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MASTER

USE OF INSTRUMENTED FUEL
ASSEMBLIES FOR THE
CORE THERMAL-HYDRAULIC ANALYSIS
GARIGLIANO DEVELOPMENT PROGRAM

D. OLIVA
A.C. DUCKART

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
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ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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USE OF INSTRUMENTED FUEL ASSEMBLIES FOR THE
CORE THERMAL-HYDRAULIC ANALYSIS

GARIGLIANO DEVELOPMENT PROGRAM

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PREFACE

The United States and the European Atomic Energy Community (Euratom), on May 29, and June 18, 1958, signed an agreement which provides a basis for cooperation in programs for the advancement of the peaceful applications of atomic energy. This agreement, in part, provides for the establishment of a Joint U.S.-Euratom research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

The work described in this report represents the Joint U.S.-Euratom effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in Western Europe and the United States.

INTRODUCTION

Power reactor development relies on the ability to predict theoretically reactor behavior and to confirm the predictions experimentally. The Garigliano Development Program had in its scope the developing of new in-core instruments and instrumentation techniques, and comparing the measurements with precalculated values. It is for this reason that special instrumented fuel assemblies were designed, calibrated in the APED heat transfer loop, and then used in the Garigliano reactor during the high void and reactor stability tests.

The functions of the instrumented fuel assemblies were to

Measure channel flow rates with inlet turbine flowmeters,

Measure channel exit steam qualities and channel powers with inlet and outlet flowmeters,

Measure channel inlet and outlet coolant temperatures with thermocouples, and

Determine axial neutron flux profiles in in-core positions adjacent to the instrumented fuel elements with movable in-core flux monitors.

Use of turbine flowmeters in other power and test boiling water reactors had been already investigated at Argonne National Laboratory (1959),⁽¹⁾ at Vallecitos (1961-62),⁽²⁾ at Big Rock Point (1963-64),⁽³⁾ and at Halden (1962-present).⁽⁴⁾

Movable in-core flux detectors were used for the first time in a boiling water reactor during the Garigliano R&D Program, and are now standard equipment in all GE BWR's as the TIP (Traversing In-Core Probe) system.

SUMMARY

This report describes the design, installation, and performance of the special in-core instrumentation used in the Garigliano R&D Program for measurements of the channel flow rate, inlet and outlet coolant temperature, and axial neutron flux distribution.

The special instrumentation consisted of

Four instrumented fuel assemblies,

Four movable in-core neutron flux detectors, and

Related special readout and signal conditioning electronic instrumentation.

The instrumented fuel assembly was a standard 9×9 fuel bundle with an inlet and outlet turbine flowmeter, and with two inlet and two outlet thermocouples. An instrument probe replaced the central fuel rod.

The inlet flowmeter indicated the channel flow rate, and together with the outlet flowmeter and inlet temperature, the channel exit quality and the channel thermal power were determined, solely from the measured values.

The movable in-core flux detectors provided a direct reading measurement of the axial flux profile. With the special instrumentation, a complete check of the calculated channel flow rate, exit quality, power, and axial power distribution could be made. The agreement between the measured and calculated values of channel flow, exit quality, and power is considered satisfactory.

The four instrumented fuel bundles and movable in-core flux detectors were installed in the Garigliano reactor early in 1966. Only three of the four movable in-core flux detectors were installed due to an undersized vessel guide tube in core position 115. It was originally planned that four flux wire guide tubes would be located along with the movable in-core flux detectors in four in-core positions for calibration and comparison purposes, but they could not be installed because of space limitations. Early failures were encountered on three of the eight turbine flowmeters, believed to be caused by water leakage into the pickup coils. Three of the sixteen thermocouples were similarly damaged because of water leakage into the electrical cables. The remaining instruments performed satisfactorily until the end of the reactor test period.

For safety purposes, the four instrumented fuel bundles had their orifice diameter increased to 4.0 inches. This allowed for a large margin of flow reduction in case of turbine flowmeters stoppage.

With rotating turbine flowmeters, the instrumented fuel channel flow rate was 1.7 times greater than the average channel flow rate in forced circulation, and 1.5 times greater in natural circulation. The higher channel flow rate values in the instrumented assemblies than in the standard fuel bundles were also caused by the presence of crud deposits on the lower tie plates of the standard fuel assemblies which had been in the reactor for about 3 years. The higher flow rate, together with the fact that the instrumented fuel elements were fresh (while the standard fuel elements had accrued an average exposure of about 5100 MWd/MT), caused in most cases the power of these assemblies to be higher than that of the surrounding standard fuel elements.

The axial power distribution of the instrumented fuel elements was also different from that of the surrounding fuel elements. This fact was clearly shown by the on-line computer calculation. The movable in-core flux detectors could not give a direct picture of this phenomenon because their traces were proportional to the thermal neutron flux in the water gap among the four fuel elements adjacent to the in-core position.

At the end of the reactor fuel cycle 1B (April 1966 – May 1967), the special in-core instrumentation was removed from the reactor. At that time, after more than 1 year of operation in the reactor, only outlet flowmeter B of assembly B was still giving a good signal, while five turbine flowmeters had failed pickup coils and two appeared to have locked rotors.* The turbine flowmeters and instrument probes were disassembled from the fuel bundles which were reloaded into the core with standard orifices.

A post-operation examination of the turbine flowmeters is considered necessary in order to understand better the causes of their failures and to check the bearing conditions. The inlet and outlet turbine flowmeters proved to be a sufficiently accurate means to measure channel flow rates, power and exit quality. Moreover, it was shown that they have the potential to provide information for the analysis of hydrodynamic stability because of their ability to show the flow-power response in case of channel flow instability and to indicate peak frequency.

The inlet and outlet thermocouples gave satisfactory values of the inlet and outlet coolant temperature and proved their good performance during temperature transients. Nevertheless, the electronic instrumentation calibration was not very accurate and differences of about 4°C, or about 1.5%, were found between the inlet thermocouple of assembly A and the others.

The movable in-core flux detectors proved their ability to give good axial flux profiles, which were comparable to the average of the four fuel elements near their location, in a short period of time instead of the 15 hours required for the flux wire irradiation method. Large relative differences between measured and calculated flux were shown at the fuel element top and bottom. Their sensitivity to local flux variation was excellent. For normal reactor operation, their design proved to be satisfactory.

* The stoppage of some of the turbine flowmeters could have occurred during the last period of operation, but sufficient data is not available at present to prove it. In the absence of hot-cell inspection of the irradiated flowmeters, the eventual stoppage of a turbine seems to be explained with alignment tolerances rather than bearing materials or turbine design, since one of the four turbine flowmeters is known to have operated for more than a year. In other BWR's, turbine flowmeters of similar design using graphite bearings have operated for periods of about 3 years.

CONCLUSIONS

The comparison of the measured data from the instrumented fuel assemblies with the calculated data from the Garigliano on-line computer and the APED thermal-hydraulic code, resulted in the following conclusions:

1. The first impression, derived from the comparison of the instrumented fuel assembly data with the on-line computer calculated values, that the instrumentation was giving measured values largely deviating from the actual ones, was erroneous. The deviation was principally caused by the fact that the on-line computer correlations and input coefficients had been chosen conservatively in order to calculate a worst-case MCHFR (minimum critical heat flux ratio) and thus assure safe operation of the reactor.
2. The APED thermal-hydraulic code calculations have demonstrated that the measured values agree well with the calculated values when the design values are input and the calculations are performed with the aim of determining the most accurate values of channel flow, active coolant power, and exit steam quality.

Notwithstanding the necessary approximations, the following agreement was shown between measured and calculated values:

Channel flow rate, within ± 4.7 percent,

Channel active coolant power, within ± 5 percent, and

Channel exit steam quality, within ± 6.6 percent.

It should be noted that for the APED thermal-hydraulic code calculations, the effect of the chimney, constituted by the outlet turbine flowmeter housing, at the instrumented fuel assembly channel outlet, was considered; while such effect was not considered when the on-line computer calculations were performed.

3. With such considerations, it appears that the coupled use of flowmetering devices at the fuel channel inlet and outlet, together with axially movable ion-chambers, constitutes a valid means to measure channel flow rate, active coolant power, exit quality, and to check the calculated values for individual fuel elements of the core. Therefore, reliable flowmeters could be used advantageously for any of the following purposes:
 - a. At the reactor startup, to actually measure the channel flow rate of the fresh fuel elements located in annular regions of a large core, and check the assumed loss coefficients and input parameters for on-line and off-line calculations (local fuel loss coefficients, effects of orifices, control rod tubes, fuel support tubes, etc.).
 - b. After the first fuel cycle, to monitor the change in local loss characteristics of the partially exposed fuel elements, due to possible danger of the local loss coefficients at the fuel element inlet, and to determine the values of the new coefficients to be adopted. In this case also, differences in flow, power, and exit quality between fresh fuel elements and partially-exposed fuel elements could be measured effectively in two adjacent fuel elements located in the same annular region of the core.

- c. For fuel development programs, to measure exactly channel flow rate, power, exit steam quality, and axial power distribution in individual fuel elements having different characteristics than the standard fuel elements that make up the core.
 - d. In-core research and development programs, as a valid means to furnish thermal-hydraulic data for stability analysis.
4. Therefore, notwithstanding the necessary limitations and problems that the instrumented fuel assemblies have revealed during the Garigliano Research and Development Program, it appears that improved flowmetering devices and movable in-core chambers could provide useful information to operate the reactor safely within more strict margins, and to aid in developing improved fuel. The later BWR's, starting with the KRB reactor (Gundremmingen), use TIP (traversing in-core probe) which is a greatly improved system over the movable chamber system used for the first time at Garigliano. The TIP system has proved to be very satisfactory for normal plant operation. In fuel research studies, a better use of the in-core flux detectors could be made if the movable flux detector could be axially located and calibrated inside the fuel element, in order to have information regarding that specific fuel element's axial flux distribution.

For turbine flowmeters to be used with confidence in power reactors, further development work is required to attain the necessary reliability and performance characteristics.

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SECTION I

GENERAL DESCRIPTION OF THE INSTRUMENTATION

1.1 INSTRUMENTED FUEL ASSEMBLIES

Each of the four instrumented fuel assemblies that were installed in the Garigliano reactor for the R&D program had an inlet and outlet flowmeter of the turbine type, two inlet and two outlet thermocouples to monitor coolant temperature, and a movable in-core neutron detector which could be axially positioned in a guide tube adjacent to one corner of the fuel element. The general arrangement is shown in Figure 1-1.

The inlet flowmeters were attached to orifice cups similar to the standard design so that the standard orifice handling tool could be used to install and remove the flowmeters from the reactor. The flow rate meters produced a 10- to 20-millivolt a-c voltage at a 5- to 10-volt d-c level; the frequency of the a-c component was proportional to the flow rate of the coolant. The probe was connected to an in-reactor flexible conduit to protect the cables with a water- and pressure-tight penetration plug and six electrical connectors.

The thermocouples produced a d-c voltage proportional to the difference in temperature between the reactor coolant and a reference temperature.

The in-core instruments were connected to a readout panel (Figure 1-2) with the required signal conditioning equipment and two strip chart recorders. The readout panel was installed in the computer room and was connected to the GE 412 computer and to the Stability Test oscillographs which provided the required data recording. The signal conditioning equipment consisted of

transistorized modular components, easily removable for repair and requiring a minimum of panel space.

A detailed description of the instrumented assembly components is included in Appendix A.

1.2 MOVABLE IN-CORE NEUTRON MONITORING SYSTEM

The movable in-core neutron monitoring system was an additional system to the standard in-core flux monitors, to provide measurements of the axial neutron flux profile. Special movable in-core neutron monitors could be axially moved at a constant rate of speed in and out of the core at three in-core positions.

These positions were in the water gap between four fuel elements, of which one was an instrumented fuel assembly (Figures 1-1, and 3-1). The system was connected to two-pen recorders mounted on the instrumented assembly readout panel (Figure 1-2) which provided a plot of the movable in-core monitor reading versus the monitor axial position.

From the measurements, a relative axial profile could be derived which was comparable to the axial relative power distribution calculated for the individual fuel elements near the movable in-core monitor position. Flux wires would have allowed comparison of the two sets of measurements and perform a calibration of the in-cores but they could not be installed due to space limitation.

A more detailed description of the movable in-core monitors is given in Appendix B.

FIGURE 1-1, INSTRUMENTED FUEL SYSTEM

FIGURE 1-2. INSTRUMENTED ASSEMBLY READOUT PANEL

SECTION II

SYSTEM CALIBRATION PROCEDURE AND DATA2.1 INSTRUMENTED ASSEMBLIES⁽⁵⁾

The four pairs of turbine flowmeters were tested to determine their flow coefficients. The turbine flowmeters were tested with cold water at ambient pressure, with hot water at 1000 psia and with water-steam mixture as indicated in Table 2-1. The tests

were performed at APED in the high-pressure heat transfer facility which was modified to house an instrumented fuel bundle, and provided with an electrical heater of 1.3 MWe. In addition to calibration of the turbine flowmeters, their single-phase flow pressure loss characteristics were measured.

TABLE 2-1

WATER-STEAM MIXTURE DURING TWO-PHASE FLOW TESTS

(Pressure = 1015, Subcooling = 15 Btu/lb, Inlet water = $T_W = 532^\circ\text{F}$)

Flow (lbs/sec)	Power (kW)	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300
	Steam Quality (%)													
4		1.3	5.0	8.7	12.3	16.0	19.7	23.3	27.2	30.9	34.0	—	—	—
8		—	1.3	3.2	5.0	6.8	8.7	10.0	12.3	13.4	16.0	17.9	19.7	21.5
12		—	0.2	1.3	2.5	3.8	4.9	6.3	7.4	8.5	9.8	11.0	12.3	13.7
16		—	—	0.5	1.3	2.2	3.1	4.1	5.0	5.9	6.7	7.9	8.7	9.7
18		—	—	0.2	0.9	1.7	2.5	3.2	4.2	5.0	5.8	6.6	7.4	8.2
20		—	—	—	0.7	1.3	2.0	2.8	3.5	4.3	4.9	5.8	6.5	7.2

The test loop with the instrumented fuel bundle is shown in Figure 2-1. The reactor vessel penetration plugs of the cables and associated seals were tested using a flange with the same thickness and with the same hole dimensions of the reactor vessel special penetration flange. Vessel extension pieces were designed to house the in-vessel cables for pickup coils and thermocouples. The fuel bundle was supported in the vessel by a lower support plate with the same internal dimensions and pin as the reactor lower grid plate. The support plate provided the sealing to the orifice cup and directed the flow through the instrumented fuel bundle. The manometer and pressure tap arrangement is also shown in Figure 2-1.

No flow calibration and pressure drop tests of the individual outlet and inlet

flowmeters were made. As the fuel bundle was of standard design, the pressure drop coefficients to be assigned to the inlet and outlet flowmeters were derived from the pressure drop of the entire instrumented fuel bundle, deducting the pressure drop due to the fuel element and subdividing the difference between the inlet and outlet flowmeter on the basis of flow area at the turbine.

The following tests were performed for each of the four instrumented fuel assemblies:

I. Low Temperature Water Calibration Tests

Flow calibration of inlet and outlet turbine flowmeters and pressure drop across complete assembly.

FIGURE 2-1a. HIGH-PRESSURE HEAT TRANSFER FACILITY

FIGURE 2-1b. HIGH-PRESSURE HEAT TRANSFER FACILITY

II. Hot Single-Phase Flow Tests

Flow calibration of inlet and outlet turbine flowmeters and pressure drop across complete assembly.

turbine flowmeters stopped, for cold, hot, and two-phase flow (one assembly only).

The total running times of each fuel bundle to the end of the loop testing are shown in Table 2-2.

III. Two-Phase Flow Tests

Flow calibration of upper flowmeter and pressure drop across complete assembly. (Flow rate and quality were limited by maximum permitted rotational speed of lower flowmeter which operates in two-phase flow, and by the electrical heater power—1.3 MW).

2.1.1 Flowmeters

The experimental evidence obtained during the calibration tests indicated that the turbine flowmeters of the type tested responded to volume flow rate, independent of fluid density. For this reason, the calibration data for both hot and cold water were plotted as output signal versus volumetric flow rate (Figure 2-2). The flow rate to turbine flowmeter output equation is:

$$W = CP,$$

IV. Stopped Turbine Flowmeter Test

Pressure drop across the complete instrumented fuel assembly with both

TABLE 2-2
RUNNING TIME FOR EACH INSTRUMENTED FUEL ASSEMBLY

Fuel Assembly	U.F. No.	L.F. No.	Cold Flow (hours)	Hot Single Phase (hours)	Hot Two Phase (hours)	Total (hours)
A	1	1	7	6	9	22
B	2	2	3	5	7	15
C	3	3	3	6	8	17
D	4	4	4	5	4	13
A	1s*	1s*	4	5	6	<u>15</u>
						82

*Denotes Turbine Flowmeter No. 1, with stopped rotor.

where

W = flow, ft^3/sec ,

P = meter output, pulses/sec, and

C = turbine flowmeter flow coefficient.

The flow coefficients, C , for the eight turbine flowmeters are:

Upper Flowmeter No. 1 $C_u = 0.00811 \text{ cfs/cps}$

Upper Flowmeter No. 2 $C_u = 0.00811 \text{ cfs/cps}$

Upper Flowmeter No. 3 $C_u = 0.00811 \text{ cfs/cps}$

Upper Flowmeter No. 4 $C_u = 0.00822 \text{ cfs/cps}$

Lower Flowmeter No. 1 $C_L = 0.00395 \text{ cfs/cps}$

Lower Flowmeter No. 2 $C_L = 0.00395 \text{ cfs/cps}$

Lower Flowmeter No. 3 $C_L = 0.00395 \text{ cfs/cps}$

Lower Flowmeter No. 4 $C_L = 0.00395 \text{ cfs/cps}$

FIGURE 2-2. SINGLE-PHASE FLOW CALIBRATION DATA, INLET AND OUTLET TURBINE FLOWMETERS NO. 4

Samples of the flowmeter single-phase flow calibration data are shown in Figure 2-2. Figure 2-3 compares the obtained two-phase data with the predicted values, based on single-phase calibration tests; that is, the actual steam flow rate through the upper flowmeter is plotted versus the difference $P_x - P_o$, where:

P_x = measured turbine flowmeter output signal in two-phase flow, and

P_o = turbine flowmeter output signal when it is measuring the same mass flow rate, but in single phase.

Although the scatter is large, the agreement in both cases is good. Polomik and Swan⁽³⁾ obtained considerably more two-phase data and at pressures of 800 to 1500 psia. Their two-phase data was replotted with meter output signal versus volumetric flow rate, and all fall along a single line. This volumetric flow relationship is important in order to predict steam quality from the meter output.

2.1.2 Pressure Drop for Entire Fuel Assembly and Turbines

$$\Delta P = \left(\frac{K}{A^2} \right) \frac{W^2}{2g\rho}$$

where

ΔP = pressure drop, psi,

W = flow, lb/sec,

ρ = water density, lb/ft³,

g = 32.2, and

$$\left(\frac{K}{A^2} \right) = \begin{cases} 6.18 & \text{for both turbines operating,} \\ 8.33 & \text{for both turbines stopped.} \end{cases}$$

The loss coefficients ($K/2gA^2$) for normal fuel bundles, instrumented fuel assembly with rotating turbine, and instrumented fuel assembly with stopped turbines are shown in Table 2-3.

TABLE 2-3
PRESSURE LOSS COEFFICIENTS

	Normal Fuel Assembly	Instrumented Fuel Assembly— Rotating Turbine	Instrumented Fuel Assembly— Stopped Turbine
Inlet Loss	0.00395	0.00395	0.00395
First Spacer Loss	0.01343	0.01343	0.01343
Second Spacer Loss	0.01343	0.01343	0.01343
Third Spacer Loss	0.01343	0.01343	0.01343
Outlet Loss	0.00395	0.00395	0.00395
Friction Loss	0.00365	0.00365	0.00365
Total Fuel Loss	0.0518	0.0518	0.0518
Nosepiece/Lower Turbine	0.1225	0.0343	0.0599
Upper Turbine	0	0.0099	0.0173
Over-all Total Loss	0.1743	0.0960	0.1290

FIGURE 2-3. TWO-PHASE FLOW READING, OUTLET TURBINE FLOWMETER NO. 2

Figure 2-4 presents the single-phase flow pressure loss data for the instrumented assembly with rotating and stopped turbines.

The pressure loss coefficient of the inlet and outlet turbine flowmeters, both rotating and stopped, were calculated using the information of Sorlie.⁽⁶⁾ Since the orifices in the nosepiece of the instrumented assemblies were removed, the loss coefficient of the nosepiece was assumed to be the same as for the tie plate. The technique used to calculate the loss coefficients was to subtract known calculated losses from the total measured loss, and attribute the remainder to the inlet and outlet flowmeters. The loss coefficient of the upper and lower flowmeters was then divided on the basis of flow area at the turbine.

2.2 THERMOCOUPLES

The thermocouples were furnished with vendor calibrations made at 212, 550, and

800°F. The "standard" accuracy of 3/4 of 1 percent (approximately 4°F) was requested, but the vendor-reported deviations from the NBS chromel-alumel curve did not exceed 1.1°F (Table 2-4). Upon receipt, the thermocouples were checked at APED's calibration facility, and differences less than 2°F from thermocouple 13 were measured. After installation in the reactor, with the reactor at temperature and pressure, the thermocouples were compared with one another, using the same readout instrument. At this time, it was observed that five of the thermocouples had shifted their calibrations from 3 to 7°F, indicating damage or wet insulation. The remaining 11 thermocouples checked within 1.4°F of the original vendor data. From these three independent checks and in view of the in-place uncertainties of the high radiation fields and thermal gradient through which the lead-in wires go, it was concluded that reactor temperatures could be measured to within only $\pm 3^\circ\text{F}$.

TABLE 2-4
THERMOCOUPLE CALIBRATION AND ESTIMATED DEVIATION FROM
TRUE TEMPERATURE (°F)

Thermocouple Designation	Vendor Data at 550°F	APED Tests* at 550°F	Reactor (7 May '66) at 545°F
A11	+ 0.4	—	- 0.2
A12	- 0.6	—	- 2.0
A13	- 0.1	—	- 0.1
A14	- 0.6	—	- 0.2
B11	- 0.8	+ 0.5	- 1.5
B12	- 0.5	+ 1.0	- 7.2 (failed)
B13	+ 0.6	0	+ 0.2
B14	+ 0.2	+ 0.2	+ 4.6 (failed)
C11	- 0.2	+ 0.9	- 5.0 (failed)
C12	- 0.6	+ 1.3	- 4.0 (failed)
C13	- 0.9	0	- 3.9 (failed)
C14	- 1.1	+ 1.7	- 1.5
D11	0.0	- 0.8	0.0
D12	+ 0.3	- 0.2	- 0.1
D13	+ 0.4	0	+ 0.1
D14	- 0.4	- 1.2	+ 0.6

*Measured relative to TC No. 13 only

FIGURE 2-4. INSTRUMENTED FUEL ASSEMBLY TOTAL PRESSURE LOSS (SINGLE-PHASE FLOW)

2.3 PICKUP COIL SENSITIVITY

To check the output signal from the pick-up coil for various excitation currents, a test

was run, spinning one of the flowmeter rotors under a water faucet while monitoring the output signal on an oscilloscope. The results are shown in Figure 2-5.

FIGURE 2-5. FLOWMETER PICKUP COIL SIGNAL VERSUS EXCITATION CURRENT

Note that above 10 ma, the coil starts to saturate and the output reduces. From the test it was concluded that the proper excitation current was 10 ma.

Since a thermal expansion clearance of about 3/8 inch was allowed in the length of the instrument probe (to allow for the fact that the

probe was Type-304 stainless steel while the fuel channel was Zircaloy-4), it was necessary to know the effect of having the pickup coil partially withdrawn from the socket on the flowmeter, since it would be in this condition during cold startup. The results of this test are shown in Figure 2-6.

FIGURE 2-6. FLOWMETER PICKUP COIL SIGNAL VERSUS DISTANCE WITHDRAWN

2.4 MOVABLE ION CHAMBER SENSITIVITY

As an estimate of the initial calibration factors for the flux amplifiers, the published sensitivity of 2×10^{-18} A/nv was assumed for the movable ion chamber and the amplifiers

were adjusted for 100 μ A full scale. After startup, it was found necessary to change the calibrations to 500 μ A for full scale. Estimates of the thermal flux were obtained from the plant physicist, and the following sensitivities were calculated:

Movable Chamber Designation	Axial Peak Current (μ A)	(5/10/66) Estimated Thermal (75% Power)	Estimated Sensitivity (amps/nv)
RE106 (No. 5477689)	119	5×10^{13}	2.38×10^{-18}
RE109 (No. 5477691, later replaced by No. 5477692)	282	3×10^{13}	9.40×10^{-18}
RE112 (No. 5477690)	200	6×10^{13}	3.34×10^{-18}

GEAP-5623

The chamber in RE109 (No. 5477691) had a high leakage current (220 μ A at 100 vdc) so this chamber was replaced by No. 5477692 on May 19, 1966.

On November 24, 1966 (after about 6 months of operation), the readings obtained were as follows:

<u>Movable Chamber Designation</u>	<u>Axial Peak Current (μA)</u>	<u>Estimated Thermal Flux (nv)</u>	<u>Estimated Chamber Sensitivity (A/nv)</u>	<u>Percent of Original Estimate</u>
RE106 (No. 5477689)	106	7×10^{13}	1.5×10^{-18}	63
RE109 (No. 5477692)	125	5×10^{13}	2.5×10^{-18}	—
RE112 (No. 5477690)	180	8×10^{13}	2.25×10^{-18}	67

This data shows that the chamber sensitivities had reduced to about 2/3 of their original (new) values.

SECTION III

INSTRUMENTED ASSEMBLY INSTALLATION AND PERFORMANCE IN REACTOR

3.1 INSTRUMENTED ASSEMBLY INSTALLATION IN REACTOR

The four instrumented fuel assemblies were installed in the reactor in the following positions (Figures 3-1 and 3-2):

<u>Assembly</u>	<u>Fuel Coordinates</u>	<u>Corresponding In-Core Chamber Locations</u>
A	71-08	109
B	59-08	106
C	61-12	112
D	55-16	115

The "B" assembly position was changed from 107 and 63-08 as originally planned, since a chamber in string 106 had failed during the previous fuel cycle.

The "B" and "C" assemblies were removed for about 3 months (January to April, 1966) along with 15 other fuel assemblies, to permit repair work on the cleanup line and the poison sparger at the reactor bottom.

Only three of the four in-core flux detector assemblies were installed in in-core positions RE-106, RE-109, and RE-112. Dimensional problems were encountered in installation of the in-core flux detector assemblies because of a restriction at the weld in the permanently installed thimble in the reactor vessel. This weld was 12 feet above the bottom flange where the assemblies were to be inserted.

To permit easy insertion and withdrawal of the in-core flux assemblies, the thimble transition welds were reamed except for position 115 which was too undersized (13.7 mm instead of 15.8 mm). In this position, a movable chamber was not installed, and a

standard flux detector assembly with a wire guide tube was installed. The flux wire guide tube of the three assemblies for positions 109, 106, and 112 had to be eliminated to reduce the diameter of the assemblies from 14.8 mm to 14 mm. The movable chamber data was used in place of the flux wire irradiations to calibrate the fixed in-core chambers in these three positions.

Figure 3-3 shows the general installation of the instrumented assemblies, the movable chamber drive units, and their connections to the instrumentation.

The procedure for installation of the instrumented assemblies was as follows:

- a. Install orifice cup with attached lower flowmeter by normal procedure, using the normal orifice handling tool.
- b. Use normal procedure and fuel handling grapple to place fuel bundle in the core.
- c. Remove the fuel handling grapple and rotate the handle to one side.
- d. Insert instrument probe. This step requires care to avoid damage to the pickup coil at the lower end of the instrument tube. Hold the instrument probe assembly in the fuel handling grapple and lower it slowly and carefully, while guiding it by hand as required. Insert instrument tube through fuel bundle. Fasten the bolt to hold down the instrument probe in the channel.
- e. Install baffle (turning vane) with the instrumented assembly cables passing through center hole.
- f. Install clamps that hold cables to the turning vane.

ION CHAMBER ELEVATIONS

TOP
D 80 %
C 60 %
B 40 %
A 20 %
0%
BOTTOM

- FIXED ION CHAMBERS
- MOVABLE ION CHAMBER
- ⊗ CONTROL ROD OSCILLATOR
- ⊗ CONTROL BLADE ("ROD")

NOTE: I, J COORDINATES ARE USED FOR COMPUTER

STAINLESS STEEL
FUEL CHANNEL
(OTHERS ARE ZIRCALOY)

INSTRUMENTED
FUEL BUNDLE

FIGURE 3-1. INSTRUMENT LOCATIONS FOR GARIGLIANO DEVELOPMENT PROGRAM

FIGURE 3-2. GARIGLIANO CORE FOR STABILITY TEST

- g. Install reactor vessel head, with the instrumented assembly cables passing through access port.
- h. Insert cables through the special reactor vessel flange, and install flange.
- i. Install penetration unit in flange.
- j. Install cables in existing 3-inch conduit, thus bypassing shield blocks above reactor vessel.
- k. Make connections at junction box above reactor vessel head, near refueling platform.

3.2 INSTRUMENTED ASSEMBLY PERFORMANCE

3.2.1 Turbine Flowmeter Operation

During the reactor tests, five of the eight turbine flowmeters performed satisfactorily. Early failures were encountered on three of the turbine flowmeters shortly after the startup.

From ohmmeter readings, it was determined that all the early failures were confined to water leakage into signal cables of the instrumented assemblies "B" (inlet) and "C" (both) (Table 3-1).

TABLE 3-1
TURBINE FLOWMETERS OPERATING DURING THE REACTOR TESTS
(Derived from the On-Line Computer Output Log)

Turbine Flowmeter	Test Conditions								After 1 year
	1	1A	3	5	6	7	8	9	
LF-A	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
LF-B	No	No	No	No	No	No	No	No	No
LF-C	No	No	No	No	No	No	No	No	No
LF-D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
UF-A	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
UF-B	(Not Connected)			Yes	Yes	Yes	(Not Connected)		Yes
UF-C	No	No	No	No	No	No	No	No	No
UF-D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

Before the installation of the instrumented assemblies in the reactor, it was noticed that some of the turbine rotors offered a certain resistance to spin freely with air flow. However, from readings taken during the initial plant startup on April 24, 1966, it was established that all flowmeters were spinning freely in the reactor. Water did not penetrate the signal cables on "C" assembly until the reactor was at pressure and temperature, so readings were obtained during initial recirculation pump operation. On "B" inlet flowmeter,

the cable became wet during the vessel hydrostatic test. However, at zero reactor power, all four outlet meter readings were 125 cycles (49.9 MT/h) showing that the "B" inlet meter had the pressure drop inherent to a freely spinning rotor.

The fact that water penetrated both pickups of the turbine flowmeters and two thermocouples of "C" assembly leads to the conclusion that the unit was possibly defective or damaged before startup on April 24, 1966.

GENERAL ELECTRIC

846D582

TITLE INSTALLATION DIAG
INSTRUMENTED FUEL SYSTEM
FIRST MADE FOR SENN DEVELOPMENT PROGRAM

FOR REF PT NOS. SEE 194X486

NOTES:

1. ARRANGEMENT AS SHOWN IS FOR INSTALLATION OF ONE (PT 6) INSTRUMENTED FUEL ASM. COMPLETE INSTALLATION WILL USE 4 ASMS. (PT 6, 28, 29, 30 REF)
2. USE THESE JUNCTION BOXES FOR ACCESS IN PULLING CABLE (PT 17 & 18), WITHOUT CUTTING, THRU CONDUIT FROM JUNCTION BOX (PT 19) AT EL 29.90 TO GE JUNCTION BOX (PT 10) THERMOCOUPLE REFERENCE JUNCTION (PT 21) AT EL 18.00.
3. TIGHTEN CABLE CLAMP FASTENING NUTS TO 300 IN-LBS OF TORQUE (4 PLACES).
4. BOLT PROBE INTO CHANNEL & TIGHTEN TO 75 IN-LBS OF TORQUE.
5. AT INSTALLATION, MAGNETIC POLES (LINE M-M) OF PT 8 MUST BE IN LINE WITH HANDLE OF PT 7.
6. INSTALL SEAL (237E608P17) ON PT 1 OR 6 BEFORE INSERTING INTO PT 3. SEALING SURFACES OF PT 3 & 1 OR 6 MUST BE CLEAN AND FREE OF NICKS & SCRATCHES.
7. INSTALL BELLEVILLE SPRING (237E608P29) CUPPED DOWNWARD & TIGHTEN NUT (237E608P28) TO COMPRESS SPRING FLAT (APPROX 30 FT-LBS TORQUE).

REFERENCE DRAWINGS

DWG	NAME	DWG NO.
A	SCHEMATIC DIAG OF CABLE RUNS	EBASCO G174423
B	TABULATION FOR CABLE RUNS	EBASCO B174424
C	ELEM DIAG	237E624
D	INSTR MANUAL	GEK-(LATER)
E	CABLE ROUTING AND TABULATION	112C 2286

DESCRIPTION OF GROUPS	REVISIONS	PRINTS TO
	1. 237E-18-65 DWS TITLE WAS INSTALLATION DIAGRAM. GEN CHANGES GCB	
DATE BY 11 MAY 65 11 MAY 65	APED SAN JOSE	846D582

FIGURE 3-3. GENERAL ARRANGEMENT-
INSTRUMENTED FUEL SYSTEM

Loss of signals was noticed 4 to 10 days after reactor startup, with loss of insulation resistance in the case of "C" outlet flowmeter. It is quite likely that "B" and "C" assembly flowmeters were damaged by handling during removal from the reactor for vessel repair and reinstallation.

It is felt that the rotor bearing performance at Garigliano was satisfactory. Previous experience at Big Rock Point confirmed that nitrided Type-304 stainless steel running on Carbone CC14 (carbon-graphite) is a good bearing combination for in-core turbine meters. Further hot laboratory examination on the single components should allow a better understanding of the problem. In regard to the flow rate electronics, an initial radio frequency noise problem was caused by voltage regulators on the 60-cycle M-G set used for the computer.

The problem was overcome by capacitor filtering each signal input to reject frequencies above 1 kHz.

The use of a two-conductor shielded cable resulted in very low line frequency noise pickup of less than 2 mV peak to peak.

Flow pickup signal strength was found to be somewhat affected by accumulated neutron exposure. After the first month, signals had decreased approximately 40 percent, and after this time appeared to be decaying very slowly. At that time the accumulated exposure was about 3×10^{17} nvt (Figure 3-4). After one year of exposure the signal strength had decreased about 60 percent. From pickup coil wave forms taken April 8, 1967, it was determined that only "B" outlet flowmeter was giving good signals. Both coils in "D" assembly appeared to be in good condition, but there was no signal, indicating that possibly both rotors were stuck in that assembly. Further examinations will be made to verify this assumption.

A survey of the turbine flowmeter status during the reactor tests is given in Table 3-1. From Table 3-1 it appears that only assemblies "A" and "D" had both inlet and outlet turbine flowmeters operating during most of the test period and generated good data. From these data, the channel flow rate, exit steam quality, and power values could be derived at all the experienced test conditions. In Table 3-2 the inlet and outlet thermocouple status during the test period is also given.

3.2.2 Movable Ion Chamber Operation

The movable chamber system operated throughout the R&D tests, with each of the three units completing about 100 traverses. The chart record shown in Figure 3-5 is typical of the traces obtained using the system. For recording the chamber position and output, a two-pen recorder was used, with position on one pen and ion chamber output on the other. As can be seen from the traces, irregularities in the core structure are easily recognized. The large perturbation in the center of the core is a support fixture on the outside of the in-core guide tube, consisting of two stainless steel rings, 4-1/2 inches apart, with axially-bowed spring rods between the rings. Other irregularities, such as fixed in-core ion chambers and fuel rod end connectors, are easily recognized, and were used to check the accuracy of the position indication.

Figures 3-6 and 3-7 are of interest because they were made during R&D Test 3 conditions, before and during control rod oscillation at 0.6 cps, respectively. In-core location RE112 is adjacent to the oscillating rod, F-6.

The instruments performed very well after correction of some initial difficulties. A summary of the difficulties encountered and their solutions is given in the following paragraphs.

FIGURE 3-4. FLOWMETER PICKUP COIL SIGNAL VERSUS TIME IN THE REACTOR

TABLE 3-2
INSTRUMENTED ASSEMBLIES INLET AND OUTLET
THERMOCOUPLES STATUS DURING THE REACTOR TESTS

THERMOCOUPLE DESIGNATION		WORKING						
		TEST CONDITIONS						
		1A	3	5	6	7	8	9
A	11	Yes						
A	12	Yes						
A	13	Yes						
A	14	Yes						
B	11	Yes						
B	12		FAILED					
B	13	Yes						
B	14		FAILED					
C	11	Yes						
C	12		FAILED					
C	13		FAILED					
C	14	Yes						
D	11	Yes						
D	12	Yes						
D	13	Yes						
D	14	Yes						

The cable worked out from between the two wheels on drive RE-109, due to a misalignment between the drive wheel and idle wheel. The problem was brought about by the bearing clearance in the idle wheel, coupled with the flat edge on the idle wheel. All three units were realigned, and the idle wheels were grooved to capture the cables positively. The problem was effectively eliminated.

Excessive slippage of the drive wheel was encountered due to increased friction caused by slight kinks in the cable. This problem was solved by straightening the cable as much as possible by hand, and increasing the spring tension to increase the friction drive force.

The required drive force on the cable was initially about 5 to 10 lb, but peaks as high as 15 to 20 lb were observed, depending on position. Spring tension was increased to about 50 lb. By

straightening the cable as much as possible and operating the drives through 20 to 30 traverses, the required drive force was reduced by about one-half.

The cable connection on chamber RE-112 was faulty, and fell off during a traverse. The cable was reinstalled, using a new connector. All three cables and their connectors were then secured with shrinkable plastic tubing, and lashed to 1/4-inch stainless steel tubing for additional support and to prevent further difficulty.

Movable chamber RE-109 developed low insulation resistance from the center conductor to ground of about 800 k ohms. It is possible that the chamber or cable was damaged when the cable worked out of the drive (as described above). The chamber was replaced with the spare (fourth unit which was not installed).

GENERAL ELECTRIC

CHART NO. 12851-N

FIGURE 3-5. TRACE FROM MOYABLE IN-CORE DETECTOR RE-109, MAY 27, 1966,
GARIGLIANO REACTOR

FIGURE 3-6. TRACE FROM MOVABLE IN-CORE DETECTOR RE-112, MAY 26, 1966,
1113, GARIGLIANO REACTOR. TEST 3 BEFORE ROD OSCILLATOR TEST

FIGURE 3-7. TRACE FROM MOVABLE IN-CORE DETECTOR RE-112, MAY 26, 1966, 1145, GARIGLIANO REACTOR. TEST 3 DURING CONTROL ROD OSCILLATION AT 9.6 cps

SECTION IV

REACTOR TEST CONDITIONS AND MEASURED DATA

The Research and Development Program Tests included reactor stability, flow transient tests, and measurement of steady-state thermal-hydraulic performance of the reactor.

The reactor was operated at seven different test conditions (1A, 3, 5, 6, 7, 8, and 9) with decreased flow and increased void content in order to obtain operating conditions simulating high power density without exceeding the maximum reactor power rating (Table 4-1).

TABLE 4-1

REACTOR TEST CONDITIONS

Date	Test No.	Reactor Power [MW(t)]	Reactor* Pressure (kg/cm ²)	Recirculation Flow (MT/h)	Core Inlet Temperature (°C)	Core Inlet Subcooling (kcal/kg)	Average Exit Steam Quality (%)
May 23, 1966	1A	497.6	69.57	9720	187.6	19.3	8.7
May 26, 1966	3	386.8	69.48	4575	178	31.3	13
May 30, 1966	5	477.1	69.59	4625	187.3	33.3	18
May 31, 1966	6	379.4	69.63	4810	175.1	18.2	15
May 31, 1966	7	260.5	69.40	2775	159.5	22.2	18
June 1, 1966	8	331.7	69.06	2875	169.3	25.5	22
June 1, 1966	9	330.8	68.85	2835	169.8	31.1	21

*On-line computer data corrected according to Reference 7.

No reactor operational limitations were exceeded by the instrumented fuel assemblies.

The maximum core exit average steam quality was 22 percent (Test 8) and the maximum channel exit steam quality was 30 percent (Test 9). The maximum value of the core average void fraction was 48 percent (that is, about three times as much as the steady-state value = 16.5 percent) and the maximum value of the channel exit void fraction was 76 percent (obtained during Test 9) (Table 4-2). These values were calculated with the on-line computer during the reactor testing period.⁽⁷⁾ The channel flow rate values varied from a minimum of 10.2 MT/h, in channel 16-51 during Test 7, to a maximum of 71.36 MT/h in channel 8-71 (instrumented

fuel assembly "A") during test 1A. The average active channel flow rate (Table 4-4) varied from 12.27 MT/h (Test 7) to 40.41 MT/h (Test 1A). Because of different orificing, the flow through the instrument fuel bundles was always higher than in the standard fuel bundles. The maximum channel power of 2.98 MW(t) was reached in channel 16-55 (instrumented fuel assembly "D", during Test 1A) with a radial power factor of 1.306.

During the tests the minimum critical heat flux ratio limits were not exceeded.

The high void test conditions are shown in Figure 4-1; the percentage values of reactor power and recirculation flow for the various test conditions are given in Table 4-3.

TABLE 4-2
EXIT STEAM QUALITY AND VOIDS DURING REACTOR TESTS

Test No.	Maximum Channel Exit Quality (%)	Maximum Exit Void Fraction (%)	Average* Channel Voids (%)	Average Core Exit Quality (%)
1A	12	62	16.5	8.7
3	20	70	24	13
5	25.8	74.6	39	18
6	19.6	70.4	42	15
7	22	72	45	18
8	29	75	48	22
9	30	76	47	21

*Average over all the water contained inside the channels.

TABLE 4-3
REACTOR POWER VERSUS RECIRCULATION FLOW

Test No.	Reactor Power	Recirculation Flow (MT/h)	Percent of Rated Reactor Power ^(a) (%)	Percent of Rated Recirculation Flow ^(b) (%)
1A	497.6	9720	98.3	97.4
3	386.7	4575	76.4	45.8
5	477.1	4625	94.30	46.3
6	379.7	4810	75.0	48.2
7	260.5	2775	51.5	27.8
8	331.7	2875	65.5	28.8
9	330.8	2835	65.3	28.4

(a) Rated Power = 506 MW(t)

(b) Rated Recirculation Flow = 9979 MT/h

TABLE 4-4
LEAKAGE FLOW COEFFICIENTS ASSUMED FOR THE
ON-LINE COMPUTER ACTIVE CHANNEL FLOW CALCULATIONS

Test No.	First Assumption (%)	Subsequent Assumption (%)	Core Active Flow (MT/h)	Average Channel Active Flow (MT/h)
1A	19	13.5	8408	40.41
3	10	10	4117	19.79
5	10	10	4162	20.00
6	10	10	4329	20.80
7	10	8	2553	12.27
8	10	7	2673	12.85
9	10	7	2637	12.67

FIGURE 4-1. GARIGLIANO REACTOR HIGH VOID TEST REGION MAP

During Test 1A, only 98.3 percent of the full power rating was reached because the 20th stage wheel of the turbine was removed and the turbine could not deliver the rated power. The total recirculation flow was 97.4 percent of the design value, because of the presence of crud deposits on the lower tie plate of the fuel elements, and the pressure drop across the core was 0.53 kg/cm^2 compared with 0.37 kg/cm^2 for clean elements.⁽⁷⁾ For the high-void tests, the reactor power had to be reduced due to the presence of safety in vessel instrumentation which would have scrambled the reactor at very high void content; namely, the low reactor level instruments gave a signal when the coolant density deviated too much from the rated conditions.⁽⁸⁾

The core active coolant flow rate was determined with the on-line computer. It is equal to the total recirculation flow less the flow through the core leakage paths (Figure 4-2):

$$WC = WR - WCL,$$

where

WC = core active coolant flow rate,

WR = total recirculation coolant flow,

WCL = leakage flow rate.

Figure 4-2 shows the core bypass leakage flow locations. The bypass leakage flow as a function of the pressure drop across the core support plate had been calculated for the initial core consisting of stainless steel channels and Zircaloy channels, and for the equilibrium core consisting of 208 Zircaloy channels.

During the tests, fixed values of the leakage flow coefficient were assumed for each test condition (Table 4-4) which was equivalent to assuming a fixed percentage of the total recirculation flow rate for the leakage flow rate:

$$WCL = (\text{Leakage Flow Coefficient}) \times WR$$

Considering the leakage flow coefficients assumed for the on-line computer calculations, the values of the average channel flow rate are derived in Table 4-4.

4.1 MEASURED DATA

During the tests, some of the signals from the inlet and outlet flowmeters and from the thermocouples of each instrumented fuel assembly were recorded and sent to the on-line computer, together with other plant instrumentation signals.

The Typewriter output of the on-line computer instrumented assembly log, together with the symbolism and the units adopted, are given in Appendix C, Part 2.

The Typewriter output values are affected by two main error categories:

- a. Errors due to instrumentation, improper setting or calibration. (For example, the assembly "A" thermocouple instrumentation had an improper zero setting and the values shown on the on-line computer were constantly higher than the actual ones.)
- b. Errors due to the use of incorrect input values because of inadequate instrumentation signal used for further calculations. For example, the readings of the damaged turbine flowmeters' pickup coils were equally used as input for the channel flow calculation, generating some meaningless values of the channel flow rate, exit steam quality, and channel power, printed on the on-line computer print-out log.

Therefore, the complete set of measured and recorded data was revised. Only the good values were taken into consideration and

FIGURE 4-2. GARIGLIANO REACTOR CORE BYPASS LEAKAGE LOCATIONS

reduced with the correct values of the reactor conditions (correct value of reactor pressure, correct values of inlet subcooling, etc.). The data analysis results are given in the following paragraphs.

4.1.1 Inlet and Outlet Turbine Flowmeter Output Signals and Derived Data

Some of the correct values of the turbine flowmeter and thermocouple signals, and the derived values of temperatures, flow exit steam quality and power, are shown in Table 4-5. During the tests, Sanborn chart recorders were used to record some of the channel flows and inlet and outlet coolant temperatures.

Figure 4-3 shows the traces of the signals of the inlet and outlet flowmeters of instrumented fuel assembly "D" during Test 5-A, control rod oscillation. It is noted that flow variation as small as 1/10 percent can be detected within a time lag of 0.05 second.

4.1.2 Channel Inlet and Outlet Coolant Temperature

The measured values of the channel inlet and outlet coolant temperature are given in

Table 4-6. Figure 4-4 shows the traces of the signals of the thermocouples at the inlet and outlet of instrumented fuel assembly "D" during the valving out of the feedwater heaters (Test 3).

4.1.3 Channel Flow Instability Detection by Turbine Flowmeter Output Signal Analysis

Channel flow instability could be monitored with the instrumented fuel assemblies using a low-frequency analyzer connected at the flow rate meter output.* Both inlet and outlet turbine flowmeters proved to be very effective means to monitor channel flow instability. More results could have been obtained if all the working flowmeters had been connected to the recorders and more data made available.

From the power spectral density versus frequency obtained from the signal of the inlet and outlet flowmeters it was noted that going from Test 3 to Test 7, a peak was shown at about 0.35 Hz.

*Measurements shown in Figures 4-5 through 4-10 were made using an ISAC computer of the Institute für Mess und Regeltechnik Technische Hochschule, München, by Messrs. Bastl and Schnurer.

TABLE 4-5

TURBINE FLOWMETER AND THERMOCOUPLE READINGS AND MEASURED CHANNEL FLOW RATE, EXIT QUALITY, AND POWER

Test No.	IFA	P _L (cps)	P _U (cps)	T _L (°C)	T _U -T _L (°C)	W _{CH} (MT/h)	X _{EXIT} (%)	Q _{CH} [MW(t)]
1A	A	231.0	175.0	273	13	71.36	2.54	2.25
1A	D	216.0	227.7	270	12	66.72	5.65	2.98
3	A	100.6	114*	264	23	31.60	6.10	1.844
3	D	100.1	149.6	261	24	31.43	9.84	2.33
5	A	101.1	129.2	262	28	31.92	7.46	2.15
5	D	96.2	178.5	259	25	30.39	13.35	2.80
6	A	104.6	117.2	273	16	32.31	6.17	1.52
6	D	98.7	167.5	270	14	30.48	12.16	2.198
7	A	52.2	—	270	18	16.16	—	—
7	D	61.9	103.6	266	18	19.17	11.84	1.464
8	A	65*	100*	267	21	20.39	10.02	1.494
8	D	60*	129.9	263	20	18.83	16.41	1.887
9	A	65.5	—	263	26	20.69	—	—
9	D	60*	120*	259	24	18.96	14.59	1.836

*Data obtained from recorded pickup coil outputs.

FIGURE 4-3. ASSEMBLY D, INLET AND OUTLET TURBINE FLOWMETER SIGNALS DURING CONTROL ROD OSCILLATION (TEST 5A)

RUN 9

0.6 Hz

TEST 3

MAY 26, 1966

FIGURE 4-4. TRACES FROM INLET AND OUTLET THERMOCOUPLES OF INSTRUMENTED ASSEMBLY D DURING VALVING OUT OF FEEDWATER HEATERS

TABLE 4-6

COMPARISON OF THE INLET AND OUTLET THERMOCOUPLE READINGS WITH
THE CCRE INLET AND THE REACTOR SATURATION TEMPERATURE

Test No.	Reactor Pressure (kg/cm ²)	Saturation Temperature (°C)	Core Inlet Subcooling (kcal/kg)	Calculated Inlet Temperature (°C)	Values Measured with the Thermocouples						
					Inlet Temperature (°C)	Difference Outlet-Inlet (°C)	Outlet Temperature (°C)	°C	Percent	°C	Percent
①	②	③	④	③-②	③-②	④-①	④-①				
								②			④
1A	69.57	284.07	19.3	267.22	273.361	13.597	286.96	6.139	2.29	+2.89	+1.02
					269.527	14.140	283.67	2.305	0.86	-0.40	-0.14
					271.345	11.650	282.995	4.123	1.54	-1.08	-0.38
					270.302	12.068	282.37	3.080	1.15	-1.70	-0.60
3	69.48	283.98	31.4	256.44	264.023	23.873	287.896	7.579	2.95	+3.91	+1.38
					260.939	23.720	284.66	4.495	1.75	+0.72	+0.25
					260.847	—	—	4.403	1.72	—	—
					261.417	24.025	285.44	4.973	1.94	+1.46	+0.51
5	69.59	284.09	33.3	254.44	262.357	28.531	290.89	7.913	3.11	+6.80	+2.39
					258.687	25.750	284.44	4.243	1.67	+0.35	+0.12
					258.816	—	—	4.372	1.72	—	—
					259.568	25.958	285.526	5.124	2.01	+1.43	+0.50
6	69.63	284.12	18.2	267.77	273.529	16.183	289.712	5.752	2.15	+5.69	+1.96
					269.527	14.292	283.82	1.750	0.65	-0.40	-0.14
					269.634	—	—	1.857	0.69	—	—
					270.748	14.640	285.39	2.971	1.11	+1.27	+0.44
7	69.40	283.91	22.2	264.44	270.861	18.923	289.78	6.417	2.43	+5.88	+2.07
					265.357	18.617	284.15	0.913	0.35	+0.25	+0.08
					266.296	—	—	1.852	0.70	—	—
					266.492	18.742	285.23	2.048	0.77	+1.33	+0.47
8	69.06	283.58	25.5	261.11	267.609	21.996	289.605	6.498	2.49	+6.02	+2.12
					261.939	21.273	283.21	0.828	0.32	-0.37	-0.13
					263.294	—	—	2.183	0.84	—	—
					263.724	20.730	284.45	2.613	1.00	+0.87	+0.30
9	68.85	283.38	31.1	255.55	263.773	26.333	290.106	8.218	3.21	+6.72	+2.37
					258.437	24.720	283.157	2.882	1.13	-0.12	+0.04
					259.777	—	—	4.222	1.65	—	—
					259.748	24.582	284.33	4.193	1.64	+0.95	+0.35

Outlet Thermocouple IFA-A rms = 1.96 percent
 IFA-B rms = 0.145 percent
 IFA-D rms = 0.455 percent
 IFA-C rms = — percent

With Test 3 conditions, the inlet flowmeter of assembly "D" showed a broad peak at 0.35 Hz, while the outlet flowmeter of the same assembly did not show any peak (Figures 4-5 through 4-10).

A definite peak at 0.33 Hz appears in the signals of both inlet and outlet flowmeters "D" with Tests 5 and 7 conditions.

Prior to Test 9, a local instability was observed in the Garigliano core, which manifested itself as a limit-cycle operation. The following paragraphs⁽⁸⁾ describe the conditions under which the limit cycle occurred and the manner in which it was terminated.

At the end of Test 8, control rods were inserted to reduce reactor power. During this maneuver, control rod D-4 (Figure 3-1) stuck between positions 20 and 19 and could not be moved farther. The symmetrical rods, D-8 and H-4, were subsequently inserted to position 5 and position 10. This left rod D-4 withdrawn farther than its symmetrical rods, and thus generated a local power peak in its vicinity. The secondary steam generator was slowly brought on-line, and reactor power was allowed to increase to the desired operating condition for Test 9 at 67 percent rated power.

Just as the power reached the desired value, a steady limit-cycle oscillation was observed for all four stationary ion chambers in station 106 (next to rod D-4; see Figures 3-1 and 3-2). The test instrumentation was connected to several in-core chambers, including 106C. A Sanborn recorder trace was immediately taken, which showed that chamber 106C had a regular sinusoidal oscillation of ± 8 to 10 percent at 0.33 cps (Figure 4-11). Adjacent control rod E-5 was inserted from notch 30 to notch 25 to reduce the local power peaking. The limit cycle flux oscillation stopped immediately. The oscillation had lasted about 3 to 5 minutes.

Test 9 was conducted at exactly these conditions. Rod oscillation at the whole range of frequencies, including 0.3 and 0.35 cps, showed no unusual behavior.

Analysis of this operation was conducted, using the FABLE code.⁽⁹⁾ The conditions before and after the flux oscillation were simulated for instrumented fuel assembly "B" before and after the insertion of control rod E-5. Nyquist plots of the hydrodynamic transfer function for these two conditions have shown that the channel was hydrodynamically unstable before, but stable after the insertion of control rod E-5. It was also found that the reactivity feedback of instrumented fuel assembly "B" was sufficiently strong to drive other channels into low amplitude oscillations. Recorder traces in Figure 4-11 show the level of the oscillations in the vicinity of these other channels.

Figure 4-11a shows the traces from the movable in-core flux monitor 106 during the limit cycle oscillation. In the first trace the periodical oscillation and the effect of the insertion of control rod E-5 are evidenced.

4.1.4 Movable Ion Chambers

Samples of typical traces obtained from the movable in-core flux monitors have already been shown in Figure 3-5. The normalized traces obtained during Tests 1A through 8 are given in Figures 4-23 through 4-28 (shown later in this section). For Test 9, no measurements could be made with the movable in-core flux monitors.

There was mention made in subsection 3.2.2 of the ability of the movable in-core flux monitors to recognize irregularities in the core structure, like the small support fixture outside the in-core guide tube. In Figure 4-12, it is shown how the movable in-core flux detector 106 responded to rapid neutron flux variation during Test 1A, Pump B trip. The perturbation at the top of the trace shows

FIGURE 4-5. CHANNEL FLOW POWER SPECTRAL DENSITY, TEST 1A, INLET FLOWMETER D

FIGURE 4-6. CHANNEL FLOW POWER SPECTRAL DENSITY, TEST 3, INLET FLOWMETER D

FIGURE 4-7. CHANNEL FLOW POWER SPECTRAL DENSITY, TEST 3, OUTLET FLOWMETER D

FIGURE 4-8. CHANNEL FLOW POWER SPECTRAL DENSITY, TEST 5A, INLET FLOWMETER D

FIGURE 4-9. CHANNEL FLOW POWER SPECTRAL DENSITY, TEST 5A, INLET FLOWMETER D

FIGURE 4-10. CHANNEL FLOW POWER SPECTRAL DENSITY, TEST 7, OUTLET FLOWMETER D

FIGURE 4-11. LIMIT CYCLE, GARIGLIANO TEST 9

the variation of the neutron flux detected by the movable in-core while it was being transferred from the top to the bottom of the core. Also shown in Figure 4-12 are the traces taken by the same movable in-core 106 just before and just after the pump B trip.

4.2 INTERPRETATION OF MEASURED DATA

As already mentioned, not all the recorded signals from the instrumented fuel assemblies' thermocouples and flowmeters were good, and a selection of them was necessary before the data reduction to generate channel inlet and outlet coolant temperatures, flow rate, exit steam quality, and power to be compared with the values calculated from the on-line computer and using the APED thermal-hydraulic code. The measured data reduction is shown in the following subsections.

4.2.1 Channel Inlet and Outlet Coolant Temperature

The selected readings of the inlet and outlet thermocouples of each instrumented

fuel assembly were compared with each other and with the core inlet and reactor saturation temperature derived from the core subcooling and reactor pressure at the eight experienced test conditions. The results of the comparison are shown in Figures 4-13 and 4-14 for the core inlet temperature, and in Figures 4-15a and 4-15b for the reactor saturation temperature. In Table 4-6, the inlet and outlet thermocouple readings and the calculated core inlet and saturation temperatures are given for each test condition.

Table 4-7 lists the values of the channel inlet subcooling, derived from the IFA-B inlet thermocouple readings at each of the experienced test conditions. The method of determining the core inlet subcooling from inlet thermocouple and reactor pressure is not as accurate as that of deriving it from flow measurements and heat balance. However, in the case where accurate measurements of recirculation flow are lacking, it may be preferred to consider inlet subcooling values derived from inlet thermocouple measurements.

TABLE 4-7
CORRECTED VALUES OF CHANNEL INLET SUBCOOLING DERIVED FROM
INLET THERMOCOUPLE READINGS AND REACTOR PRESSURE

Test No.	Reactor Pressure		Core Inlet Temperature*		Core Inlet Enthalpy		Subcooling	
	(kg/cm ²)	(psi)	(°C)	(°F)	(kcal/kg)	(Btu/lb)	(kcal/kg)	(Btu/lb)
1A	69.57	987.4	269.5	517.1	282.3	508.16	17.9	32.3
3	69.48	986.1	260.9	501.6	272	489.6	28.1	50.6
5	69.59	987.7	258.7	497.6	269.4	484.9	30.9	55.6
6	69.63	988.3	269.5	517.1	282.3	508.16	18	32.4
7	69.40	985.0	265.3	509.5	277.2	499.0	22.8	41
8	69.06	980.2	261.9	503.4	273.1	491.7	26.7	48
9	68.85	977.2	258.4	497.1	269	484.3	30.3	54.6

*From readings of inlet thermocouple of Assembly "B".

FIGURE 4-11a. TRACES FROM MOVABLE IN-CORE DETECTOR 106 TAKEN DURING THE TEST 9 - LIMIT-CYCLE OSCILLATION

FIGURE 4-12. MOVABLE IN-CORE FLUX MONITOR 106 TRACES TAKEN BEFORE, DURING, AND AFTER PUMP B TRIP (TEST 1-A)

FIGURE 4-13. COMPARISON OF MEASURED AND CALCULATED CORE INLET TEMPERATURE

FIGURE 4-14: MEASURED AND CALCULATED INLET TEMPERATURE PERCENT DIFFERENCE

FIGURE 4-15a. COMPARISON OF MEASURED AND CALCULATED SATURATION TEMPERATURE

FIGURE 4-15b. RELATIVE DIFFERENCE BETWEEN CALCULATED AND MEASURED REACTOR SATURATION TEMPERATURE

4.2.2 Channel Flow Rate

where

Listed in Table 4-8 are the selected readings in cycles per second of the inlet and outlet turbine flowmeters, together with the inlet thermocouple readings. They were reduced by using the corrected values of the reactor operating parameters (Table 4-1). The channel flow rates indicated in Table 4-8 were generated by using the following equation:

$$W = \frac{C_L \times P_L}{v_{\text{inlet}}}$$

W = mass flow rate (lb/sec),

P_L = lower turbine flowmeter output, counts/sec,

C_L = lower turbine flowmeter flow coefficient⁽⁵⁾

= 0.00395 (ft³/sec)/cps

= 111.9 (cc/sec)/cps, and

v_{inlet} = specific volume of saturated liquid at the channel inlet.

TABLE 4-8

CHANNEL FLOW RATE MEASURED WITH THE INLET TURBINE FLOWMETER

Test No.	LF	P_L (cps)	T_L (°F)	Pressure (lb/in. ²)	v_{inlet} (ft ³ /lb)	W_v (ft ³ /sec)	W_{CH} (lb/sec)	(MT/h)
1A	A	231.0	527	989.5	0.02088	0.9124	43.70	71.36
	D	216.0	518	989.5	0.02088	0.8532	40.86	66.72
3	A	100.6	507	988.2	0.02053	0.3974	19.35	31.60
	D	100.1	502	988.2	0.02053	0.3954	19.25	31.43
5	A	101.1	504	989.8	0.02042	0.3993	19.56	31.92
	D	96.2	500	989.8	0.02042	0.3800	18.61	30.39
6	A	104.6	523	990.3	0.02088	0.4132	19.79	32.31
	D	98.7	518	990.3	0.02088	0.3898	18.67	30.48
7	A	52.2	518	987.1	0.02083	0.2062	9.90	16.16
	D	61.9	511	987.1	0.02083	0.2445	11.74	19.17
8	A	65*	513	982.3	0.02056	0.2567	12.49	20.39
	D	60*	506	982.3	0.02056	0.2370	11.53	18.83
9	A	65.5	506	979.2	0.02041	0.2587	12.67	20.69
	D	60*	498	979.2	0.02041	0.2370	11.61	18.96

*Data obtained from recorded pickup coil outputs.

Figure 4-16 shows the turbine flowmeter flow rate (ft³/sec) plotted versus the inlet turbine flowmeter output signal.

where

v_f = specific volume of saturated liquid,

v_{fg} = difference ($v_g - v_f$) between specific volume of saturated vapor and saturated liquid,

4.2.3 Channel Exit Steam Quality

The channel exit steam quality, from the IFA signals, was calculated with the following equation:

$$X_{\text{exit}} = \frac{P_u C_u v_{\text{inlet}}}{P_L C_L v_{fg}} - \frac{v_f}{v_g}$$

$$\frac{C_u}{C_L} = \frac{0.00811}{0.00395} = 2.05316 \text{ for IFA-A, B, and C, and}$$

$$\frac{C_u}{C_L} = \frac{0.00822}{0.00395} = 2.08101 \text{ for IFA-D.}$$

FIGURE 4-16. VOLUME FLOW RATE VERSUS INLET TURBINE FLOWMETER OUTPUT SIGNAL.

The values of the channel exit steam quality at different test conditions for IFA-A and IFA-D are given in Table 4-9. The channel exit steam

quality versus the ratio of the outlet and inlet turbine flowmeter output signals is shown in Figure 4-17.

TABLE 4-9
CHANNEL EXIT STEAM QUALITY MEASURED WITH
THE INSTRUMENTED FUEL ASSEMBLIES

Test No.	IFA	P_L (cps)	P_u (cps)	P_{reactor} (lb/in ²)	v_{inlet} (ft ³ /lb)	v_f/v_{fg}	$\frac{C_u}{C_L \times v_{fg}}$ (ft ³ /lb) ⁻¹	$\frac{P_u}{P_L}$	X_{exit} (percent)
1A	A	231.0	175.0	989.5	0.02088	0.05022	4.785	0.7576	2.54
	D	216.0	227.7	989.5	0.02088	0.05022	4.849	1.054	5.65
3	A	100.6	114*	988.2	0.02053	0.050162	4.779	1.133	6.10
	D	100.1	149.6	988.2	0.02053	0.050162	4.844	1.494	9.84
5	A	101.1	129.2	989.8	0.02042	0.05022	4.785	1.278	7.46
	D	96.2	178.5	989.8	0.02042	0.05022	4.849	1.855	13.35
6	A	104.6	117.2	990.3	0.02088	0.05022	4.785	1.120	6.17
	D	98.7	167.5	990.3	0.02088	0.05022	4.849	1.697	12.16
7	A	52.2	—	987.1	0.02083	0.05002	4.765	—	—
	D	61.9	103.6	987.1	0.02083	0.05002	4.830	1.674	11.84
8	A	65*	100*	982.3	0.02056	0.04963	4.739	1.538	10.02
	D	60*	129.9	982.3	0.02056	0.04963	4.803	2.165	16.41
9	A	65.5	—	979.2	0.02041	0.04943	4.720	—	—
	D	60*	120*	979.2	0.02041	0.04943	4.785	2.00	14.59

*Data obtained from recorded pickup coil outputs.

The linear response of the outlet turbine flowmeter with steam flow is shown in Figure 4-18. In this case, the difference of the outlet flowmeter two-phase flow signal minus the outlet flowmeter single-phase flow signal has been plotted versus the channel exit steam flow rate. In fact, from the calibration, in single phase flow, is derived:

$$\frac{P_L}{P_u} = \frac{C_u}{C_L} = \begin{cases} 2.05316 & \text{IFA-A} \\ & \text{IFA-B} \\ 2.08101 & \text{IFA-C} \\ & \text{IFA-D} \end{cases}$$

and as the lower turbine flowmeter always operates in single phase flow, the value of the upper flowmeter output due to the single-phase flow component through it is:

$$P_u 1 \phi = \frac{C_L}{C_u} P_L \frac{v_{f \text{ outlet}}}{v_{L \text{ inlet}}} (1 - X_{\text{exit}})$$

(considering the effect of the higher coolant temperature at the channel outlet).

In two-phase flow, the output of the upper flowmeter is

$$P_u 2 \phi - P_u \text{ (measured)}.$$

Therefore, the value of the outlet flowmeter output due to the steam flow is given by the difference, $P_u 2 \phi - P_u 1 \phi$; that is,

$$P_u \text{ steam flow} = P_u 2 \phi - P_u 1 \phi$$

$$= P_u - \frac{C_L}{C_u} P_L \frac{v_{f \text{ outlet}}}{v_{L \text{ inlet}}} \times$$

$$(1 - X_{\text{exit}}).$$

The calculated values are shown in Table 4-10.

FIGURE 4-17. EXIT STEAM QUALITY VERSUS RATIO OF OUTLET AND INLET TURBINE FLOWMETER SIGNALS

FIGURE 4-18. DIFFERENCE OF OUTLET TURBINE FLOWMETER OUTPUT ($P_{u2\phi} - P_{u1\phi}$) VERSUS CHANNEL EXIT STEAM FLOW RATE

TABLE 4-10

CALCULATED VALUES OF $(P_u^{2\phi} - P_u^{1\phi})$ VERSUS CHANNEL EXIT STEAM FLOW RATE

Test No.	IFA	① P_L	② $\frac{C_L P_L}{C_u}$	③ $\frac{v_L}{v_{L, \text{inlet}}}$	④ $(1 - X_{\text{exit}})^2$	⑤ $P_u^{1\phi}$	$P_u^{2\phi} - P_u^{1\phi}$	Exit Steam Flow Rate (a) (ft ³ /sec)
1A	A	231.0	112.5	1.029	97.46	112.8	62.2	0.500
1A	D	216.0	103.8	1.029	94.35	103.8	123.9	1.040
3	A	100.6	49	1.047	93.90	48.2	65.8	0.532
3	D	100.1	48.1	1.047	90.16	45.4	104.2	0.853
5	A	101.1	49.2	1.053	92.54	47.9	81.3	0.657
5	D	96.2	46.2	1.053	86.65	42.15	136.35	1.120
6	A	104.6	50.9	1.029	93.83	49.15	68.05	0.550
6	D	98.7	47.4	1.029	87.84	42.84	124.66	1.022
7	A	52.2	25.4	1.032	—	—	—	—
7	D	61.9	29.7	1.032	88.16	27.02	76.58	0.626
8	A	65*	31.6	1.046	89.98	29.74	70.26	0.570
8	D	60*	28.83	1.046	83.59	25.2	104.7	0.861
9	A	65.5	31.9	1.053	—	—	—	—
9	D	60*	28.83	1.053	85.41	25.93	94.07	0.771

** Data obtained from recorded pickup coil outputs.

- (a) Assuming: $v_g = 0.4507 \text{ ft}^3/\text{lb}$ per Tests 1A through 7 (Reactor pressure $\approx 990 \text{ psi}$)
and $v_g = 0.4557 \text{ ft}^3/\text{lb}$ per Tests 8 and 9 (Reactor pressure $\approx 980 \text{ psi}$)

4.2.4 Channel Active Coolant Power

The channel active coolant power is:

Channel Active Coolant Power

$$\left[X_{\text{exit}} \times h_{fg} + \Delta h_{\text{sub}} \right] W_{\text{CH}}$$

and using the relationships of subsections

4.2.2 and 4.2.3,

Channel Active Coolant Power

$$\left[\left(\frac{P_u C_u v_{L, \text{inlet}}}{P_L C_L v_{fg}} - \frac{v_{fg}}{v_{fg}} \right) h_{fg} + \Delta h_{\text{sub}} \right] \times \frac{C_L P_L}{0.9479 v_{L, \text{inlet}}} \quad [\text{kW}]$$

where:

 h_{fg} = latent heat of vaporization, Btu/lb; Δh_{sub} = channel inlet subcooling, Btu/lb,
and specific volumes in ft³/lb.

Using the inlet and outlet turbine flowmeters

and the inlet thermocouple readings, the

channel active coolant power was calculated

as shown in Table 4-11. The channel inlet

subcooling was derived from the readings of

the inlet thermocouple of the Instrumented

Fuel Assembly "B", as indicated in Table 4-7.

4.2.5 Axial Flux Distribution

The movable in-core neutron flux moni-

tors were used throughout the testing period

to obtain traces typical of the testing condi-

tions, and during the reactor transients.

Samples of these traces have been shown in

Figures 3-6 through 3-8.

The normalized traces at each of the

reactor testing conditions 1A through 9 are

given in Figures 4-23 through 4-28 (shown

later in this section). As discussed in

subsection 4.3.4, the traces from the mov-

able in-core neutron flux detectors could

be used to derive information regarding the

axial flux distribution in the adjacent fuel

elements.

TABLE 4-11

CHANNEL ACTIVE COOLANT POWER DERIVED FROM THE INSTRUMENTED
FUEL ASSEMBLY READINGS

Test No.	IFA No.	P _L (cps)	P _u (cps)	W _{CH} ^(a) (lb/sec)	X _{exit} ^(b) (percent)	h _{fg} (Btu/lb)	Δh _{sub} ^(c) (Btu/lb)	Channel Active Coolant Power [MW(t)]
1A	A	231.0	175.0	43.70	2.54	651.45	32.3	2.25
	D	216.0	227.7	40.86	5.65	651.45	32.3	2.98
3	A	100.6	114*	19.35	6.10	651.8	50.6	1.844
	D	100.1	149.6	19.25	9.84	651.8	50.6	2.33
5	A	101.1	129.2	19.56	7.46	651.4	55.6	2.15
	D	96.2	178.5	18.61	13.35	651.4	55.6	2.80
6	A	104.6	117.2	19.79	6.17	651.3	32.4	1.52
	D	98.7	16	18.67	12.16	651.3	32.4	2.198
7	A	52.2	—	9.90	—	652.0	41	—
	D	61.9	103.6	11.74	11.84	652.0	41	1.464
8	A	65*	100*	12.49	10.02	652.9	48	1.494
	D	60*	129.9	11.53	16.41	652.9	48	1.887
9	A	65.5	—	12.67	—	653.5	54.6	—
	D	60*	120*	11.61	14.59	653.5	54.6	1.836

(a) Values of channel flow rate derived from the turbine flowmeters output (Table 4-8).

(b) Values of channel exit steam quality derived from the turbine flowmeter readings (Table 4-9).

(c) Subcooling at the fuel channel inlet derived from the Instrumented Fuel Assembly "B" inlet thermocouple readings (Table 4-7).

*Data obtained from recorded pickup coil outputs.

4.3 COMPARISON OF MEASURED WITH CALCULATED DATA FROM THE ON-LINE COMPUTER

A comparison was made of the channel flow rate, exit steam quality, and channel power, as measured with the instrumented fuel assemblies and calculated with the on-line computer.

4.3.1 Channel Flow

During the reactor tests, the on-line computer used an iterative procedure to calculate the channel flow distribution. Starting with an assumed flow rate for all channels in the core (208), the calculations were iterated until each individual channel pressure drop agreed satisfactorily with the core pressure drop value.

Because of the presence of crud deposits on the lower tie plates of the fuel elements, the actual channel flow rate was lower than expected in all the fuel elements except for the instrumented fuel elements, which were fresh. Increased hydraulic pressure drop coefficients

(about 2.3 times as much as the design value) were assumed for the fuel elements, except for the instrumented fuel elements which presented no deposits, until the calculated and measured core pressure drop were equal. (7)

In these conditions, the measured and calculated channel flow in the instrumented fuel assemblies were almost the same (Figure 4-19 and Table 4-12) for Tests 1A through 6. The difference between the measured and calculated channel flow values in the instrumented fuel assemblies depended also on the assumed values of the leakage flow coefficient for the different test conditions. (Table 4-4). The larger difference between the measured and calculated values for tests 7 (IFA, D), 8, and 9 may be justified because the on-line computer used correlations which were valid at rated conditions.

Moreover, the high void effect was not properly taken into account; i.e., the outlet turbine flowmeter housing (20 inches long, 5-1/2 inches in diameter) was practically a chimney which extended the fuel channel length,

FIGURE 4-19. COMPARISON OF MEASURED TO CALCULATED CHANNEL FLOW FROM THE ON-LINE COMPUTER

TABLE 4-12

COMPARISON OF MEASURED AND CALCULATED CHANNEL FLOW

Test No.	IFA	Measured Flow (1) (MT/h)	Calculated Flow (2) (MT/h)	Difference (1)-(2) (MT/h)	Difference Percent [(1)-(2)]/1 (Percent)
1A	A	71.36	73.94	-2.58	-3.61
1A	D	66.72	70.58	-3.86	-5.78
3	A	31.60	31.61	+0.01	+0.03
3	D	31.43	31.19	+0.24	+0.76
5	A	31.92	30.83	+1.09	+3.41
5	D	30.39	28.92	+1.47	+4.83
6	A	32.31	31.87	+0.44	+1.36
6	D	30.48	30.51	+0.03	+0.98
7	A	16.16	15.92	+0.24	+1.48
7	D	19.17	16.18	+2.99	+15.59
8	A	20.39	16.90	+3.49	+17.11
8	D	18.83	16.73	+2.10	+11.15
9	A	20.69	16.71	+3.98	+19.23
9	D	18.96	16.63	+2.33	+12.33

rms = ± 9.52 percent

Average = 6.97 percent

and with the reactor in natural circulation, contributed to causing the instrumented fuel assembly flow rate to be larger than the standard fuel element flow rate. In fact, this helps to explain why the computer overestimated the instrumented assembly channel flow when the reactor was in forced circulation (Test 1A), and underestimated it with the reactor in natural circulation and with high voids. This could have partially derived also from the assumption of slightly different leakage flow coefficients than actual for the different test conditions. Also the values assumed for the pressure loss coefficients at the instrumented fuel assembly inlet and outlet may have been slightly incorrect. To check the accuracy of the on-line computer calculation and verify the validity of these hypotheses, a complete set of calculations was performed, using the APED thermal-hydraulic code and giving as input the best available design values and steam property correlations (see subsection 4.4). No check could be made on the accuracy of the calculation of the total recirculation flow.

The Garigliano plant does not have total recirculation flowmeter devices, and the total

recirculation flow was calculated with a loop analysis.

During the natural circulation tests, the digital computer always demonstrated lower channel flow rates and consequently slightly higher steam contents in the channels than the actual ones, because in order to maintain the calculation of the reactor safety margins more conservative, higher hydraulic coefficients of the recirculation loops were adopted in the natural circulation tests; namely, ⁽⁷⁾

$$K_A = 0.06300 \times 10^{-6},$$

$$K_B = 0.06305 \times 10^{-6},$$

instead of the calculated values (at 273.5°C):

$$K_A = 0.05001 \times 10^{-6},$$

$$K_B = 0.04855 \times 10^{-6}.$$

From Table 4-12, it is concluded that for Test 1A through 6, the on-line computer and the inlet turbine flowmeters channel flow rates agree within ± 3.3 percent. For test conditions 7, 8, and 9, a larger difference

(within ± 14.0 percent) between measured and calculated channel flow rate values is noted. The agreement which is found between the measured and calculated flow from the on-line computer for Tests 1A through 9 is within ± 9.5 percent. This difference is believed to be due mainly to the assumptions made for the last three tests in the computer calculations. In fact, the inlet turbine flowmeters were always working with single-phase flow, and sudden shifts in calibration could not be explained for both the inlet turbine flowmeters of Assemblies "A" and "D".

In Table 4-13, the ratio of the measured channel flow rate of the instrumented fuel assembly and the core average channel flow rate is given for the experienced test conditions.

From this, it appears that no definite change of the IFA channel flow ratio occurred during the last tests. The average value of the IFA channel flow ratio is 1.70 with the reactor in forced circulation and rated power, and 1.53 with the reactor in natural circulation and reduced power (Figure 4-20), when the crud deposits on the lower tie plates of the standard fuel elements are considered (see also subsection 4.4.5). Calculations performed with the clean fuel element values indicate that in the absence of crud deposit at the standard fuel element inlet, the ratio of the instrumented fuel assembly flow and the average channel flow rate would have been 1.25 with the reactor in forced circulation, and 1.15 with the reactor in natural circulation (Table 4-14). This is assuming the same radial power factors and core leakage flow of the experienced test conditions.

TABLE 4-13
IFA CHANNEL FLOW RATIO

Test No.	IFA	Measured IFA Channel Flow (MT/h)	Average Channel Active Flow* (MT/h)	IFA Channel Flow Ratio IFA/AVG
		①	②	① / ②
1A	A	71.36	40.41	1.76
1A	D	66.72	40.41	1.65
3	A	31.60	19.79	1.59
	D	31.43	19.79	1.59
5	A	31.92	20.00	1.59
	D	30.39	20.00	1.52
6	A	32.31	20.80	1.55
	D	30.48	20.80	1.47
7	A	16.16	12.27	1.32
	D	19.17	12.27	1.56
8	A	20.39	12.85	1.59
	D	18.83	12.85	1.47
9	A	20.69	12.67	1.63
	D	18.96	12.67	1.50

*Values from Table 4-4.

4.3.2 Channel Power

The channel active coolant power values for the instrumented fuel assemblies IFA-A and IFA-D, as derived from the turbine flowmeter and thermocouple readings and calculated with the on-line computer, are given in

Table 4-15. From the calculated and measured values comparison, it appears that the agreement is satisfactory (Figure 4-21).

The channel power was calculated from the on-line computer radial power factor, assuming the leakage flow power fraction

FIGURE 4-20. INSTRUMENTED FUEL ASSEMBLY CHANNEL FLOW RATIO

TABLE 4-14

IFA CHANNEL FLOW RATIO WITH CLEAN STANDARD FUEL ELEMENTS^(a)

Test No.	IFA	Calculated IFA Channel Flow (MT/h)	Average Channel Active Flow* (MT/h)	IFA Channel Flow Ratio IFA/AVG
		① (b)	②	① / ②
1A	A	52.76	40.41	1.30
1A	D	48.60	40.41	1.20
3	A	23.08	19.79	1.166
	D	23.22	19.79	1.173
5	A	24.72	20.00	1.236
	D	21.90	20.00	1.095
6	A	25.07	20.80	1.20
	D	23.72	20.80	1.14
7	A	14.15	12.27	1.15
	D	14.58	12.27	1.188
8	A	14.75	12.85	1.147
	D	15.12	12.85	1.176
9	A	14.54	12.67	1.147
	D	13.69	12.67	1.080

*Values from Table 4-4.

(a) Lower tie plate of standard fuel elements clean; flow area = 16.76 in.²

(b) For simplicity's sake, it has been assumed that the core leakage and the IFA's radial power factors are the same as for the testing period (Code I calculations).

TABLE 4-15

COMPARISON OF MEASURED AND CALCULATED CHANNEL POWER VALUES

Test No.	IFA No.	Core Average Channel Power [MW(t)]	Calculated Radial Power Factor	Calculated Channel Power* [MW(t)]	IFA Measured Channel Power [MW(t)]	Channel Power Difference [MW(t)]	Relative Channel Power Difference (percent)
				①	②	② - ①	② - ①
							②
1A	A	2.332	1.019	2.377	2.25	-0.12	-5.3
	D	2.332	1.346	3.139	2.98	-0.17	-5.7
3	A	1.813	1.030	1.867	1.844	-0.023	-1.2
	D	1.813	1.342	2.433	2.33	-0.103	-4.4
5	A	2.23	0.929	2.078	2.15	+0.072	3.3
	D	2.23	1.288	2.88	2.80	-0.08	-2.8
6	A	1.778	0.900	1.60	1.52	-0.08	-5.3
	D	1.778	1.235	2.196	2.198	+0.002	+0.4
7	A	1.221	0.906	1.10	—	—	—
	D	1.221	1.157	1.413	1.464	+0.051	3.5
8	A	1.555	0.864	1.344	1.494	+0.15	10.0
	D	1.555	1.180	1.835	1.887	+0.052	2.7
9	A	1.551	0.896	1.389	—	—	—
	D	1.551	1.109	1.72	1.836	+0.116	6.3

rms = ±4.9 percent

Average = 4.2 percent

*Assuming the leakage flow power fraction equals 2.5 percent.

FIGURE 4-21. COMPARISON OF CALCULATED AND MEASURED CHANNEL POWER

equaled 2.5%. The channel inlet subcooling was assumed to be the same for instrumented fuel assemblies IFA-A and IFA-D and equal to the value derived from instrumented fuel assembly "B" inlet thermocouple readings, as given in Table 4-7.

The measured and calculated channel power values compare within 4.9 percent for the test conditions 1A through 9. Table 4-16 shows the comparison of the measured and calculated⁽⁷⁾ radial power factors.

TABLE 4-16
COMPARISON OF MEASURED AND CALCULATED IFA RADIAL POWER FACTOR

Test No.	IFA No.	On-line Computer	Measured with the IFA	Difference	Relative Difference
		①	②	② - ①	② - ① ②
1A	A	1.019	0.965	-0.054	-5.3
	D	1.346	1.278	-0.033	-5.7
3	A	1.030	1.017	-0.013	-1.2
	D	1.342	1.285	-0.057	-4.4
5	A	0.929	0.961	+0.032	+3.3
	D	1.288	1.252	-0.036	-2.8
6	A	0.900	0.855	-0.045	-5.3
	D	1.235	1.236	+0.001	+0.4
7	A	0.906	—	—	—
	D	1.157	1.199	+0.042	3.5
8	A	0.864	0.961	+0.097	10.0
	D	1.180	1.213	+0.043	2.7
9	A	0.896	—	—	—
	D	1.109	1.184	+0.075	6.3

rms = ± 4.9 percent
Average = 4.2 percent

4.3.3 Channel Exit Steam Quality

The on-line computer printout values of the exit steam quality calculated for the individual instrumented channels were not correct. To make a comparison of the measured exit steam quality with the on-line computer data, the channel exit steam quality was calculated again for the instrumented assemblies, starting from the on-line computer calculated channel power and flow rate. The values so obtained were compared with the measured exit steam quality (Table 4-17 and Figure 4-22). The agreement between measured and calculated exit steam quality is within ± 11.1 percent.

Because of the adopted method, large differences between measured and calculated exit steam quality were obtained, especially in those cases when a higher channel power together with a lower value of the channel flow rate were calculated. In fact, as it has already been stated, in the high void testing conditions, the on-line computer underestimated the channel flow rate because the assumed local loss coefficients were conservative values in order to calculate the MCHFR and be in the safest reactor operating conditions.

In subsection 4.4, the values of the exit steam quality calculated with the APED thermo-hydraulic code, assuming the design values,

FIGURE 4-22. COMPARISON OF MEASURED AND CALCULATED EXIT STEAM QUALITY (DERIVED FROM THE ON-LINE COMPUTER CHANNEL POWER AND FLOW VALUES)

TABLE 4-17

COMPARISON OF MEASURED AND CALCULATED CHANNEL EXIT STEAM QUALITY

Test No.	IFA	Values Calculated with the On-Line Computer		Derived Value of the Exit Steam Quality	Measured Exit Steam Quality	Difference	Relative Difference
		[MW(t)]	(MT/h)	(1) (percent)	(2) (percent)	(2) - (1) (percent)	$\frac{(2) - (1)}{(2)}$ (percent)
1A	A	2.377	73.94	2.70	2.54	-0.16	-6.3
1A	D	3.139	70.58	5.61	5.65	+0.04	0.8
3	A	1.867	31.61	6.26	6.10	-0.16	-2.6
3	D	2.43	31.19	10.74	9.84	-0.90	-9.1
5	A	2.078	30.83	7.48	7.46	-0.02	-0.3
5	D	2.88	28.92	15.13	13.35	-1.78	-13.3
6	A	1.60	31.87	6.95	6.17	-0.78	-12.6
6	D	2.196	30.51	12.13	12.16	+0.03	2.4
7	A	1.10	15.92	10.11	—	—	—
7	D	1.413	16.18	14.44	11.84	-2.60	-21.9
8	A	1.344	16.90	11.50	10.02	-1.48	-14.8
8	D	1.835	16.73	18.65	16.41	-2.16	-13.1
9	A	1.389	16.71	11.33	—	—	—
9	D	1.72	16.63	16.14	14.59	-1.55	-10.6

$$X_{\text{exit}} = \frac{1}{h_{fg}} \left(\frac{\text{Channel Power}}{W_{CH}} - \Delta h_{\text{sub}} \right)$$

rms = 11.1 percent
Average = 9 percent

are compared with the IFA measured exit steam quality, and a better agreement is found.

4.3.4 Axial Flux Distribution

The axial flux distribution in the water gap between four fuel elements could be determined with the movable in-core flux monitors in in-core locations 106, 109, and 112. The on-line computer calculated the nodal flux and the nodal power for eight axially-located nodes of each fuel element. The analytical calculation was integrated with measured data from the standard fixed in-core monitoring system.

No straight comparison can be made between the movable in-core flux monitor data and the calculated nodal flux and nodal power of the four fuel elements surrounding the movable in-core flux monitor position. The movable in-core flux monitor gives only indications regarding the local thermal neutron flux in the water gap between the fuel elements.

However, it is interesting to compare the calculated relative axial power distribution of the four fuel elements surrounding the movable in-core flux monitor with the axial flux distribution determined from the movable in-core monitor.

Figures 4-23 through 4-28⁽⁷⁾ compare the on-line computer nodal flux data with the movable in-core flux monitor traces for positions 106, 109, and 112, at each of the experienced test conditions 1A through 8.

For each node, the average value of the four surrounding fuel elements' calculated relative nodal flux is compared to the normalized axial shape of the movable in-core flux monitor. The relative nodal flux calculated for the adjacent instrumented fuel assembly is also shown (in-core location 109, IFA-A; in-core location 106, IFA-B; and in-core location 112, IFA-C).

In Table 4-18, the average value of the relative nodal flux of the four surrounding fuel elements is compared with the equivalent nodal value of the movable in-core flux monitor.

It appears that the relative difference between the calculated average nodal flux in the four fuel elements and the value derived from the movable in-core chamber reading is a large one. This gives no indication regarding either the movable in-core flux monitor performance or the on-line computer nodal flux calculation accuracy. It indicates only that the relative axial power shapes as derived from the movable in-core flux monitor and the on-line computer calculation are fairly close (Figures 4-23 through 4-28), notwithstanding the large relative error at the fuel element top and bottom.

In the thermal-hydraulic calculation, the interest lies on the availability of reliable relative nodal power values to be used as input for the channel flow, voids, and MCHFR determination. Therefore, a comparison has also been made between the movable in-core flux monitor data and the on-line computer calculated nodal power for the four fuel elements surrounding the movable in-core location. The results of the comparison for Test 3 are given in Table 4-19.

Table 4-20 shows the relative difference between the measured data from the movable in-core detectors and the calculated nodal flux and nodal power for Test 3. The relative difference between the movable in-core flux monitor data and the calculated power data appears to be ± 17.6 percent against ± 21.5 percent which is calculated when the nodal flux is considered instead of the nodal power.

The largest difference between the movable in-core flux monitor reading and the calculated relative nodal power (or flux) is generally found at the first node from the fuel element bottom.

TABLE 4-18

COMPARISON OF THE NODAL FLUX CALCULATION WITH THE MOVABLE IN-CORE PROBE MEASUREMENTS

Test No.		1A								3								5										
Movable In-core Position No.		109			106			112			109			106			112			109			106			112		
Movable In-core Reading		①			①			①			①			①			①			①			①			①		
Calculated Average Nodal Flux		②			②			②			②			②			②			②			②			②		
Relative Difference $\frac{②-①}{①}$ (percent)		③			③			③			③			③			③			③			③			③		
NODE																												
Top	8	0.84	0.922	9.7	0.96	1.166	21.4	1.14	1.295	13.6	0.58	0.627	8.1	0.80	0.918	14.7	0.98	1.068	8.9	0.32	0.422	31.9	0.54	0.65	20.3	0.64	0.733	14.5
	7	1.34	1.558	16.3	1.50	1.77	11.3	1.72	1.994	15.9	0.98	1.093	11.5	1.26	1.444	14.6	1.42	1.712	20.2	0.50	0.707	41.4	0.80	1.032	29.0	0.88	1.146	30.2
	6	1.78	1.896	6.5	1.82	1.968	8.1	2.02	2.137	5.8	1.37	1.455	6.2	1.58	1.745	10.4	1.68	1.989	18.4	0.70	0.883	26.1	0.92	1.189	29.2	1.02	1.302	27.6
	5	1.58	1.698	7.5	1.53	1.472	-3.8	1.46	1.355	-7.2	1.67	1.726	3.3	1.44	1.534	6.5	1.45	1.452	0	0.88	1.049	19.2	0.98	1.12	14.2	1.08	1.22	12.9
	4	1.12	0.954	-14.8	1.00	0.842	-15.8	0.78	0.620	-20.5	1.50	1.474	-1.7	1.15	1.10	-4.3	0.95	0.799	-15.9	1.28	1.319	3.0	1.14	1.22	7.0	1.12	1.146	2.3
	3	0.72	0.548	-23.9	0.68	0.47	-30.1	0.48	0.336	-30.0	0.98	0.878	-10.4	0.88	0.712	-8.7	0.70	0.514	-26.6	1.62	1.65	1.8	1.40	1.34	-4.3	1.30	1.216	-6.5
	2	0.42	0.307	-26.9	0.36	0.236	-34.4	0.28	0.194	-30.7	0.64	0.53	-17.2	0.56	0.399	-28.6	0.50	0.335	-33	1.70	1.42	-16.5	1.38	1.06	-23.2	1.16	0.896	-22.7
Bottom	1	0.20	0.116	-42.0	0.15	0.08	-40	0.12	0.069	-42.5	0.28	0.216	-22.8	0.33	0.145	-56	0.32	0.128	-60	1.00	0.55	-45.0	0.84	0.38	-54.7	0.80	0.339	-57.6

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Test No.		6								7								8										
Movable In-core Position No.		109			106			112			109			106			112			109			106			112		
Movable In-core Reading		①			①			①			①			①			①			①			①			①		
Calculated Average Nodal Flux		②			②			②			②			②			②			②			②			②		
Relative Difference $\frac{②-①}{①}$ (percent)		③			③			③			③			③			③			③			③			③		
NODE																												
Top	8	0.34	0.31	-8.8	0.60	0.468	-2.2	0.70	0.525	-25.0	0.30	0.313	4.33	0.49	0.484	-1.2	0.58	0.533	-8.1	0.32	0.3176	0.7	0.52	0.468	-10.0	0.52	0.525	1.0
	7	0.57	0.54	-5.3	0.84	0.7548	-8.9	0.90	0.846	-6.0	0.44	0.519	17.9	0.60	0.666	11.0	0.75	0.802	6.9	0.50	0.545	9.	0.72	0.765	6.2	0.84	0.846	0.7
	6	0.74	0.70	-5.4	0.94	0.943	+3.0	1.00	1.001	0	0.60	0.652	8.7	0.68	0.752	10.6	0.85	0.914	7.5	0.62	0.700	12.9	0.86	0.943	9.6	1.00	1.007	0.7
	5	0.88	0.83	-5.7	0.92	1.045	+13.6	0.96	1.00	+2.0	0.80	0.8368	4.6	0.80	0.869	8.6	0.90	0.928	3.1	0.75	0.839	11.8	0.92	1.045	13.6	1.02	1.008	1.2
	4	1.16	1.048	-9.6	1.08	1.067	-1.2	0.96	1.019	+6.1	1.14	1.058	-7.2	1.10	1.084	-1.4	1.10	1.028	6.5	1.00	1.048	4.8	1.04	1.067	2.5	1.06	1.019	-3.8
	3	1.5	1.477	-1.8	1.34	1.354	+1.1	1.16	1.317	+13.5	1.43	1.542	+4.2	1.50	1.523	1.5	1.42	1.405	1.0	1.30	1.477	13.6	1.24	1.354	9.2	1.26	1.316	4.4
	2	1.81	1.988	+9.8	1.50	1.647	+9.8	1.30	1.62	+24.6	1.93	2.053	3.6	1.76	1.871	6.3	1.50	1.716	14.4	1.80	1.988	10.4	1.58	1.647	4.2	1.42	1.621	14.1
Bottom	1	1.00	1.08	+8.00	0.78	0.71	-9.0	1.00	0.657	-34.3	1.26	1.058	-16.0	1.07	0.750	-29.9	0.90	0.673	-25.2	1.71	1.082	-36.7	1.12	0.710	-36.6	0.88	0.656	-25.4

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Test No.		6									7									8								
Movable In-core Position No.		109			106			112			109			106			112			109			106			112		
Movable In-core Reading		①			①			①			①			①			①			①			①			①		
Calculated Average Nodal Flux		②			②			②			②			②			②			②			②			②		
Relative Difference		③			③			③			③			③			③			③			③			③		
②-① ① (percent)		③			③			③			③			③			③			③			③			③		
①		%			%			%			%			%			%			%			%			%		
NODE																												
Top	8	0.34	0.31	-8.8	0.60	0.468	-2.2	0.70	0.525	-25.0	0.30	0.313	4.33	0.49	0.484	-1.2	0.58	0.533	-8.1	0.32	0.3176	0.7	0.52	0.468	-10.0	0.52	0.525	1.0
	7	0.57	0.54	-5.3	0.84	0.7348	-8.9	0.90	0.846	-6.0	0.44	0.519	17.9	0.60	0.666	11.0	0.75	0.802	6.9	0.50	0.545	9	0.72	0.765	6.2	0.84	0.846	0.7
	6	0.74	0.70	-5.4	0.94	0.943	+3.0	1.00	1.001	0	0.60	0.652	8.7	0.68	0.752	10.6	0.85	0.914	7.5	0.62	0.700	12.9	0.86	0.943	9.6	1.00	1.007	0.7
	5	0.88	0.83	-5.7	0.92	1.045	+13.6	0.98	1.00	+2.0	0.80	0.8368	4.6	0.80	0.869	8.6	0.90	0.928	3.1	0.75	0.839	11.8	0.92	1.045	13.6	1.02	1.008	1.2
	4	1.16	1.048	-9.6	1.08	1.067	-1.2	0.96	1.019	+6.1	1.14	1.058	-7.2	1.10	1.084	-1.4	1.10	1.028	6.5	1.00	1.048	4.8	1.04	1.067	2.5	1.06	1.019	-3.8
Bottom	3	1.5	1.477	-1.8	1.34	1.354	+1.1	1.16	1.317	+13.5	1.43	1.542	+4.2	1.50	1.523	1.5	1.42	1.405	1.0	1.30	1.477	13.6	1.24	1.354	9.2	1.26	1.316	4.4
	2	1.81	1.988	+9.8	1.50	1.647	+9.8	1.30	1.62	+24.6	1.98	2.053	3.6	1.76	1.871	6.3	1.50	1.716	14.4	1.80	1.988	10.4	1.58	1.647	4.2	1.42	1.621	14.1
	1	1.00	1.08	+8.00	0.78	0.71	-9.0	1.00	0.637	-34.3	1.26	1.058	-16.0	1.07	0.750	-29.9	0.90	0.673	-25.2	1.71	1.082	-36.7	1.12	0.710	-36.6	0.88	0.656	-25.4

GARIGLIANO R & D TEST 1A

- a) ——— CONTINUOUS SHAPE = MOVABLE IN-CORE FLUX MONITOR PROFILE
- b) - - - DASH BARS = AVERAGE CALCULATED FLUX OF THE FOUR FUEL ELEMENTS SURROUNDING THE MOVABLE IN-CORE CHAMBER PORTION
- c) ——— BARS = CALCULATED FLUX FOR THE ADJACENT INSTRUMENTED FUEL ASSEMBLY

SOURCE: REFERENCE 7

FIGURE 4-23. COMPARISON OF MEASURED AND CALCULATED AXIAL FLUX PROFILE (TEST 1A)

GARIGLIANO R & D I TEST 3

- a) ——— CONTINUOUS SHAPE = MOVABLE IN-CORE FLUX MONITOR PROFILE
- b) - - - DASH BARS = AVERAGE CALCULATED FLUX OF THE FOUR FUEL ELEMENTS SURROUNDING THE MOVABLE IN-CORE CHAMBER PORTION
- c) ——— BARS = CALCULATED FLUX FOR THE ADJACENT INSTRUMENTED FUEL ASSEMBLY

SOURCE: REFERENCE 7

FIGURE 4-24. COMPARISON OF MEASURED AND CALCULATED AXIAL FLUX PROFILE (TEST 3)

GARIGLIANO R & D TEST 5

- a) ——— CONTINUOUS SHAPE = MOVABLE IN-CORE FLUX MONITOR PROFILE
- b) - - - - - DASH BARS = AVERAGE CALCULATED FLUX OF THE FOUR FUEL ELEMENTS SURROUNDING THE MOVABLE IN-CORE CHAMBER PORTION
- c) ——— BARS = CALCULATED FLUX FOR THE ADJACENT INSTRUMENTED FUEL ASSEMBLY

SOURCE: REFERENCE 7

FIGURE 4-25. COMPARISON OF MEASURED AND CALCULATED AXIAL FLUX PROFILE (TEST 5)

SOURCE: REFERENCE 7

FIGURE 4-26. COMPARISON OF MEASURED AND CALCULATED AXIAL FLUX PROFILE (TEST 6)

GARIGLIANO R & D TEST 7

- a) ——— CONTINUOUS SHAPE = MOVABLE IN-CORE FLUX MONITOR PROFILE
 b) - - - - - DASH BARS = AVERAGE CALCULATED FLUX OF THE FOUR FUEL ELEMENTS SURROUNDING THE MOVABLE IN-CORE CHAMBER PORTION
 c) ——— BARS = CALCULATED FLUX FOR THE ADJACENT INSTRUMENTED FUEL ASSEMBLY

SOURCE: REFERENCE 7

FIGURE 4-27. COMPARISON OF MEASURED AND CALCULATED AXIAL FLUX PROFILE (TEST 7)

GARIGLIANO R & D TEST 8

- a) ——— CONTINUOUS SHAPE = MOVABLE IN-CORE FLUX MONITOR PROFILE
- b) - - - DASH BARS = AVERAGE CALCULATED FLUX OF THE FOUR FUEL ELEMENTS SURROUNDING THE MOVABLE IN-CORE CHAMBER PORTION
- c) ——— BARS = CALCULATED FLUX FOR THE ADJACENT INSTRUMENTED FUEL ASSEMBLY

SOURCE: REFERENCE 7

FIGURE 4-28. COMPARISON OF MEASURED AND CALCULATED AXIAL FLUX PROFILE (TEST 8)

TABLE 4-19

COMPARISON OF MOVABLE IN-CORE FLUX MONITOR MEASUREMENTS WITH CALCULATED RELATIVE NODAL POWER

TEST 3

		109			106			112		
Movable In-Core Position		①			①			①		
Movable In-Core Reading		②			②			②		
Calculated Average Nodal Power										
Relative Difference $\frac{②-①}{①}$ (percent)		③			③			③		
	Node									
Fuel Element Top	8	0.58	0.566	-2.4	0.80	0.82	+2.5	0.98	0.961	-1.9
	7	0.98	0.997	+1.7	1.26	1.324	5.0	1.42	1.577	+11.0
	6	1.37	1.359	0.8	1.58	1.677	6.1	1.68	1.957	16.5
	5	1.67	1.705	2.1	1.44	1.613	12.0	1.45	1.571	8.3
	4	1.50	1.596	6.4	1.15	1.192	3.6	0.95	0.867	-8.7
	3	0.98	0.961	-1.9	0.88	0.773	-12.1	0.70	0.559	-20.1
Fuel Element Bottom	2	0.64	0.581	-9.2	0.56	0.435	-22.3	0.50	0.366	-26.8
	1	0.28	0.234	-16.4	0.33	0.159	-51.8	0.32	0.140	-56.2

TABLE 4-20

RELATIVE DIFFERENCE BETWEEN MOVABLE IN-CORE FLUX MONITOR DATA AND
CALCULATED NODAL FLUX AND POWER

Test 3

In-Core Position	109	106	112	Average
Average Relative Difference (rms) (with flux values)	12.11	24.05	28.45	→ 21.53
Average Relative Difference (rms) (with power values)	7.2	21.0	24.55	→ 17.58
Average Relative Difference (rms) (with power values, excluding the bottom node value)	4.52	10.26	15.4	→ 10.06

If the relative difference at this node is not considered, the average relative difference of the three movable in-core monitors (106, 109, and 112) for Test 3 results in ± 10 percent, which may be considered fairly satisfactory, given the existing differences between the measured and calculated data that are compared.

For the new on-line computer thermal-hydraulic analysis, the information from the standard in-core neutron flux monitoring system is directly input and the computer does not perform any theoretical neutron flux calculation. Movable in-core chambers of TIP (Traversing In-Core Probe) are used for the in-core calibration.

4.4 APED THERMAL-HYDRAULIC CODE CALCULATIONS AND COMPARISON WITH THE IFA MEASURED DATA

4.4.1 APED Thermal-Hydraulic Code Calculations

The instrumented fuel assembly channel flow rate, active coolant power, exit steam quality, and pressure drop were calculated using the APED Thermal-hydraulic Core Design Code. Two slightly different editions of the APED Code were used.

The first edition (hereinafter indicated as APED Code I) was very similar to the Garigliano on-line computer thermal-hydraulic code, and used steam-water pressure drop correlations which are not considered satisfactory to attain a sufficient degree of accuracy for individual channel flow rate analysis with the reactor in natural circulation and high voids.

The second edition of the code (APED Code II) used up-to-date correlations which agree better with experimental results and allow for a more accurate determination of channel flow rate and exit steam quality.

In both cases, the steam properties corresponding to the measured reactor pressure and flow at each of the testing conditions were input. The best available core parameters for the experienced Tests 1A through 9 were considered (Table 4-1). The channel radial power factors and the axial power distributions were derived from the Garigliano on-line computer data. Axial power distributions derived from the movable in-core neutron flux monitors were also considered for the instrumented fuel assemblies.

The design values of the fuel local loss coefficients were used, except for the lower tie plates of standard fuel elements which were recalculated as shown in subsection 4.4.5. This allowed consideration of the effect of crud deposits on core pressure drop and channel flow rate.

Measured values of core pressure drop were known only for Test 1A. The reactor pressure gage was out of calibration during the reactor testing period.⁽⁷⁾ For Tests 3 through 9, the core pressure drop was calculated considering the same values of total recirculation flow rate and core leakage flow coefficients used for the on-line computer analyses (Tables 4-1 and 4-4).

Subsection 4.4.4, includes the procedure used to double-check the assumed values of the core leakage flow coefficients, using the measured flow rate with the instrumented fuel assemblies for each of the reactor test conditions.

The channel flow for the instrumented fuel assemblies was calculated considering the chimney effect of the outlet turbine flowmeter housing. In fact, the outlet turbine flowmeter housing and its channel adapter constituted a chimney which extended the channel length by 20 inches. This added a driving head to the four instrumented fuel assemblies, causing their flow to be higher than would be expected.

4.4.2 Comparison of Calculated with Measured Values

The calculated values of channel flow rate, power, and exit quality were compared with the measured values from the instrumented fuel assemblies. The results of the calculations performed with the two different editions of the APED Thermal-Hydraulic Code are given separately and are designated as Code I and

Code II (Code II indicates the one with up-to-date correlations). With each code, two separate calculations were performed—one with and one without the chimney effect at the instrumented fuel assemblies' outlet (Tables 4-20a, 4-20b, 4-20c, and 4-20d).

The results of the comparison of the calculated with measured channel flow from the instrumented fuel assemblies show that the agreement is within:

+7.5 percent when using Code I and
no chimney effect,

±4.7 percent when using Code I and
with chimney effect,

±7.14 percent when using Code II and
no chimney effect, and

±5.15 percent when using Code II and
with chimney effect.

The channel active coolant power was calculated for all the cases using as input the radial power factors determined from the Garigliano on-line computer. The agreement between the calculated and measured channel coolant power from the instrumented fuel assemblies is within ±4.9 percent.

The calculated and measured channel exit steam quality values compared within:

±11.4 percent when using Code I and
no chimney effect,

± 6.6 percent when using Code I and
with chimney effect,

±10.15 percent when using Code II and
no chimney effect, and

±6.93 percent when using Code II and
with chimney effect.

4.4.2.1 Channel Flow

Tables 4-21 through 4-24 show the comparison of measured to calculated channel flow rate for the instrumented fuel assemblies.

The results of the calculations performed using the APED Code I, not considering the chimney effect, are given in Table 4-21; when considering the chimney effect, the results are as shown in Table 4-22. The positive effect on channel flow rate of the chimney is evident, which is larger with larger voids.

The results of the calculations using APED Code II are given in Tables 4-23 and 4-24, respectively, without and with the chimney effect.

Figure 4-29 compares the results of the calculations with the measurements from the instrumented fuel assembly.

4.4.2.2 Channel Active Coolant Power

The active coolant power of the instrumented fuel assemblies was calculated using the on-line computer radial power factors.⁽⁷⁾ The core leakage flow power fraction was assumed to be equal to 2.5 percent. Therefore, the agreement between the instrumented fuel assembly measured and calculated active coolant power is the same as found in subsection 4.3.2, Table 4-15, and is within ± 4.9 percent.

The same values of active coolant power are calculated with the two editions of APED Thermohydraulic Code and for the cases with or without chimneys (Table 4-25).

4.4.2.3 Channel Exit Steam Quality

The comparison of the measured with calculated channel exit steam quality is given in Tables 4-26 through 4-29.

The results of the calculations performed using the APED Code I are given in Table 4-26 (no chimney effect) and in Table 4-27 (with chimney effect).

The results of the calculations using APED Code II are given in Table 4-28 (no chimney effect) and in Table 4-29 (with chimney effect).

To evaluate the ability of the inlet and outlet turbine flowmeters in order to measure the channel exit steam quality, reliable values of it should be available. In the absence of true values, it is believed that the comparison can be made with the exit steam quality values calculated using the APED Code II, which also shows the best agreement between measured and calculated flow rate.

Figure 4-30 compares the exit steam quality versus channel flow rate as calculated using the APED Code, with the measured values from the instrumented fuel assemblies.

4.4.3 Calculated Instrumented Assembly Pressure Drop

No instrumentation for a direct measurement of the instrumented fuel assembly pressure drop was provided for the reactor tests. The standard core pressure drop instrumentation was considered sufficient to provide the necessary information. Unfortunately, no satisfactory measurements of core pressure drop could be obtained because the reactor gage was out of calibration. The only available value of measured core pressure drop is 0.53 kg/cm^2 for test 1A.⁽⁷⁾

TABLE 4-20a
DATA SUMMARY OF THE THERMAL AND HYDRAULIC ANALYSIS FROM CODE I

System Description-Core Analysis	Case 1A				Case 3				Case 5				Case 6				Case 7				Case 8				Case 9			
Core Power Level, MW(l)	497.6				386.7				477.1				379.4				260.5				331.7				330.8			
Core Flow Rate, Mlb/h	21.428				10.086				10.198				10.604				8.118				6.338				6.250			
Core Exit Steam Flow, Mlb/h	1.535				1.236				1.624				1.455				0.975				1.269				1.203			
Plenum to Plenum Pressure Drop, psi	7.506				3.638				3.379				3.741				2.421				2.458				2.409			
Core Inlet Enthalpy, Btu/lb	508.2				489.6				484.9				508.2				499.0				491.7				484.3			
System Pressure Level, psia	989.5				988.2				989.8				990.3				987.1				982.3				979.2			
Moderator % of Power Generation	3.500				3.500				3.500				3.560				3.500				3.500				3.500			
Leakage % of Power Generation	2.500				2.500				2.500				2.500				2.500				2.500				2.500			
Leakage % of Total Core Flow	13.500				8.000				8.000				5.000				3.000				1.000				0.			
Average Heat Flux, kBtu/h-ft ²	79.22				61.56				75.96				60.36				41.47				52.80				52.66			
Core Heat Transfer Area, kft ²	20.688				20.688				20.688				20.688				20.688				20.688				20.688			
Reactor Core Length, in.	115.4				115.4				115.4				115.4				115.4				115.4				115.4			
Core Active Coolant Avg Exit Qual	0.087				0.135				0.174				0.142				0.161				0.196				0.186			
Reactor Avg Exit Quality	0.072				0.123				0.159				0.137				0.159				0.200				0.193			
Core Average Void Fraction	0.168				0.255				0.429				0.300				0.426				0.457				0.468			
Core Minimum CHF Ratio	3.638				4.601				4.172				4.795				5.046				4.407				3.957			
Number of Channels in Reactor Core	208				208				208				208				208				208				208			
Channel Descriptions	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D
Channel Core Locations	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516
Number Channels/Type	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Number Rods/Channel	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	
Rod Diameter, in.	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	
Active Fuel Length, in.	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400
Radial Power Factor	1.019	1.230	1.278	1.346	1.030	1.147	1.171	1.342	0.929	1.243	1.094	1.288	0.900	1.266	1.106	1.235	0.906	1.239	1.062	1.157	0.864	1.256	1.072	1.180	0.896	1.150	1.012	
Axial Peaking Factor	1.796	2.012	2.197	1.690	1.714	1.817	2.078	1.746	1.963	1.685	1.379	1.640	2.017	1.888	1.600	1.427	2.090	2.032	1.811	1.660	1.970	1.731	1.566	1.393	2.267	1.481	1.792	
Hot Spot Factor	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	
Hydraulic Diameter, in.	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	
Channel Flow Area, in. ²	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	
Heat Transfer Area, ft ²	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	
Non-Boiling Length, in.	52.700	52.700	52.700	39.525	39.525	52.700	52.700	39.525	13.175	13.175	26.350	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175
Peak Flux, MBtu/h-ft ²	0.173	0.233	0.265	0.214	0.129	0.153	0.178	0.172	0.165	0.189	0.136	0.191	0.130	0.172	0.127	0.127	0.093	0.124	0.095	0.095	0.107	0.137	0.106	0.103	0.127	0.107	0.114	
Minimum CHF Ratio	5.666	4.135	3.638	4.454	6.412	5.357	4.601	4.777	5.030	4.300	5.940	4.249	6.406	4.795	6.542	6.518	6.903	5.336	6.952	6.954	6.312	4.957	6.468	6.542	5.325	8.348	5.627	
Friction Delta P, psi	1.313	1.436	1.459	1.552	0.424	0.416	0.419	0.542	0.518	0.675	0.521	0.707	0.672	0.744	0.633	0.711	0.209	0.299	0.233	0.267	0.247	0.364	0.288	0.330	0.246	0.300	0.255	
Elevation Delta P, psi	2.732	2.633	2.612	2.466	2.393	2.477	2.457	2.213	1.915	1.686	2.039	1.638	2.138	1.855	2.032	1.918	1.913	1.719	1.054	1.700	1.066	1.616	1.766	1.686	1.807	1.685	1.780	
Acceler., Delta P, psi	0.156	0.221	0.235	0.252	0.061	0.065	0.071	0.086	0.074	0.104	0.078	0.106	0.065	0.094	0.086	0.093	0.022	0.035	0.029	0.032	0.029	0.048	0.040	0.029	0.042	0.036	0.040	
Local Delta P, psi	3.306	3.217	3.202	3.206	0.763	0.680	0.695	0.796	0.871	0.913	0.739	0.927	0.970	1.047	0.993	1.023	0.276	0.369	0.304	0.334	0.328	0.434	0.367	0.401	0.329	0.375	0.341	
Active Coolant																												
Energy Add, MBtu/h	8.112	9.792	10.174	10.719	6.372	7.096	7.245	8.302	7.091	9.488	8.350	9.831	5.463	7.684	6.713	7.496	3.776	5.164	4.426	4.822	4.586	6.666	5.689	6.262	4.741	6.086	5.356	
Flow Rate, klb/h	158.345	150.780	149.789	145.216	70.443	63.711	65.006	64.886	70.678	61.813	59.421	60.169	74.547	67.431	72.345	68.492	35.798	37.834	37.466	37.388	39.014	39.255	39.853	39.083	39.150	39.120	40.014	
Mass Rate, Mlb/h-ft ²	1.130	1.076	1.089	1.036	0.503	0.455	0.464	0.463	0.504	0.441	0.424	0.429	0.532	0.481	0.516	0.489	0.256	0.270	0.267	0.267	0.278	0.280	0.284	0.279	0.279	0.286	0.282	
Inlet Velocity, ft/sec	6.553	6.240	6.199	6.010	2.865	2.591	2.644	2.639	2.862	2.503	2.406	2.437	3.085	2.791	2.994	2.835	1.469	1.552	1.537	1.534	1.590	1.600	1.624	1.593	1.504	1.583	1.610	
Exit Quality, %	2.854	4.959	5.416	6.321	6.055	9.265	9.275	11.809	6.815	14.976	12.087	16.196	6.223	12.468	9.219	11.776	9.826	14.582	11.768	13.430	10.663	18.670	14.524	17.201	10.133	15.408	12.083	
Exit Void, %	31.718	41.061	42.871	46.011	47.592	51.626	53.970	58.901	54.797	67.193	60.621	68.688	45.519	58.957	53.596	67.893	54.244	63.180	59.524	61.549	57.531	69.145	64.926	67.633	58.050	66.859	62.954	
Average Voids, %	9.978	12.246	12.792	17.351	20.266	16.857	17.412	25.176	35.921	42.468	30.770	44.020	28.831	37.198	31.508	35.053	35.829	41.657	37.244	39.348	37.521	44.676	39.799	42.273	39.341	42.191	39.691	

TABLE 4-20b
DATA SUMMARY OF THE THERMAL AND HYDRAULIC ANALYSIS FROM CODE I--(CHIMNEY EFFECT INCLUDED)

System Description-Core Analysis	Case 1A				Case 3				Case 5				Case 6				Case 7				Case 8				Case 9					
Channel Descriptions	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5510	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516		
Channel Core Locations	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
Number Channels/Type(a)	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81			
Number Rods/Channel	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534			
Rod Diameter, in.	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000			
Active Fuel Length, in.	0.836	1.010	1.049	1.105	0.878	0.978	0.999	1.145	0.816	1.092	0.961	1.131	0.800	1.123	0.981	1.096	0.831	1.136	0.973	1.060	0.790	1.149	0.981	1.080	0.861	1.104	0.971	1.064		
Radial Power Factor (Equival.)	1.796	2.012	2.197	1.690	1.714	1.817	2.078	1.746	1.963	1.685	1.379	1.640	2.017	1.888	1.600	1.427	2.090	2.032	1.811	1.660	1.970	1.731	1.566	1.393	2.207	1.401	1.792	1.740		
Axial Peaking Factor(b)	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190		
Hot Spot Factor	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502		
Hydraulic Diameter, in.	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175		
Channel Flow Area, in. 2	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084		
Heat Transfer Area, ft 2	65.625	65.625	65.625	52.500	52.500	65.625	65.625	52.500	26.250	26.250	39.375	26.250	26.250	13.125	26.250	26.250	13.125	13.125	26.250	26.250	26.250	13.125	26.250	26.250	26.250	26.250	26.250	26.250		
Non-Boiling Length, in.	0.173	0.234	0.265	0.215	0.130	0.153	0.179	0.172	0.165	0.190	0.137	0.191	0.131	0.172	0.128	0.127	0.094	0.125	0.095	0.095	0.107	0.137	0.106	0.104	0.128	0.107	0.114	0.121		
Peak Flux, MBtu/h-ft. (c)	5.674	4.147	3.648	4.468	6.410	5.408	4.627	4.804	5.010	4.327	6.030	4.285	6.326	4.779	6.482	6.480	7.126	5.560	7.056	7.173	6.425	5.134	6.535	6.739	5.417	6.509	6.039	5.781		
Minimum CHF Ratio	1.359	1.501	1.525	1.620	0.439	0.452	0.454	0.583	0.529	0.716	0.570	0.756	0.569	0.764	0.633	0.722	0.221	0.323	0.244	0.285	0.258	0.391	0.301	0.353	0.257	0.317	0.263	0.320		
Friction Delta P, psi	3.170	3.009	2.988	2.860	2.894	2.883	2.881	2.629	2.613	2.269	2.557	2.193	2.522	2.154	2.408	2.243	2.435	2.214	2.389	2.298	2.398	2.119	2.309	2.198	2.413	2.285	2.402	2.277		
Elevation Delta P, psi (d)	0.159	0.231	0.246	0.263	0.057	0.069	0.071	0.088	0.063	0.099	0.083	0.103	0.063	0.095	0.082	0.093	0.021	0.035	0.027	0.031	0.027	0.047	0.037	0.043	0.026	0.038	0.031	0.037		
Acceler. Delta P, psi	3.387	3.327	3.305	3.320	0.785	0.773	0.766	0.876	0.865	0.987	0.858	1.015	0.915	1.052	0.946	1.009	0.299	0.406	0.317	0.362	0.343	0.469	0.379	0.432	0.345	0.399	0.344	0.407		
Local Delta P, psi	***Active Coolant***																													
Energy Add, MBtu/h	8.097	9.782	10.164	10.705	6.369	7.095	7.247	8.306	7.087	9.484	8.347	9.823	5.471	7.687	6.709	7.496	3.778	5.160	4.420	4.819	4.582	6.664	5.689	6.263	4.746	6.086	5.353	5.866		
Flow Rate, klb/h	160.654	154.053	152.896	148.562	71.914	70.040	69.828	69.691	70.327	66.551	68.297	65.622	71.307	67.751	69.674	67.750	38.511	41.394	38.832	40.059	40.683	42.439	41.003	41.824	40.931	41.472	40.429	41.953		
Mass Rate, Mlb/h-ft 2	1.148	1.100	1.091	1.060	0.513	0.500	0.498	0.497	0.502	0.475	0.487	0.468	0.509	0.483	0.497	0.484	0.275	0.296	0.277	0.286	0.290	0.303	0.293	0.299	0.292	0.296	0.289	0.299		
Inlet Velocity, ft/sec	6.649	6.375	6.327	6.148	2.925	2.849	2.840	2.834	2.848	2.695	2.766	2.657	2.951	2.804	2.883	2.804	1.580	1.698	1.593	1.644	1.658	1.729	1.671	1.704	1.656	1.678	1.636	1.698		
Exit Quality, %	2.727	4.737	5.195	6.051	5.767	7.720	8.101	10.465	6.884	13.291	10.174	14.393	6.752	12.391	9.756	11.959	8.695	12.769	11.106	12.101	9.904	16.706	13.905	15.590	9.345	14.059	11.863	12.998		
Exit Void, %	32.388	42.191	43.921	46.885	43.076	49.068	50.156	55.493	46.697	60.581	54.943	62.355	46.499	59.287	54.202	58.548	48.601	57.009	53.919	55.896	51.816	63.256	59.209	61.696	50.442	59.430	55.705	57.666		
Average Voids, %	7.427	10.035	10.281	13.681	14.194	12.767	12.674	19.666	22.550	30.528	22.030	32.680	25.470	34.665	27.095	31.675	28.021	33.319	27.968	30.631	28.417	34.778	29.288	32.487	28.420	30.249	27.212	31.107		

(a) The active fuel rods in the instrumented fuel assemblies numbered 80, the central fuel rod having been replaced by the instrument probe.
(b) Axial power distribution from the on-line computer nodal power.
(c) The actual heat transfer area corresponded to 80 fuel rods.
(d) This includes the chimney effect of the outlet turbine flowmeter housing.

TABLE 4-20c
DATA SUMMARY OF THE THERMAL AND HYDRAULIC ANALYSIS FROM CODE II

System Description-Core Analysis	Case 1A				Case 3				Case 5				Case 6				Case 7				Case 8				Case 9			
Core Power Level, MW(t)	497.6				386.7				477.1				379.4				260.47				331.68				330.81			
Core Flow Rate, Mlb/h	21.428				10.086				10.198				10.604				6.118				6.338				6.250			
Core Exit Steam Flow, Mlb/h	1.534				1.236				1.623				1.455				0.975				1.268				1.202			
Plenum to Plenum Pressure Drop, psi	7.429				3.692				3.613				3.703				2.650				2.66				2.69			
Core Inlet Enthalpy, Btu/lb	508.2				489.6				484.9				508.2				490.000				491.7				484.3			
System Pressure Level, psia	989.5				988.2				989.8				990.3				987.100				982.30				979.20			
Moderator % of Power Generation	3.500				3.500				3.500				3.500															
Leakage % of Power Generation	2.500				2.500				2.500				2.500															
Leakage % of Total Core Flow	13.500				10.000				8.000				8.000				3.000				1.000				1.000			
Average Heat Flux, kBtu/h-ft ²	79.20				61.55				75.94				60.35															
Core Heat Transfer Area, kft ²	20.688				20.688				20.688				20.688				41.460				52.79				52.65			
Reactor Core Length, in.	115.4				115.4				115.4				115.4															
Core Active Coolant Avg Exit Quality	0.087				0.139				0.174				0.148				0.159				0.200				0.192			
Reactor Average Exit Quality	0.072				0.123				0.159				0.137				0.148											
Core Average Void Fraction	0.175				0.229				0.366				0.367				0.367				0.405				0.390			
Core Minimum CHF Ratio	3.970				5.272				4.393				5.343				5.495				4.907				4.020			
Number of Channels in Reactor Core	208				208				208				208															
Channel Descriptions	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D	IFA-A	IFA-B	IFA-C	IFA-D
Channel Core Locations	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516	7108	5908	6112	5516
Number Channels/Type	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Number Rods/Channel (a)	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	
Rod Diameter, in.	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	
Active Fuel Length, in.	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400	105.400
Radial Power Factor	1.019	1.230	1.278	1.346	1.030	1.147	1.171	1.342	0.929	1.243	1.094	1.288	0.900	1.266	1.106	1.235	0.906	1.239	1.062	1.157	0.864	1.256	1.072	1.180	0.895	1.150	1.012	1.109
Axial Peaking Factor (b)	1.780	1.820	2.020	1.820	1.670	1.580	1.680	1.580	1.700	1.400	1.300	1.400	1.810	1.500	1.300	1.500	1.980	1.760	1.500	1.760	1.800	1.580	1.420	1.580	2.267	1.481	1.792	1.740
Hot Spot Factor	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190
Hydraulic Diameter, in.	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502
Channel Flow Area, in. ²	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175
Heat Transfer Area, ft ² (c)	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461	99.461
Non-Boiling Length, in.	52.700	39.525	52.700	39.525	39.525	39.525	39.525	39.525	39.525	13.175	13.175	26.350	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175	13.175
Peak Flux, MBtu/h-ft ²	0.171	0.211	0.243	0.231	0.126	0.133	0.144	0.155	0.143	0.157	0.129	0.163	0.117	0.136	0.103	0.133	0.089	0.108	0.079	0.100	0.098	0.125	0.096	0.117	0.127	0.107	0.114	0.121
Minimum CHF Ratio (c)	5.717	4.585	3.970	4.163	6.541	6.194	5.698	5.284	5.770	5.196	6.378	5.008	7.091	6.037	8.004	6.193	7.322	6.246	8.232	6.633	6.873	5.456	6.934	5.786	5.280	6.252	5.807	5.577
Friction Delta P, psi	1.178	1.275	1.268	1.329	0.350	0.368	0.360	0.428	0.439	0.553	0.459	0.574	0.469	0.583	0.509	0.571	0.188	0.264	0.198	0.242	0.225	0.322	0.246	0.298	0.222	0.252	0.214	0.258
Elevation Delta P, psi	2.610	2.600	2.718	2.631	2.604	2.571	2.593	2.434	2.317	2.071	2.285	2.026	2.294	2.048	2.208	2.073	2.182	2.001	2.160	2.052	2.094	1.883	2.059	1.937	2.129	2.068	2.153	2.047
Accelerator Delta P, psi	0.163	0.226	0.240	0.257	0.053	0.064	0.065	0.080	0.050	0.001	0.076	0.094	0.060	0.090	0.078	0.088	0.019	0.032	0.024	0.028	0.025	0.043	0.033	0.039	0.024	0.035	0.029	0.033
Local Delta P, psi	3.271	3.232	3.206	3.215	0.687	0.693	0.677	0.754	0.795	0.895	0.796	0.915	0.879	0.981	0.907	0.970	0.263	0.356	0.270	0.329	0.318	0.414	0.324	0.389	0.311	0.330	0.290	0.347
Active Coolant																												
Energy Add. MBtu/h	8.110	9.789	10.171	10.713	6.371	7.094	7.243	8.300	7.089	9.485	8.348	9.829	5.461	7.682	6.712	7.494	3.775	5.162	4.425	4.821	4.585	6.665	5.688	6.261	4.740	6.085	5.354	5.868
Flow Rate, klb/h	158.281	152.343	151.520	148.677	67.278	66.175	65.525	65.230	67.386	63.607	65.171	62.954	71.080	67.390	69.286	67.751	36.127	38.870	36.011	38.222	38.587	39.604	37.616	39.304	38.464	37.906	37.069	38.735
Mass Rate, Mlb/h-ft ²	1.130	1.087	1.081	1.061	0.480	0.472	0.468	0.466	0.481	0.454	0.465	0.449	0.507	0.481	0.495	0.484	0.258	0.277	0.257	0.273	0.275	0.283	0.268	0.281	0.275	0.271	0.265	0.276
Inlet Velocity, ft/sec	6.526	6.281	6.247	6.130	2.723	2.678	2.652	2.640	2.715	2.562	2.625	2.536	2.931	2.779	2.857	2.793	1.476	1.568	1.471	1.561	1.565	1.606	1.526	1.594	1.549	1.526	1.493	1.560
Exit Quality, %	2.912	4.871	5.309	6.061	6.715	8.628	9.137	11.702	7.588	14.307	11.081	15.382	6.778	12.481	9.851	11.961	3.7	14.0	12.5	13.0	10.9	18.4	15.8	17.1	10.5	16.2	13.7	14.8
Exit Void, %	33.715	42.791	44.422	46.955	45.943	51.068	52.232	57.490	48.437	61.645	56.282	63.146	46.374	58.981	54.060	58.096	43.6	58.4	55.3	56.6	52.8	64.7	60.9	62.9	52.0	61.5	57.7	59.7
Average Voids, %	8.708	12.031	11.495	14.119	15.747	16.443	15.540	20.783	25.088	32.914	25.869	34.418	25.837	33.742	28.262	32.890	23.7	35.6	30.1	33.9	32.4	39.4	33.4	37.6	31.7	33.1	30.3	34.0

TABLE 4-20d
DATA SUMMARY OF THE THERMAL AND HYDRAULIC ANALYSIS FROM CODE II (CHIMNEY EFFECT INCLUDED)

System Description-Core Analysis	Case 1-A				Case 3				Case 5				Case 6				Case 7				Case 8				Case 9			
Identification	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516	IFA-A 7108	IFA-B 5908	IFA-C 6112	IFA-D 5516
Relative Assembly Power Factor (Equivalent Value)	0.836	1.010	1.049	1.105	0.878	0.978	0.999	1.145	0.816	1.092	0.961	1.131	0.800	1.123	0.981	1.096	0.831	1.136	0.973	1.060	0.790	1.149	0.981	1.080	0.861	1.104	0.971	1.064
Maximum Axial Peaking Factor (b)	1.796	2.012	2.197	1.690	1.714	1.817	2.078	1.746	1.963	1.685	1.379	1.640	2.017	1.888	1.600	1.427	2.090	2.032	1.811	1.660	1.970	1.731	1.566	1.393	2.267	1.481	1.792	1.740
Maximum Local Peaking Factor	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190	1.190
Number of Fuel Assemblies/Type	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Number of Fuel Rods/Assembly (a)	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81
Fuel Rod Cladding o.d., in.	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534	0.534
Cladding Crud-Oxide Allowance, in.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
Active Fuel Length, in.	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000
Heat Transfer Area/Assembly, ft ² (c)	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084	99.084
Maximum Heat Flux, MBtu/h-ft ²	0.172	0.233	0.264	0.214	0.129	0.153	0.179	0.172	0.165	0.189	0.136	0.191	0.131	0.172	0.127	0.127	0.094	0.126	0.096	0.096	0.108	0.138	0.106	0.104	0.127	0.107	0.114	0.121
Minimum Critical Heat Flux Ratio (c)	5.664	4.143	3.644	4.464	6.400	5.405	4.622	4.813	5.026	4.345	6.053	4.303	6.335	4.787	6.494	6.496	7.190	5.599	7.107	7.242	6.409	5.123	6.493	6.705	5.392	6.451	5.979	5.739
*** Active Coolant ***																												
Energy Added, MBtu/h	8.069	9.740	10.122	10.660	6.353	7.077	7.229	8.285	7.058	9.446	8.312	9.783	5.456	7.659	6.690	7.475	3.801	5.197	4.451	4.849	4.599	6.689	5.711	6.287	4.726	6.060	5.330	5.841
Rodded Assembly Flow Area, in. ²	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175	20.175
Rodded Assembly Hydraulic Diameter, in.	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502	0.502
Flow Rate, klbs/h	157.314	151.038	149.910	145.645	69.911	68.544	68.048	69.387	69.927	66.487	68.162	65.691	70.630	67.152	69.197	67.623	39.701	42.546	39.925	41.351	40.777	42.578	40.784	41.721	40.192	40.369	39.260	40.973
Mass Rate, Mlb/h-ft ²	1.123	1.078	1.070	1.040	0.499	0.489	0.486	0.495	0.499	0.475	0.487	0.469	0.504	0.479	0.494	0.483	0.283	0.304	0.285	0.295	0.291	0.304	0.291	0.298	0.287	0.288	0.280	0.292
Rodded Assembly Inlet Velocity, ft/sec	6.486	6.227	6.181	6.005	2.829	2.174	2.754	2.808	2.817	2.678	2.746	2.646	2.912	2.769	2.853	2.788	1.622	1.738	1.631	1.689	1.654	1.727	1.654	1.692	1.618	1.625	1.581	1.650
Friction Pressure Drop, psi	1.486	1.623	1.647	1.725	0.479	0.503	0.496	0.618	0.572	0.727	0.605	0.759	0.596	0.763	0.653	0.727	0.252	0.354	0.273	0.315	0.285	0.419	0.326	0.376	0.280	0.336	0.285	0.339
Elevation Pressure Drop, psi (d)	3.178	3.054	3.044	2.910	2.932	2.925	2.945	2.707	2.653	2.374	2.632	2.310	2.569	2.254	2.486	2.335	2.543	2.328	2.504	2.413	2.474	2.209	2.405	2.299	2.468	2.370	2.474	2.355
Acceleration Pressure Drop, psi	0.162	0.224	0.237	0.252	0.054	0.064	0.066	0.083	0.059	0.093	0.078	0.097	0.059	0.089	0.077	0.087	0.021	0.034	0.026	0.030	0.026	0.045	0.036	0.041	0.025	0.036	0.029	0.035
Local Loss Pressure Drop, psi	3.422	3.342	3.314	3.354	0.765	0.738	0.722	0.872	0.895	0.986	0.865	1.013	0.955	1.072	0.964	1.030	0.303	0.404	0.314	0.360	0.355	0.445	0.353	0.402	0.328	0.358	0.311	0.372
Non-Boiling Length, in.	54.323	55.807	57.976	46.366	45.039	53.399	57.057	42.745	22.044	23.452	29.409	22.176	15.829	15.675	18.375	17.270	15.832	16.861	19.164	18.411	16.491	17.364	20.050	19.418	16.668	21.007	20.590	19.424
Exit Quality (Thermal Equilibrium)	0.029	0.049	0.054	0.062	0.061	0.080	0.085	0.105	0.069	0.132	0.101	0.143	0.068	0.125	0.098	0.119	0.083	0.124	0.107	0.116	0.099	0.167	0.141	0.157	0.096	0.146	0.124	0.134
Void Fraction at Top of Active Fuel	0.338	0.429	0.446	0.475	0.443	0.497	0.508	0.555	0.468	0.602	0.546	0.617	0.465	0.590	0.540	0.581	0.471	0.563	0.527	0.547	0.512	0.630	0.590	0.615	0.505	0.597	0.559	0.580
Average Void Fraction over Fuel Length	0.071	0.086	0.084	0.120	0.129	0.116	0.107	0.174	0.216	0.273	0.200	0.290	0.241	0.315	0.247	0.288	0.250	0.299	0.246	0.272	0.263	0.322	0.263	0.293	0.270	0.275	0.250	0.287

(a) The active fuel rods in the instrumented fuel assemblies numbered 80, the central fuel rod having been replaced by the instrument probe.

(b) Axial power distribution from the on-line computer nodal power.

(c) The actual heat transfer area corresponded to 80 fuel rods.

(d) This includes the chimney effect of the outlet turbine flowmeter housing.

TABLE 4-21

COMPARISON OF MEASURED WITH CALCULATED CHANNEL FLOW RATE USING THE
APED CODE I (NO CHIMNEY EFFECT)

Test No.	IFA	Measured Flow ① (MT/h)	Calculated Flow ② (MT/h)	Difference ① - ② (MT/h)	Difference Percent [(①-②)/①] (percent)
1A	A	71.36	71.82	-0.46	-0.64
1A	D	66.72	65.87	0.85	1.27
3	A	31.60	31.95	-0.35	-1.11
3	D	31.43	29.43	2.00	6.36
5	A	31.92	32.06	-0.14	-0.44
5	D	30.39	27.29	3.10	10.20
6	A	32.31	31.18	1.13	3.50
6	D	30.48	28.85	1.63	5.35
7	A	16.16	16.24	-0.08	-0.04
7	D	19.17	16.96	2.21	11.52
8	A	20.39	17.69	2.70	13.24
8	D	18.83	17.72	1.11	5.89
9	A	20.69	17.76	2.93	14.16
9	D	18.96	17.90	1.06	5.59

rms = ±7.53 percent
Average = 5.66 percent

NOTE

In this and in the following tables, the standard deviation of the calculated values from the measured values is defined as

$$\text{rms (root mean square)} = \sqrt{\frac{\sum_{i=1}^n (\text{calculated} - \text{measured})^2}{n}}$$

TABLE 4-22

COMPARISON OF MEASURED WITH CALCULATED CHANNEL FLOW USING
APED DESIGN CODE I (CHIMNEY EFFECT INCLUDED)

Test No.	IFA	Measured Flow ① (MT/h)	Calculated Flow ② (MT/h)	Difference ① - ② (MT/h)	Difference Percent [(①-②)/①] (percent)
1A	A	71.36	72.87	-1.51	-2.1
1A	D	66.72	67.38	-0.66	-1.0
3	A	31.60	32.62	-1.02	-3.2
3	D	31.43	31.61	-0.18	-0.6
5	A	31.92	31.90	0.02	0.06
5	D	30.39	29.76	0.63	2.1
6	A	32.31	32.34	-0.03	-0.1
6	D	30.48	30.73	-0.25	-0.8
7	A	16.16	17.46	-1.30	-8.0
7	D	19.17	18.17	1.00	5.2
8	A	20.39	18.45	1.94	9.5
8	D	18.83	18.97	-0.14	-0.7
9	A	20.69	18.57	2.12	10.2
9	D	18.96	19.03	-0.07	-0.4

rms = ±4.68 percent
Average = 3.14 percent

TABLE 4-23
COMPARISON OF MEASURED WITH CALCULATED CHANNEL FLOW USING
APED DESIGN CODE II (NO CHIMNEY EFFECT)

Test No.	IFA	Measured Flow	Calculated Flow	Difference	Difference Percent
		① (MT/h)	② (MT/h)	① - ② (MT/h)	$ \text{①} - \text{②} / \text{①}$ (percent)
1A	A	71.36	71.79	-0.43	-0.59
1A	D	66.72	67.44	-0.72	-1.70
3	A	31.60	30.52	+1.08	3.41
3	D	31.43	29.59	+1.84	5.85
5	A	31.92	30.57	+1.35	4.22
5	D	30.39	28.56	+1.83	6.00
6	A	32.31	32.24	+0.07	0.20
6	D	30.48	30.73	-0.25	-0.80
7	A	16.16	16.39	-0.23	-2.2
7	D	19.17	17.34	+1.83	8.9
8	A	20.39	17.50	+2.89	14.17
8	D	18.83	17.83	+1.00	5.31
9	A	20.69	17.45	+3.24	15.66
9	D	18.96	17.57	+1.39	7.33

NOTE

No control rod guide tube losses

rms = ± 7.14 percent

Average = 5.45 percent

TABLE 4-24
COMPARISON OF MEASURED AND CALCULATED CHANNEL FLOW USING THE
APED DESIGN CODE II (CHIMNEY EFFECT INCLUDED)

Test No.	IFA	Measured Flow	Calculated Flow	Difference	Difference Percent
		① (MT/h)	② (MT/h)	① - ② (MT/h)	$ \text{①} - \text{②} / \text{①}$ (percent)
1A	A	71.36	71.35	0.01	0
1A	D	66.72	66.07	0.65	0.10
3	A	31.60	31.73	-0.13	-0.41
3	D	31.43	31.47	-0.04	-0.12
5	A	31.92	31.72	0.20	0.62
5	D	30.39	29.80	0.59	1.56
6	A	32.31	32.04	0.27	0.83
6	D	30.48	30.67	-0.19	-0.62
7	A	16.16	18.01	-1.85	-11.4
7	D	19.17	18.76	0.41	2.14
8	A	20.39	18.49	1.90	9.32
8	D	18.83	18.92	-0.09	-0.48
9	A	20.69	18.23	2.46	11.89
9	D	18.96	18.58	0.38	2.00

rms = ± 5.15 percent

Average = 2.96 percent

TABLE 4-25
COMPARISON OF MEASURED WITH CALCULATED CHANNEL ACTIVE
COOLANT POWER USING APED DESIGN CODE I*

Test No.	IFA	Measured Power [MW(t)]	Calculated Power [MW(t)]	Difference [MW(t)]	Relative Difference (percent)
		①	②	② - ①	② - ① / ①
1A	A	2.25	2.374	0.124	5.5
	D	2.98	3.136	0.156	5.2
3	A	1.844	1.866	0.022	1.2
	D	2.33	2.433	0.103	4.4
5	A	2.15	2.077	-0.073	-3.4
	D	2.80	2.878	0.078	2.8
6	A	1.52	1.603	0.083	5.4
	D	2.198	2.196	-0.002	-0.09
7	A	—	1.107	—	—
	D	1.464	1.412	-0.052	-3.5
8	A	1.494	1.343	-0.151	-10.1
	D	1.887	1.836	-0.051	-2.7
9	A	—	1.390	—	—
	D	1.836	1.719	-0.117	-6.4

rms = ±4.9
Average = 4.3

*Core leakage power fraction = 2.5 percent

TABLE 4-26
COMPARISON OF MEASURED WITH CALCULATED EXIT STEAM QUALITY
USING THE APED DESIGN CODE I (NO CHIMNEY EFFECT)

Test No.	IFA	IFA Measured Exit Steam Quality	APED Code Calculated Exit Steam Quality	Difference	Relative Difference
		①	② ^(a)	② - ①	$\frac{② - ①}{①}$
		(wt percent)	(wt percent)	(wt percent)	(percent)
1A	A	2.54	2.84	0.30	12.20
1A	D	5.65	6.32	0.67	11.86
3	A	6.10	6.06	-0.04	-0.65
3	D	9.84	11.81	1.97	20.02
5	A	7.46	6.81	-0.65	-8.71
5	D	13.35	16.50	3.15	23.59
6	A	6.17	6.22	0.05	0.81
6	D	12.16	11.77	-0.39	-3.20
7	A	—	9.82	—	—
7	D	11.84	13.43	1.59	13.42
8	A	10.02	10.66	0.64	6.38
8	D	16.41	17.20	0.79	4.81
9	A	—	10.13	—	—
9	D	14.59	14.36	-0.23	-1.57

rms = ±11.45 percent

Average = 8.88 percent

(a) The values of the exit steam quality correspond to the calculated channel flow and power as indicated in Tables 4-21 and 4-25.

TABLE 4-27

COMPARISON OF MEASURED WITH CALCULATED EXIT STEAM QUALITY
USING THE APED DESIGN CODE I (CHIMNEY EFFECT INCLUDED)

Test No.	IFA	IFA Measured Exit Steam Quality	APED Code Calculated Exit Steam Quality	Relative Difference	
		(1) (wt percent)	(2) ^(a) (wt percent)	Difference (2)-(1) (wt percent)	$\left(\frac{(2)-(1)}{(1)} \right)$ (percent)
1A	A	2.54	2.72	0.18	7.1
1A	D	5.65	6.05	0.40	7.1
3	A	6.10	5.77	-0.33	-5.4
3	D	9.84	10.46	0.62	6.4
5	A	7.46	6.89	-0.57	-7.6
5	D	13.35	14.39	1.04	7.8
6	A	6.17	6.75	0.58	9.4
6	D	12.16	11.96	-0.20	-1.6
7	A	—	8.69	—	—
7	D	11.84	12.10	0.26	2.2
8	A	10.02	9.9	-0.12	-1.2
8	D	16.41	15.59	-0.82	-5.0
9	A	—	9.34	—	—
9	D	14.59	13.00	-1.59	-10.9

rms = ±6.6 percent
average = 6.0 percent

(a) The values of the exit steam quality correspond to the calculated channel flow and power as indicated in Tables 4-22 and 4-25.

TABLE 4-28

COMPARISON OF MEASURED WITH CALCULATED EXIT STEAM QUALITY
USING THE APED DESIGN CODE II (NO CHIMNEY EFFECT)

Test No.	IFA	IFA Measured Exit Steam Quality	APED Code Calculated Exit Steam Quality	Relative Difference	
		(1) (wt percent)	(2) ^(a) (wt percent)	Difference (2)-(1) (wt percent)	$\left(\frac{(2)-(1)}{(1)} \right)$ (percent)
1A	A	2.54	2.91	0.37	14.5
1A	D	5.65	6.06	0.41	7.2
3	A	6.10	6.71	0.61	10.0
3	D	9.84	11.70	1.86	18.9
5	A	7.46	7.58	0.12	1.6
5	D	13.35	15.38	2.03	15.2
6	A	6.17	6.77	0.60	9.7
6	D	12.16	11.96	-0.20	-1.6
7	A	—	9.7	—	—
7	D	11.84	13.0	1.16	9.7
8	A	10.02	10.9	0.88	8.8
8	D	16.41	17.1	0.69	4.2
9	A	—	10.5	—	—
9	D	14.59	14.8	0.21	1.4

rms = ±10.15 percent
average = 8.56 percent

(a) The values of the exit steam quality correspond to the calculated channel flow and power as indicated in Tables 4-23 and 4-25.

TABLE 4-29

COMPARISON OF MEASURED WITH CALCULATED EXIT STEAM QUALITY
USING THE APED DESIGN CODE II (CHIMNEY EFFECT INCLUDED)

Test No.	IFA	IFA Measured Exit Steam Quality	APED Code Calculated Exit Steam Quality	Relative Difference	
		① (wt percent)	② (wt percent)	Difference ②-① (wt percent)	$\left(\frac{②-①}{①}\right)$ (percent)
1A	A	2.54	2.9	0.36	14.17
1A	D	5.65	6.2	0.55	9.73
3	A	6.10	6.1	0	0
3	D	9.84	10.5	0.64	6.50
5	A	7.46	6.9	-0.56	-7.50
5	D	13.35	14.3	0.95	7.11
6	A	6.17	6.8	0.63	10.21
6	D	12.16	11.9	-0.26	-2.14
7	A	-	8.3	-	-
7	D	11.84	11.6	-0.24	-2.0
8	A	10.02	9.9	-0.12	-1.2
8	D	16.41	15.7	-0.71	-4.32
9	A	-	9.6	-	-
9	D	14.59	13.4	-1.19	-0.81

rms = ±6.93
Average = 5.47 percent

- (a) The values of the exit steam quality correspond to the calculated channel flow and power as indicated on Tables 4-24 and 4-25.

FIGURE 4-29. COMPARISON OF MEASURED TO CALCULATED CHANNEL FLOW RATE USING APED DESIGN CODES I AND II (CHIMNEY EFFECT INCLUDED)

FIGURE 4-30. COMPARISON OF APED CODE CALCULATION WITH MEASURED DATA FROM THE INSTRUMENTED FUEL ASSEMBLY

Calculations of core pressure drop from the APED computer indicate that slightly different results are obtained using Code I or Code II. The results are plotted versus the core leakage flow coefficient in Figure 4-31. For the calculation, the reactor total recirculation flow rates indicated in Table 4-1 were assumed for the different test conditions. For Test 1A, the measured core pressure drop is indicated. The local loss coefficient of the standard fuel element lower tie plate was determined as indicated in subsection 4.4.5.

4.4.4 Core Leakage Flow Determination

The following procedure was used to determine the core leakage flow coefficient using the measured flow rate from the instrumented fuel assemblies.

- a. Because of the presence of crud deposit on the lower tie plate of the standard fuel elements, it was first necessary to determine the lower tie plate flow area reduction as indicated in subsection 4.4.5. For Test 1A, the measured core pressure drop value of 0.53 kg/cm^2 , reactor total recirculation flow rate of 9,720 MT/h, and core leakage flow coefficient of 13.5 percent were assumed.
- b. For Tests 3 through 9, no measured values of core pressure drop were available. The core pressure drop was calculated assuming the available values of the reactor total recirculation flow rate and varying the core leakage flow coefficient for each test condition (Figures 4-32a and 4-32b).
- c. With the values of the core pressure drop obtained, the channel flow rate was calculated for the individual instrumented fuel assemblies, considering the effect of the outlet turbine flow-meter housing, which constitutes a chimney at the fuel channel outlet.
- d. The values of calculated and measured channel flow rate for the instrumented fuel assemblies were then compared (Figures 4-32a and 4-32b). When an agreement within ± 5 percent was found, the corresponding core leakage flow coefficient was considered a reliable value.

When measured core pressure drop values are available, this procedure allows for a double-check of the core leakage flow coefficient as determined with the procedure indicated in subsection 4.4.3.

This procedure was necessary because the core leakage flow cannot be directly measured. During the reactor tests, a core leakage flow coefficient was assumed for each test condition in order to perform the on-line computer calculation. The values have been given in Table 4-24. The instrumented fuel assembly channel flow rate calculation has shown a large effect of the assumed core leakage flow coefficient on the calculated IFA flow rate. In Figures 4-32a and 4-32b, the results of the IFA channel flow calculation with the APED Thermohydraulic Code for Tests 1A, 3, 5, 6, 7, 8, and 9, are compared with the IFA measured channel flow rate.

The core leakage flow coefficients that make it possible to calculate the same channel flow rate as measured at each experienced test condition are indicated in Table 4-30. As a reference, the values assumed for the on-line computer calculation are also given. It is noted that the total recirculation flow for each test condition was chosen the same as calculated at the time of the reactor tests. These values could be slightly incorrect, having been calculated and not measured, and the derived values of the core leakage flow coefficients may result in being incorrect also.

FIGURE 4-31. CALCULATED CORE PRESSURE DROP VERSUS CORE LEAKAGE FLOW COEFFICIENT
(APED CODE CALCULATIONS)

TABLE 4-30
CORE LEAKAGE FLOW COEFFICIENT DE-
RIVED FROM THE INSTRUMENTED FUEL
ASSEMBLIES AND APED CODE II DATA

Test No.	Core Pressure Drop (psi)	Derived Core Leakage Flow Coefficient (percent)	On-Line Computer Leakage Flow Coefficient (percent)
	(a)	(b)	
1A	7.53	13	13.5
3	3.69	10.5	10
5	3.64	9	10
6	3.64	10	10
7	2.58	10	8
8	2.58	8	7
9	2.56	8	7

- (a) Core pressure drop from APED Code II calculations, when considering the chimney effect of the outlet turbine flowmeter at the fuel element channel outlet.
- (b) Core leakage flow coefficient derived from Figure 4-31.

4.4.5 Analysis of the Effects of Crud Deposits on the Standard Fuel Elements, Lower Tie Plates—Core Pressure Drop Calculation versus Standard Fuel Element Lower Tie Plate Flow Area

The crud deposits, accumulated on the standard fuel element lower tie plates during the previous reactor operation period, had partially obstructed their flow areas. To take into account the effect of these deposits on core pressure drop and channel flow rate, two different approaches were used:

- (a) In the first approach, leaving the value of the local loss coefficient of the standard fuel element tie plates the same as nominal, the lower tie plate flow area was reduced until the meas-

ured core pressure drop of Test 1A, 0.53 kg/cm^2 ,⁽⁷⁾ was calculated (Figure 4-33).

- (b) In the second approach, leaving the lower tie plate flow area the same as nominal, the equivalent local pressure loss coefficient of the standard fuel element lower tie plate was increased until the same value as the measured core pressure drop was calculated (Figure 4-34).

For the calculation, the total recirculation flow rate of 9,720 MT/h and the core leakage flow coefficient of 13.5 percent were assumed. The results in the first approach were that a standard fuel element lower tie plate flow area reduction was calculated, equivalent to about 15.5 percent of nominal, and in the second approach a lower tie plate equivalent loss coefficient of about 16.

Neither of these models represents the actual phenomenon, which consists of a simultaneous decrease of the lower tie plate flow area and an increase of the equivalent local loss coefficient. However, both allow us to calculate theoretically the measured core pressure drop and channel flow rate.

Figures 4-33 and 4-34 show the results of the core pressure drop calculation decreasing the standard fuel element lower tie plate flow area, and increasing the equivalent local loss coefficient, respectively. On the figures, the results of the calculations are given for both cases in which the loss due to the presence of the control rod guide tubes at the bottom of the core are considered or neglected.

4.4.6 Calculation of the Effect of Increased Channel Flow Rate on MCHFR

In Figure 4-35, the results of the calculation of MCHFR for the instrumented fuel

FIGURE 4-32a. CHANNEL FLOW RATE VERSUS CORE PRESSURE DROP (APED CODE I CALCULATIONS)

FIGURE 4-32b. CHANNEL FLOW RATE VERSUS CORE PRESSURE DROP (APED CODE II CALCULATIONS)

FIGURE 4-33. CORE PRESSURE DROP VERSUS LOWER TIE PLATE FLOW AREA REDUCTION (TEST 1A CONDITIONS)

FIGURE 4-34. CORE PRESSURE DROP VERSUS STANDARD FUEL ELEMENT LOWER TIE PLATE LOSS COEFFICIENT

FIGURE 4-35. MINIMUM CRITICAL HEAT FLUX RATIO VERSUS RELATIVE TOTAL POWER PEAKING FACTOR

assembly and the standard fuel element are plotted versus the relative total peaking factor.* From this, the positive effect that the increase of channel flow rate has on MCHFR is apparent. In Table 4-13, the channel flow ratio of the instrumented fuel assembly has been given. It is concluded that with the reactor with two

loops in forced circulation, the increase in channel flow rate of 70 percent decreases the MCHFR about 0.6 over a large range of power. In natural circulation, the MCHFR will be decreased about 0.7 (with the reactor either in two-loop or one-loop natural circulation) for a flow increase of about 50 percent.

*The relative total power peaking factor is defined as the total power peaking factor (product of radial, axial, and local power factors) multiplied by the relative reactor power [ratio of the considered reactor power and nominal power, 506 MW(t)]. The relative total power peaking factor is therefore proportional to the fuel element peaking power.

From the heat transfer viewpoint, this effect may be of limited interest when the reactor is operated at nominal power; its significance assumes a larger weight when reactor uprating is considered, and when the MCHFR limit is lowered to values that slightly exceed the present design limit.

APPENDIX A

DESCRIPTION OF THE INSTRUMENTED FUEL ASSEMBLY DESIGN AND
SYSTEM COMPONENTS

A.1 FLOWMETERS

The flowmeters measured the volumetric flow rate of coolant passing into and out of the fuel bundle. They were of the turbine type, similar in design to those of the Consumers R&D Program, Phase II. They consisted of a rotor and a pickup coil, plus bearings and housing. The blades were twisted in order to minimize the pressure drop (free and locked rotor). The two flowmeters of each assembly—one at the channel inlet and one at the channel outlet—were identical in design except for diameter. The size of the outlet meter was designed so that at rated reactor conditions, the rotational speed was the same as the speed of the inlet flowmeter. See Figures A-1a and A-1b.

A completed inlet flowmeter is shown in Figure A-2. The inlet flowmeter housing was 18 inches long and 4 inches in outside diameter. The outlet flowmeter housing was 16 inches long and 5-1/2 inches in outside diameter. The turbine flowmeter assembly is shown outside of the housing. The retainer ring is used to fix it into the housing. The nosepiece to be welded at the housing inlet is also shown.

Figure A-3 is a photo of the flowmeter parts assembled into the rotor and bearing housings. The sleeve and retainer rings are used to position the bearings in their proper relationship in the final assembly; they are also shown disassembled in Figure A-4. Figure A-5 is an exploded view of the precision parts making up the turbine flowmeter assembly. Figure A-6 shows the turbine flowmeter shaft and graphite bushings.

A.1.1 Rotor

The flowmeter had a six-bladed, turbine-type rotor. The rotor was a precision, stainless steel casting. As the coolant turned the rotor, the attached 12-tooth armature cut the magnetic fields set up by the pickup coil, inducing an a-c voltage in the pickup coil.

Electrical output was generated by means of the 12-tooth armature through the three-prong fingers to the pickup coil.

A.1.2 Pickup Coil

Each flowmeter required a pickup coil to sense the speed of the rotor. The pickup coil contained 3000 turns of ceramic-insulated magnet wire wound on a ceramic-insulated Hy Mu 80 bobbin and energized by approximately 10 mA dc. The rotor cut the induced magnetic fields 12 times each revolution, producing an a-c component with a frequency proportional to flow rate. The a-c frequency was 12 times the frequency of rotation, and was approximately 0.02 volt, peak to peak. The coil was enclosed in a pressure-proof, stainless steel capsule and attached to an aluminum-insulated cable. Figure A-7 shows a flowmeter pickup coil before assembly. The magnetic poles were inserted between the fingers (see Figure A-5). The signals from the flowmeter pickup coils went to a portion of the readout panel designated as flow rate electronics.

A.2 FLOW RATE ELECTRONICS

The flow rate electronics converted the a-c outputs of the flowmeters to pulsed outputs

to the scaler jacks, and also to 0- to 80-mV dc signals proportional to the rotational rate of the flowmeter. The flow rate electronics consisted of two 4-channel signal conditioners (Figure A-8), eight linear count rate meters (Figure A-9), and eight filter networks.

The signal conditioners separated the a-c component of the flowmeter output from the 5-volt coil energizing d-c voltage, amplified the a-c portion, and sent pulse signals to the linear count rate meter.

The linear count rate meters converted the input pulse frequencies to a linear d-c voltage, sent pulses to the scaler output jacks, and sent a d-c voltage (0 to 80 mV), proportional to the input frequency, to the recorders and on-line computer.

A.3 THERMOCOUPLES

Chromel-alumel thermocouples sensed the temperature of the reactor coolant. The thermocouple consisted of wires of chromel and alumel, joined to form a loop circuit.

The thermo-electric power of a chromel-alumel thermocouple is approximately $40 \mu\text{V}/^\circ\text{C}$ over the range of 250 to 1000°C . Temperature differences of as little as $1/10$ degree could be detected. The thermocouples were insulated with high-purity alumina and enclosed in $1/16$ -inch-diameter stainless steel tubing. Each thermocouple was terminated in a hermetically-sealed, two-pin connection.

In each instrumented assembly, two of the thermocouples measured the temperature of the incoming water, and two measured the temperature of the outgoing water. Three of the thermocouples had grounded junctions to hasten reaction time and to minimize the effects of gamma ray heating, and one of the thermocouples had an ungrounded junction to allow series opposition connection for Δt measurements.

The signal from the thermocouples went to a section of the readout panel designated as Temperature Electronics.

A.4 TEMPERATURE ELECTRONICS

The Temperature Electronics converted the -0.68 to +12.86 mV dc output from the thermocouples to a 0 to 80 mV output to the recorders. Any four thermocouple outputs could be patched to the recorders, or any eight could be connected to external recorders or the computer.

The electronics consisted of eight millivolt-to-current transmitters (Figure A-10) and four temperature indicator modules (Figure A-11). The millivolt-to-current transmitters were each equipped with three different interchangeable range plug-in units. The input ranges of the plug-in units corresponded to 0 to 600°F , 500 to 600°F , and 0 to 100°F . The outputs of the thermocouples could be patched in various ways to record various parameters. Each millivolt-to-current transmitter sent a 10- to 50-mA signal to the temperature indicators.

Each temperature indicator accommodated two millivolt-to-current transmitters. The temperature indicators converted the 10- to 50-mA signal from the millivolt-to-current transmitters into a 0- to 80-mV output for the recorders and computer, and a 0- to 800-mV output for expanded scale operation. The temperature indicator also provided a 0 to 100°F reading on the front panel meter.

A.5 INSTRUMENT PROBE AND CHANNEL ADAPTER

The probe (Figure A-12) was designed to replace the center fuel rod of a standard 81-rod fuel bundle. It was 132 inches long and 0.54 inch in outside diameter.

FIGURE A-1a. INLET TURBINE FLOWMETER

FIGURE A-2. COMPLETED INLET FLOWMETER, NOSEPIECE, AND HOUSING

FIGURE A-3. TURBINE FLOWMETER ASSEMBLY WITHOUT THE HOUSING – SEEN FROM THE INLET SIDE

FIGURE A-4. TURBINE FLOWMETER-PARTIALLY ASSEMBLED-AND SLEEVE

FIGURE A-5. TURBINE FLOWMETER-EXPLODED VIEW

FIGURE A-6. TURBINE FLOWMETER SHAFT AND GRAPHITE BUSHINGS

FIGURE A-7. FLOWMETER PICKUP COIL BEFORE ASSEMBLY

FIGURE A-8. SIGNAL CONDITIONER (FRONT AND REAR VIEWS)

FIGURE A-9. LINEAR COUNT RATE METER (FRONT AND REAR VIEWS)

FIGURE A-10. MILLIVOLT TO CURRENT TRANSMITTER (FRONT AND REAR VIEWS)

FIGURE A-11. TEMPERATURE INDICATORS (FRONT AND REAR VIEWS)

The probe tube housed the pickup coils, the thermocouples, and relative leads. The channel adapter provided support for the probe tube and support for the outlet flowmeter. The channel adapter formed a seal between the top of the channel and the outlet flowmeter (Figure A-13).

The fuel channel was extended about 2 inches to provide a seat and fluid seal for the upper flowmeter housing. A hold-down bolt was provided on the channel adapter to keep the probe from working out of the fuel bundle during reactor operation.

A.6 FLEXIBLE CONDUIT AND CABLE CLAMPS

A stainless steel flexible hose protected the thermocouple, pickup coil, and ion chamber cables from damage.

The flexible conduit went from the tube of the outlet flowmeter adapter to the vessel penetration plug. It was approximately 20 feet long and 3/4 inch in diameter.

Cable clamps were installed on the rim of the center opening of the turning vane, to minimize vibration of cables and tubes.

A.7 VESSEL PENETRATION PLUG

Each instrumented assembly had an individual penetration plug (Figure A-14). The penetration plug made a watertight, pressure-tight seal as it passed through a special four-hole reactor vessel flange. The individual stainless-steel-jacketed leads were brazed into the plug. Locating pins prevented rotation while the plug was being tightened. The pressure seal between the plug and the flange was formed by a gold-plated, K-type seal. A nut and 3000-pound Belleville spring washer provided the proper preloading and seating of the seal.

The special flange on the head of the reactor vessel was an ASME Section VIII Code-designed, 14-inch, 900-pound flange. The flange was thicker than a normal flange to allow for the four penetration holes.

A.8 MODIFIED FUEL BUNDLE

The four instrumented fuel bundles (Figure A-15) were spare standard 9 x 9 rod fuel elements slightly modified as follows:

- a. Each bundle contained 80 fuel rods, because the center rod was removed to accommodate the instrument probe.
- b. The upper and lower fuel rod spacers and tie plates allowed for easy insertion of the instrument probe with the fuel bundle in the reactor.
- c. The Zircaloy-4 channel was extended 2 inches at the top to make a seal with the outlet flowmeter adapter.
- d. The handle was modified to rotate to the side, leaving the center of the fuel bundle open to receive the instrument probe.

A.9 MODIFIED ORIFICE CUP

The lower turbine flowmeter housing was attached to a modified orifice cup. The cup design was similar to the standard, with the exception of an increase of the orifice diameter and an additional skirt on the bottom for attaching the inlet flowmeter (Figure A-16). Pins on the flowmeter housing locked into the slots on the orifice. After calibration was complete, the orifice and the flowmeter were welded together.

The orifice diameter (standard design 2.780 inches) was increased 4.00 inches inside diameter to compensate for the flowmeters'

FIGURE A-12. INSTRUMENTED ASSEMBLY PROBE, CABLE, AND PENETRATION UNIT

FIGURE A-13. INSTRUMENT PROBE, SHOWING OUTLET FLOWMETER ADAPTER

FIGURE A-14. PENETRATION UNIT DURING ASSEMBLY, BEFORE WELDING OF THE PARTS

FIGURE A-16. MODIFIED ORIFICE CUP

additional pressure drop and assure safe operation of the bundle even with both the turbines stopped.

A.10 READOUT PANEL AND STRIP CHART RECORDERS

The instrumentation system readout panel (Figure 1-2) was located in the computer room. The readout panel contained eight millivolt-to-current transmitters, four temperature indicators, two signal conditioners, eight linear count rate meters, two component boards, four types of power supplies [one type for the in-core (+115 volt, 100 volt, 85 volt), (Figure A-17), a second type also for the in-core (± 15 volt), (Figure A-18), a third type for the flow rate meters and the temperature indicators (± 24 volt), (Figure A-19)], two recorders, and a patch panel. The functions of the readout panel could be separated into temperature function, flow rate function, and recording function.

Also included were the electronics for the movable ion chambers and signal condi-

tioning for the standard plant fixed in-core monitoring system.

The flow rate function and the temperature function have been already described in subsections A.2 and A.4.

The recorder function connected and recorded 0- to 80-mV analog signals from the temperature function, the flow rate function, or a variety of external signals from the stability test instrumentation and control rod oscillator. The functions were manually patched into the recorder on the patch board (Figure A-20) and the on-line computer.

The two recorders each recorded simultaneously two channels of 0- to 80-mV analog information. The scales on charts were linear 0-100 divisions. A simplified block diagram of the readout panel electronics is shown in Figure A-21. The elementary schematic diagram of the flow rate and temperature metering system is included in Figure A-22. The electrical cable routing of the instrumentation, including the control rod oscillator, is shown in Figure A-23.

FIGURE A-17. IN-CORE POWER SUPPLY (FRONT AND REAR VIEWS)

FIGURE A-18. ± 15 -VOLT POWER SUPPLY (FRONT AND REAR VIEWS)

FIGURE A-19. ± 24 -VOLT POWER SUPPLY (FRONT AND REAR VIEWS)

FIGURE A-20. PATCH BOARD

FIGURE A-21. SIMPLIFIED BLOCK DIAGRAM OF READOUT PANEL

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FIGURE A-23. ELECTRICAL CABLE ROUTING

APPENDIX B

MOVABLE ION CHAMBER DESIGN AND
DESCRIPTION OF THE SYSTEM COMPONENTS

**B.1 MOVABLE ION CHAMBERS AND
STANDARD FLUX MONITORS**

The in-core flux monitoring system comprised two systems: a fixed in-core monitoring system which was part of the standard plant instrumentation, and a special movable in-core monitoring system. The fixed in-core monitoring system was used to measure the neutron flux at specific points in the reactor core. The special movable in-core monitoring system provided a method of making direct measurements of the neutron flux axial profile. The need for flux wire guide tubes was also foreseen, in the four preselected positions of the movable ion-chambers, but they could not be installed because of space limitations.

**B.1.1 Standard Fixed In-Core
Monitoring System**

This system consisted of 20 radially-located channels of instrumentation, each with four, fixed, U-235-coated, in-core ion chambers spaced axially per channel. The current output signal from each ion chamber was applied to an in-core flux amplifier. The in-core flux amplifier converted the input to a voltage, amplified it, and provided an output voltage proportional to the input current. Because of the design of the in-core flux amplifiers, this output voltage was not referenced to ground but to +100 vdc. To condition this signal for recording and analysis, the +100 vdc reference component was removed from the in-core flux amplifier output voltage. The removal of the 100 vdc component was accomplished by a specially-designed instrument

called a flux converter. Twenty flux converter channels (Figure B-1) provided 20 separate output signals, each one representing the flux level seen by a fixed in-core ion chamber at a specific location in the reactor core.

B.1.2 Movable In-Core Monitoring System

The second in-core flux monitoring system was designed to utilize the inputs from the movable in-core ion chambers. The movable in-core ion chambers were B-10 coated miniature ion chambers that could be axially moved at a constant rate from the top to the bottom of the core at each of in-core locations 106, 109, and 112 (Figure 3-1). The locations were next to the corners of three of the four instrumented fuel assemblies (Assemblies "A", "B", and "C"). At each of these locations, an in-core flux monitoring system, which is shown in Figure B-2, was located. It included:

- a. A standard in-core flux detector system with four fixed chambers each modified to replace the 1/8-inch flux wire guide tube by a 1/4-inch outside diameter, 0.049-inch wall guide, nitrided stainless steel tube in each assembly.
- b. A subminiature in-core detector, 0.090-inch outside diameter (Figure B-3) mounted, inside of the 1/4-inch guide tube on the end of a 35-foot-long, 0.125-inch-outside diameter, steel-jacketed triaxial cable.
- c. A chamber drive mechanism (Figures B-4, B-5, and B-6).

FIGURE B-1. FLUX CONVERTER (FRONT AND REAR VIEWS)

FIGURE B-3. MOVABLE IN-CORE NEUTRON FLUX DETECTOR

Three flux monitor modules (Figure B-7), mounted in the instrumented assembly readout panel, controlled the position of the movable chamber and displayed position and flux signals. Trip circuits allowed the chamber to be moved only between preset limits.

The drive mechanism was positioned immediately below and connected to the in-core detector assembly. Its function was to position the movable ion-chamber. The drive mechanism was contained in a cylindrical housing approximately 8.6 inches in diameter and 21.6 inches high. Its weight was approximately 4 pounds.

The drive mechanism was composed of

- a. A driver, consisting of a reversible drive motor (1/15 hp, 500 rpm, 115 volts, 50 cps), and a 745:1 reducing gear box which transmitted torque to a driving wheel (3-inch-diameter). The driving wheel engaged the in-core detector cable to which a 50-pound-maximum starting force and a 10-pound-maximum running force (at a speed of 1.000 inch/sec) were transmitted.
- b. An idling wheel (3-inch-diameter), which drove a position indicating potentiometer and was provided with springs to clamp the ion chamber cable between the two wheels with the necessary friction force.
- c. A potentiometer (1000 ohm, 10 turn), which delivered a voltage indicating the axial position of the in-core detector in the core.
- d. A limit switch, which removed the "insert" excitation voltage from the drive motor when the in-core detector was fully inserted and permitted the detector to be withdrawn only.

The elementary schematic diagram of the flux detector system is shown in Figure B-8.

The subminiature in-core detector (movable chamber) was a 0.125-inch-outside diameter by 0.247-inch-long, boron-coated, neutron-sensitive ion chamber. The use of a boron coating on the chamber ensured that the maximum operating temperature (650 °F) would not be exceeded. Depletion of the boron with accumulated neutron exposure was expected to reduce the chamber sensitivity to 50 percent of initial sensitivity after about 1.9×10^{20} nvt exposure. This means that with the chamber left in the peak reactor flux for about 70 hours, the sensitivity of the chamber would have been reduced by about 5 percent.

Sensitivity versus exposure follows the equation:

$$S = S_0 e^{\left(\frac{-nvt}{2.7 \times 10^{20}} \right)},$$

where

S = sensitivity at time t ,

S_0 = sensitivity at time 0,

nv = neutron flux (thermal), and

t = time.

Because of the decrease in sensitivity with exposure, the chambers had to be retracted out of the high-flux region when measurements were not being made.

Calibration of the movable chambers was made by following the same procedures used for wire irradiations; the integral flux curve was equated to channel power to normalize the values. Traverses with the movable chambers could not be made during wire irradiations nor their results compared because of the dimensional problem which also prevented installation of the flux wire guide tube.

FIGURE B-4. DRIVE MECHANISM FOR MOVABLE CHAMBERS

REV NO. 01

TITLE ELEM DIAG

CONT ON SHEET

SH NO.

159A2925

DRIVE MECHANISM

CONT ON SHEET

SH NO.

FIRST MADE FOR INSTRUMENTED FUEL SYSTEM

FCF 237E640

REVISIONS

MADE BY *R. Bacon May 28, 1965*
 ISSUED *May 28-1965*

APPROVALS
ACD 5-28-65

APED
 SAN JOSE

DIV OR
 DEPT.
 LOCATION

CONT ON SHEET

159A2925

SH NO.

FIGURE B-5. ELEMENTARY DIAGRAM FOR MOVABLE CHAMBER DRIVE MECHANISM

IN-CORE
INSTRUMENT
THIMBLE (20)

CONTROL
ROD DRIVE
THIMBLES (89)

FIGURE B-6. INSTALLATION OF THREE MOVABLE CHAMBER DRIVE MECHANISMS
UNDER THE REACTOR

FIGURE B-7. IN-CORE FLUX MONITOR FOR MOVABLE CHAMBER (FRONT AND REAR VIEWS)

B-13/B-14

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APPENDIX C

PART 1

ON-LINE COMPUTER INSTRUMENTED ASSEMBLY LOG

OD-15 Instrumented Assembly Log

OD-15.1 Description

This log presents information obtained from the four instrumented assemblies and compares these values with the values calculated during the normal hourly cycle.

Table OD-15-A Input to the Instrumented Assembly Log

Symbol	Description	S. F.	Units	Origin
IFA	Inlet Flowmeter "A"	B10	pulses/sec	Scan
IFB	Inlet Flowmeter "B"	B10	pulses/sec	Scan
IFC	Inlet Flowmeter "C"	B10	pulses/sec	Scan
IFD	Inlet Flowmeter "D"	B10	pulses/sec	Scan
OFA	Outlet Flowmeter "A"	B10	pulses/sec	Scan
OFB	Outlet Flowmeter "B"	B10	pulses/sec	Scan
OFC	Outlet Flowmeter "C"	B10	pulses/sec	Scan
OFD	Outlet Flowmeter "D"	B10	pulses/sec	Scan
ITA	Inlet Temperature "A"	B10	°C	Scan
ITB	Inlet Temperature "B"	B10	°C	Scan
ITC	Inlet Temperature "C"	B10	°C	Scan
ITD	Inlet Temperature "D"	B10	°C	Scan
OTA	Outlet Temperature "A"	B10	°C	Scan
OTB	Outlet Temperature "B"	B10	°C	Scan
OTC	Outlet Temperature "C"	B10	°C	Scan
OTD	Outlet Temperature "D"	B10	°C	Scan
WFA	Secondary Feedwater Flow "A"	B11	MT/hr	Scan
WFB	Secondary Feedwater Flow "B"	B11	MT/hr	Scan
DHS	Core Inlet Subcooling	B10	-	C18
VFG	Specific Volume Change of Evaporation at Reactor Pressure	B7	cm ³ /g	C1
VRL	Specific Volume of Saturated Liquid Inside Vessel	B3	cm ³ /g	C1
HIL	Reactor Inlet Plenum Saturated Liquid Enthalpy	B10	cal/g	C1
HFG	Enthalpy Change of Evaporation at Reactor Pressure	B10	cal/g	C1
QR	Core Thermal Power	B11	10 ⁶ kg-cal/hr	C1
A06	Internal Monitor 106-A	B8	Percent	Scan
B06	Internal Monitor 106-B	B8	Percent	Scan
C06	Internal Monitor 106-C	B8	Percent	Scan
D06	Internal Monitor 106-D	B8	Percent	Scan
A09	Internal Monitor 109A	B8	Percent	Scan
B09	Internal Monitor 109-B	B8	Percent	Scan
C09	Internal Monitor 109-C	B8	Percent	Scan
D09	Internal Monitor 109-D	B8	Percent	Scan
A12	Internal Monitor 112-A	B8	Percent	Scan
B12	Internal Monitor 112-B	B8	Percent	Scan
C12	Internal Monitor 112-C	B8	Percent	Scan
D12	Internal Monitor 112-D	B8	Percent	Scan
A15	Internal Monitor 115-A	B8	Percent	Scan
B15	Internal Monitor 115-B	B8	Percent	Scan
C15	Internal Monitor 115-C	B8	Percent	Scan
D15	Internal Monitor 115-D	B8	Percent	Scan
PKIJ	Relative Nodal Power	B1	-	C4
W	Channel Flow Rate	B6	-	C3

OD-15.2 Calculationsa. Measured Channel Flow

$$WCH_{A, B, C, D} = \frac{0.40654}{VL} (IF_{A, B, C, D})$$

b. Measured Channel Exit Steam Quality

$$XEM_{A, B, C, D} = 2.04 \frac{IF_{A, B, C, D}}{OF_{A, B, C, D}} \frac{VL}{VFG} - \frac{VRL}{VFG}$$

c. Measured Channel Inlet Subcooling

$$DHMA_{A, B, C, D} = HIL - 16.9953 + (0.7805 + (0.000749 \cdot (IT_{A, B, C, D})) \\ (IT_{A, B, C, D}) + 0.01126 \text{ PPS})$$

d. Channel Relative Power

$$PWR_{A, B, C, D} = (1.163)(10^{-3}) \cdot WCH_{A, B, C, D} DHMA_{A, B, C, D} + HFG \cdot XEM_{A, B, C, D}$$

e. Calculated Channel Exit Steam Quality

$$XE_{A, B, C, D} = \frac{PCH_{A, B, C, D} \cdot QR \cdot 100}{W_{A, B, C, D} \cdot HFG \cdot 208} - \frac{DHS}{HFG}$$

$$PCH_{A, B, C, D} = \text{Calculated Channel Power}$$

f. Secondary Flow

$$WSS = WFA + WFB$$

	A	B	C	D
Core Location	7108	5908	6112	5516
TEMP OUT (CORE ΔT)	0-100F	0-100F	0-100F	0-100F
TEMP IN	0-600F	0-600F	500-600F	500-600F
FLOW IN	0-200 cps	0-200 cps	0-200 cps	0-200 cps
FLOW OUT	0-200 cps	0-200 cps	0-200 cps	0-200 cps

$$IFA, IFB, \dots, OFC, OFD = (2.5000) \cdot (\text{Scan mV})$$

$$ITA, ITB = (-17.78) + (4.1667) \cdot (\text{Scan mV})$$

$$ITC, ITD = 260.00 + (0.69445) \cdot (\text{Scan mV})$$

$$OTA, \dots, OTD = (0.69445) \cdot (\text{Scan mV})$$

Table OD-15-B Typewriter Output

<u>Symbol</u>	<u>Description</u>	<u>S. F.</u>	<u>Units</u>	<u>Origin</u>
DAY	Day	B19	-	M-ITC
MONTH	Month	B19	-	M-ITC
YEAR	Year	B19	-	M-ITC
-	Log Title	-	-	-
QRW	Core Thermal Power	B13	MWT	C1
MWG	Gross Power Output	B14	MW	C1
PRV	Reactor Vessel Pressure	B7	kg/cm ²	Scan
PPS	Primary Steam Drum Pressure	B7	kg/cm ²	Scan
PSA	Secondary Steam Generator "A" Pressure	B7	kg/cm ²	Scan
PSB	Secondary Steam Generator "B" Pressure	B7	kg/cm ²	Scan
HBRC	Hourly Minimum Critical Heat Flux Ratio	B7	-	C8
WFP	Primary Feedwater Flow	B11	MT/hr	Scan
WSS	Secondary Flow	B11	MT/hr	OD-15
WR	Recirculation Flow	B15	MT/hr	C17
CEXP	Core Average Fuel Exposure	B15	MWD/MT	L2
-	Failed Sensor List	-	-	-
-	Off-Limit Sensor List	-	-	-
PCH	"Calculated" Channel Power	B1	-	OD-15
PWR	"Measured" Channel Power	B1	-	OD-15
WIJ	"Calculated" Channel Flow	B6	MT/hr	C3
WCH	"Measured" Channel Flow	B6	MT/hr	OD-15
XE	"Calculated" Channel Exit Steam Quality	B1	-	OD-15
XEM	"Measured" Channel Exit Steam Quality	B1	-	OD-15
DHS	Core Inlet Subcooling	B10	-	C18
DHM	"Measured" Channel Inlet Subcooling	B10	-	OD-15
DPR	Core Pressure Drop	BO	kg/cm ²	C2
ITA	Inlet Temperature	B10	°C	Scan
OTA	Outlet Temperature	B10	°C	Scan

GEAP-5623

APPENDIX C

PART 2

ON-LINE COMPUTER INSTRUMENTED ASSEMBLY LOG TYPEWRITER OUTPUT

RESULTS - TEST 1A, May 23, 1966

23 5 66 11 INSTRUMENTED ASSEMBLY LOG

492.6 154.7 70.5 69.1 48.7 48.2 3.01 687 195. 9724 19.2 4736

A07 A04 DPC PB1 T04 A20 A17 A15 A11 A08

0.981	0.501	1.156	0.025	1.190	0.006	1.278	0.649
54.20	71.55	52.84	3.21	52.68	0.81	50.71	67.25
0.02	0.02	0.02	0.14	0.02	0.14	0.01	0.05
19.22	69.93	19.22	74.55	19.22	71.52	19.22	72.39
0.48		0.14		0.14		0.49	
0.728		1.222		1.378		1.169	
1.729	56.5	1.930	52.1	2.209	53.6	1.877	55.3
1.694		2.326		2.634		2.159	
1.760	78.0	1.830	72.0	1.784	72.4	2.088	68.3
1.13		0.977		0.795		1.568	
0.687	43.1	0.556	37.8	0.438	36.6	0.893	40.6
0.408		0.301		0.260		0.357	
0.159	14.7	0.104	13.8	0.094	13.8	0.114	9.0

0.404

231	175	10	9	2	2	215	228
274	13	268	14	272	11	271	11

RESULTS - TEST 3, May 26, 1966

27 5 66 10 INSTRUMENTED ASSEMBLY LOG

386.7 118.1 69.5 68.7 41.6 41.1 3.94 522 152 4039 31.5 4736

	A02	DPC	PB1	PSB	PSA	A11	A08	A07	A06	A04
1.031	0.266		1.124	0.000		1.142	0.000		1.314	0.657
26.28	31.92		25.22	0.00		24.72	0.00		25.38	31.94
0.04	0.01		0.03	0.04		0.03	0.05		0.03	0.09
31.58	76.95		31.58	79.36		31.58	79.43		31.58	78.99
0.96			0.14			0.14			0.49	
0.481			0.905			1.026			0.810	
0.825	24.3		1.419	35.6		1.632	32.8		1.320	33.9
1.076			1.703			1.928			1.619	
1.316	43.5		1.619	62.9		1.683	51.0		1.770	59.8
1.530			1.235			1.035			2.022	
1.373	43.8		1.026	33.6		0.841	27.2		1.701	45.0
1.114			0.759			0.686			0.905	
0.535	17.1		0.326	11.5		0.302	12.6		0.362	10.5
0.351										
100	37		0	29		0	0		100	149
264	23		260	23		260	0		261	24

RESULTS - TEST 3, May 26, 1966 (Continued)

27 5 66 10 VALORI DI INGRESSO (Input Values)

386.7 118.1 69.5 68.7 41.6 41.1 3.94 522 152 4039 31.5 4736

	A02	DPC	PB1	PSB	PSA	A11	A08	A07	A06	A04
TD4	177.031	TD3	128.156	TD2	76.218	TD1	70.093			
TO3	146.031	TO2	112.375	TO1	70.718	T11	45.343			
TCR	36.093	TFW	178.000	TA1	272.888	TB1	272.576			
TAO	259.326	TBO	257.919	T1A	16.843	T1B	17.218			
TOA	26.312	TOB	23.312	TCU	238.794		0.000			
PPT	68.164	PST	41.061	PCD	0.058	PPS	68.791			
PSA	41.642	PSB	41.135	PX4	10.495	PX3	4.808			
PX2	2.277	WFP	522.613	WFA	76.761	WFB	75.390			
WPS	619.312	WSA	79.375	WSB	86.406	PA1	0.887			
PB1	0.901	PRV	69.523	DPC-	0.060	HDA	0.248			
HDB	0.266	PLS-	0.025	PLN	3.761	SLA-	8.955			
SLB-	1.970		0.000	KWG	118188.000	KW1	58212.000			
KW2	52712.000		0.000	CH1	73.843	CH2	74.343			
CH3	72.781	CH4	73.250	CH7	37.691	CHX	244.000			
A01	16.424	B01	43.725	C01	52.799	D01	27.750			
A02	8.250	B02	33.299	C02	39.000	D02	21.899			
A03	15.524	B03	48.975	C03	56.324	D03	32.024			
A04	10.274	B04	41.774	C04	47.699	D04	36.000			
A05	13.350	B05	43.424	C05	53.850	D05	29.174			
A06	11.549	B06	33.600	C06	62.924	D06	35.699			
A07	11.399	B07	29.024	C07	54.000	D07	32.174			
A08	10.875	B08	40.049	C08	50.250	D08	27.449			
A09	17.100	B09	43.875	C09	43.500	D09	24.375			
A10	14.174	B10	38.174	C10	52.725	D10	34.725			
A11	10.799	B11	28.424	C11	51.975	D11	33.449			
A12	12.600	B12	27.299	C12	51.074	D12	32.850			
A13	11.549	B13	40.725	C13	52.274	D13	29.625			
A14	14.625	B14	42.524	C14	48.674	D14	25.574			
A15	10.575	B15	45.074	C15	59.849	D15	33.975			
A16	10.799	B16	42.149	C16	53.174	D16	32.174			
A17	12.375	B17	43.574	C17	55.500	D17	31.725			
A18	15.524	B18	48.449	C18	54.524	D18	29.174			
A19	11.549	B19	33.750	C19	51.299	D19	28.424			
A20-	1.200	B20	54.824	C20	49.424	D20	1.799			
ITA	264.023	ITB	260.939	ITC	260.847	ITD	261.417			
OTA	23.873	OTB	23.720	OTC-	0.904	OTD	24.025			
IFA	100.623	IFB	0.000	IFC	0.000	IFD	100.123			
OFA	37.873	OFB	29.748	OFC	0.000	OFD	149.623			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			
	0.000		0.000		0.000		0.000			

RESULTS - TEST 5, May 30, 1966

30 5 66 8 INSTRUMENTED ASSEMBLY LOG

477.1	152.2	69.3	68.9	40.0	39.5	2.67	692	160	4090	33.5	4741
	DPC	PB1	WPS	PSB	PSA	OTC	ITD	ITC	D20	A20	
0.927	0.491		1.214	0.016		1.081		0.004	1.257	0.625	
25.68	32.20		23.96	3.16		24.75		1.04	23.78	30.83	
0.04	0.07		0.02	0.03		0.03		0.04	0.02	0.12	
33.55	78.07		33.55	80.93		33.55		80.83	33.55	80.25	
	0.47			0.15			0.13			0.50	
0.288			0.640			0.684			0.594		
0.486	19.2		1.000	30.8		1.077		30.2	0.976	27.0	
0.617			1.160			1.244			1.179		
0.751	30.3		1.182	50.0		1.165		39.1	1.259	45.9	
1.021			1.415			1.178			1.547		
1.614	61.4		2.054	55.4		1.493		54.6	2.062		
										73.6	
1.814			1.642			1.281			1.774		
0.826	53.7		0.622	37.0		0.526		41.0	0.666	33.8	
0.024											
101	129		9	151		3		0	96	178	
262	28		258	25		258		0	259	25	

3

RESULTS - TEST 6, May 31, 1966 (Power reduced to 75% of rated)

31 5 66 9 INSTRUMENTED ASSEMBLY LOG

	D20	A20	DPC	PB1	WFB	OFC	OTC		
379.7	121.5	68.6	67.8	56.0	55.4	3.49	654	5	4101 17.2 4747
	0.883	0.232	1.299	0.003	1.154	0.000	1.264	0.586	
	25.81	32.41	23.92	3.13	24.76	1.05	24.05	31.01	
	0.01	0.01	0.01	0.03	0.00	0.04	0.00	0.11	
	17.29	68.59	17.29	71.72	17.29	71.64	17.29	70.72	
	0.94		0.16		0.14		0.53		
	0.307		0.699		0.736		0.671		
	0.506	16.0	1.063	25.8	1.129	25.2	1.081	23.6	
	0.617		1.178		1.250		1.263		
	0.704	22.1	1.137	37.7	1.100	29.6	1.270	36.6	
	0.873		1.281		1.046		1.435		
	1.235	41.5	1.732	39.0	1.376	37.9	1.722	51.6	
	1.776		2.397		1.829		1.780		
	1.049	59.0	0.903	39.2	0.769	44.1	0.886	34.2	
0.020									
	104	117	9	126	3	0	99	168	
	273	16	269	14	269	0	270	14	

31 5 66 9 DATI DI IMPIANTO

	D20	A20	DPC	PB1	WFB	OFC	OTC		
379.7	121.5	68.6	67.8	56.0	55.4	3.49	654	5	4101 17.2 4747
	115.9	82.1	33.2	0.5	1579.4				
	2828	2636	86.804	68.092					
0.05	3.5	1.2	7.2	1.3	6.8	1.5	5.6	1.4	0.9 0.3
	4.8	0.8	5.8	0.7	5.3	1.9	3.4	1.6	

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RESULTS - TEST 7, May 31, 1966

31 5 66 18 INSTRUMENTED ASSEMBLY LOG

260.5	78.9	69.1	68.9	33.0	51.6	4.70	434	0	2340	21.9	4747
	DPC	PB1	WFB	WFA	PSA	D07	D04	D03	D02	D01	
0.887	0.031	1.222	0.005	1.101	0.002	1.164	0.571				
12.32	16.32	12.76	3.16	11.97	1.06	12.19	19.52				
0.00	0.04	0.01	0.04	0.00	0.04	0.01	0.11				
21.99	71.20	21.99	75.50	21.99	74.76	21.99	74.61				
0.11		0.15		0.13		0.50					
0.264		0.554		0.595		0.520					
0.436	9.8	0.796	13.5	0.898	13.6	0.780	12.7				
0.548		0.907		1.022		0.926					
0.663	13.3	1.015	20.1	0.985	16.5	1.088	20.6				
0.858		1.249		1.022		1.349					
1.231	30.7	1.754	28.2	1.406	27.2	1.698	37.4				
1.853		2.485		1.994		1.929					
1.239	45.9	1.019	31.3	0.888	33.2	1.021	26.7				
0.020											
52	0	9	0	3	0	61	103				
270	18	265	18	266	0	266	18				

9

2

RESULTS - TEST 8, May 1, 1966

1 6 66 19 INSTRUMENTED ASSEMBLY LOG

331.7	102.8	67.8	68.4	49.7	49.3	33.38	561	5	2421	23.7	4747
		D04	D02	DPC	PB1	WFB	OFB	OTC	D20	A20	
	0.837		0.002	1.248		0.006	1.115		0.003	1.193	0.048
	12.91		1.10	12.78		2.94	12.16		1.23	12.27	12.61
	0.00		0.04	0.02		0.04	0.02		0.04	0.02	0.03
	23.78		72.07	23.78		76.50	23.78		75.44	23.78	75.10
	0.10				0.15			0.13			0.14
	0.292			0.659			0.694			0.614	
	0.485		12.6	1.026		19.0	1.084		18.6	1.003	17.4
	0.598			1.196			1.237			1.216	
	0.674		17.5	1.229		33.0	1.115		22.6	1.306	29.1
	0.799			1.252			1.011			1.341	
	1.089		35.2	1.562		33.0	1.258		32.2	1.507	43.6
	1.649			2.161			1.746			1.662	
	1.109		47.1	0.903		39.2	0.775		37.3	0.893	22.2
0.020											
	3		25	9		0	3		0	39	129
	267		21	261		21	263		0	263	20

RESULTS - TEST 8, May 1, 1966 (Continued)

1 6 66 19 VALORI DI INGRESSO (Input Values)

331.7 102.8 67.8 68.4 49.7 49.3 3.38 561 5 2421 23.7 4747

	D04	D02	DPC	PB1	WFB	OFB	OTC	D20	A20
TD4	166.406		TD3	119.312	TD2		71.781	TD1	66.125
TO3	138.906		TO2	106.718	TO1		66.562	TI1	44.000
TCR	35.468		TFW	169.312	TAI		232.982	TBI	264.044
TAO	232.982		TBO	262.638	TIA		17.187	TIB	17.531
TOA	25.500		TOB	22.875	TCU		238.794		0.000
PPT	67.098		PST	48.936	PCD		0.061	PPS	68.491
PSA	49.770		PSB	49.320	PX4		8.498	PX3	3.932
PX2	1.950		WFP	561.882	WFA		5.957	WFB-	0.003
WPS	657.531		WSA	2.093	WSB		2.187	PA1	0.832
PB1	0.530		PRV	67.835	DPC-		0.061	HDA-	0.000
HDB	0.400		PLS-	3.812	PLN		2.224	SLA	12.281
SLB-	5.111			0.000	KWG	102852.000		KW1	68684.000
KW2	25872.000			0.000	CH1		62.968	CH2	61.906
CH3	62.375	CH4	63.531	CH7		21.338	CHX	144.000	
A01	50.850	B01	35.475	C01		18.825	D01	12.149	
A02	41.699	B02	30.299	C02		16.875	D02	11.174	
A03	33.524	B03	37.350	C03		24.674	D03	14.700	
A04	34.875	B04	31.125	C04		24.000	D04	11.924	
A05	39.449	B05	44.174	C05		25.350	D05	16.424	
A06	39.299	B06	33.000	C06		33.000	D06	19.049	
A07	47.475	B07	32.774	C07		28.125	D07	15.075	
A08	32.024	B08	38.549	C08		29.850	D08	19.049	
A09	47.174	B09	35.250	C09		17.549	D09	12.600	
A10	50.625	B10	42.750	C10		24.824	D10	18.600	
A11	37.875	B11	33.899	C11		28.649	D11	17.774	
A12	37.350	B12	32.250	C12		22.649	D12	18.674	
A13	37.199	B13	36.750	C13		26.924	D13	18.225	
A14	39.524	B14	33.000	C14		23.850	D14	13.575	
A15	22.274	B15	43.649	C15		29.100	D15	17.475	
A16	35.850	B16	43.574	C16		33.000	D16	19.799	
A17	29.024	B17	39.149	C17		29.699	D17	15.149	
A18	43.799	B18	40.350	C18		31.875	D18	19.125	
A19	39.524	B19	32.850	C19		21.299	D19	13.575	
A20-	1.200	B20	36.149	C20		22.875	D20	2.174	
ITA	267.609	ITB	261.939	ITC		263.294	ITD	263.724	
OTA	21.996	OTB	21.273	OTC-		0.876	OTD	20.730	
IFA	3.498	IFB	9.248	IFC		3.873	IFD	39.748	
OFA	25.998	OFB-	0.125	OFC		0.123	OFD	129.873	
	0.000		0.000			0.000		0.000	

RESULTS - TEST 9, June 1, 1966

2 6 66 0 INSTRUMENTED ASSEMBLY LOG

330.8	100.7	67.7	68.3	41.7	41.5	3.67	510	55	2364	29.5	4750
0.869	0.093	1.170	0.013	1.077	0.004	1.115	0.022				
12.46	20.79	11.82	3.21	11.89	0.95	12.03	4.08				
0.01	0.04	0.01	0.04	0.00	0.04	0.00	0.03				
29.57	74.90	29.57	79.07	29.57	78.02	29.57	78.04				
2.33		0.14		0.13		0.13					
0.244		0.601	0.597	0.489							
0.402	10.5	0.937	17.5	0.911	15.8	0.732	13.9				
0.505		1.115	1.034	0.870							
0.609	14.7	1.208	32.3	0.970	19.2	1.016	22.9				
0.801		1.327	0.930	1.265							
1.196	36.2	1.526	35.4	1.324	32.1	1.624	44.6				
1.970		1.732	1.930	1.941							
1.226	48.8	0.914	35.6	0.869	38.4	0.985	22.3				
0.020											
65	0	9	0	2	0	12	94				
263	26	258	24	259	0	259	24				

RESULTS - TEST 9, June 1, 1966 (Continued)

2 6 66 O VALORI DI INGRESSO (Input Values)

	330.8	100.7	67.7	68.3	41.7	41.5	3.67	510	55	2364	29.5	4750
TD4	166.406	TD3	120.656	TD2	71.750	TD1	66.281					
TO3	139.156	TO2	107.187	TO1	66.875	TI1	43.406					
TCR	34.250	TFW	169.781	TAI	231.263	TBI	265.451					
TAO	230.201	TBO	257.357	TIA	15.781	TIB	16.125					
TOA	24.156	TOB	21.187	TCU	238.794		0.000					
PPT	67.166	PST	41.104	PCD	0.057	PPS	68.342					
PSA	41.754	PSB	41.501	PX4	8.577	PX3	3.954					
PX2	1.963	WFP	510.335	WFA	7.058	WFB	48.710					
WPS	607.750	WSA	2.187	WSB	58.468	PA1	0.830					
PB1	0.779	PRV	67.704	DPC-	0.061	HDA-	0.000					
HDB	0.389	PLS	6.048	PLN	11.824	SLA	8.716					
SLB	0.703		0.000	KWG	100764.000	KW1	94336.000					
KW2-	1496.000		0.000	CH1	59.937	CH2	63.031					
CH3	58.718	CH4	61.812	CH7	18.541	CHX	99.000					
A01	53.774	B01	36.937	C01	17.399	D01	10.687					
A02	43.049	B02	32.812	C02	17.024	D02	10.612					
A03	34.049	B03	39.787	C03	24.299	D03	13.762					
A04	35.399	B04	31.537	C04	19.125	D04	9.487					
A05	39.975	B05	46.912	C05	24.975	D05	15.112					
A06	35.699	B06	35.437	C06	32.324	D06	17.512					
A07	47.250	B07	33.187	C07	23.699	D07	12.787					
A08	33.600	B08	38.287	C08	19.949	D08	14.587					
A09	48.824	B09	36.262	C09	14.700	D09	10.537					
A10	53.549	B10	44.362	C10	22.875	D10	16.462					
A11	37.875	B11	34.237	C11	24.299	D11	15.112					
A12	38.475	B12	32.137	C12	19.200	D12	15.862					
A13	39.524	B13	36.637	C13	21.149	D13	15.112					
A14	40.574	B14	33.862	C14	20.399	D14	11.512					
A15	22.350	B15	44.662	C15	22.949	D15	13.912					
A16	37.500	B16	43.012	C16	22.199	D16	15.337					
A17	30.975	B17	39.112	C17	24.149	D17	12.712					
A18	46.049	B18	40.387	C18	22.199	D18	16.312					
A19	40.424	B19	32.812	C19	17.924	D19	11.212					
A20-	1.274	B20	36.787	C20	19.500	D20	2.062					
ITA	263.773	ITB	258.437	ITC	259.777	ITD	259.748					
OTA	26.333	OTB	24.720	OTC-	0.904	OTD	24.582					
IFA	65.498	IFB	9.998	IFC	2.998	IFD	12.748					
OFA	0.623	OFB	0.000	OFC	0.000	OFD	94.498					
	0.000		0.000		0.000		0.000					
	0.000		0.000		0.000		0.000					

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