inc.	RSN-77 A#	-	3	-1.7
Start-Up	BF ₃ Proportional Chamber	Anton	Type 805	4	4	-

* Elevation of detector-sensitive volume center above core midplane.

† Surrounded by neutron (zirconium hydride) moderating material

‡ Denoted ND-1, when connected to Keithley Co. model 415 micromicroammeter.

Connected to Keithley Co. ammeter before intermediate range spare was used.
Chamber and ammeter designated as RSN-77 A detector.

III. INSTRUMENTATION AND REACTOR CONFIGURATION

Most of the instrumentation used in these tests was available as part of the normal permanent plant operating equipment. Reactor flow rates and temperatures were measured by permanent operating instruments. Most of the neutron-level detector instruments used in the study were also plant operating instruments. However, one modification to the reactor was required. An instrument thimble was installed to allow the insertion of a fission chamber in the reactor core.

The power calibration and linearity tests were performed over a period which extended through both the low-power testing period when levels ranged from ~100 w to a maximum of 1 Mw, and the high-power period in which a maximum power of 100 Mw was reached. No deviations from normal operating procedures were required. Other tests were being performed concurrently, and occasional changes were required, such as in the core loading. No significant experimental difficulties occurred, however, and only two core loadings need be considered here.

A. REACTOR TEMPERATURE DETECTORS

Reactor temperature readings were obtained from plant temperature detectors installed in the reactor primary and secondary coolant systems. Iron-constantan thermocouples and platinum resistance temperature detectors were connected to precision readout devices. Thermocouple cold junctions were at room temperature; corrections were made for the ambient changes. The locations of the detectors and types of loading are listed in Table 2.

Approximately 25 per cent of the core subassemblies are instrumented with temperature detectors which monitor the outlet coolant temperature of individual subassemblies. Each detector is an iron-constantan thermocouple mounted in a finger that protrudes downward from the hold-down mechanism into the path of the outlet coolant of the subassembly. Four of these detectors were connected to the potentiometer bridge and were used in the studies listed here. Their core locations are shown in Fig. 5B.

B. SODIUM COOLANT FLOWMETERS

Plant sodium flowmeters were used to determine coolant flow rates. Nine electromagnet-type flowmeters employing permanent magnets were available, with three installed in each coolant loop system. The flow rate of each primary loop was measured by individual flowmeters installed in

(A) FOR NUCLEAR POWER CALIBRATION OF
RSN-77A, SEPT. 28, 1963 (99 1/2
EQUIVALENT CORE FUEL SUBASSEMBLIES)

(B) FOR HIGH-POWER TESTS, 1966
(103 CORE FUEL SUBASSEMBLIES)

DESCRIPTION

Inner Radial Blanket Subassembly (depleted U-3 w/o Mo alloy)	Operating Control Rod (B_4C) R-Regular Rod S-Shim Rod
Temporary Instrument Thimble	Safety Rod (B_4C)
Oscillator Rod (B_4C)	Core Subassembly (25.6 o/o enriched U-10 w/o Mo alloy; ~4.74kg U-235 per subassembly)
Neutron Source Subassembly (Sb-Be)	Core Shim Subassembly; ~2.32kg U-235 per subassembly
Dummy Subassembly (No Uranium)	Materials Surveillance Subassembly (stainless steel, zirconium samples, etc.)
	Monitored Subassembly Outlet Thermocouple

FIG.5 FERMI CORE CONFIGURATIONS DURING DETECTOR TESTS

TABLE 2 - REACTOR SODIUM TEMPERATURE DETECTORS

<u>Detector No.</u>	<u>Type</u>	<u>Temperature Monitored</u>	<u>Loading</u>
TE 209-1*	RTD [†]	Reactor Inlet	In Well In Blanket Coolant Inlet Line
TE 201	RTD [†]	Reactor Outlet	In Well In 30-in. Outlet Line
TE 308	RTD [†]	Secondary Loop Hot Leg	Steam Generator Na Supply Line
TE 301	TC [#]	Secondary Loop Cold Leg	Steam Generator Na Outlet Line

* Mounted in coolant Loop 1. Such coolant loop detectors are duplicated on the other two loops and they are designated for loop number.

† Resistance temperature detector

Iron-constantan thermocouple

the 14-in. (FE 201) and 6-in. (FE 202) supply lines to the reactor high-pressure (core and IRB) and low-pressure (outer blanket) regions, respectively. Total loop flow was obtained from the sum of the readings. A flow-meter in each secondary loop (FE 301) monitors its flow. Readout devices are provided which convert the voltage signals to flow rate indication.

C. TEMPORARY INSTRUMENT THIMBLE

A stainless steel temporary instrument thimble (T.I. T.) was installed in the reactor for the low-power tests, to provide access to the core for the power calibration and other studies such as measurement of activation rates. The T.I. T. extended downward about 25 ft from the reactor floor into an available safety rod location at position P03-P00 (see Fig. 5). This installation provided access to the reactor as far as 20 in. below the core midplane. The effective diameter of the sodium-free channel inside the T.I. T. was 2 in.

D. NEUTRON-LEVEL DETECTORS

Neutron-level detectors were primarily the permanent plant instruments (Table 1) installed in the graphite surrounding the reactor vessel.

The readout electronics provided for the detectors were in most cases integrated into the reactor safety system. Intermediate range detectors 1 through 3 were read on a three-channel recording 10-in. strip chart fed by a log n-type amplifier which also fed the period circuits. Output signal was proportional to the logarithm of the neutron level; range was six orders of magnitude. The power range detectors were read on a five-channel, 10-in. linear strip-chart recorder driven by the output of linear amplifiers. The recorder was adjusted for a range of 0 to 300 Mw. The spare intermediate chamber was connected to a micromicroammeter (Keithley Co. Model 415). A start-up system detector for the low-power tests, a high-sensitivity ion chamber (Reuter Stokes Model RSN-77A), was connected to the Model 415 ammeter. Since the ND-1 was also independent of the safety system, it was useful in monitoring other detectors. The intermediate range system provided monitoring of power over a wide range but with limited accuracy of readout; the power range instrument could be read to within ± 1 per cent at sufficiently high powers (≥ 30 Mw); but only the ND-1 combination could provide a precision indication (± 1 per cent) of power level over the full operational power range.

The absolute fission counters Nos. 1 and 2 described in Table 1 were designed and constructed at Argonne National Laboratory.³ They were connected to linear amplifiers (Hamner Instrument Co. Model N-300) through plant preamplifiers. Output of the amplifier from fission counter No. 1 was fed to a single channel pulse height analyzer (Hamner Co. Model N-302) used in the integral mode as a discriminator; and fission counter No. 2 was fed to a discriminator (Hamner Co. Model N-301). Two scalers were also used (Radiation Instrument Development Laboratories Model 39-51). Prior to their installation in NCT 3, each fission chamber was employed in the T. I. T. in the power calibration. The electronic system containing the N-302 analyzer was then used exclusively. For these early tests fission counter No. 1 had a loading of 199 μg of U-235. In some of the linearity tests, the amplifier and scaler systems were replaced by an ammeter, a d-c amplifier (General Radio Co. Type 1230 A) and an electrometer.

One of the temporary start-up instruments employed in a portion of these tests used an Anton-type 805 BF₃ proportional counter. It was connected to the amplifier (Hamner Co.) and Model N-301 discriminator and designated channel 4. (Ref. 2)

E. REACTOR LOADING

During the course of reactor investigation, changes were made as to the number and location of the core subassemblies. Frequently, these adjustments were simple exchanges or rearrangements. On occasion, net large changes such as the addition of several subassemblies were required to compensate for reactivity effects. As an example, two pertinent core loadings depicted here represent, essentially, the difference caused by insertion of a

high-power oscillator test rod in place of the T.I. T. The core loading during the portion of the low-power test program when the nuclear calibration was performed in the T.I. T. is represented in Fig. 5A. The loading during all the high-power studies reported here is represented in Fig. 5B.

IV. TEST DESCRIPTION

A. NUCLEAR POWER CALIBRATION

The absolute power calibration was performed at a power of 100 w, using absolute fission counters in the T.I. T. The temporary start-up neutron detectors were power calibrated at this time. Later, the T.I. T. was removed and permanent plant neutron detectors were installed in the neutron-counter tubes. The plant detectors were calibrated from the start-up detectors and they were subsequently employed in the high-power test to 100 Mw.

To maintain an accurate calibration, an evaluation was required of the effects from reactor core configuration and temperature changes, and from disturbance of the neutron-detector positions. Also necessary was a determination of linearity of detector response to power from 100 w to 100 Mw.

1. Basic Power Calibration

The nuclear power calibration was performed in the Enrico Fermi reactor in September, 1963, during the low-power test program. Temporary start-up neutron-level detectors were then in use for monitoring. The temporary instrument thimble (T.I. T.) was located in the safety rod location at P03-P00. The calibration was performed with absolute fission counter No. 2 with a 97 μ g U-235 loading, positioned at the core midplane in the T.I. T. during a normal test operation.

Levels above ~ 100 w had been found to produce desirable fission-counter rates and a fundamental mode for the flux distribution. When this level was achieved and stabilized, readings were taken from the fission chamber as well as from all available start-up detectors. The calibration was obtained by correlating the fission-counter response to power level by means of analytical calculations. The start-up detectors, including RSN-77A, were then normalized to power.

The analytical calculations were based on the CRAM multigroup diffusion theory code. U-235 fission rate distributions per unit reactor power were obtained from CRAM R-Z calculations in 8 groups, using the cross-section library designated 6-APDA* which incorporates a value of

* See page 35 of Ref. 4

194 Mev/uranium fission and appropriate values for energy yield from capture events. From the distributions, the ratio of fission rate at core midplane elevation in the T.I. T. location to total reactor power was obtained.

2. Maintenance of the Power Calibration

Comparison with the computed T.I. T. detector response provided the power calibration of the in-graphite detectors, and particularly the RSN-77A which was used in later operations when preparations for high powers required removal of the T.I. T. The calibration was, however, dependent on a constant relationship of fission-counter response and the magnitude and spectrum of leakage neutrons. Since several other sources of disturbance were known to exist, ancillary experiments were carried out to determine their importance. The effect of the (poison) control rod on the absolute fission-counter response was investigated for several rod positions by normalizing to constant power as indicated by start-up system readings. The effect on start-up detector response from core subassemblies in fuel storage positions located in the outermost row of the radial blanket was determined. Start-up detector readings were normalized to constant T.I. T. detector indication for runs with and without subassemblies in storage areas.

A somewhat extended test of the effect of reactor temperature on leakage was performed as part of the ancillary program. An increase of about 100 F in isothermal reactor temperature was accomplished and detector comparisons were made. The relation between the T.I. T. and start-up detector readings was measured before, immediately after, and several days after the temperature change. In this manner, the effect of core and blanket temperature change could be separated from that of the graphite shielding, which requires a much longer time to change temperature. An understanding of the thermal effects on leakage requires consideration of several partially compensating effects. Several supportive calculations were performed, to identify and separate the causes.

The primary calibration of September, 1963, was repeated several times before the T.I. T. was removed in November, 1964. Thereafter, to maintain the calibration, it was necessary to preserve the neutron-level detector location and operating characteristics so that the relation between reactor power and leakage rate would continue. Two events, however, occurred which changed the detector calibration and required further consideration. At least once, abnormally high temperatures were intentionally induced in the reactor graphite region surrounding the start-up detectors, to complete another test program. To prevent possible damage to the electrical cables, the racks in which all the detectors were mounted were removed from the neutron-counter tubes. When temperatures had subsided, the racks were carefully returned, to duplicate their original locations. Later, comparisons between readings of the relocated detectors suggested that the calibrations were no longer as accurately known.

The second event related to maintenance of the calibration involved installation of the temperature-resistant permanent plant detectors. Their installation extended over a period of time prior to removal of the various start-up detectors. When a sufficient portion of the changeover had occurred, a reactor operation was carried out, April 26, 1965, in which the calibrated response of the RSN-77A detector was compared with that of the permanent plant ND-1 detector. Later, the removal of the start-up system was completed and the power calibration was subsequently maintained with ND-1.

B. LINEARITY OF DETECTOR RESPONSE TO POWER

Response of the plant neutron detectors as a function of reactor power level was investigated by relating their response to that of other selected comparison detectors. ND-1 was chosen as a typical plant instrument, which was available for use with the attached ammeter readout device to give accurate indications of power level over the full operating power range. To discover any nonlinear effects resulting from changes in neutron leakage, reactor coolant thermocouples were chosen as comparison detectors above 20 Mw because their response is independent of leakage. Intrinsic nonlinear response of the ion chamber, e. g., by current saturation at high output levels, was investigated over a larger power range by using comparison detectors of a dissimilar nature of operation, i. e., the absolute fission counters. These and other comparisons are described in the following sections, for each of which the basic procedure is quite similar. The nature of the effect studied, however, is dependent on the choice of comparison detector.

1. Thermal Detector Comparison

Reactor power can be determined from thermal detectors, independent of neutron leakage, by use of the heat balance method. Under stable conditions, power transferred from a reactor coolant loop is proportional to the coolant temperature difference between the hot and cold legs:

$$P = C_o \sum_{i=1}^3 \Delta T_i F_i + E \quad (1)$$

where,

- P = reactor power, Mw
- C_o = sodium mean specific heat, Mw-hr/lb/F
- ΔT_i = hot to cold leg temperature difference in loop i, F
- F_i = coolant flow rate in loop i, lb/hr
- E = corrections for extraneous power sources, which, under these circumstances, can be ignored⁵

The measurement can be performed in both the primary and secondary coolant systems, using independent instruments. For normal coolant flow rates, ΔT_i is about 1 F per Mw for Fermi 3-loop operations. The temperature difference at about 20 Mw becomes large enough to be useful in the linearity studies.

Coolant outlet thermocouples for individual core subassemblies are also available for response investigations. Though it is possible to relate the indicated subassembly temperature rises directly to power, it is more straightforward to examine for proportional response.

Then,

$$P = K(n) \sum_{i=1}^n \Delta T_i \cdot F/F_o = CR \quad (2)$$

where,

- P = reactor power, Mw
- ΔT_i = indicated temperature rise through subassembly i, F
- K(n) = proportionality constant between power and the sum of the ΔT_i readings for the n selected thermocouples, at a base reactor coolant flow rate F_o (lb/hr), Mw/F
- F = reactor coolant flow rate at the time of the measurement, lb/hr
- R = reading of ND-1, amp
- C = ND-1 power calibration constant, Mw/amp

in which the net power correction, E of Eq. (1) is ignored.

If flow is constant at the base value, Eq. (2) reduces to:

$$C = K(n) \frac{\sum_{i=1}^n \Delta T_i}{R} \quad (3)$$

where K(n) is a constant for a given set of temperature detectors. Then the ratio of the sum of the subassembly temperature readings to the ND-1 reading can be examined to determine whether C varies with power. Inaccuracies in the measurement can be further reduced by increasing the number (n) of reliable selected thermocouples if accurate readout is available.

It is also possible to perform a heat balance and then base a thermal linearity study on the feedwater-steam system.⁵ However, the power determination can be performed only if superheated steam is produced. For 3-loop operations, this restricts such tests to powers above ~80 Mw. The Fermi reactor has not been operated above 100 Mw and the data thus available do not provide information on linearity over a significant power range.

Linearity investigations were performed using the reactor thermal instrumentation during a rise to 100 Mw on July 12, 1966. Stable operations occurred at levels of about 20, 35, 55, 70, 90 and 100 Mw. Following establishment of stable operating temperatures, readings were taken from appropriate temperature detectors and flowmeters from all three operating loops. The detectors used were:

Detectors Used in the Thermal Comparison Study

<u>Variable Monitored</u>	<u>Detector In Primary System</u>	<u>Detector In Secondary System</u>
Reactor Temperature	TE 201 TE 209 Four Core Outlet T. C. (Fig. 5B)	TE 308 TE 301
Flow	FE 201 FE 202	FE 301

Readings were also taken from ND-1 at each level and they were converted to power by means of the nuclear calibration. Flowmeter signals were corrected by means of the flow-level independent correction obtained in the Fermi heat balance tests.⁵ Temperature detector readings were corrected for the assumed error in zero reading.⁵ Power values were derived from the primary and secondary instruments and these values were compared with the power indicated by the ND-1 detector at each operating level. The indicated average temperature rise of the four core subassemblies was also compared to the ND-1 power indications.

2. Detector Intrinsic Response

Comparison of permanent plant detector response was made with nuclear detectors which have different operational characteristics. ND-1 was selected as the plant detector to be compared with the absolute fission counters Nos. 1 and 2. Such possible intrinsic effects of the ND-1 ion chamber as current saturation or nonlinear gamma compensation could then be observed.

During many operations in the high-power tests, readings were taken from the ND-1 detector and from absolute fission counters Nos. 1 and 2. Both the fission chamber scalers and ammeter readouts were used. All low-power data were taken with the system at about 515 F; high-power data were taken with steam generator sodium outlet temperature at 515-525 F. Comparisons were made between the various fission-counter readings and the power indication of the ND-1.

In the range above 5×10^3 cps it was found that, because of the finite resolving time of the scaler used with the No. 1 absolute fission counter*, significant losses in counting rate occurred. A correction was applied, based on a scaler dead time evaluated with the use of an oscilloscope. A dead-time correction was made which assumes that the dead time for each count is independent of counting rate. The correction is described by:

$$R = \frac{C}{1 - DC} \quad (3)$$

where,

- R = counting rate expected for zero scaler dead time, cps
- C = observed counting rate, cps
- D = scaler dead time for each count, 2×10^{-6} sec/count (measured)

3. Extrapolation of the Nuclear Power Calibration

Application of the power response curve of the ND-1 detector is necessary in extending the nuclear power calibration to high-power levels. The calibration can therefore be extended from the 800-kw level at which it was calibrated from the RSN-77A. To ensure the accuracy of determination of that level, the response of the RSN-77A detector between 800 kw and the 100-w level at which it was calibrated must also be known. The RSN-77A detector was investigated in that range by surveying previously obtained test data; a BF_3 proportional counter was selected for comparison with it. No fission-counter results were available; however, the data used had been collected using appropriate procedures.

4. Comparison of Permanent Plant Detectors

After study of the thermal and neutron leakage effects on the ND-1 detector, responses of other permanent plant detectors were compared with it. Establishment of linearity between ND-1 and the other detectors would assure no individual detector abnormalities and it would also provide comparison of the noncompensated power range detectors with the compensable ND-1. Data were obtained from the various standard readout devices during many of the high-power tests after operating variables had been stabilized.

* Losses in fission counter No. 2 were minimized by its lower sensitivity and by a faster electronic system.

V. RESULTS

A. NUCLEAR POWER CALIBRATION

1. Basic Power Calibration

The calibrations and detector comparisons performed in the nuclear power experiments usually included tests on all appropriate detectors. However, as the reactor test program progressed, interest usually settled on one instrument selected because of changes to some detectors, integration into the reactor safety system, and ease of obtaining and accuracy of the readout. Moreover, maintenance of a single calibrated detector provided sufficient information. For this reason, and in an effort to provide the reader with a simplified but accurate report, much of the calibration information will not be reported. However, in situations where gaps in the maintenance of the calibration are reported, there was no other information available.

The required analytical procedures were carried out and a sensitivity of 454 cpm/w was derived for the No. 2, 97 μ g fission counter positioned at the core midplane in the T.I.T.* The steps involved in the analytical procedure are summarized in Table 3.

The nuclear calibration experiment was performed September 28, 1963. The RSN-77A, as well as other portions of the start-up instrumentation, was calibrated initially. The readings taken and the resultant calibration are listed in Table 4. The test was repeated during the next six months and the calibration obtained was within the error in reproducibility of the readings, estimated to be ± 3 per cent or less.

In the latter part of 1964, installation of the permanent plant neutron detectors began. Initial installations were those in NCT 5 and NCT 6, to avoid disturbing the start-up instruments in NCT 3 and NCT 4. By April 26, 1965, they had been completed and an experiment was performed to calibrate the permanent plant detectors. The reactor was

* An earlier analytical calculation of the power sensitivity of the No. 1 fission counter was used as the basis for many of the Fermi tests and studies. The sensitivity obtained, 863 cpm/w, yielded powers about 10 per cent higher than reported here. The revised value, consistent with the data of Table 3, is 951 cpm/w for the No. 1 fission counter. The revision is due mainly to an improved multigroup analysis.

TABLE 3 - ANALYTICAL DERIVATION OF FISSION-
COUNTER SENSITIVITY TO POWER

<u>Symbol</u>	<u>Definition</u>	<u>Value</u>
ϕ	Specific Flux At The Core Center	2.40×10^7 nv/w*
σ	Average U-235 Fission Cross Section At The Core Center	1.53 barns*
f_t/f_c	U-235 Fission Ratio: T.I. T. To Core Center	0.863*
N	Atoms of U-235 In No. 2, 97 μ g Fission Counter	2.49×10^{17} atoms
F_{25}/F_{28}	Fission Ratio In T.I. T. (per atom): U-235 To U-238	26 †
E	Counter Effective U-238 Loading	0.06 U-238 atoms/uranium atom †
ϵ	Counting Efficiency, Fission Counter No. 2	0.96 cps/fps ‡
Counting Rate Per Unit Reactor Power, Fission Counter No. 2 $= \phi \cdot \sigma \cdot \frac{f_t}{f_c} \cdot N \cdot \left(1 + \frac{E}{F_{25}/F_{28}}\right) \cdot \epsilon$ $= 454 \text{ cpm/w}$		

* From companion two-dimensional RZ - and - XY geometry CRAM code calculations (Ref. 6). The RZ calculation is described in Ref. 6, where it is designated as 8 GP RZ.

† Ref. 7

‡ Ref. 8

TABLE 4 - BASE NUCLEAR POWER CALIBRATION

TEST DATE: September 28, 1963

SYSTEM TEMPERATURE: 515 F

<u>Detectors</u>	<u>Readings</u>	<u>Results</u>
Absolute Fission Counter No. 2 At Core Midplane in T.I. T.	5.805×10^4 cpm	$(5.805 \times 10^4 \text{ cpm}) / (454 \text{ cpm/w})^* = 128 \text{ w}$
Ion Chamber RSN-77A In Standard Position, NCT 3	7.88×10^{-10} amp	$(7.88 \times 10^{-10} \text{ amp}) / (128 \text{ w}) = 6.16 \times 10^{-12} \text{ amp/w}$

* Derived in Table 3.

TABLE 5 - POWER CALIBRATION OF ND-1 DETECTOR

TEST DATE: April 26, 1965

SYSTEM TEMPERATURE: 515 F

<u>Detectors</u>	<u>Readings</u> <u>(From $\mu\mu$ Ammeter)</u>	<u>Results</u>
Ion Chamber RSN-77A In Standard Position, NCT 3	5.00×10^{-6} amp	$(5.00 \times 10^{-6} \text{ amp}) / (6.16 \times 10^{-12} \text{ amp/w})^*$ $= 8.12 \times 10^5 \text{ w}$
ND-1 Ion Chamber In Standard Position, NCT 5	3.00×10^{-7} amp	$(3.00 \times 10^{-7} \text{ amp}) / (8.12 \times 10^5 \text{ w})$ $= 3.69 \times 10^{-13} \text{ amp/w}$

* Derived in Table 4.

operated at about 800 kw, and the comparison was made between response of the RSN-77A start-up detector and the permanent plant detectors in NCT 5 and NCT 6. The calibration of the ND-1 detector is described in Table 5. Shortly after this calibration, the changeover to the permanent plant system was completed, RSN-77A was removed, and the power calibration was maintained with the use of the ND-1 detector.

A series of heat balance experiments was carried out at power levels between 90 and 100 Mw. From them, a calibration of reactor power by thermal means was also obtained. Comparison of the results of the three heat balance tests for thermal and nuclear calibration is shown in Appendix A of Reference 5. The two methods are in agreement within 2 per cent, which is much less than the uncertainty involved in the measurements.

2. Disturbance to the Location of the Calibrated Detector

Installation of permanent plant detectors began in late 1964 with the installation of the NCT 6 rack and chambers. On March 27, 1965, the NCT 3 and NCT 4 racks were removed to prevent cable damage during operations which significantly raised the temperature of the graphite shielding. After temperatures had returned to normal, these start-up detectors were carefully returned to what was thought to be their previous locations. The effect of the movement on the RSN-77A could be examined by comparison with the undisturbed detectors of NCT 6. The data imply that its sensitivity to power had increased between 7 and 10 per cent after its replacement. However, the change must be considered in light of the fact that the core boundary was also changed, and that an accurate record of the ammeter calibration was not available.

A similar disturbance of the RSN-77A detector had occurred previously in October, 1964, when the detectors in NCT 3 and NCT 4 were again removed and replaced. There were no comparison detectors available then in any other NCT (NCT 6 was not yet loaded). Since no measure of the effect on RSN-77A could be made, its calibration could not be appropriately corrected.

Since the value for the one replacement which was monitored by NCT 6 could not be separated from the changes in boundary and ammeter calibration, and since the 1964 disturbance could not be evaluated, it has been assumed that the disturbances to detector location have introduced a probable error of 8 per cent in the reactor nuclear power calibration.

3. Ancillary Experiments

The ancillary experiments were carried out at the time of the original RSN-77A calibration. Considerable data were collected, but, because of the complexity of the analysis performed and the small size of

some of the effects investigated, only a summary of the results will be presented here. It was found that the presence of the shim rod affects response of a detector in the T.I. T. Maximum effect was found to be a 3 per cent reduction in counting rate for full insertion of the shim rod. An implied correction for shim rod position for the basic power calibration of RSN-77A was a 0.5 per cent increase in the observed counting rate of the fission counter, but it was not included in Table 4. It was found that storage of core fuel subassemblies in storage positions near an NCT could produce up to a 10 per cent increase in the sensitivity of some detectors. Use of such locations for core fuel storage was therefore avoided in all sensitive tests.

It was also found that neutron leakage varies with reactor temperature. An increase of 7-1/2 per cent was found for the response of start-up detectors positioned in NCT 3 directly behind some borated graphite, for an isothermal increase in reactor temperature from 410 to 520 F. The increase was measured at the end of the 24-hr period required to achieve the full rise of 110 F. After several more days had elapsed, a further increase in response of about 3 per cent was attributed to heating of the borated graphite shielding in close proximity to the detectors. The shielding was observed to heat this slowly because of its large mass and the presence of insulation on the outside of the reactor vessel.

Analytical calculations made with the one-dimension diffusion theory AIM code predicted the 7 per cent short-term increase in response to an isothermal system temperature increase of 100 F. The calculations further indicated that the heating of the 6-in. layer of borated graphite directly in front of the detectors contributed 3 of the 7 per cent increase. An increase in reactor temperature rise of only 4 per cent per average 100 F would be expected for detectors separated from the borated region by plain graphite or for temperature increases in which the borated graphite essentially does not increase in temperature, as in the case for a high-power run of short duration.

4. High-Power Calibration

The Fermi reactor high-power tests began in December, 1966. To date, power levels as high as 100 Mw have been achieved. To use the power calibration of ND-1 for these tests, it was required that corrections for two perturbations of the leakage be applied. One was for the effect of elevated reactor temperatures reached in the high-power tests. The other was required because the Fermi core loading had changed from the time of the original calibration.

Temperatures achieved under normal sodium flow conditions for the highest power level reached, about 100 Mw, were 550 F at the reactor inlet and 660 F at the outlet. Since the nuclear power calibration was performed at a temperature of 515 F under isothermal conditions, a correction

was made for the difference in leakage rate that these temperatures produce. It was assumed that the temperature of the borated graphite shielding could be raised only to reactor inlet temperature, i. e., to the temperature of the reactor bypass coolant flow to the outer reactor vessel. Since the permanent plant detectors are not close to the borated region, no correction for this part of the temperature effect was made. However, the reactor average temperature of 605 F is 90 F higher than that of the power calibration temperature. Based on the value of +4 per cent per 100 F, an increase in leakage of 3-1/2 per cent is therefore implied at 100 Mw.

The core boundary for the basic power calibration was nearly symmetric (Fig. 5A) but was somewhat different for the high-power tests (Fig. 5B). The number of core fuel subassemblies had been increased from 99-1/2 to 103, primarily to compensate for installation of the oscillator rod. CRAM code calculations available for the 103-subassembly core and a 101-1/2 subassembly core (a configuration achieved during other low-power tests) were examined, to determine the effects of the changes on leakage. While the effects of shape and size could not be completely separated, the calculations implied that the high-energy leakage flux directed radially toward the appropriate NCT was more strongly affected by local variations in boundary shape than by reactor size. Therefore, the variation in size was ignored and the change between the two calculations was corrected to the change from 99-1/2 to 103 by a very approximate technique in considering the boundary shape. The result obtained for the ND-1 detector location was a decrease in sensitivity of about 3 per cent from the original calibration for the high-power tests.

The net effect of these two leakage changes on the high-power calibration of the ND-1 was zero. It should be noted, however, that this was fortuitous. In less fortunate circumstances, up to a 6 per cent change in sensitivity of some of the detectors can be expected for 100-Mw operation. Further, analysis implied that for some temporary core configurations already achieved, detector response was changed by up to 7 per cent. Some detectors were increased and others were decreased, depending upon their location relative to the core change. Change in detector response of more than 10 per cent can therefore be anticipated from a combination of reasonable changes in core configuration and system temperature.

5. Error Analysis

Power calibration for the high-power program required evaluation of the several experiments leading to a final answer:

- (1) basic power calibration of RSN-77A
- (2) compromise of calibration due to relocation of detector
- (3) transferral of calibration to ND-1

- (4) high-power program corrections
- (5) maintainance over a two-year period

Similarly, the error analysis also required consideration of the error involved in each experiment.

The error estimate of the basic calibration, item (1), is of importance since it represents the effective minimum error achievable by optimum operating schedule and experimental conditions. Estimates of probable error are listed in Table 6 for each part of the experiment tabulated in Table 3; a resultant value of ± 4 per cent is indicated.

TABLE 6 - ERROR ANALYSIS OF THE
FISSION-COUNTER CALIBRATION

<u>Symbol</u>	<u>Item (see also Table 3)</u>	<u>Probable Error, %</u>
ϕ	Specific Flux at the Core Center	3
σ	Average U-235 Fission Cross section at the Core Center	Negligible*
f_t/f_c	U-235 Fission Ratio: T.I.T. To Core Center	2
N	Atoms of U-235 In No. 2, 99 μg Fission Counter	1
F_{25}/F_{28}	Fission Ratio In T.I.T.: U-235 To U-238	Negligible
E	Counter Effective U-238 Loading	
ϵ	Counting Efficiency, Fission Counter No. 2	2
	Nonachievement of Fundamental Mode of Flux Distribution	0.5
	Reproducibility In Readings of Counter And Ammeter	0.5
	Total Estimated Probable Error in Calibration Analysis and Experiment	4

* The U-235 fission cross section is used in determining both the fission-counter fission rate and reactor power. Hence, the error in the cross section is significant only insofar as it affects ϕ and f_t/f_c ; and the errors in those quantities include such uncertainties in σ .

Probable error for items (2), (3), and (4) above were estimated at ± 8 (see Section IV-A-2), ± 2 , and ± 2 per cent, respectively. Item 5 cannot be estimated directly; however, it was judged to produce only a minor effect in the final error. Considering the respective errors of 4, 8, 2, and 2 per cent, the resultant probable error in the high-power nuclear calibration of the permanent neutron detector was found to be ± 9 per cent.

B. LINEARITY OF DETECTOR RESPONSE TO POWER

1. Thermal Detector Comparison

Comparison of the response of ND-1 with power determined from primary, secondary, and core outlet detectors is contained in Fig. 6. The data are from the July 12, 1966 test, summarized in Table 7.

TABLE 7 - SUMMARY OF ND-1 COMPARISON
WITH THERMAL DETECTORS

<u>Thermal Detectors</u>	<u>Average Ratio</u>	<u>Maximum Deviation, %</u>	<u>Standard Deviation, %</u>
Primary (Mw/Mw)	1.026	1.0	0.6
Secondary (Mw/Mw)	1.021	1.6	0.8
Core Thermocouples (Mw/F)	0.573	1.6	0.8

Estimated errors were obtained in readings of the temperature detectors and flowmeters, to determine the accuracy of the experiment. For these studies, only the relative variation in the detector ratio is important. Hence, only errors associated with reproducibility of a given reading were examined. Based on estimated probable errors of ± 1 F and ± 3 per cent in the individual temperature and flow readings, respectively, the probable error in the determination of power was 4 per cent at 20 Mw and 1.3 per cent at 100 Mw. The error ranged from 7 per cent to 1.4 per cent at 100 Mw for the core outlet temperature comparison. No estimates were made for the degree of stability achieved at each power level.

Comparison of the variance data of Table 7 with the estimated probable errors leads to several conclusions. The data of Fig. 6 are not abnormally scattered; rather, they are somewhat more consistent than can be expected. Nevertheless, it is concluded that no abnormal response of ND-1 with high temperatures was observed. Assuming a value of 4 per cent change in leakage per 100 F average rise in reactor average temperature (Section IV-A-3), the expected change in response of the ND-1

FIG.6 RELATIVE DETECTOR RESPONSE: ND-1 TO THERMAL DETECTORS

detector can be derived. Assuming that only the change between 40 and 100 Mw would be accurately observable, then for an average increase in reactor temperature to 100 Mw of 70 F ($(660-520)/2$), a change of 2 per cent ($4\%/100 \text{ F} \times 70\text{F}/100 \text{ Mw} \times (100-40) \text{ Mw}$) would be expected for the ND-1. It is concluded that such a small increase could not have been discovered in these experiments of thermal comparison.

2. Detector Intrinsic Response

Results of the comparison of ND-1 with response of absolute fission counters Nos. 1 and 2 are shown in Figs. 7 and 8, respectively. Both current and pulse response of fission counter No. 1 are displayed, as is the pulse response corrected for dead-time counting losses. The useful range of the pulse mode is thus extended somewhat; but at powers above $\sim 800 \text{ kw}$, other electronic circuit limitations make invalid the assumption of a constant value of the dead time for each counting event. The use of the counter in the current mode was designed to provide reliable fission-counter data above this power level. Probable error in the determination of the detector ratio varies with total counts or current, but is 3 per cent or less for all points. Within this error, which compares favorably with the observed scatter in the data, no detectable nonlinearities in the response of ND-1 were found for the power range studied.

3. Low-Power Extrapolation of the Power Calibration

The data available allowed comparison of the RSN-77A with the proportional counter of channel 4 between 90 w and 38 kw (Fig. 9). Again, no observable nonlinearities were found within a maximum range of variation in the range of ± 6 per cent. No estimate of probable error was made for the data. No data are available for the range to 800-kw level at which ND-1 was calibrated from RSN-77A. However, the manufacturer's specifications indicate that this type detector was not operating beyond or even near its maximum reliable output level.

4. Comparison of Permanent Plant Detectors

Comparison of the response of some of the power range detectors is shown in Fig. 10. Their response is deemed linear within a reading error of about ± 1.5 per cent in establishing the detector ratio. Data available for the other power range detector also implied that their response was linear. No data are presented for the other intermediate range detectors. Their readout instrument, a log amplifier system which feeds the neutron period indicator circuits, was known to be somewhat nonlinear. Detector response indications were as expected from the device.

FIG.7 RELATIVE DETECTOR RESPONSE: AFC NO. 1 TO ND-1

FIG.8 RELATIVE DETECTOR RESPONSE: AFC NO. 2 TO ND-1

FIG.9 RELATIVE DETECTOR RESPONSE: BF₃ PROPORTIONAL COUNTER TO RSN-77A

FIG.10 RELATIVE DETECTOR RESPONSE: POWER RANGE DETECTORS TO ND-1

CONCLUSIONS

The objectives of providing and maintaining the Fermi nuclear power calibration at low levels and extending it to high powers were accomplished. The investigation of detector linearity with reactor power, which is required for the calibration extension, was also accomplished. Pertinent conclusions from each of these tasks are listed below.

- The probable error in the nuclear power calibration was ± 9 per cent, a considerable portion of which resulted from disturbance of the detector positions. Under optimum conditions, the probable calibration error would be reduced to ± 4 per cent.
- No nonlinear response of the permanent plant neutron detectors over their normal operating ranges was found for power levels between 100 w and 80 Mw. No intrinsic nonlinear response of the ion chambers was observed.
- A modest variation in leakage rate with system temperature was confirmed in isothermal zero-power experiments. The effect was too small to be observed in the high-power experiments, to 100 Mw.
- Analytical calculations show that leakage effect on detector response was varied by up to 7 per cent from changes that occurred in the core geometry during the course of the Fermi testing program. This and the previously cited effect can complement each other and produce changes in detector response greater than 10 per cent for normal operations.
- The ND-1 nuclear power conversion factor of 2.71×10^6 Mw/amp agrees within 2 per cent of the conversion factor obtained from thermal power measurements. It can be seen from the errors cited above that the agreement is satisfactory.

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