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FZK-263-2
29 OCTOBER 1965

NERVA MATERIALS IRRADIATION PROGRAM

Volume 2

GTR Test 16 — WANL Materials Test

Prepared for
Space Nuclear Propulsion Office
of the
National Aeronautics and Space Administration
Cleveland, Ohio

Contract No. AF 29(601)-6643
Supplement 2

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NUCLEAR AEROSPACE RESEARCH FACILITY

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NERVA MATERIALS IRRADIATION PROGRAM

Volume 2

GTR Test 16 — WANL Materials Test

10 E. E. Palmer
W. D. McMillan

37/W202 Cemented Orfices

15/W401 O-Ring Seals

37/W401 Tensile Specimens
Resistivity Specimens
Steel Springs

Prepared for
Space Nuclear Propulsion Office
of the
National Aeronautics and Space Administration
Cleveland, Ohio

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FOREWORD

GTR Test 16 is the first of two NERVA materials tests to be performed by the Nuclear Aerospace Research Facility (NARF) at General Dynamics/Fort Worth, under Supplemental Agreement No. 2, Contract AF29(601)-6643, for the Space Nuclear Propulsion Office, Cleveland, Ohio (SNPO-C). The 3-Mw Ground Test Reactor (GTR) was used as the source of nuclear radiation in these tests.

The test was designed to measure the combined effects of nuclear radiation and liquid hydrogen or liquid nitrogen on metallic and graphite materials. This document describes those tests conducted at liquid-nitrogen temperatures for Westinghouse Astronuclear Laboratory. The tests conducted at liquid-hydrogen temperatures for Aerojet-General Corporation are described in GD/FW Report FZK-263-1.

Previous SNPO-C tests on NERVA components, conducted at NARF under Contract AF33(657)-7201, are reported in GD/FW Report FZK-170, Volumes 1 through 9. Other NERVA component tests, conducted under Supplement 1 to Contract AF29(601)-6213, are reported in GD/FW Report FZK-184, Volumes 1 through 6.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the following persons:

Mr. Jim Begley of Westinghouse Astronuclear Laboratory for his assistance in the conduction of the test program.

Mr. J. B. Wattier of General Dynamics/Fort Worth for his statistical analysis of the data.

Mr. R. L. Trittipo and other General Dynamics personnel for their assistance in the experimental setup, conduction of the test, and reduction of data.

SUMMARY

The nuclear facility of GD/FW performed three tests for the Westinghouse Astronuclear Laboratory in accordance with test specifications described in WANL Reports TME-1037 and TME-1090. These ~~three~~ tests were: ~~briefly~~

37/W401 (1) 1000 metal and graphite tensile specimens, 4 steel-wire resistivity specimens, and 8 stainless-steel spring specimens tested at LN_2 and elevated temperatures. Of these, 700 tensile specimens, 4 resistivity specimens, and 4 spring specimens were irradiated at LN_2 temperatures.

15/W401 (2) 2 O-ring seal test fixtures, irradiated in a gaseous-hydrogen environment.

37/W202 (3) 14 unfueled fuel-element segments containing cemented orifices, irradiated at LN_2 and ambient-air temperatures.

The tensile specimens were divided into irradiation and control specimens. The irradiation specimens were irradiated at LN_2 temperatures to a maximum integrated neutron flux of 1.0×10^{18} n/cm^2 (E > 1 Mev). After a storage period in LN_2 of approximately 30 days, the specimens were tested in tension to break under various test conditions ranging from a -320°F test temperature without an annealing treatment to a 1290°F test temperature after a 1-hr annealing treatment at some elevated temperature. All specimens were maintained at LN_2 temperatures without warmup from before the irradiation until the annealing cycles were begun (a period of approximately 60 days). Those specimens that were not annealed were maintained in LN_2 without warmup until after they were pulled in tension to break.

Ultimate tensile strength, tensile yield strength, notched tensile strength, notched-to-unnotched tensile-strength ratio, percent elongation, and percent reduction in area were determined from the test results. Significant changes in one or more properties were noted in all materials maintained in LN_2 without warmup, with appreciable to complete recovery evident after the annealing treatments.

Changes in ultimate tensile strength were generally slight except for a highly significant decrease of 70% in beryllium specimens maintained at LN_2 temperature. Recovery was apparent in all materials after the annealing treatments.

Changes in tensile yield strength were generally significant, with increases of from 7% to 47% experienced by all materials maintained in LN_2 except beryllium, which showed a highly significant decrease of 70%. Appreciable recovery was experienced by all materials after the annealing treatments.

Changes in notched tensile strength were generally slight to significant, with increases of from 2% to 22% experienced by all materials maintained in LN_2 except titanium and beryllium, which showed decreases of 7% and 9%, respectively. Appreciable recovery was noted in all materials after annealing treatments.

Significant decreases in ductility were evident in all specimens maintained in LN_2 except beryllium, which had no measurable elongation for either the control or the irradiated specimens. Appreciable recovery was apparent after the annealing treatments.

In general, material properties experiencing apparent changes when maintained in LN_2 without warmup indicated almost full recovery after a room-temperature anneal.

The four Inconel wire resistivity specimens were irradiated at LN_2 temperature to a maximum integrated neutron flux of 4.5 x 10^{17} n/cm^2 (E >1 Mev). During irradiation, the resistance of one of the Inconel 718 wire specimens was measured periodically. After a storage period of approximately three months at LN_2 temperature, the resistance of the specimens as a function of annealing temperature and time was measured. The specimens were maintained at LN_2 temperatures without warmup until the annealing cycles were begun.

During irradiation, resistance measurements of the Inconel 718 specimen indicated an increase of approximately 0.02 ohm. Postirradiation resistance measurements after the annealing treatments indicated a maximum resistance increase of approximately 0.013 ohm. This would correspond to an increase in resistance during irradiation of something greater than 13 milliohms.

Four of the eight stainless-steel springs were irradiated at LN_2 temperature to a maximum integrated neutron flux of 4.5 x 10^{17} n/cm^2 (E >1 Mev). The other four springs were used as control specimens. Several postirradiation measurements, including spring constant, were made on the specimens. Radiation-induced changes in the specimens, if any, were insignificant.

One of the two O-ring test fixtures irradiated was mounted in the gaseous-hydrogen space inside one of the LH_2 dewars used in the AGC tests being performed during GTR-16. The other specimen was placed inside a sealed aluminum container and mounted to the outside of the LH_2 dewar. A gaseous-hydrogen environment was maintained inside the aluminum container during the irradiation.

The test fixtures received an average integrated neutron flux of 4×10^{16} n/cm^2 (E > 2.9 Mev) and a gamma dose of 2.6×10^{10} ergs/gm(C). After the irradiation, the fixtures were disassembled and the O-ring seals returned to Westinghouse for testing at their facilities. No results from these tests are available for this report.

The 14 unfueled fuel-element segments containing cemented orifices were divided into two groups of seven each. One group was irradiated at LN_2 temperature; the other group was irradiated at ambient-air temperatures. The specimens irradiated at LN_2 temperatures received a maximum integrated neutron flux of 2.5×10^{17} n/cm^2 (E > 1 Mev); those irradiated under ambient conditions received a maximum integrated neutron flux of 4.0×10^{17} n/cm^2 (E > 1 Mev). All testing of these specimens was performed at Westinghouse by Westinghouse personnel and no results are available for this report.

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I. INTRODUCTION

Under Supplement 2 of Contract AF29(601)-6643, the Nuclear Aerospace Research Facility (NARF) of General Dynamics/Fort Worth is conducting a series of tests to determine the effects of nuclear radiation, in combination with other environmental factors, on materials proposed for application in the NERVA engine. Aerojet-General Corporation (AGC) has prime responsibility for development of the NERVA engine; the nuclear reactor in the engine is being developed by Westinghouse Electric Corporation.

This document reports the procedures and results of tests performed on materials during irradiation test GTR-16 for Westinghouse Astronuclear Laboratory (WANL). Other NERVA tests performed during GTR-16 were sponsored by AGC and are reported separately in Reference 1. The purpose of the WANL tests was to determine the serviceability of metals and graphite under the extremes of temperature and nuclear radiation.

The tests were performed in accordance with specifications submitted by WANL. The test specimens were supplied by WANL; test fixtures and instrumentation were supplied by GD/FW.

Section II contains a discussion of the test setup and procedures and a description of the test specimens. Section III includes a presentation of data in tabular and graphical form, a statistical analysis of the data, and a discussion and analysis of the results.

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II. TEST PROGRAM

The GTR Radiation Effects Testing System at NARF is described briefly in Appendix A and in more detail in Reference 2. Figure A-2 shows the reactor, the reactor "closet" and the three test positions (east, north, and west) in the irradiation cell adjacent to the closet. For this test the reactor was moved to the "full-in" position in the closet (2 in. of water on the north face, 4 in. of water on the east and west faces) and operated at a power level of 3 Mw for 368.2 hr. The total megawatt hours was 1104.8. The plot of integrated power vs real time shown in Figure 2-1 depicts the radiation history of the GTR Test 16. GTR Test 16 was divided into two irradiation periods with a six-day shutdown in between. The first irradiation period was for 570 Mw-hr and the second was for 534.8 Mw-hr. The Westinghouse materials tests were run on the north irradiation position (Fig. 2-2) and remained in the test cell at LN_2 temperatures without warmup for the total 1104.8 Mw-hr. The east and west irradiation positions were used for the AGC materials tests at LH_2 temperature. The six-day shutdown between the two irradiation periods was required for a changeover of experiments being conducted on the east and west irradiation positions.

2.1 Test Description and Procedures

2.1.1 Tensile Tests

The tensile test was designed to determine the effects of nuclear radiation and LN_2 temperatures on the mechanical

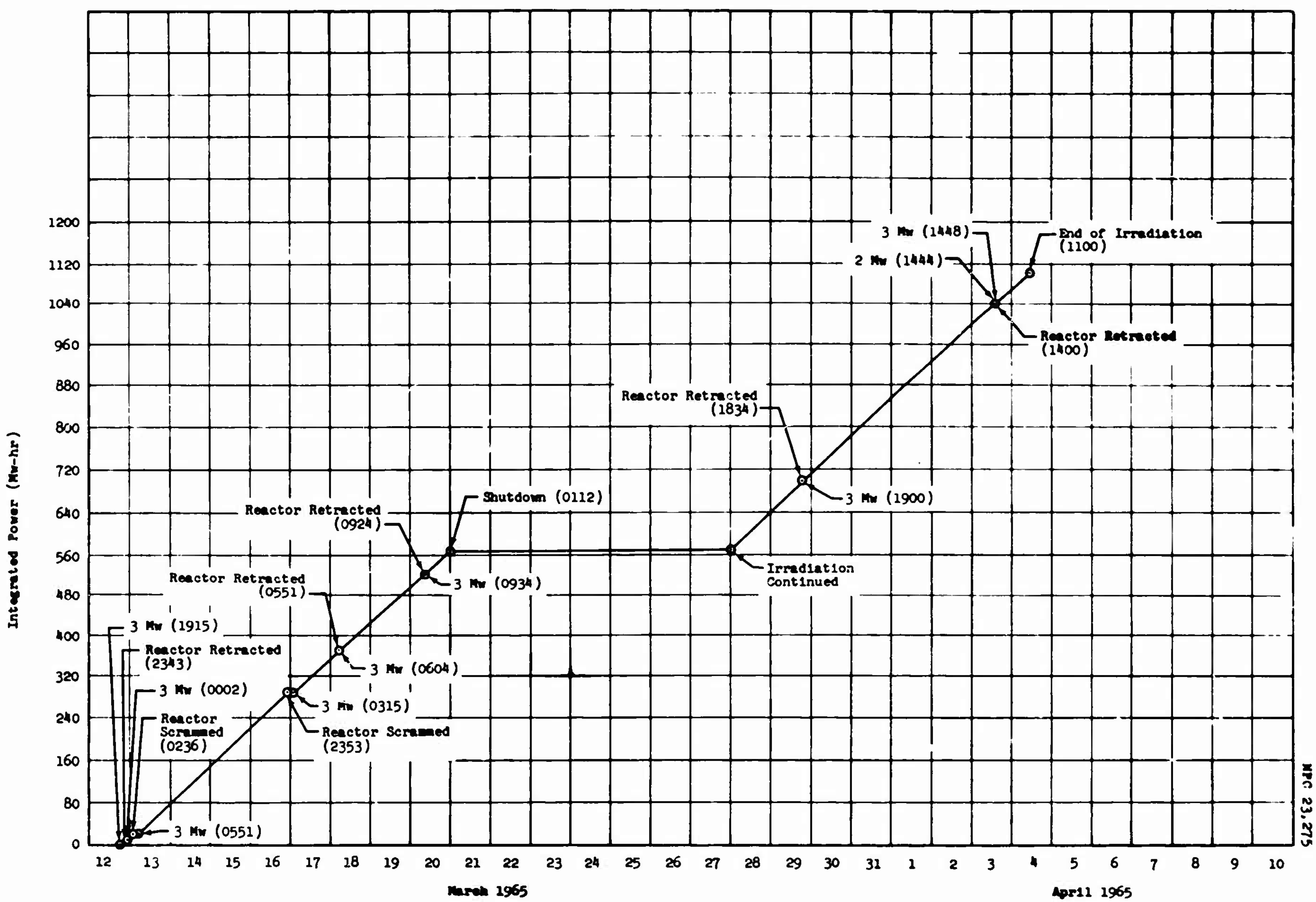
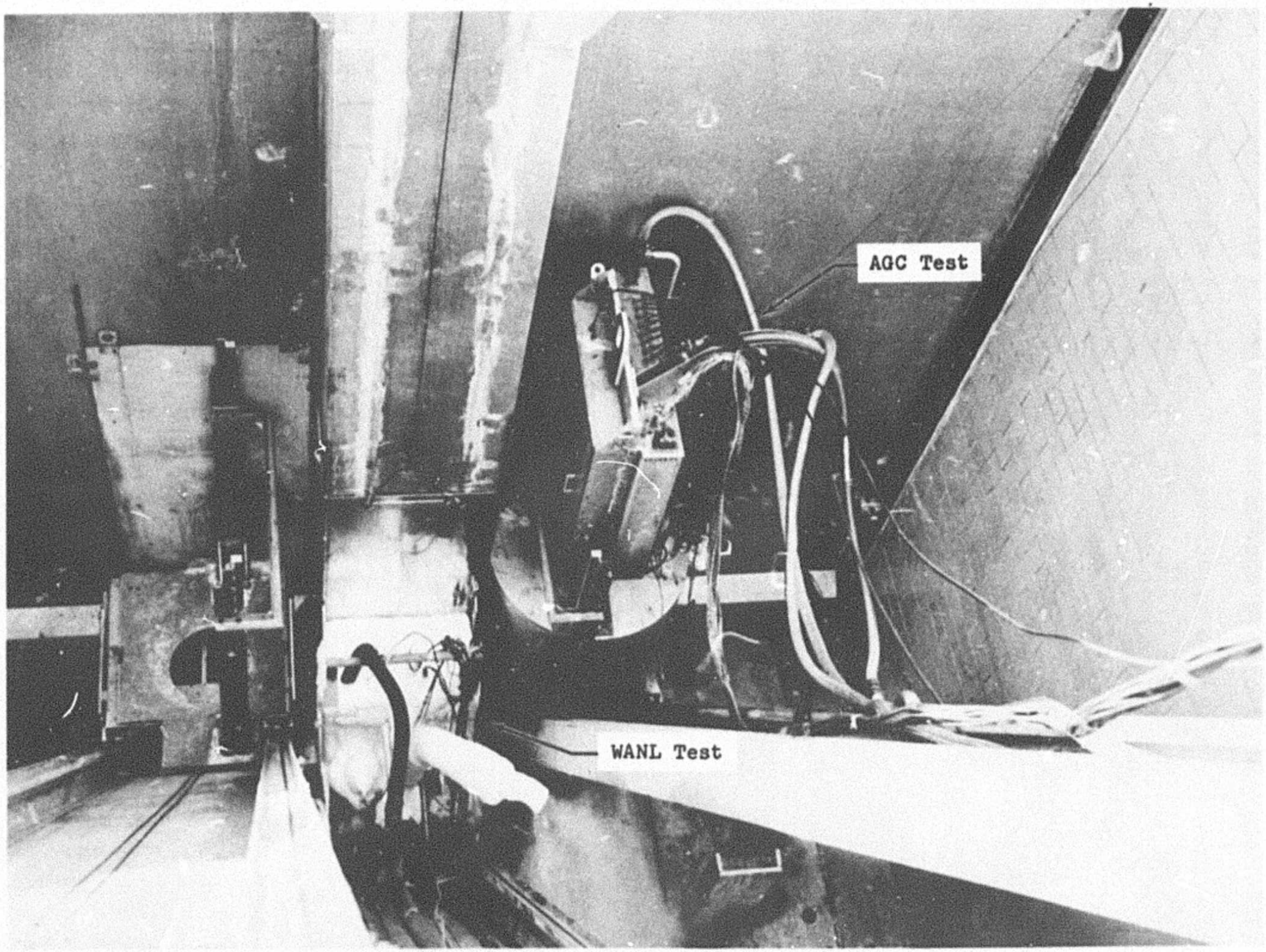


Figure 2-1 Reactor Profile for GTR Test 16



NPC 22,732
31-8348

Figure 2-2 Test Hardware in Irradiation Position properties of metallic and graphite specimens. Of the more than 1,000 metal and graphite specimens included in the program, approximately 700 were irradiated. The graphite specimens, 277 in number, were returned to WANL after the irradiation for postirradiation tests to be performed at their facilities. Tests on the other specimens were performed at GD/FW.

The test consisted of (1) irradiating the specimens at LN_2 temperatures, (2) storing the specimens at LN_2 temperatures for approximately four weeks for radioactivity decay, and (3) pulling the specimens in tension to break at LN_2 and elevated temperatures. Some of these specimens were held at LN_2 temperatures without warmup from the beginning of the irradiation until after they were pulled in tension to break. Others were held at LN_2 temperatures from the start of the irradiation until the beginning of tensile testing. Control specimens were stored in LN_2 during the time that the irradiated specimens were stored for radioactive decay.

Table 2-1 lists the test conditions imposed on the specimens, including the annealing temperatures and the symbols used in this document and related WANL documents to designate each test condition. Table 2-2 lists the number of specimens, control plus irradiated, that were tested under each test condition. Figures 2-3 through 2-5 illustrate the various specimen types used in the test.

After the storage period all specimens were pulled in tension to break in a Model TT Instron tensile testing machine. All specimens were pulled at a crosshead speed of 0.1 in./min with

Table 2-1

Description of Tensile-Specimen Test Conditions

Test Condition*	Description
	Tensile Tests
Ai	Specimens were maintained in LN_2 without warmup until after they were pulled in tension to break.
B, Bi	Specimens were warmed up to room temperature, then tested at room temperature.
C, Ci	Specimens were warmed up to room temperature, then cooled to LN_2 temperature (-320°F) and tested.
D_A, D_{Ai}	Specimens were warmed up to room temperature, then annealed for 1 hr at 540°F and tested at 540°F.
D_B, D_{Bi}, D_{Bi}'	Specimens were warmed up to room temperature, then annealed for 1 hr at 790°F and tested at 790°F.
D_C, D_{Ci}, D_{Ci}'	Specimens were warmed up to room temperature, then annealed for 1 hr at 1040°F and tested at 1040°F.
D_C, D_{Di}, D_{Di}'	Specimens were warmed up to room temperature, then annealed for 1 hr at 1290°F and tested at 1290°F.
E_A, E_{Ai}	Specimens were warmed up to room temperature, annealed for 1 hr at 540°F, then cooled to LN_2 temperature (-320°F) and tested.
E_C, E_{Ci}	Specimens were warmed up to room temperature, annealed for 1 hr at 1040°F, then cooled to LN_2 temperature (-320°F) and tested.
	Strain-Rate Study
Fi, F_{1i}	Specimens were warmed up to room temperature, then cooled to LN_2 temperature (-320°F) and tested.
Gi, G_{1i}	Specimens were warmed up to room temperature, then cooled to -110°F and tested.
Hi, H_{1i}, H_{2i}	Specimens were warmed up to room temperature, then tested at room temperature.

*Letter (i) - irradiated specimens.
Prime (') - specimens irradiated in gadlinium foil.
Subscript (1) - specimens pulled at a crosshead speed of 0.01 in./min.
Subscript (2) - denotes specimens pulled at a variable crosshead speed of from 0.01 to 0.1 in./min.

All other specimens were pulled at a crosshead speed of 0.1 in./min.

Table 2-2

Number and Type of Tensile Specimens Tested Under Each Condition

Material	Specimen Type	Test Condition																					Strain Rate Study	Instron Checkout	Calibration Specimens	Returned to WANL	Totals
		A1	B	B1	C	C1	D_A	D_{A1}	D_{A1}'	D_B	D_{B1}	D_{B1}'	D_C	D_{C1}	D_{C1}'	D_D	D_{D1}	D_{D1}'	E_A *	E_{A1}	E_C	E_{C1}					
Inconel 718, Type 3	3P & 3N	6	6	7	4	8	2	2	2	2	2	2	6	6	2	1	4	2			6	7		8	2	[illegible]	98
Inconel 718, Type 1	1P & 1N	5	7	8	6	8							7	7							6	6	20*			1	81
Inconel 718-WS Type 3	3P & 3N	7	9	7	9	7																					39
Inconel X-750 Type 1	1P & 1N	6	6	7	7	8							6	6							8	7		1		9	71
Inconel X-750 Type 3	3P & 3N	6	7	9	8	6							7	14							7	6		3			73
AISI 301-CW, Type 3	3P & 3N	6	8	8	8	8	8	6											8	8				2	2	7	79
AISI 303-Se, Type 1	1P & 1N	6	7	10	8	9	8	7																1	2		72
Al 2219-T6, Type 3	3P & 3N	6	6	8	4	7	6	8											6	8				5	2		56
Al 2219-T6-Transverse Type 2	2P & 2N	6	9	12	9	12																				5	53
Al 2219-T6-Radial Type 2	2P & 2N	6	5	6	5	4													7	7				1	1		28
Beryllium, Type 4	4P & 4N	8	8	8	13	13																					50
Ti A-110-AT-E11 Type 2	2P & 2N	6	6	6	6	6																			2		32
Graphite	G1 & G2																									277	277
Inconel 718	Threaded																									4	[illegible]
TOTALS		74	84	96	87	96	24	23	2	2	2	2	26	33	2	1	4	2	21	23	27	26	20	21	11	304	**1013

* $F1$ (4), F_{11} (3), $G1$ (3), G_{11} (3), $H1$ (2), H_{11} (3) and H_{21} (2).

** In addition to these, ten specimens were irradiated for AGC.

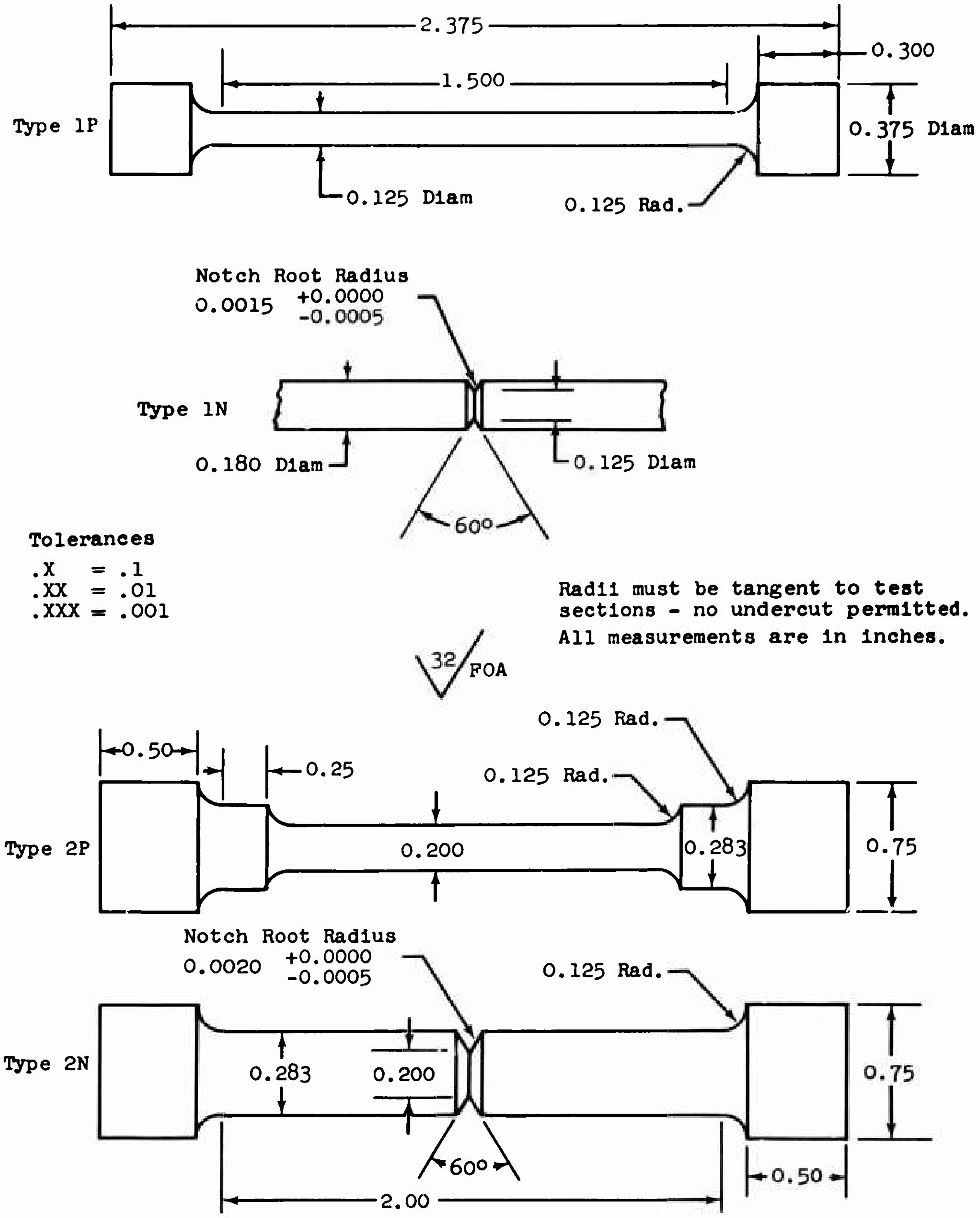


Figure 2-3 Metal Tensile Specimens - Types 1 and 2

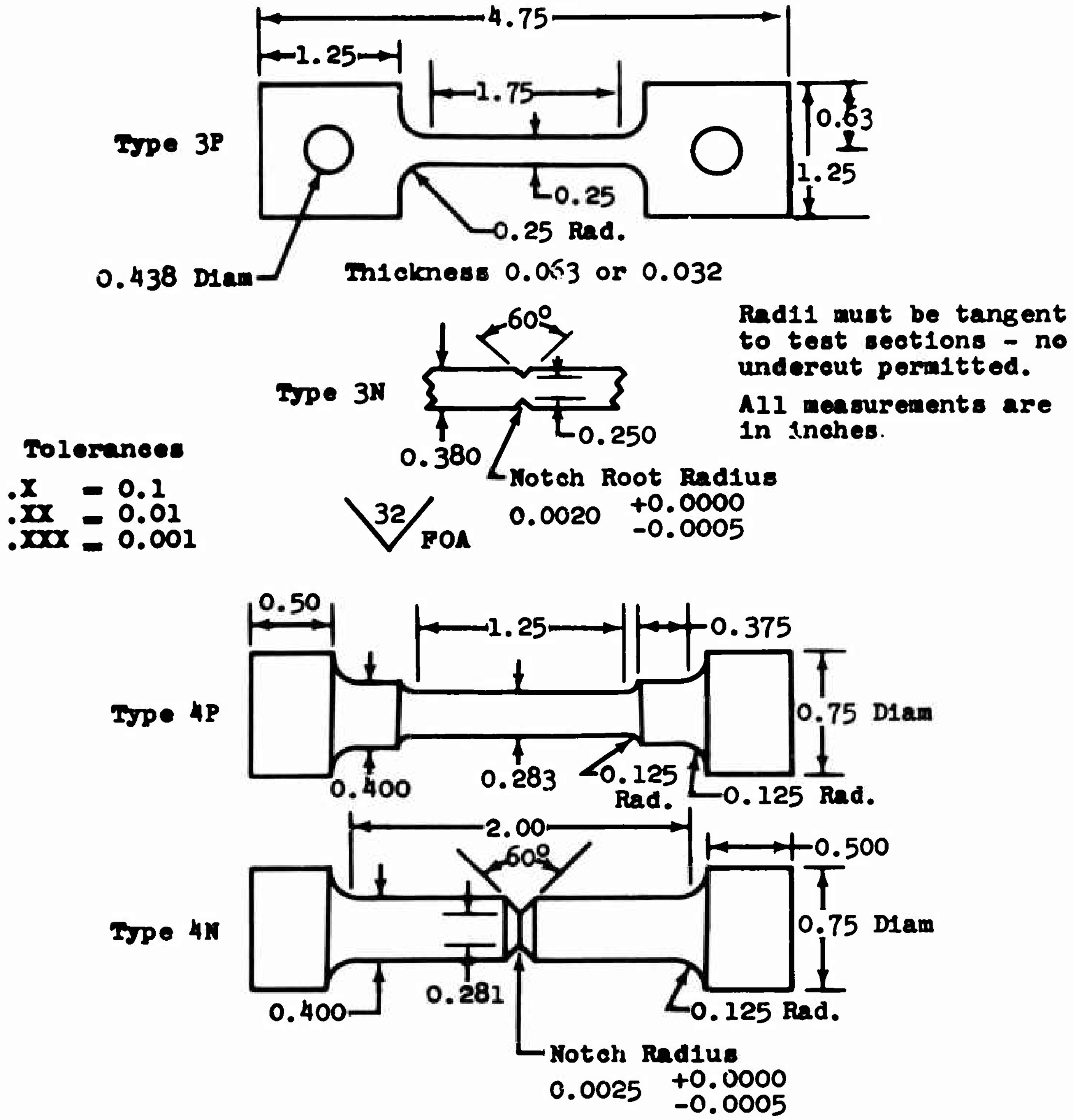
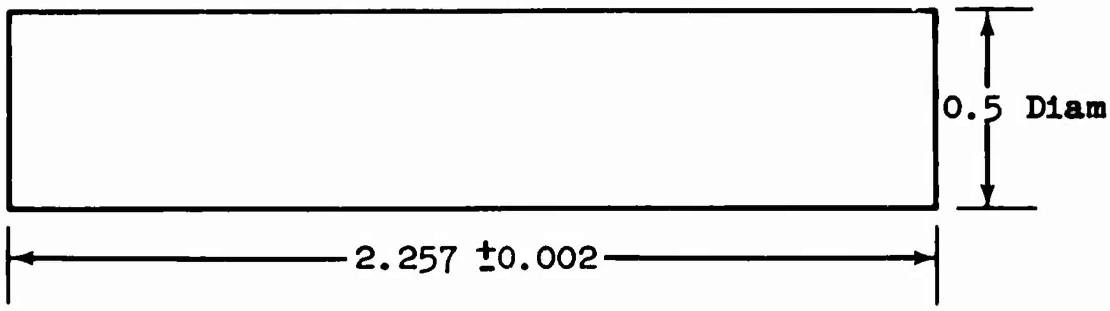


Figure 2-4 Metal Tensile Specimens - Types 3 and 4

Graphite Compression Specimen
Type G-1



Diameter or Radius
B = 0.55
C = 0.125
D = 0.40

All radii are to be smooth blended

All measurements are in inches

Graphite Tensile Specimen
Type G-2

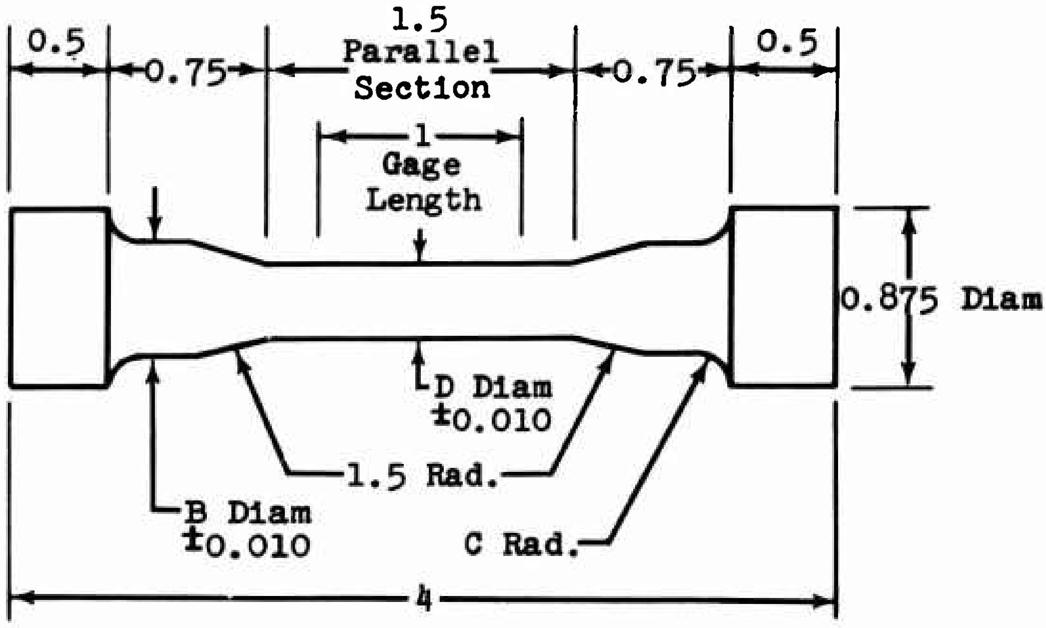


Figure 2-5 Graphite Specimens

the exception of five Inconel 718 specimens pulled at 0.01 in./min as part of a strain-rate study. After the specimens were pulled in tension to break, the two halves of each broken specimen were fitted together and the dimensional measurements required for the calculation of percent elongation and reduction in area were made. These measurements were made with a special test jig and micrometers supplied by Westinghouse. From the results of the Instron data and the specimen dimension measurements, the following tensile properties were determined: ultimate tensile strength, 0.2% tensile yield strength, notched tensile strength, notched-to-unnotched tensile-strength ratio, percent elongation, and percent reduction in area.

To satisfy test condition A1, specimens were transferred in LN_2 from the irradiation dewar to the Instron dewar where they were loaded into specimen grips while submerged in LN_2. This was accomplished using dippers and tongs as required.

Specimens that had to be pulled at elevated temperatures were pulled inside a cylindrical oven (see Sec. 2.2.1). Before the actual test specimens were inserted, the oven was calibrated for each specimen type at each temperature desired. Specimens that had to be annealed were subjected to the specified temperature for 1 hr in a forced-air oven. Control of the annealing oven was better than $\pm 5^{\circ}F$; control of the cylindrical Instron oven was $\pm 10^{\circ}F$ of the set point, from the top of the upper grip to the bottom of the lower grip. The oven was calibrated to hold the middle of the specimens to within $\pm 5^{\circ}F$ of the desired set point.

A strain-rate study was performed on 18 Inconel 718 specimens. Specimens were tested at 80°, -110°, and -320°F at crosshead speeds of 0.01 and 0.1 in./min. The -110°F temperature was obtained with a mixture of crushed dry ice and ethyl alcohol.

The possibility of ozone crystals forming in the LN_2 dewar during irradiation and the subsequent storage period was lessened by two safety measures. The first was the sampling and testing of the LN_2 supply for oxygen content. The oxygen content was found to be always less than 20 ppm. The second precaution was the periodic dumping of a portion of the LN_2 from the bottom of the dewar, the flow of which would tend to carry off any ozone crystals which might form in the dewars. The necessary precautions were taken during dumping of the dewar to insure that the LN_2 level always remained above the test specimens.

2.1.2 Resistivity Tests

Electric resistivity is a sensitive measure of lattice irregularities in metals. Therefore, resistance measurements of several Inconel specimens were made to determine the extent of lattice irregularities caused by neutron bombardment.

Two specimens each of Inconel X-750 and Inconel 718 were irradiated. The specimens consisted of 10-15 ft of 0.020-in.-diam wire wound upon an aluminum mandrel. The wire was insulated from the mandrel by a coating of Bean H cement on the mandrel. The mandrel was placed inside a tubular aluminum vessel open at one end. The vessel, mandrel, and wire can be seen in Figure 2-6. The aluminum vessels were placed in the north dewar where they remained submerged in LN_2 until removed from the dewar.

During irradiation the resistance of one of the Inconel 718 specimens was measured periodically. After the irradiation and subsequent radioactivity decay period, the specimens were cryogenically transferred to a smaller dewar for testing. Postirradiation resistance measurements were made before and after annealing treatments at temperatures ranging from -270°F to room temperature. The temperature steps were achieved with a heater placed around the specimen and inside the aluminum vessel containing the specimen. When power was supplied to the heater, the LN_2 in the aluminum vessel evaporated and the temperature was allowed to increase to the desired level. The vessel was then refilled with LN_2 and the resistance measured. This procedure was repeated for each desired annealing treatment.

The desired annealing temperature was detected by two copper-constantan (Cu-Cn) thermocouples attached to the specimen heater. A calibration of heater temperature vs sample temperature was performed using a spare specimen with three Cu-Cn thermocouples attached to the specimen mandrel.

2.1.3 Steel-Spring Specimen Tests

Eight AISI 304 stainless-steel spring specimens were provided. One of the springs is shown in Figure 2-7. Four of the eight specimens were irradiated at LN_2 temperatures on the north irradiation position along with the tensile specimens. The other

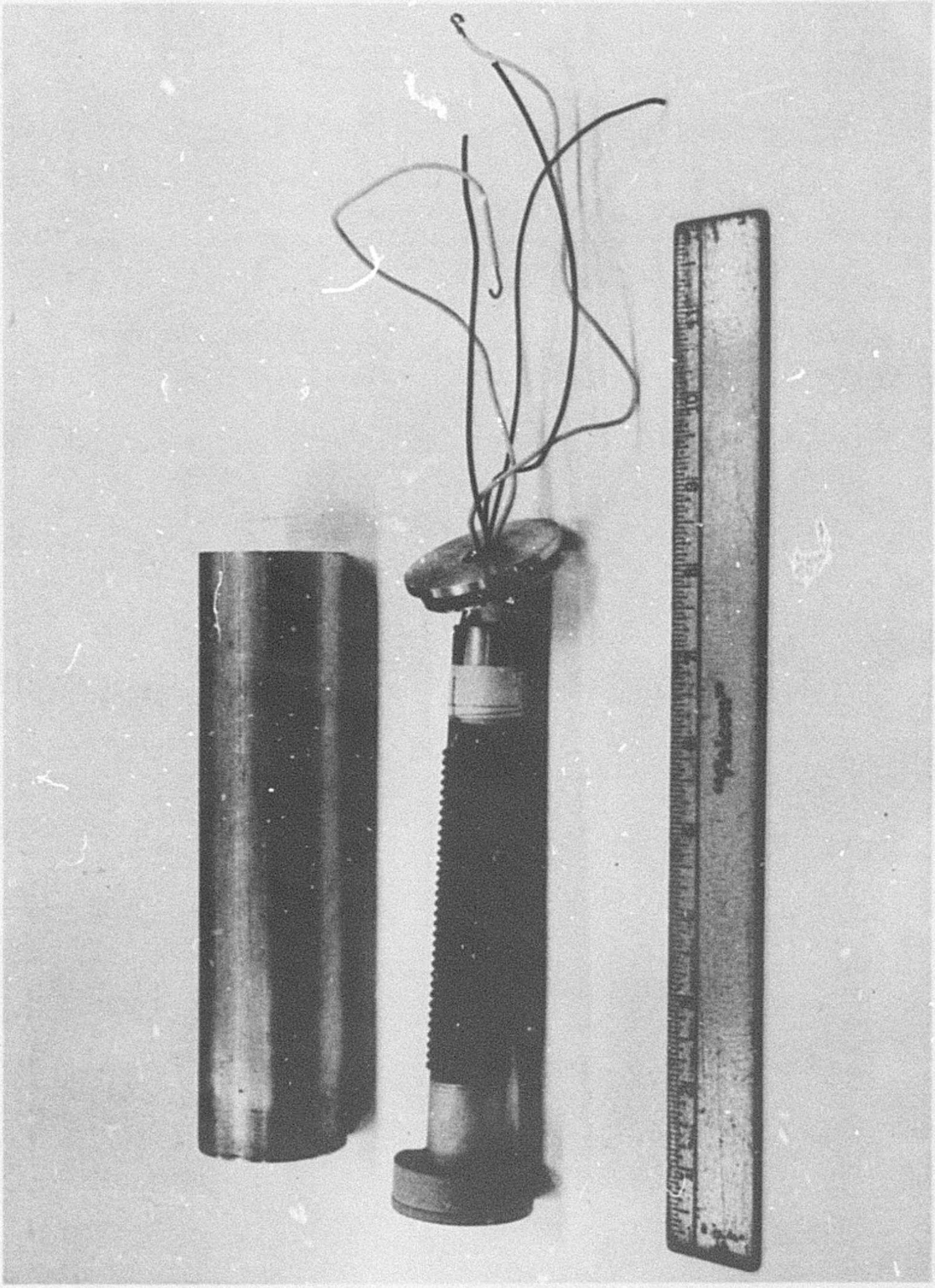


Figure 2-6 Resistivity Specimen and Container

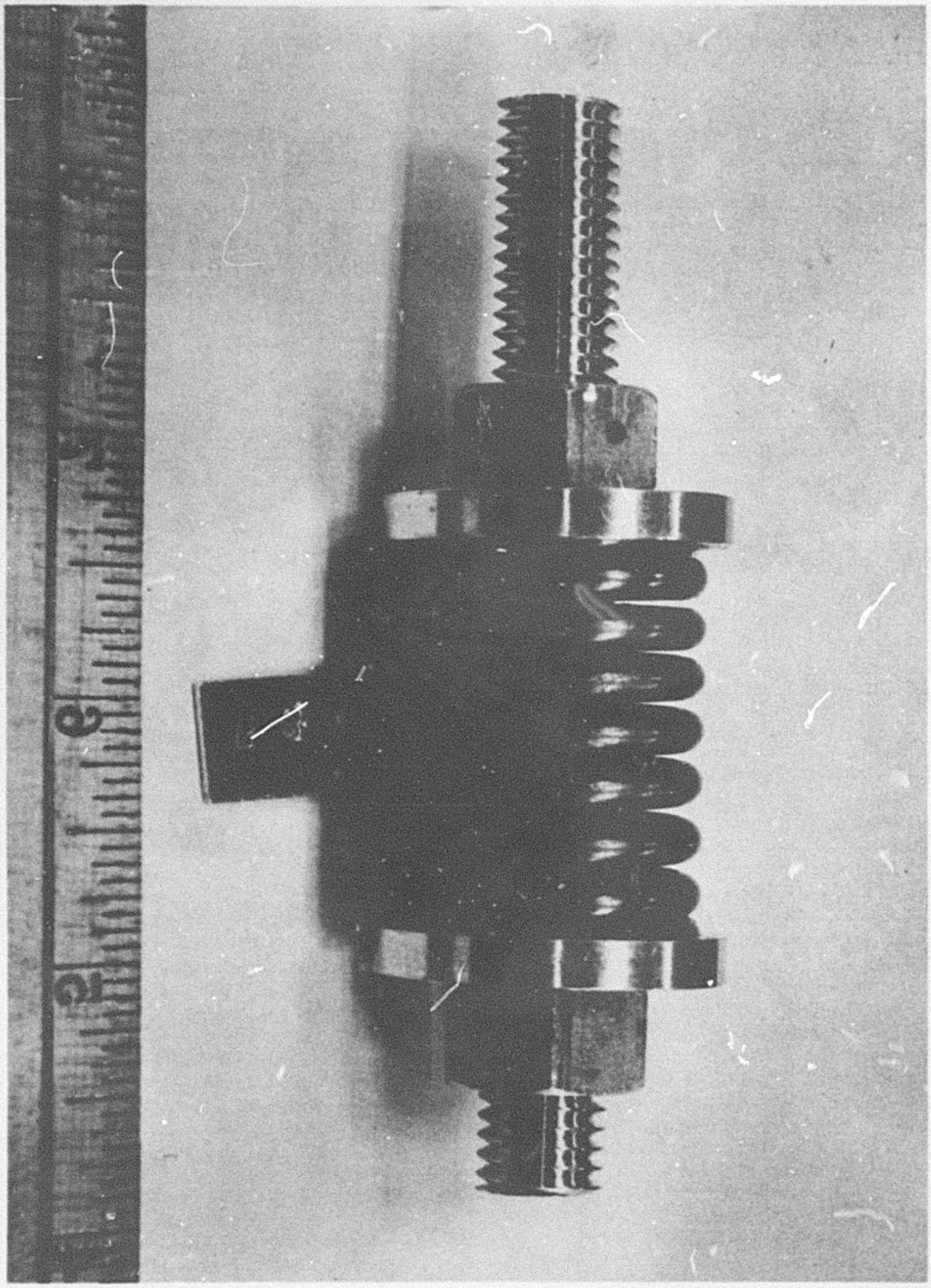


Figure 2-7 Loaded Spring Specimen

four specimens were used for control measurements.

Before the irradiation the free length of all specimens, irradiation and control, was measured at room temperature. The springs were then compressed by means of a bolt, washer, and nut arrangement through the axial centerline of the springs. The compression ranged from 0.947 in. to 0.983 in. for the eight springs. After the nuts were tightened to the desired deflection, they were pinned to the bolt to insure that the compression remained constant during the irradiation. After the irradiation and subsequent storage period for radioactivity decay, the specimens were removed from the LN_2 and the load removed. The control specimens were stored in LN_2 under load during the time the irradiation specimens were stored for radioactivity decay. The following measurements were made on both the irradiated and the control specimens.

1. Specimen free length at room temperature.

2. Specimen free length of two control and two irradiated specimens after a 1-hr anneal at 1000°R.

3. Spring constant at room temperature (by means of load-deflection curves) of two control and two irradiated specimens after a room-temperature anneal.

4. Spring constant at room temperature of two control and two irradiated specimens after a 1-hr anneal at 1000°R.

5. Free length of all specimens after the spring constant tests.

2.1.4 O-Ring Seal Tests

This test was conducted to evaluate O-ring seals (PMP-6188A phenylmenthylvinyl silicone elastomers) at cryogenic-and ambient-temperature conditions. Two test fixtures, each containing four O-ring seal specimens, were supplied by WANL. One of the fixtures after disassembly is shown in Figure 2-8. One test fixture was capsulated in an aluminum container leak-tested to 50 psi helium with a helium-leak detector. The other test fixture (without capsule) was located in the hydrogen-gas space inside the east LH_2 dewar used in the test (Ref. 1). The capsulated fixture was placed on the outside of the east LH_2 dewar and irradiated under ambient-temperature conditions. The capsulated fixture contained a Cu-Cn thermocouple, the output of which was monitored during the irradiation. Sufficient hydrogen gas was bled through the capsulated fixture to maintain it in a hydrogen environment during the irradiation. After the irradiation the test fixtures were dismantled and the eight O-ring seals returned to WANL. All testing of the seals was done at Westinghouse by WANL personnel.

2.1.5 Cemented-Orifice Tests

Fourteen unfueled fuel-element segments containing cemented orifices were irradiated. Photographs of the test specimens are deleted from this report because of their security classification. The specimens were divided into two groups of seven each. One group was placed inside the north dewar in LN_2; the other group was placed on the outside of the north dewar in ambient air. The specimen types located inside and outside the dewar are listed below.

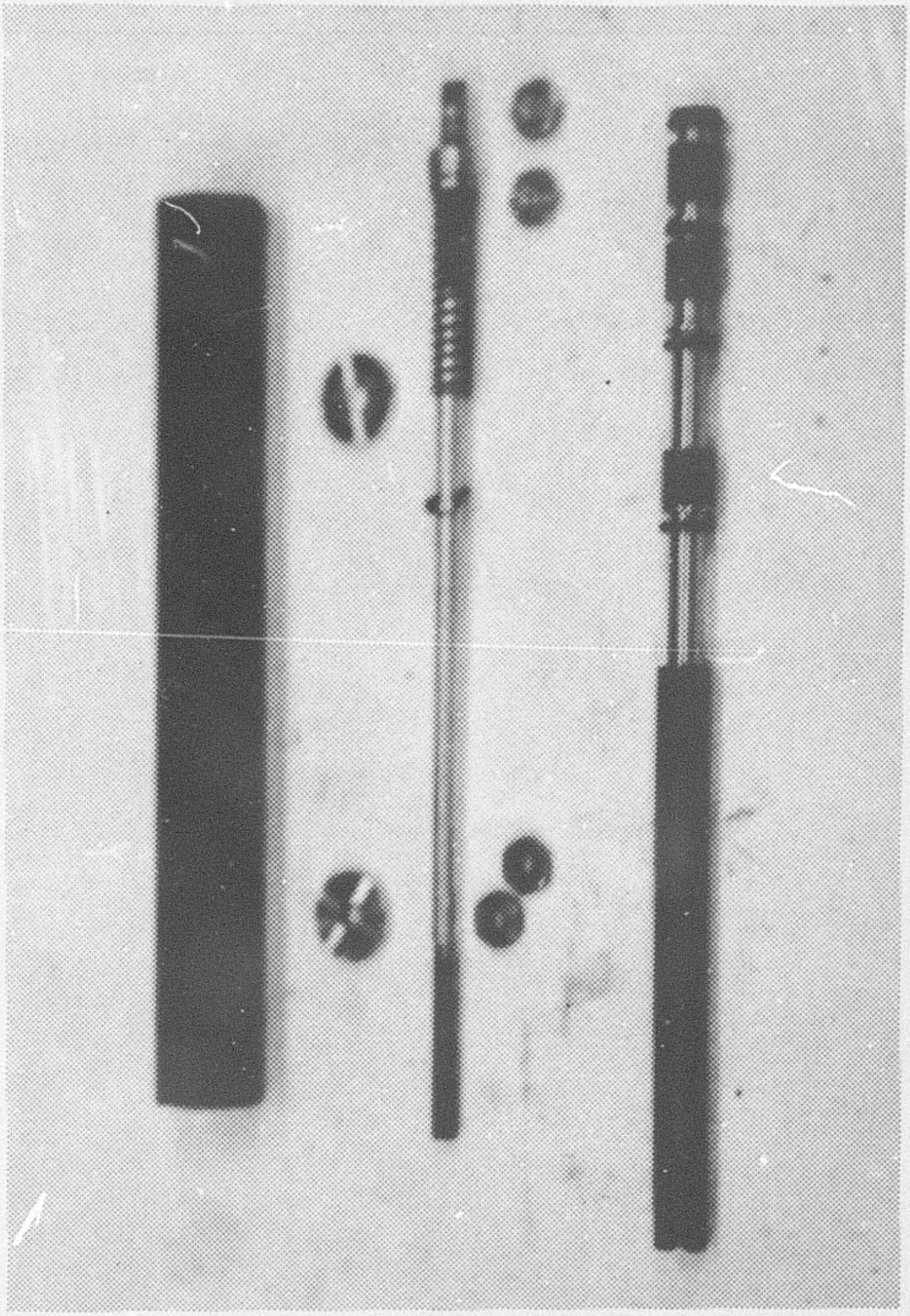


Figure 2-8 Dismantled O-Ring Test Fixture

Material	Specimen Number	
	Inside LN_2 Dewar	Outside LN_2 Dewar
Glyptol	1 and 2	3 and 4
AC-09-10197	1	2 and 3
AC-09-06957	1 and 2	3
RK-692	1 and 2	3 and 4

The temperature of the specimens located outside the dewar was monitored with a Cu-Cn thermocouple and a Minneapolis-Honeywell multipoint recorder. These items were returned to Westinghouse after the irradiation. All tests performed on these specimens were performed by Westinghouse personnel at their facilities.

2.2 Test Hardware and Instrumentation

2.2.1 Tensile Tests

The tensile specimens were irradiated in aluminum loading racks which were mounted in an aluminum framework (Figs. 2-9 through 2-13). The location of specimens by specimen number in each of the racks is depicted in Figure 2-14. The configuration of the racks and framework was such that the racks could be removed from the framework in sequence from top to bottom while submerged in LN_2. This allowed for the systematic removal, with tongs and dippers, of individual specimens from the irradiation dewar to the Instron dewar, maintaining them in LN_2 during transfer without interfering with the other specimens in the dewar.

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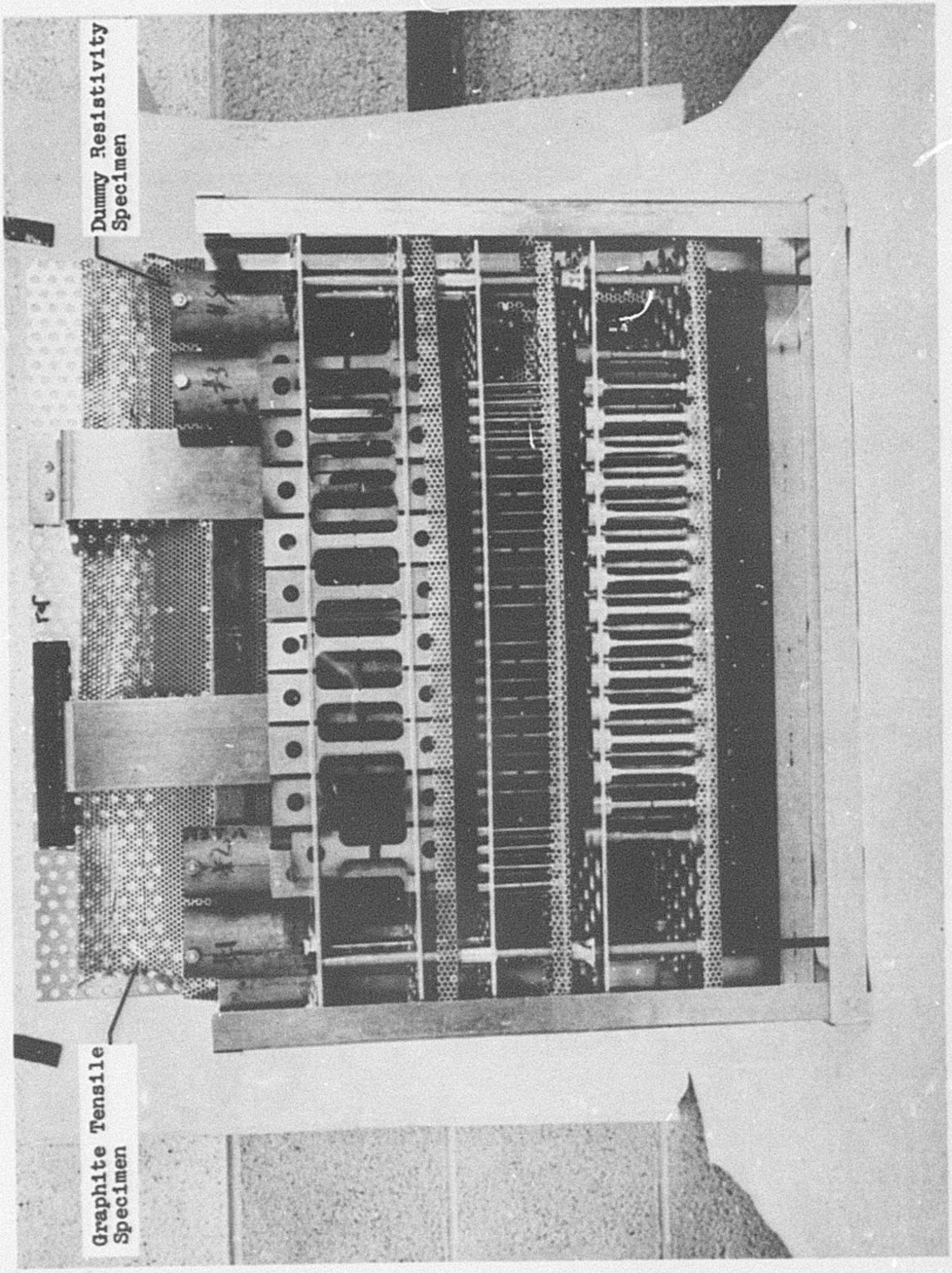

Figure 2-9 Tensile Specimen Loading for Irradiation Test - Front View

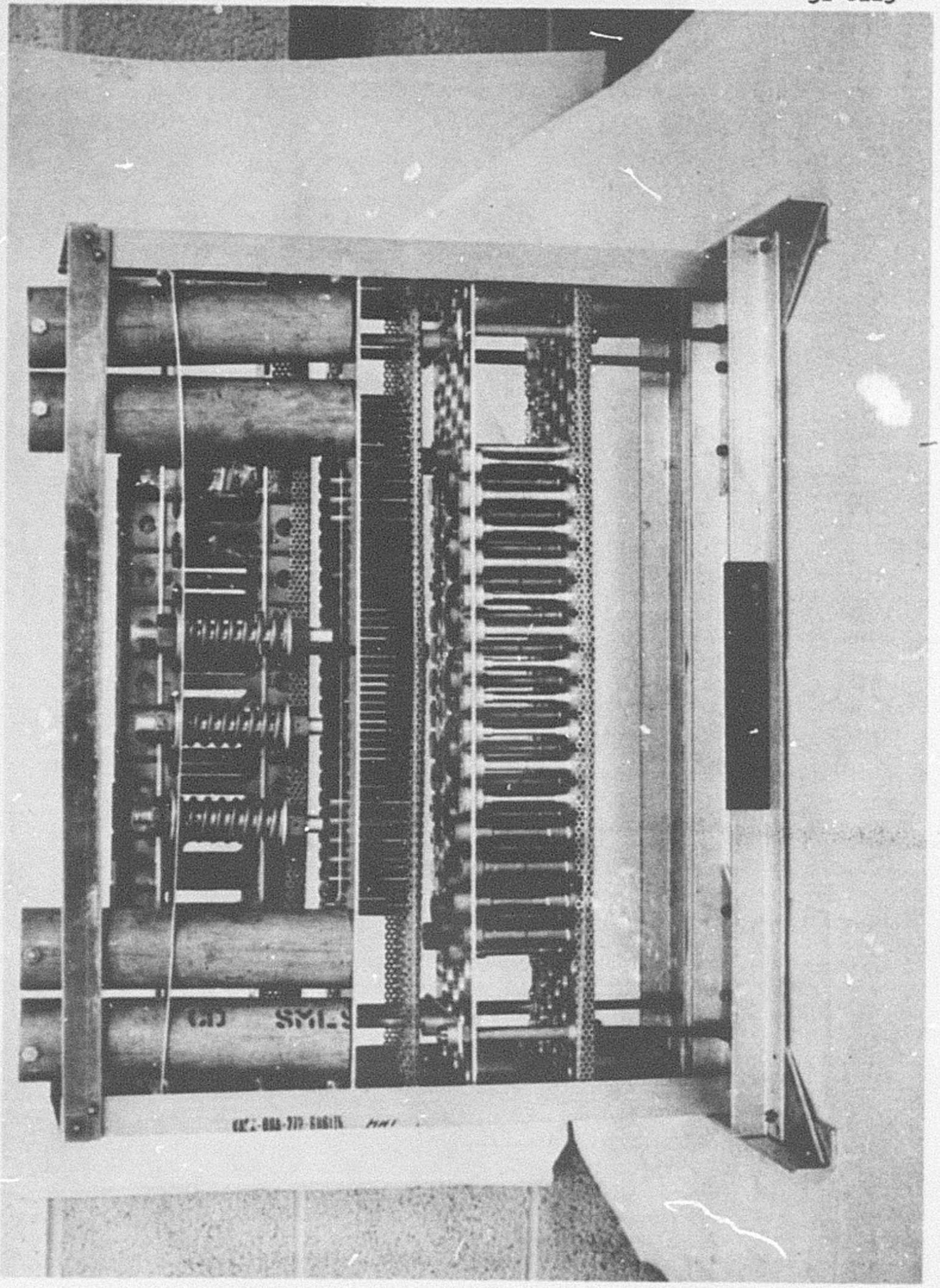

Figure 2-10 Tensile Specimen Loading for Irradiation Test - Rear View

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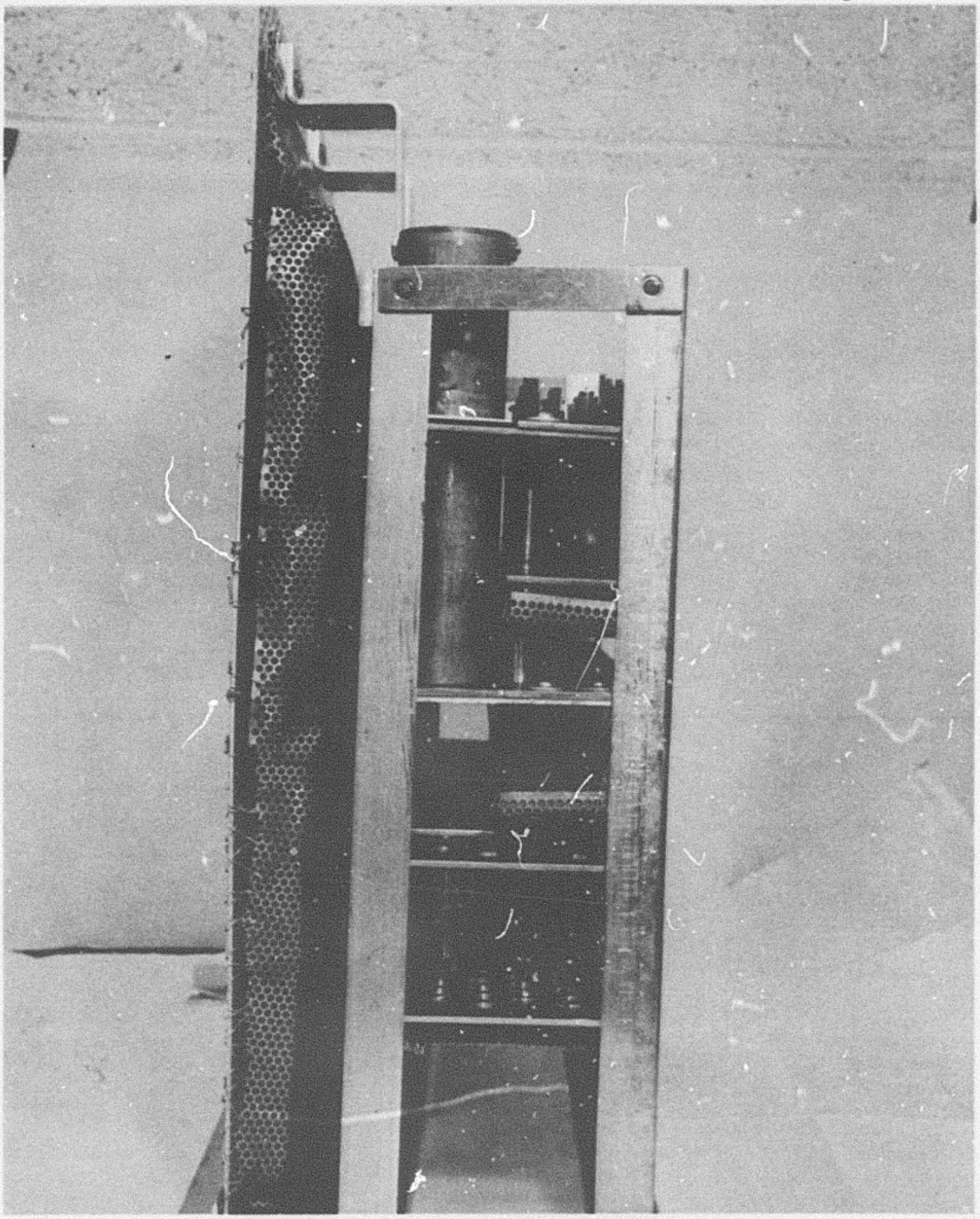
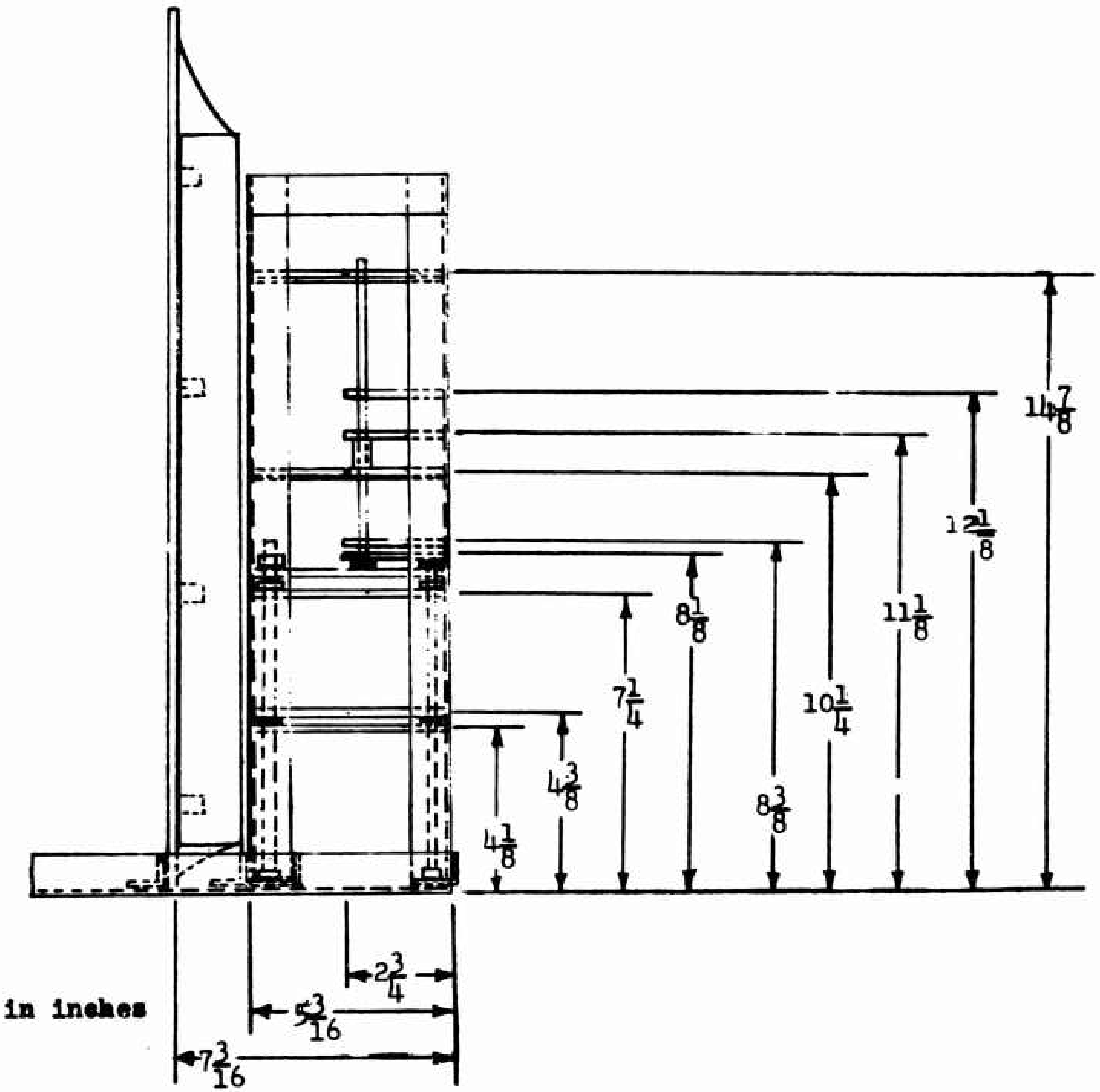
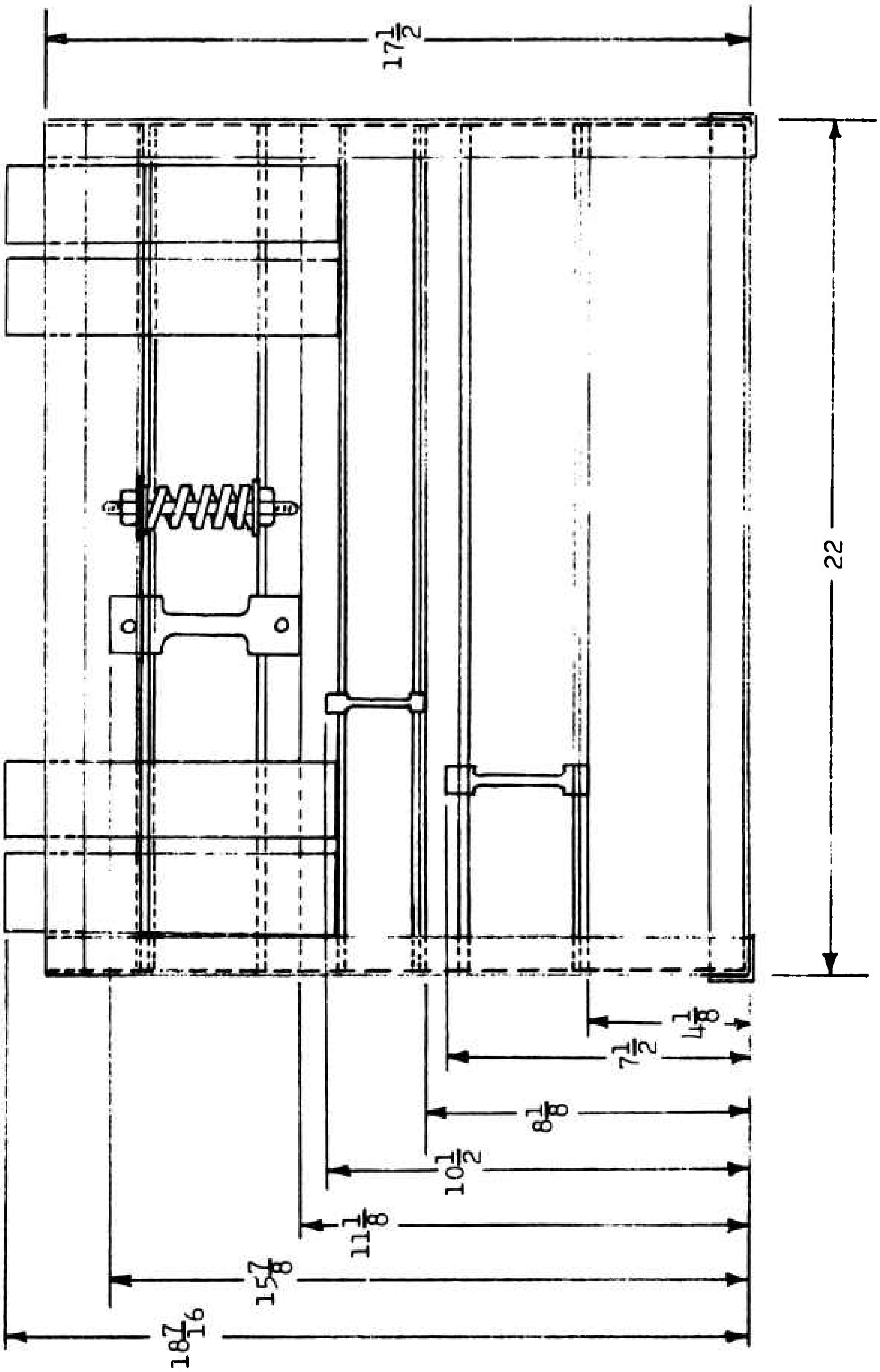


Figure 2-11 Tensile Specimen Loading for Irradiation Test - Side View



All dimensions in inches

Figure 2-12 Tensile Specimen Trays in Framework - Side View



All dimensions in inches

Figure 2-13 Tensile Specimen Trays in Framework - Front View

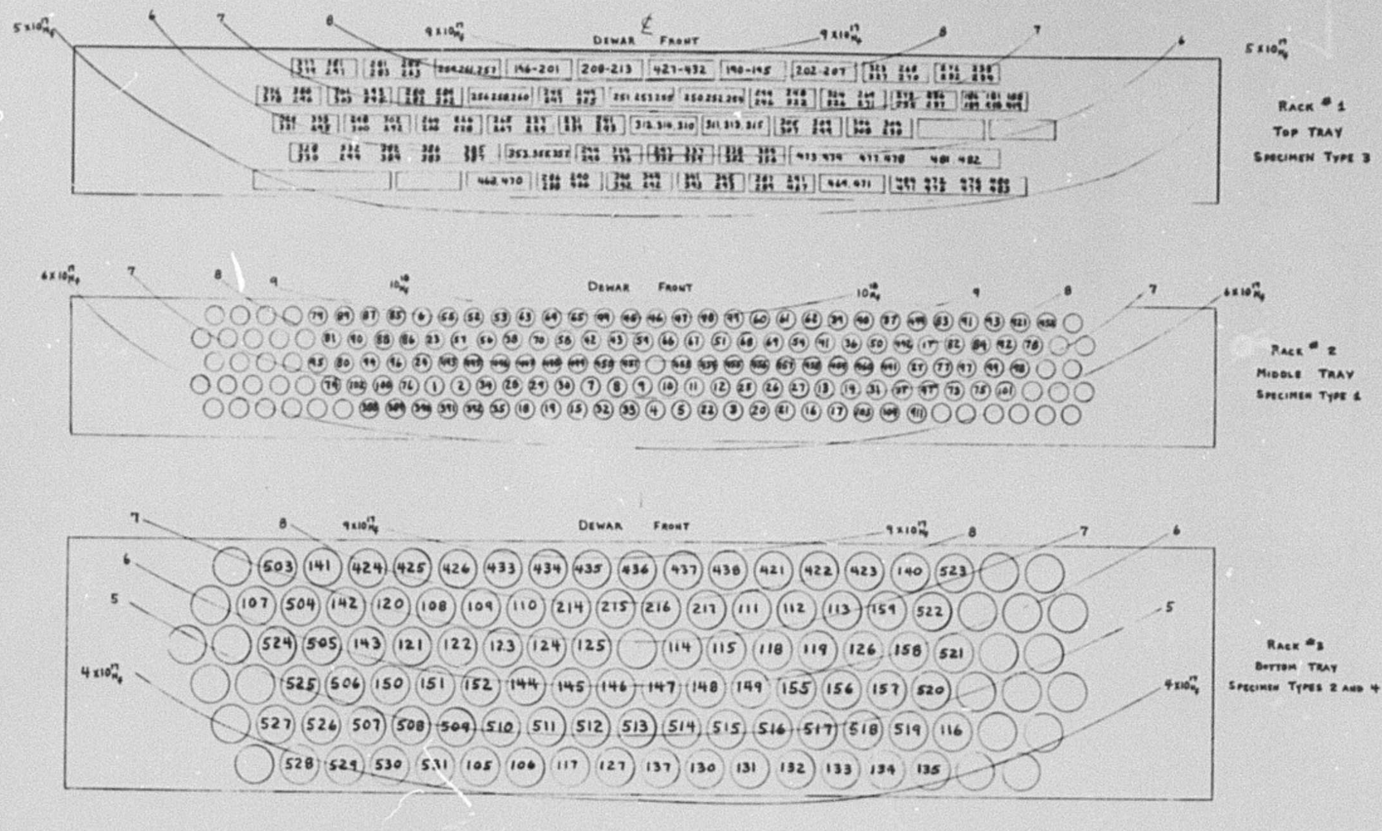


Figure 2-14 Tensile Specimen Locations and Integrated Neutron Flux (E > 1 Mev) Profile

The 277 graphite specimens were secured to a perforated aluminum tray and mounted to the back of the aluminum framework. The tray can be seen in Figure 2-11. The locations of specimens on the tray are shown in Figure 2-15. The graphite specimen tray was mounted in the framework in such a way that it could be lifted from the irradiation dewar (filled with LN_2) independent of other specimens in the dewar.

The irradiation dewar is shown in Figure 2-16. The loading racks, graphite specimen tray, and framework were placed in the dewar and the dewar filled with LN_2. The LN_2 level was maintained above the specimens from before the irradiation, through the storage period for radioactivity decay, until the annealing cycles were begun during the postirradiation testing of the specimens, a period of approximately 60 days.

The instrumentation used to monitor the liquid level in the dewar during the irradiation is shown in Figures 2-17 and 2-18. This instrumentation, working in conjunction with a liquid-level probe mounted in the dewar, gave a visual and/or audible indication of liquid level.

The liquid-level probe consisted of seven 0.25-watt carbon resistors mounted in a rake 28-1/2, 11-3/4, 9-3/4, 7-3/4, 5-5/8, 4-1/8, and 1-3/4 in. below the bottom of the dewar flange and of three Cu-Cn thermocouples mounted 11, 9, and 7 in. below the flange. The level was maintained between the resistors at 5-5/8 and 4-1/8 in. Each resistor in the probe was excited to dissipate its rated power for maximum sensitivity and response. The changes

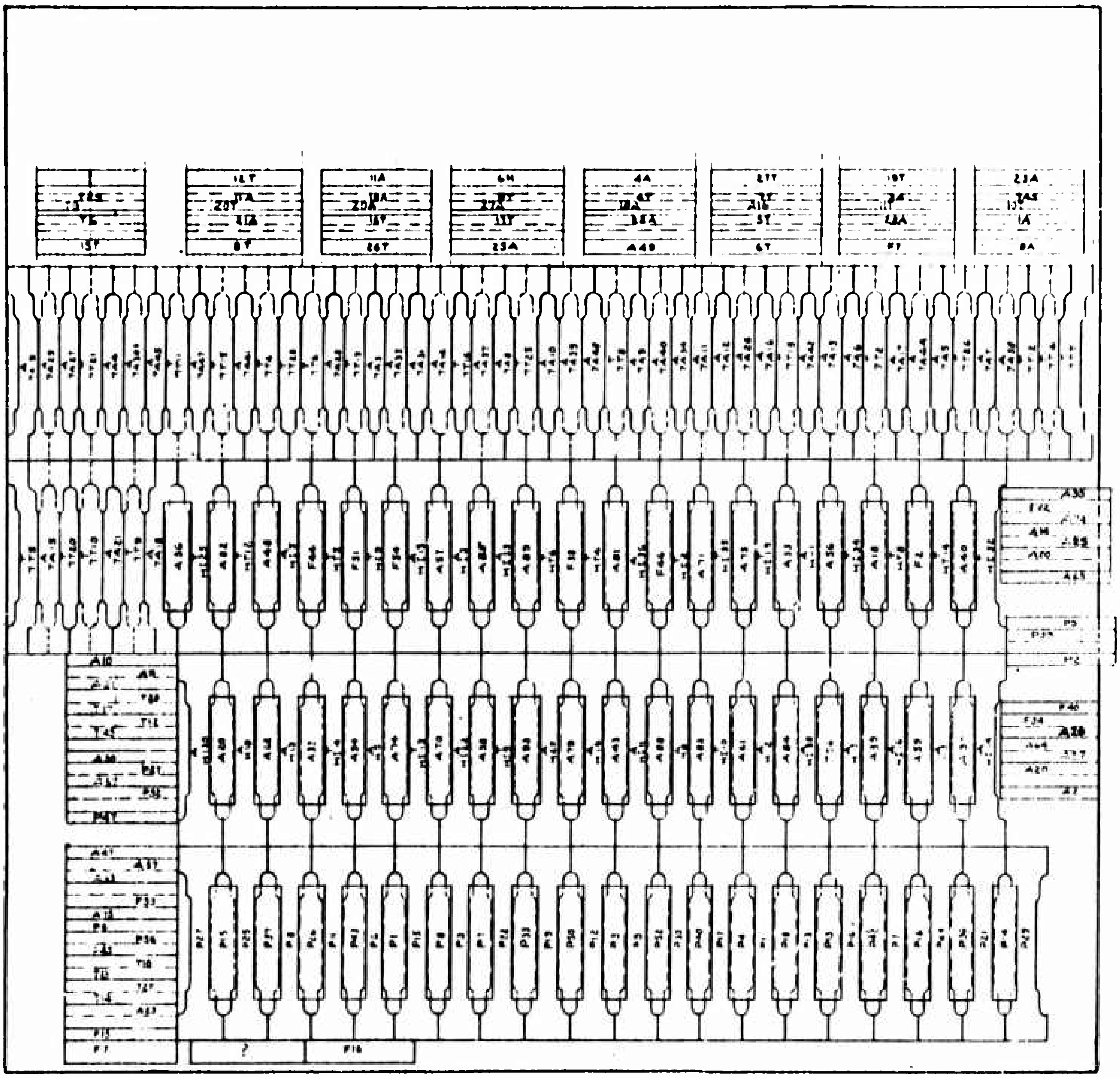
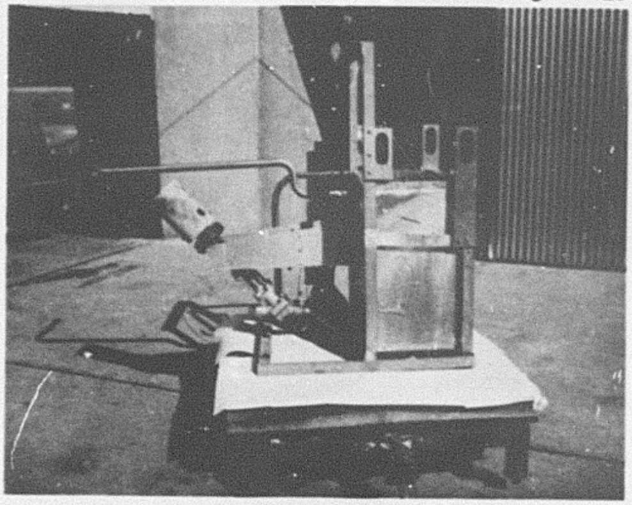


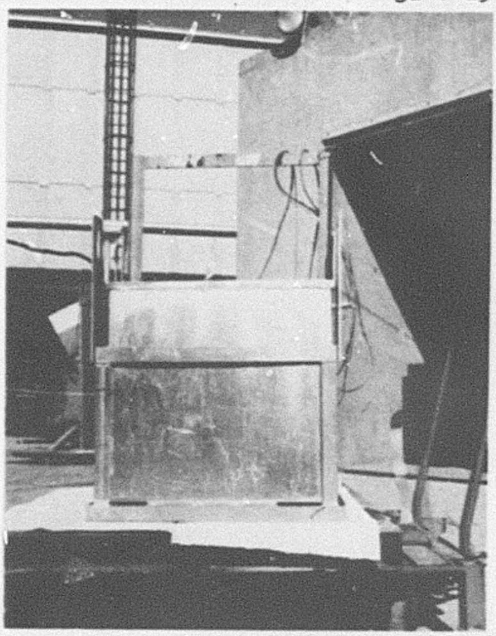
Figure 2-15 Location of Graphite Specimens on Rack

31-8428 NPC 23,288



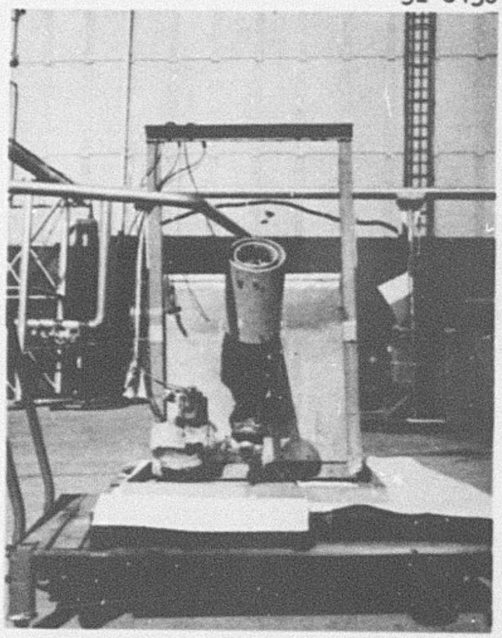
Side View

31-8429



Front View

31-8430



Rear View

Figure 2-16 WANL Liquid-Nitrogen Dewar

NPC 23,546
31-8343

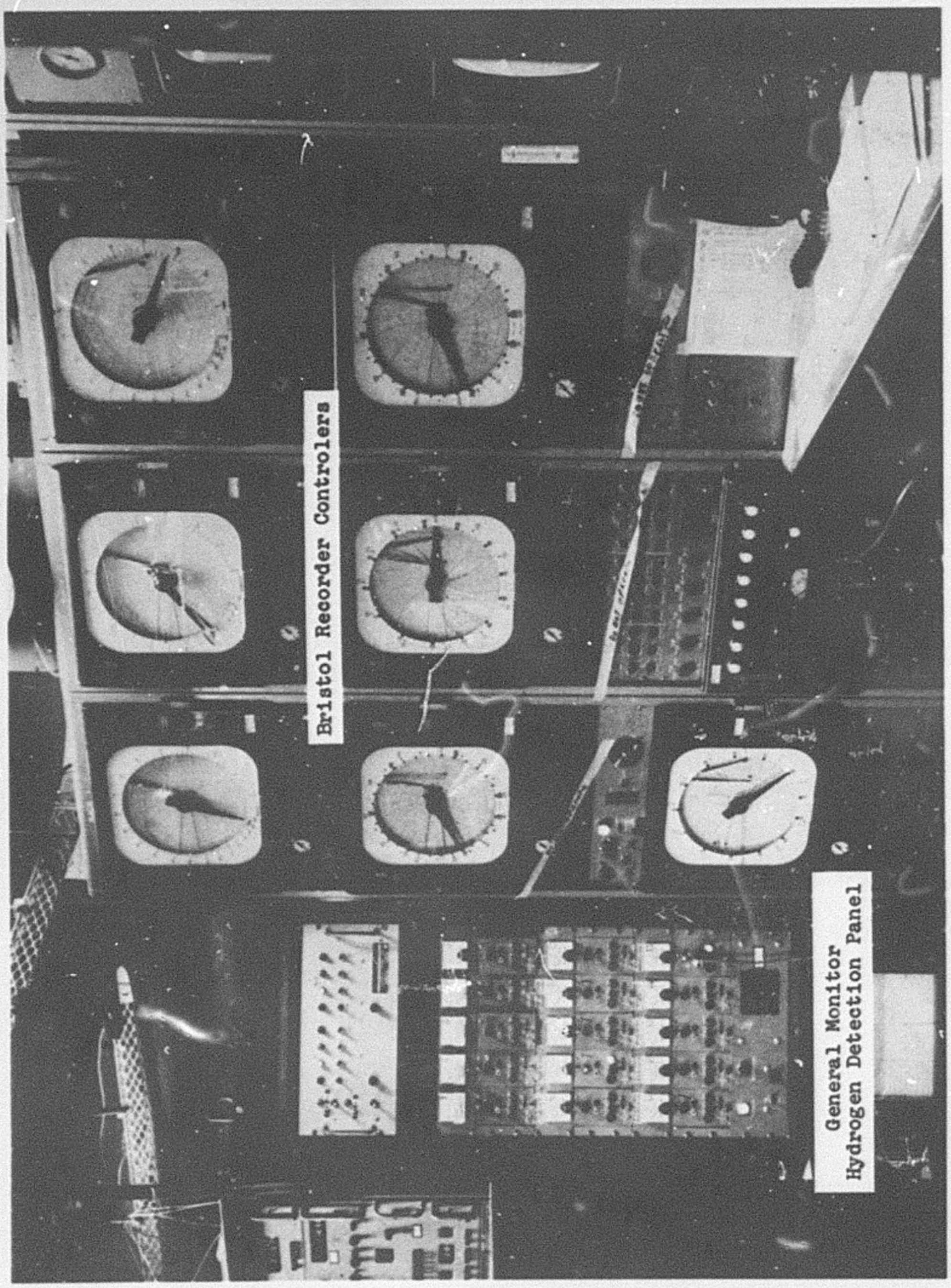


Figure 2-17 Radiation Effects Console in Reactor Control Room-Left Side

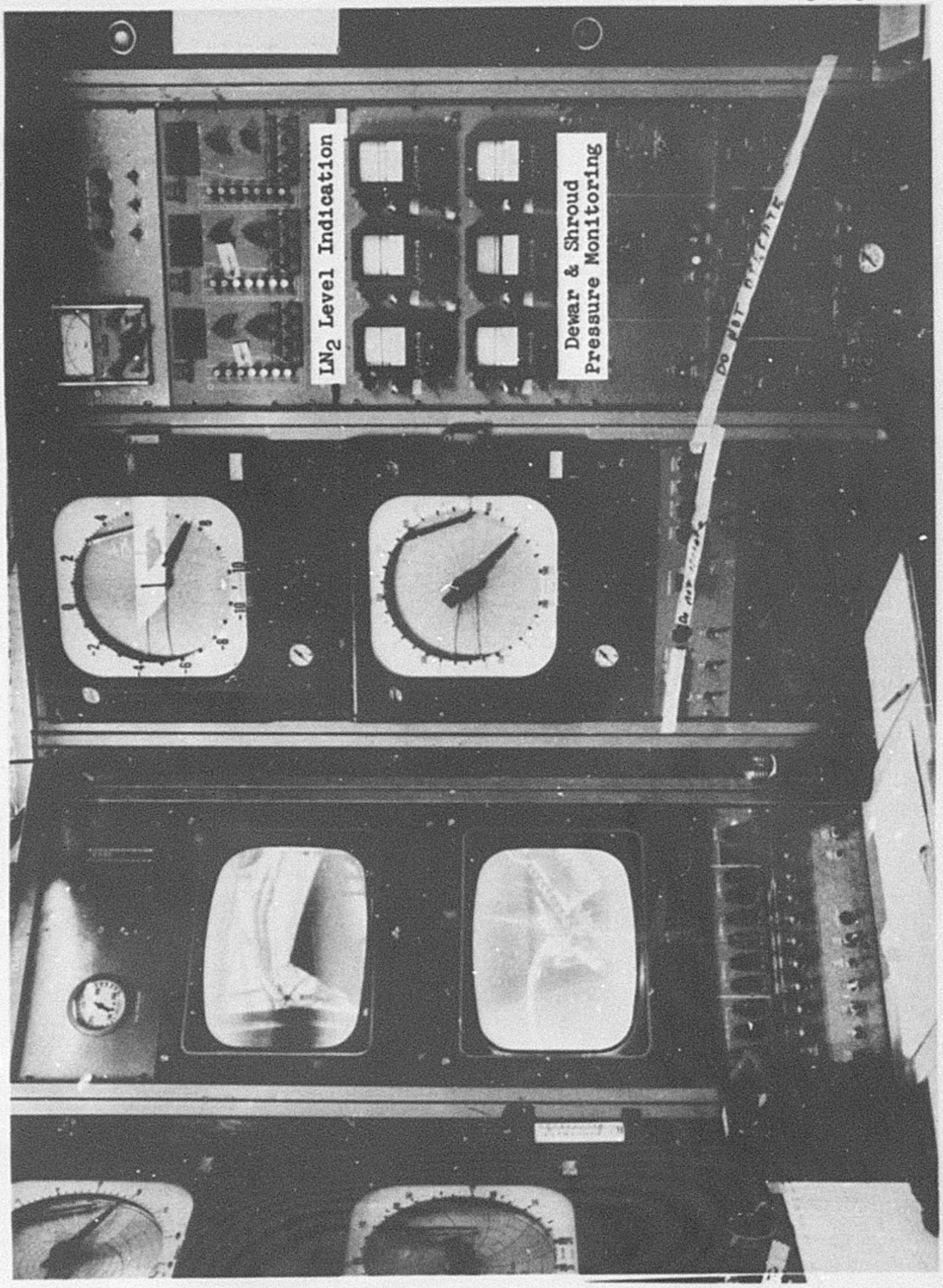


Figure 2-18 Radiation Effects Console in Reactor Control Room—Right Side

in resistance as a function of temperature were used to trigger the alarm-system instrumentation, which indicated the liquid level by visual and/or audible means.

The level in the dewar was automatically controlled by Bristol recorders operating in conjunction with the thermocouples mounted in the liquid-level probe. The outputs of the thermocouples were converted by the Bristol controller to a pneumatic signal which was used to operate a Fischer Proportional Positioner mounted on the LN_2 cryogen supply valve.

The instrumentation used to monitor the level in the dewar after the irradiation, during the storage period, and during the subsequent pulling of the specimens is shown in Figure 2-19. This system also gives visual and audible indication of liquid level and automatically controls the liquid level in the dewar by electric signals to a solenoid valve in the LN_2 supply line. The same type of liquid-level probe was used during the storage period as was used during the irradiation, and the liquid level in the dewar was maintained at the same level.

Figure 2-20 depicts the instrumentation employed in the pulling of specimens in tension to break. A 1/2-in.-thick lead shield, not shown in the photograph, was installed on the front of the Instron machine to shield personnel during the pulling of irradiated specimens. A sketch of the oven control system is presented in Figure 2-21.

Figure 2-22 depicts representative calibration specimens, with thermocouples attached, and tools used in the transfer

NPC 23,281
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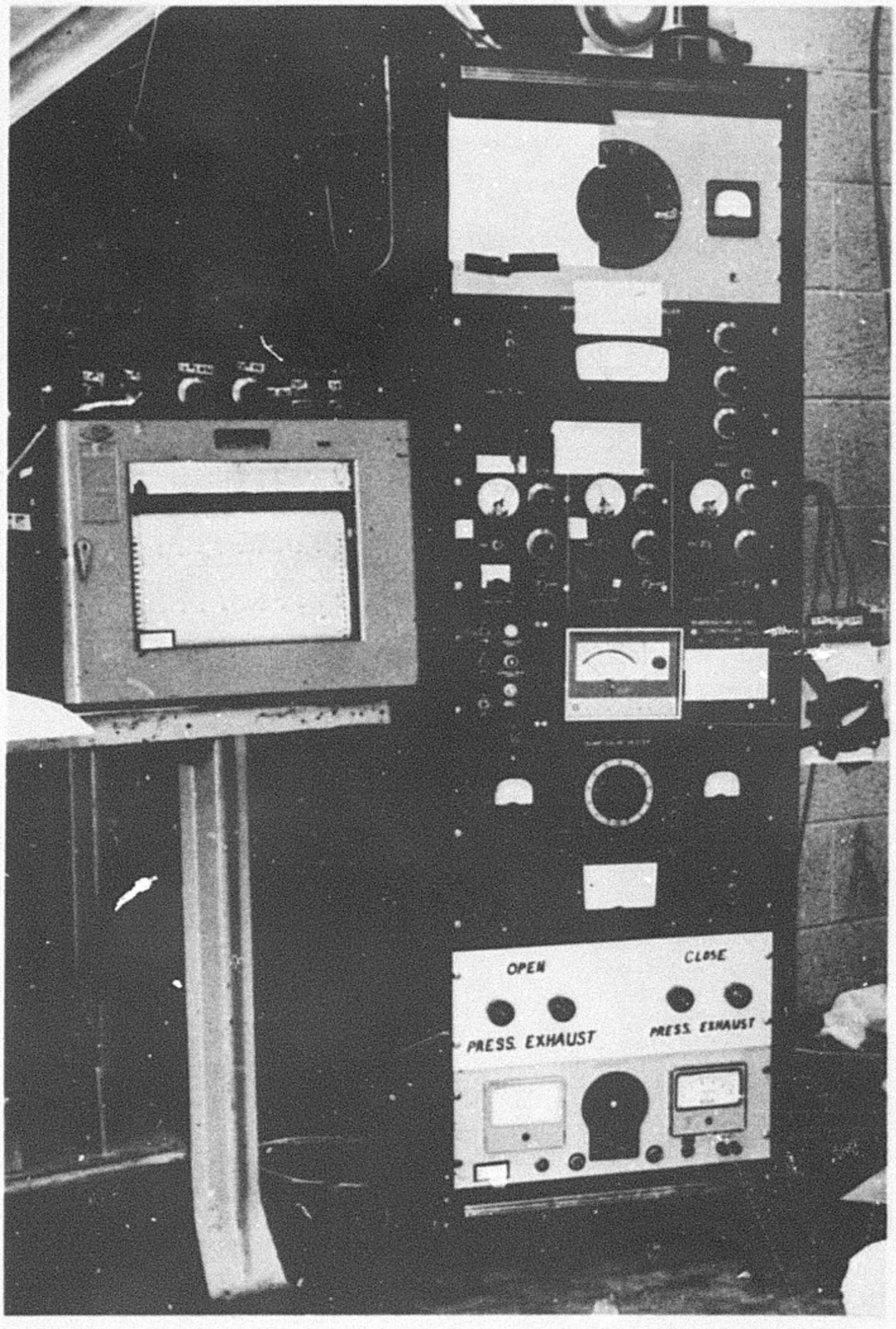


Figure 2-19 Liquid-Level Control System (IML)

NPC 23,280
31-8363

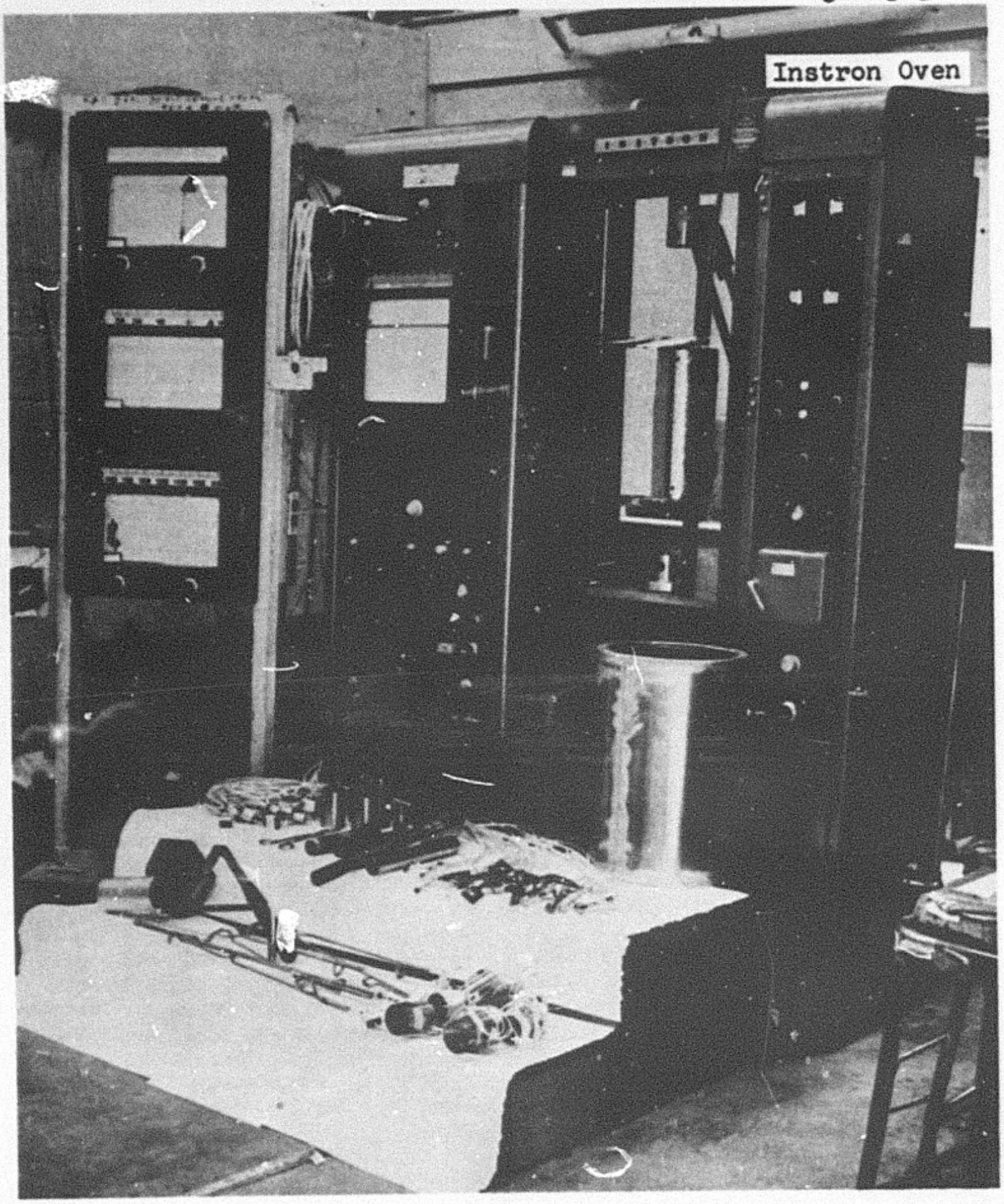


Figure 2-20 Tensile Test Instrumentation

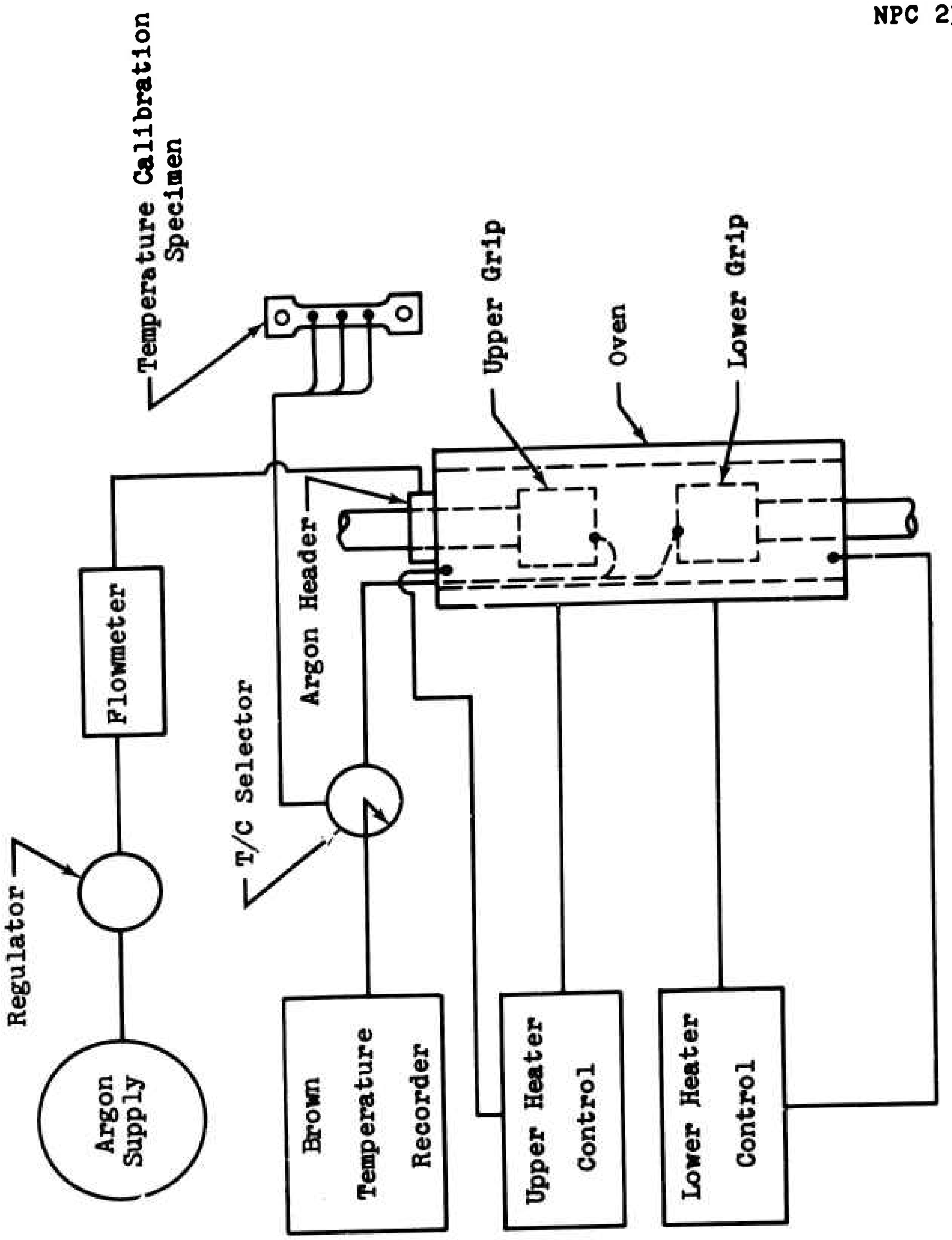
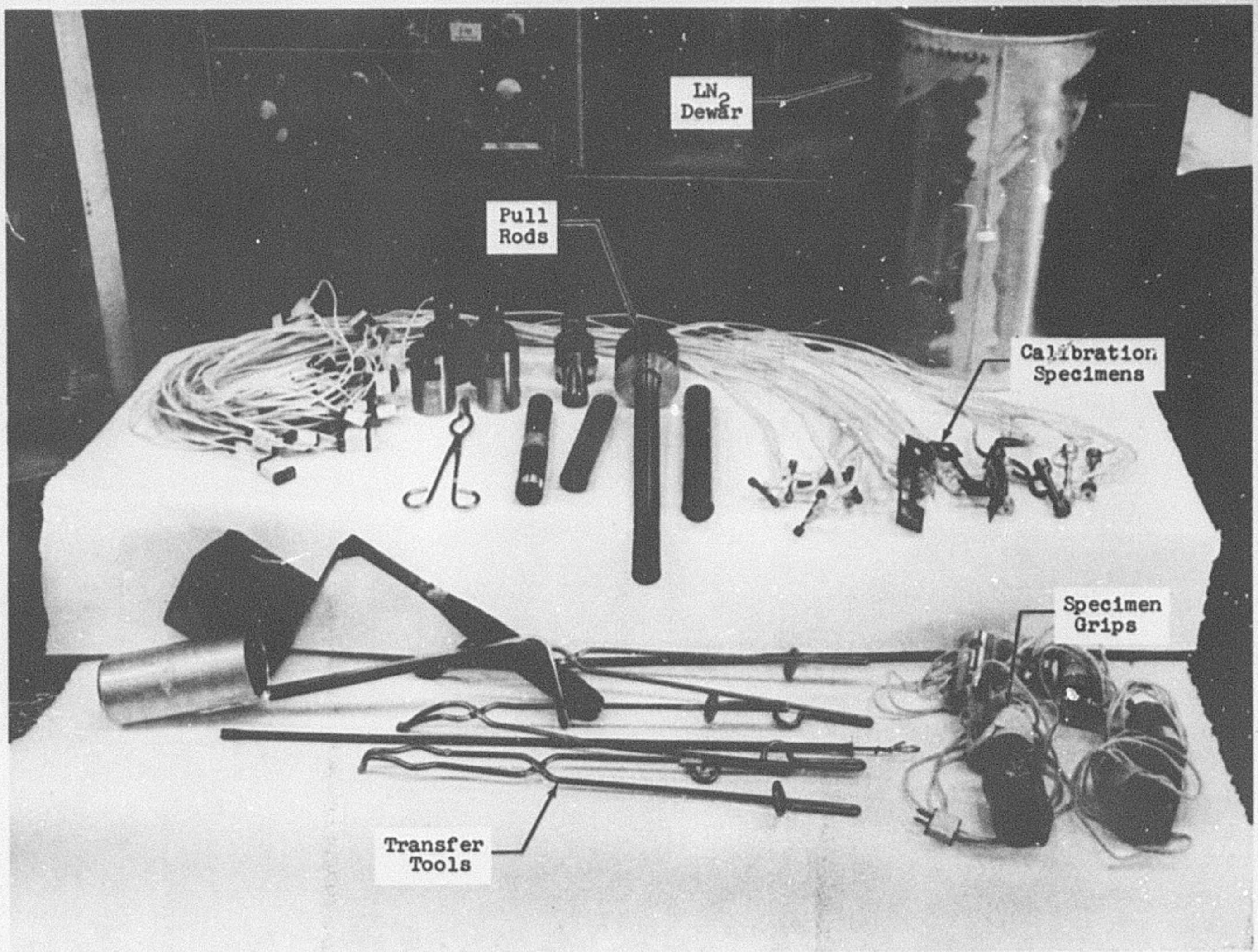


Figure 2-21 IML Oven Control Setup



NPC 22,758
31-8366

Figure 2-22 Accessory Hardware for Tensile Tests of specimens at LN_2 temperatures.

The irradiation dewar in its storage area can be seen in Figure 2-23. The irradiation dewar was placed in the IML hot cave and the cave shielding augmented with concrete blocks. In addition, 4 in. of lead shielding was placed in front of the dewar and on top of the steel dump valve at the rear of the dewar to further shield personnel when removing specimens from the dewar.

2.2.2 Resistivity Tests

Resistance measurements of one Inconel 718 wire specimen were made during irradiation. After irradiation, resistance measurements of two Inconel X-750 specimens and one Inconel 718 specimen were made at LN_2 temperatures before and after various annealing treatments.

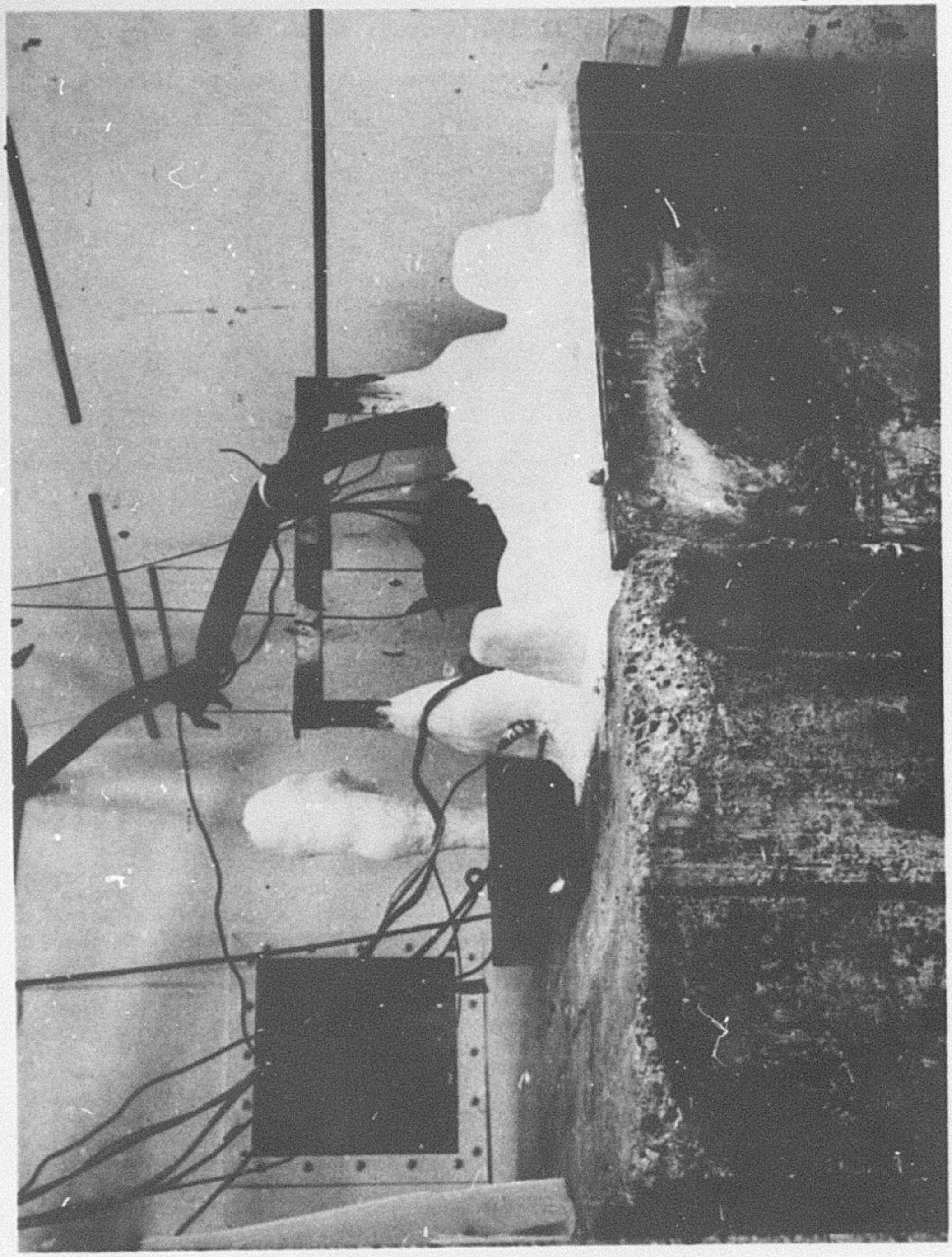
The resistance measurements made during and after irradiation were accomplished with the instrumentation setups represented in Figures 2-24 and 2-25, respectively. A schematic diagram of the resistivity bridge circuit is presented in Figure 2-26. The same resistance bridge circuit was used for measurements during and after irradiation. The test instrumentation and LN_2 dewar are shown in Figure 2-27.

The location of the resistivity specimens in the aluminum framework of the north irradiation dewar can be seen in Figures 2-9, 2-10, and 2-11. The actual specimens were not available when the picture was taken and dummy specimens were substituted.

2.2.3 Steel-Spring Specimen Test

The location of the springs on the aluminum framework of

NPC 22,756
31-8361



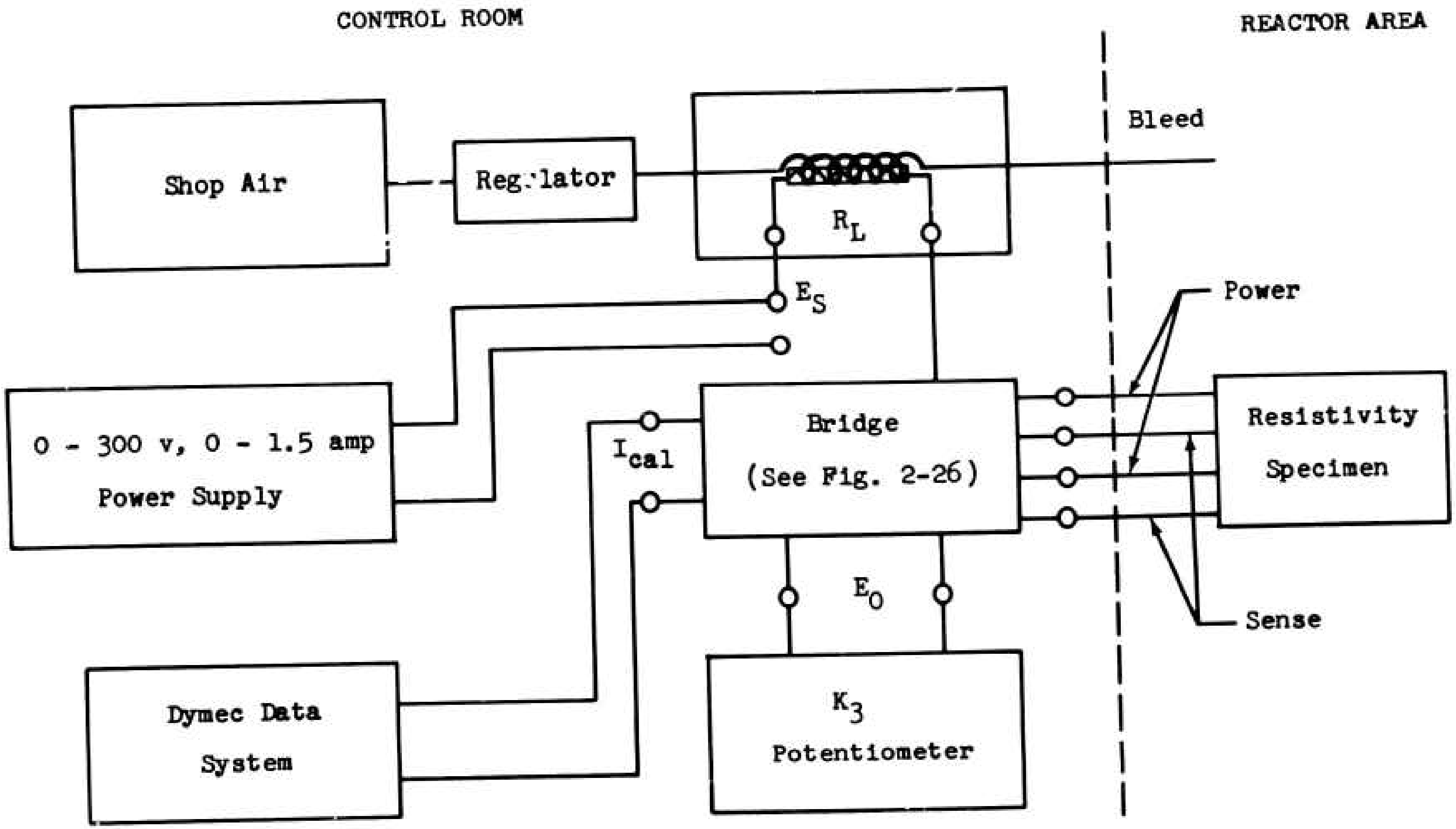


Figure 2-24 Resistivity Test Setup in Reactor Area

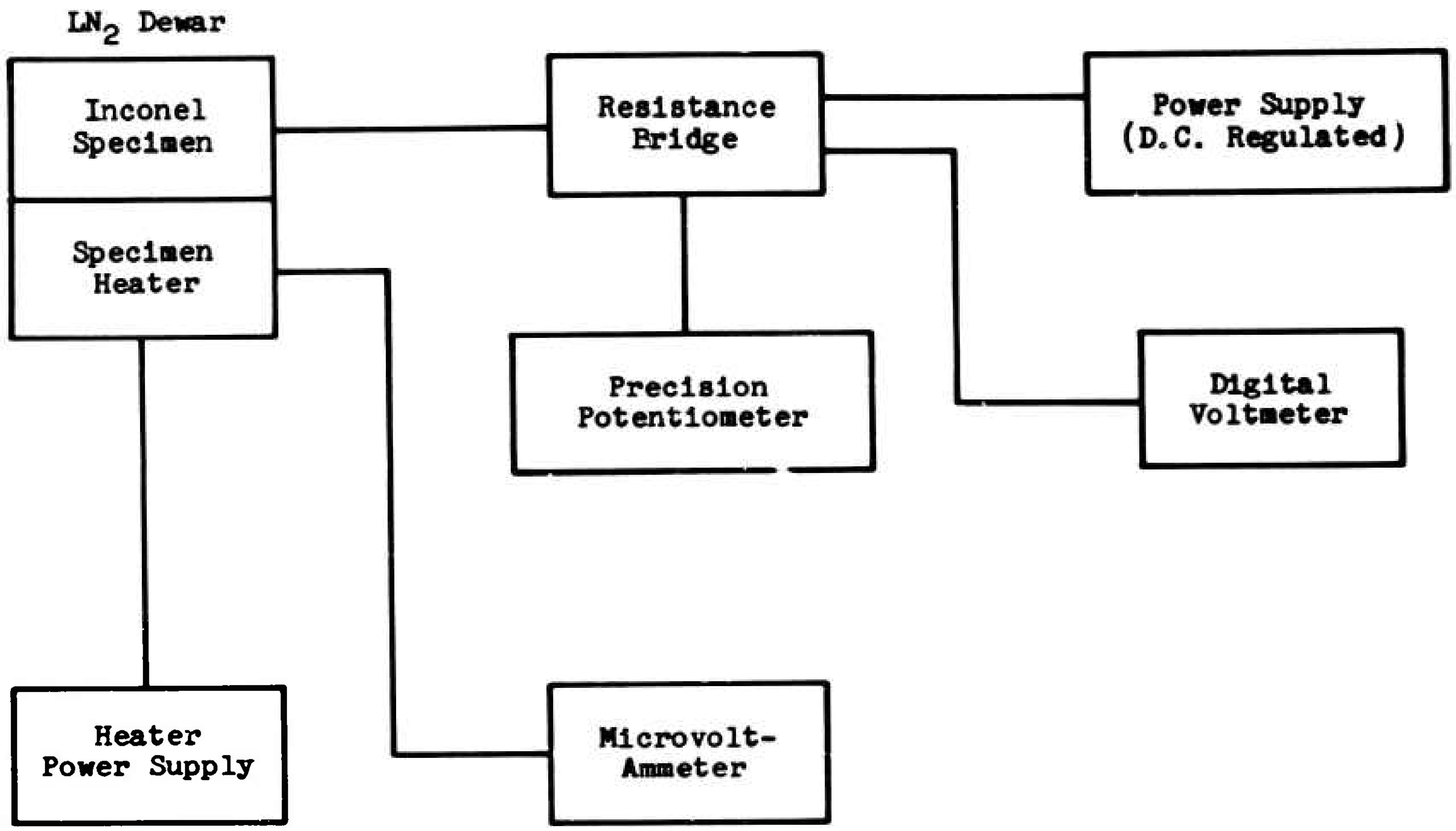


Figure 2-25 Diagram for Postirradiation Resistivity Test

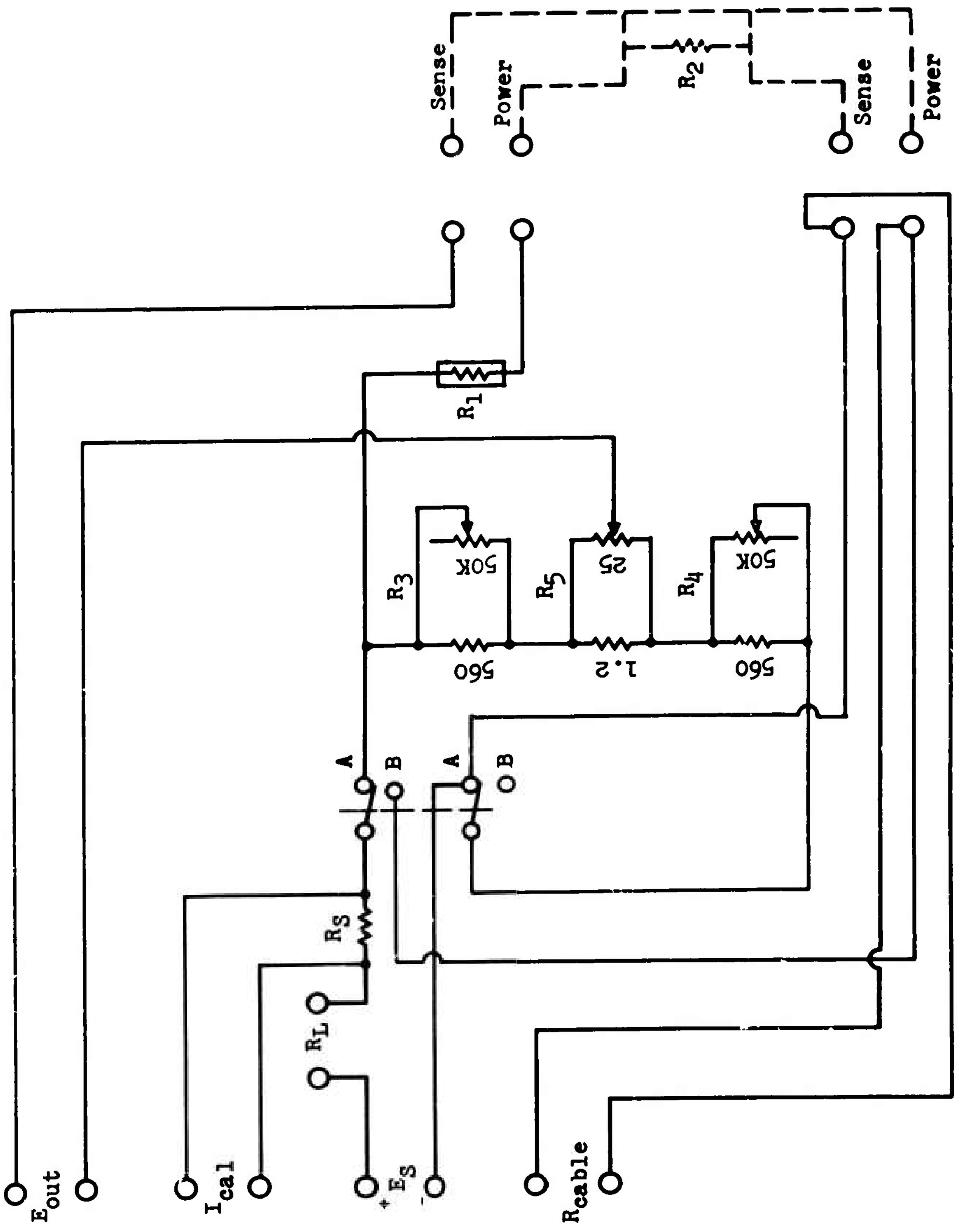


Figure 2-26 Schematic of Resistivity Bridge Circuit

NPC 23,282
31-8432

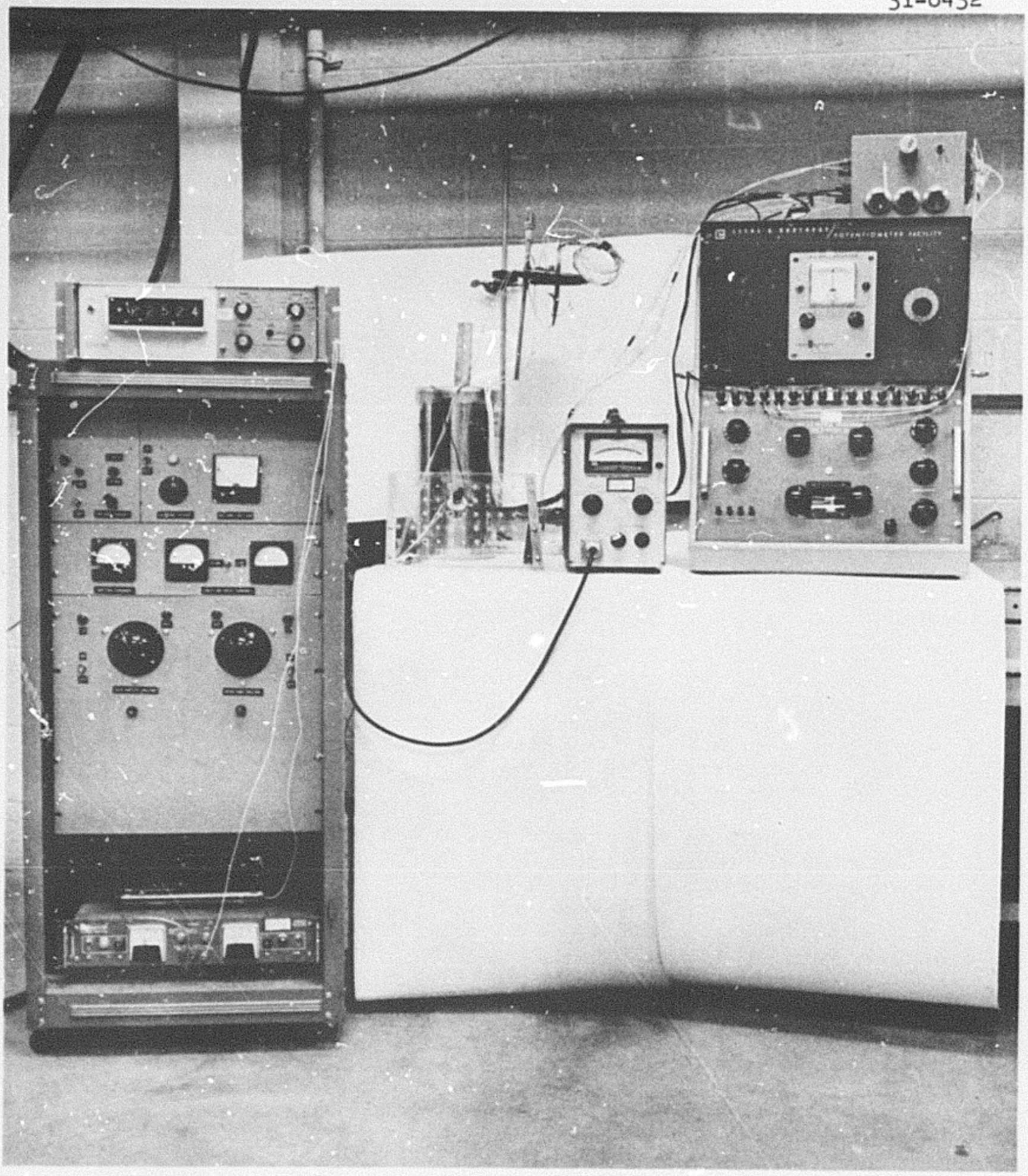


Figure 2-27   Resistivity Test Instrumentation

the north dewar can be seen in Figure 2-10. Only three specimens were available at the time this picture was taken; a fourth spring was added at a later date.

The Model TT Instron tensile testing machine used for the tensile tests was used in this test to determine the spring constant. Dimensional measurements on the springs were made with a Lufkin micrometer mounted in a test jig.

2.2.4 O-Ring Seal Tests

Two test fixtures were supplied by WANL. One fixture was mounted on the front dosimeter rack inside the east LH_2 dewar in the gaseous hydrogen. The other fixture was enclosed in an aluminum capsule and mounted on the outside of the east LH_2 dewar (Fig. 2-28). The capsule after disassembly is shown in Figure 2-29.

The encapsulated fixture had one Cu-Cn thermocouple placed inside the capsule. The output of the thermocouple was monitored continuously with a Minneapolis-Honeywell multipoint recorder. Aluminum tubing, 1/4-in. in diameter, was run from a bottled helium and hydrogen supply to the capsule and from the capsule to the north hydrogen vent stack. A sufficient amount of hydrogen gas was bled through the capsule during irradiation to maintain the test specimen in a hydrogen environment. Helium was used to purge the system before and after hydrogen flow. A sketch of the experimental setup is shown in Figure 2-30.

2.2.5 Cemented-Orifice Tests

The cemented-orifice specimens were placed in two aluminum containers approximately 1 in. thick by 7 in. deep by 7 in. wide.

NPC 23,283
31-8351

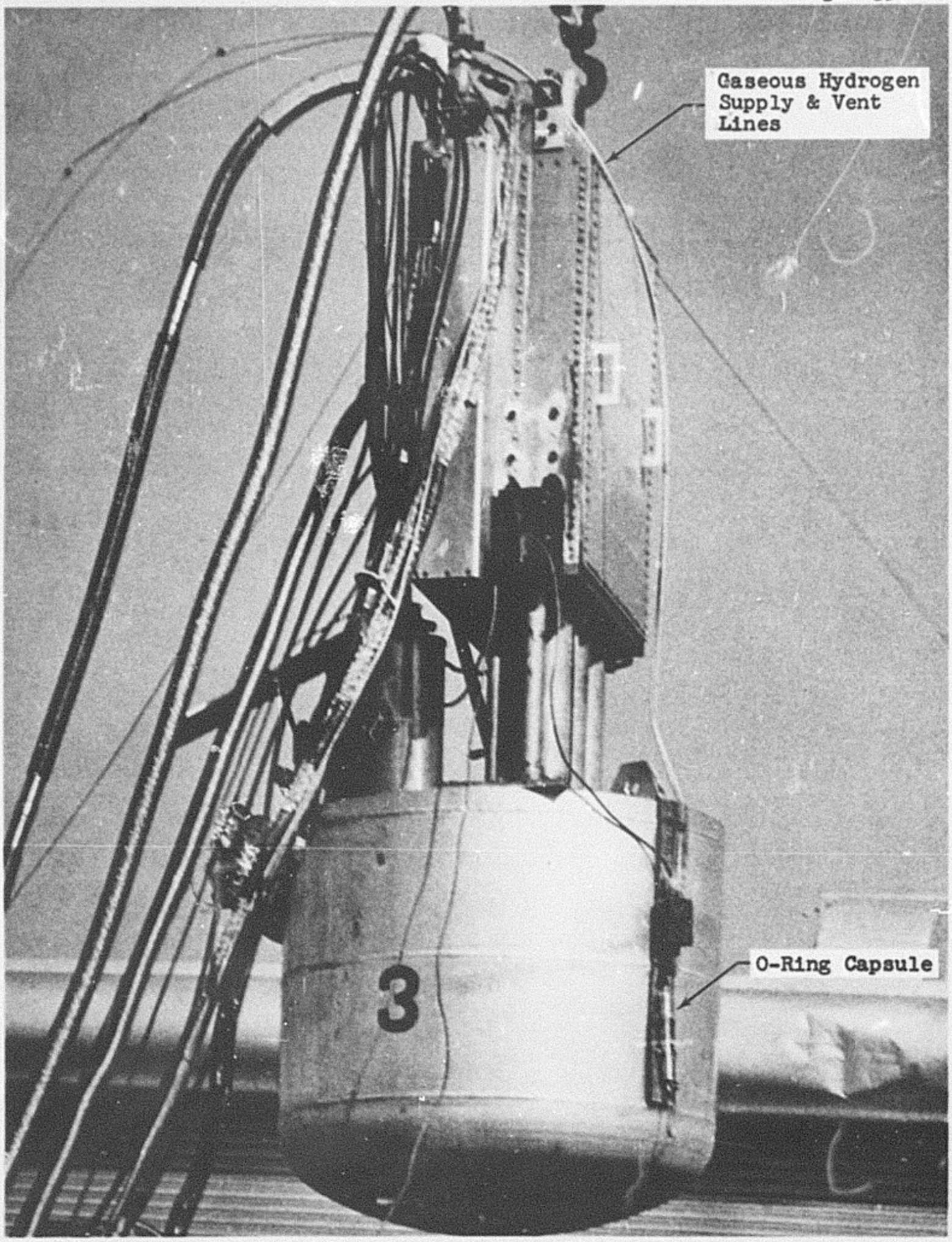


Figure 2-28 O-Ring Capsule Irradiation Configuration - East Dewar

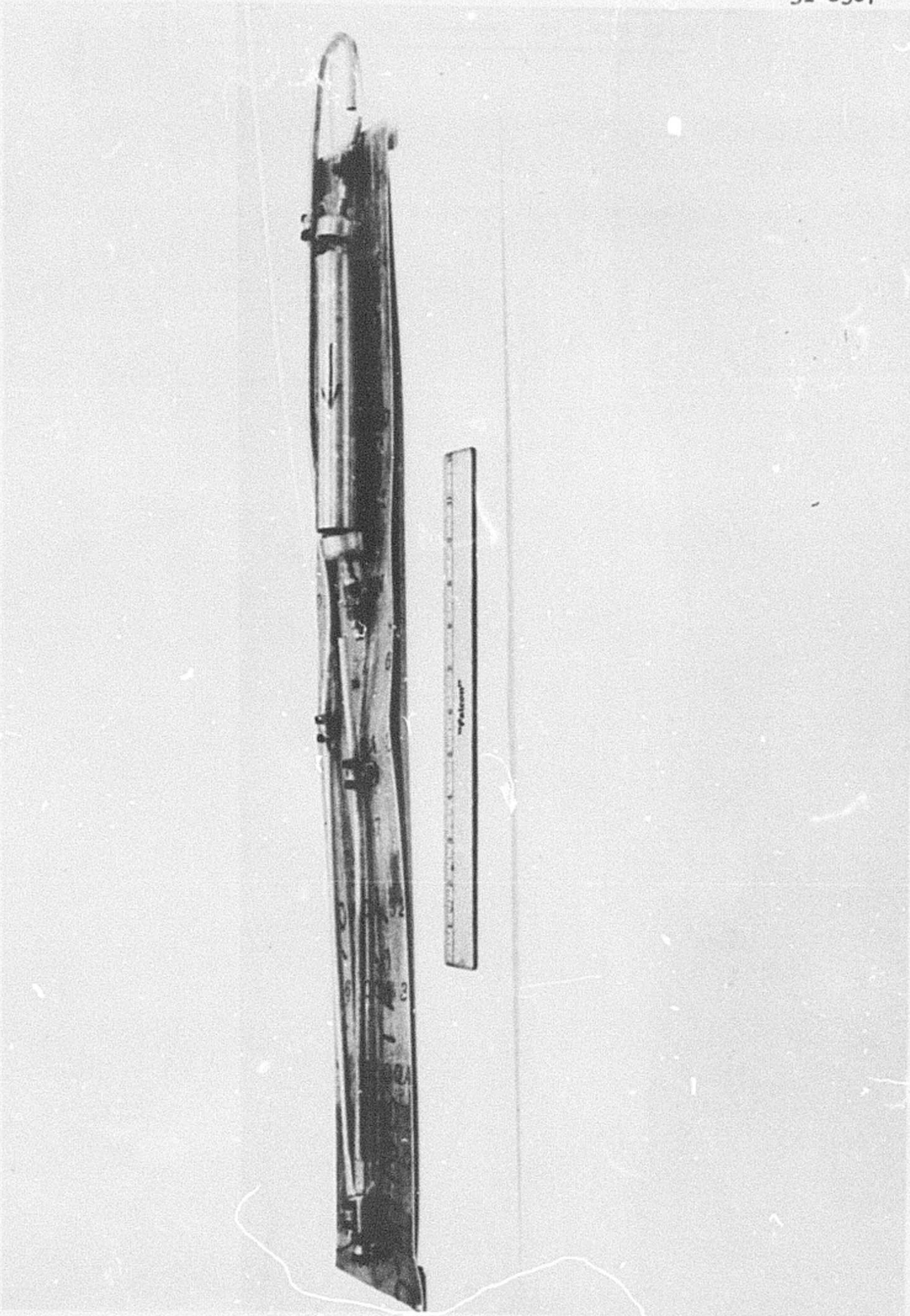


Figure 2-29 Dismantled O-Ring Test Capsule

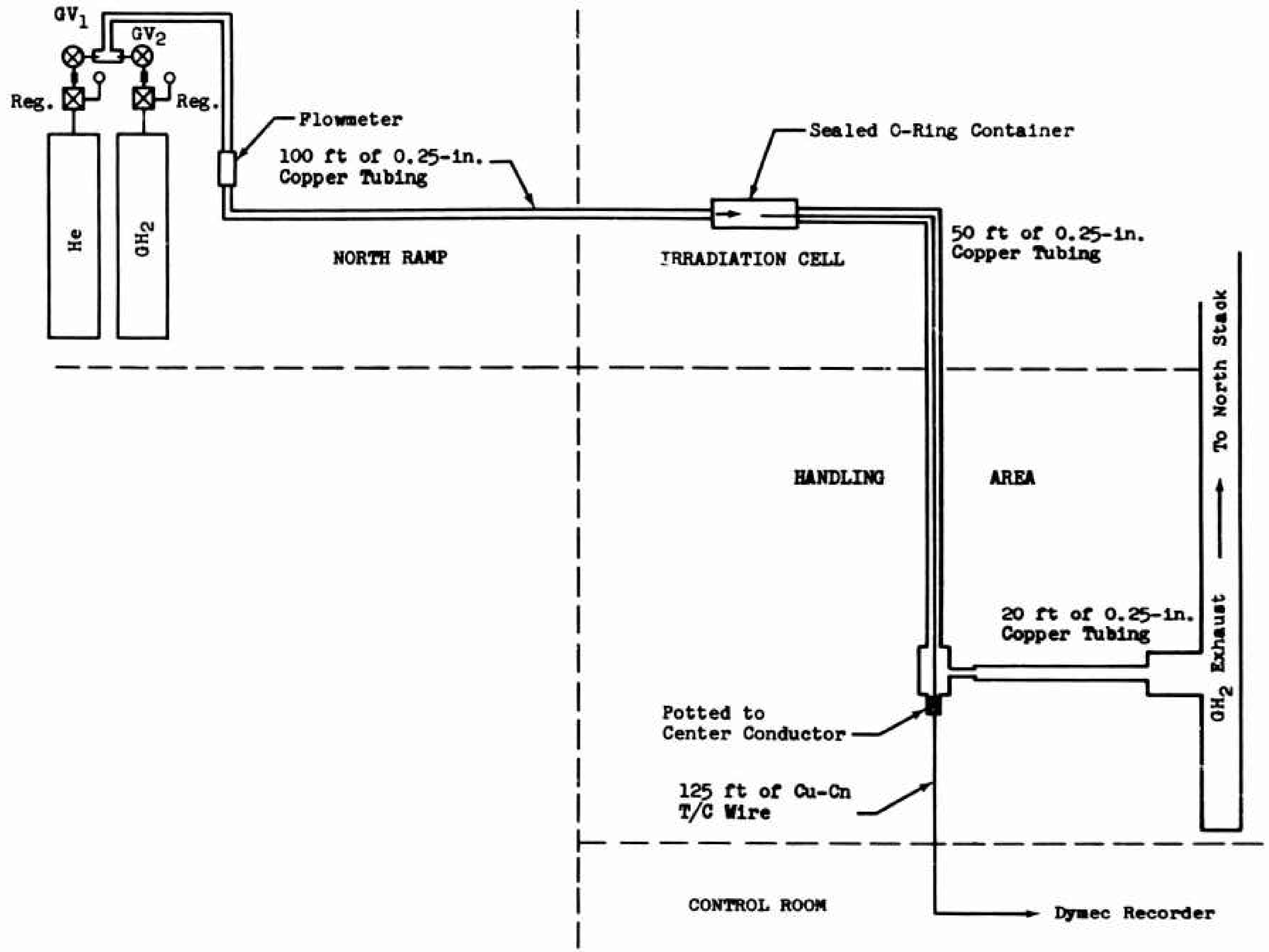


Figure 2-30 O-Ring Experimental Setup

One container was mounted inside the north dewar below the LN_2 liquid level. This container was mounted on the rear centerline of the graphite-tensile-specimen tray. The other container was mounted on the front center of the west side of the north dewar. One Cu-Cn thermocouple was installed in the container and its output monitored during the irradiation with a Minneapolis-Honeywell multipoint recorder.

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III. EXPERIMENTAL RESULTS

3.1 Tensile Tests

3.1.1 Data Presentation

The integrated neutron fluxes received by the tensile specimens are presented in Table 3-1. Detailed dosimetry data on these specimens are presented in Appendix B.

Three irradiation specimens and three control specimens of each material type were generally assigned for testing under each test condition. A number of specimens of each material type were assigned as spares. After all specimens except the spares had been pulled, a preliminary analysis of the data was made and the spares assigned to test conditions exhibiting questionable data. Table 2-2 lists the actual number of specimens, including spares, that were tested under each test condition. The results of all tensile tests are tabulated in Tables 3-2 through 3-8 and presented in bar graph form in Figures 3-1 through 3-7. Table 3-9 identifies the specimen numbers associated with each bit of data presented in Tables 3-2 through 3-8. An explanation of column headings is given in Table 2-1.

The tensile data on specimens pulled during the strain-rate study are tabulated in Table 3-10. The specimens are identified by number in Table 3-11. No analysis of the effect of strain rate on the properties of the specimens was made by GD/FW personnel. The original Instron charts for this test have been forwarded to Westinghouse for analysis by Westinghouse personnel.

Table 3-1

Integrated Neutron Fluxes Received by Tensile Specimens
(10^{17} n/cm^2, E > 1 Mev)

Specimen Material	Ref. No.*	Test Condition																			
		A1	C1	B1	D_{A1}	D_{A1}'	D_{B1}	D_{B1}'	D_{C1}	D_{C1}'	D_{D1}	D_{D1}'	E_{C1}	E_{A1}	E_{C1}	F1	F_{11}	G1	G_{11}	H1	H_{11}
Inconel 718, Type 3	3P	7.5	7.5	7.5-7.0	6.0	5.5	6.0	5.5	7.0	5.0	6.0	5.0	7.0-7.5								
	3N	7.5	7.0-7.5	7.5					7.0-7.5		7.0		7.0								
Inconel 718, Type 1	1P	10	8.5	8.5-9.5					8.5				8.5-9.5								
	1N	10	8.5	9.5					8.5				8.5-9.0								
Inconel 718-W, Type 3	3P	8.0	6.5	6.5																	
	3N	7.5	6.5	6.5-7.0																	
Inconel X-750, Type 1	1P	7.5	6.5-8.5	7.5					6.5-7.0						6.5						
	1N	7.5	6.5-9.0	6.5-7.5					6.5-7.5						6.5						
Inconel X-750, Type 3	3P	6.0	6.0	6.0-7.5					5.5				5.5								
	3N	6.0	5.5	6.0-6.5					5.5-6.5				5.5								
AISI 301-CW, Type 3	3P	6.5	6.0-7.0	6.0-6.5	6.0-7.0									6.0							
	3N	6.5	6.0-6.5	6.0-6.5	6.0									6.0							
AISI 303-Se, Type 1	1P	8.5	6.5-8.5	6.5-8.5	6.5-7.5									6.5							
	1N	8.5	6.5-7.5	6.5-7.5	6.5-7.5									7.0-8.0							
Al 2219-T6, Type 3	3P	8.5	8.5	6.5-8.5	8.5									8.0							
	3N	8.5	6.5-8.5	6.5-8.5	8.5									6.5-8							
Al 2219-T6-T, Type 2	2P	7.0-7.5	4.5-6.5	4.5-6.5																	
	2N	7.5	4.5-6.5	4.5-7.0																	
Al 2219-T6-R, Type 2	2P	8.5	8.0	8.0-8.5																	
	2N	8.5	8.0	8.0-8.5																	
Beryllium, Type 4	4P	5.0-7.0	4.0-7.0	5.0																	
	4N	5.0-6.5	4.0-6.5	5.0																	
Ti A-110-AT-E11, Type 2	2P	6.0	5.5-6.5	6.0-7.5																	
	2N	6.0	5.5-7.5	5.5-6.5																	
Inconel 718 Strain Rate Study	1P															8.0	7.5-8.0	8.0	8.0	8.0	8.0-8.5

* See Table 3-9, under same Ref. No. and Test Condition, for identification of specimen.

Table 3-2

Tensile Test Results

Inconel 718, Type 3

Property Measured	Ref. No.*	Test Condition																		
		C	A1	C1	B	B1	D_A	D_{A1}	D_{A1}'	D_B	D_{B1}	D_{B1}'	D_C	D_{C1}	D_{C1}'	D_D	D_{D1}	D_{D1}'	E_C	E_{C1}
UTS (ksi)	1P	269.9	270.6	269.3	219.7	214.7	196.3	199.3	200.7	195.1	194.3	192.7	188.6	189.2	189.4	154.7	149.0	152.7	273.6	272.4
	2P	270.2	269.8	265.0	218.2	211.1	200.0	200.8	199.7	180.2	193.0	187.9	190.1	187.8	187.3		150.8	150.6	271.2	27[illegible].7
	3P		268.2	268.0	218.7	213.6							192.2	191.6					271.8	273.5
	4P					215.3														272.7
	5P																			
Average		270.0	269.6	267.4	218.9	213.7	198.2	200.0	200.2	187.7	193.6	190.3	190.3	189.5	188.3	154.7	149.9	151.7	272.2	272.6
TYS (ksi)	1P	213.1	233.1	219.6	185.8	189.4	162.7	166.6	168.7	162.6	166.2	165.5	157.8	156.6	159.4	140.9	138.6	139.4	212.2	211.7
	2P	211.8	234.6	216.4	184.7	185.4	167.1	166.6	168.4	162.9	168.1	160.4	158.5	153.2	157.5		141.0	139.4	212.3	213.2
	3P		228.5	216.8	184.1	186.7							159.4	158.1					212.2	213.9
	4P					189.2														215.1
	5P																			
Average		212.4	232.1	217.6	184.9	188.2	164.9	166.6	168.5	162.7	167.1	162.9	158.6	155.9	158.4	140.9	139.8	139.4	212.2	213.5
NTS (ksi)	1N	243.5	257.9	257.4	220.5	218.5							193.0	179.0			182.4		247.9	241.9
	2N	241.7	261.0	247.3	219.1	217.6							191.6	180.9			183.2		258.3	238.0
	3N		260.8	254.1	218.0	219.9							183.9	183.0					246.5	246.4
	4N			251.7																
	5N			251.5																
Average		242.6	259.9	252.4	219.2	218.7							189.5	180.9			182.8		250.9	242.1
NTS/UTS	Max	0.90	0.97	0.97	1.01	1.04							1.02	0.97			1.23		0.95	0.91
	Min	0.894	0.95	0.92	0.99	1.01							0.96	0.93			1.21		0.90	0.87
Average		0.90	0.96	0.94	1.00	1.02							1.00	0.95			1.22		0.92	0.88
Percent Elongation	1P	12.9	11.6	10.2	10.5	12.4	10.0	10.1	9.82	9.98	10.1	8.54	7.79	8.28	9.39	6.23	3.29	3.74	13.01	13.94
	2P	12.4	13.1	14.1	11.75	11.4	11.3	9.7	11.71	8.78	9.26	8.26	8.71	9.09	9.26		3.60	3.64	15.12	13.26
	3P		13.0	14.7	10.3	11.5							7.75	8.01					14.06	11.20
	4P					11.7														13.44
	5P																			
Average		12.6	12.6	13.0	10.8	11.8	10.7	9.9	10.71	9.38	9.68	8.40	8.08	8.46	9.33	6.23	3.45	3.69	14.06	12.96
Percent Reduction in Area	1P	19.0	20.3	11.2	26.6	19.5	22.4	23.7	23.5	26.3	21.0	22.97	16.1	29.5	16.6	8.36	6.35	5.76	17.0	15.46
	2P	15.1	22.7	17.6	26.1	24.1	24.9	18.8	18.8	22.4	22.2	22.87	16.2	16.9	22.3		5.97	9.50	24.2	16.75
	3P		21.5	13.9	20.6	22.0							12.8	15.9					22.7	15.60
	4P					28.9														22.61
	5P																			
Average		17.1	21.5	14.2	24.4	23.6	23.6	21.3	21.14	24.4	21.6	22.92	15.0	20.8	19.45	8.36	6.16	7.63	21.30	17.61

* See Table 3-[illegible], under same Ref. No. and Test Condition, for identification of specimen.

Table 3-3

Tensile Test Results

Inconel 718, Type 1

Property Measured	Ref. No.*	Test Condition								
		C	A1	C1	B	B1	D_C	D_{C1}	E_C	E_{C1}
UTS (ksi)	1P	256.8	267.5	276.3	216.6	213.7	188.3	193.9	267.7	270.8
	2P	271.2	272.4	270.0	221.6	217.4	192.2	193.0	274.9	276.3
	3P	275.7	265.1	272.4	215.3	210.8	192.4		273.0	272.4
	4P			275.5		217.5	193.7			
	5P					212.8				
Average		267.9	268.3	273.6	217.8	214.4	191.7	193.5	271.9	273.2
TYS (ksi)	1P	205.0	234.1	225.7	177.6	185.2	154.9	156.6	203.1	210.0
	2P	203.9	234.9	220.2	183.2	192.5	159.9	155.3	212.9	211.6
	3P	211.3	236.5	218.6	177.8	188.4	155.7		205.0	208.8
	4P			225.8		188.9	159.6			
	5P					187.5				
Average		206.7	235.2	222.6	179.5	188.5	157.5	156.0	207.0	210.2
NTS (ksi)	1N	314.8	329.4	325.7	276.3	291.1	228.5	227.0	324.3	307.3
	2N	298.6	354.7	333.5	279.2	296.2	240.8	241.3	318.8	327.2
	3N	324.4		349.5	282.3	284.0	244.5	223.8	306.6	312.7
	4N			344.1	285.7			228.9		
	5N							224.4		
Average		312.6	342.0	338.2	280.9	290.5	237.9	229.1	316.5	315.8
NTS/UTS	Max	1.26	1.34	1.29	1.33	1.41	1.30	1.25	1.21	1.21
	Min	1.08	1.21	1.18	1.25	1.31	1.18	1.15	1.12	1.11
Average		1.17	1.27	1.24	1.29	1.35	1.24	1.18	1.16	1.16
Percent Elongation	1P	7.49	6.57	12.7	10.5	13.3	10.9	9.83	15.0	12.3
	2P	12.9	13.2	10.7	10.6	12.1	8.11	12.6	14.2	12.9
	3P	17.1	5.31	16.7	11.6	9.37	11.8		13.8	15.7
	4P			10.7		11.2	8.46			
	5P					10.9				
Average		12.5	8.36	12.7	10.9	11.4	9.82	11.2	14.4	13.7
Percent Reduction in Area	1P	25.5	25.3	24.1	25.4	26.7	24.0	13.9	26.6	21.1
	2P	19.7	30.7	30.8	24.3	29.5	19.9	18.5	23.9	31.0
	3P	26.7	18.2	29.4	29.5	28.2	19.7		26.8	25.4
	4P			20.6		26.4	4.8			
	5P					22.5				
Average		24.0	24.7	26.2	26.4	26.7	17.1	16.2	25.8	25.8

Inconel 718-WS, Type 3

Property Measured	Ref. No.*	Test Condition				
		C	A1	C1	B	B1
UTS (ksi)	1P	207.3	206.2	216.5	179.7	170.6
	2P	205.7	202.7	211.6	178.9	169.3
	3P	213.3	220.4	209.1	171.8	170.3
	4P	205.6	216.9	219.4	164.5	165.3
	5P	199.8			171.6	
Average		206.3	211.6	214.2	173.3	168.9
TYS (ksi)	1P	196.4	206.2	209.4	168.9	165.4
	2P	196.2	202.7	201.8	167.3	162.6
	3P	199.8	216.6	201.8	162.2	185.4
	4P	191.7	211.8	210.0	152.7	158.0
	5P	194.6			162.0	
Average		195.7	209.4	205.8	162.6	167.8
NTS (ksi)	1N	159.3	154.9	149.2	145.5	163.3
	2N	153.8	172.5	185.1	146.6	140.8
	3N	168.8	169.9	160.6	148.6	144.2
	4N	166.2			152.2	
	5N					
Average		162.0	165.8	165.0	148.2	149.6
NTS/UTS	Max	0.85	0.85	0.89	0.93	0.99
	Min	0.72	0.70	0.68	0.81	0.83
Average		0.79	0.78	0.77	0.86	0.89
Percent Elongation	1P	0.98	0.90	0.84	0.89	1.29
	2P	0.89	0.80	1.25	0.93	1.16
	3P	1.20	0.80	1.02	0.62	1.11
	4P	1.02	1.05	0.71	0.84	1.02
	5P	0.71			0.71	
Average		0.96	0.89	0.96	0.80	1.15
Percent Reduction in Area	1P	9.89	7.02	3.15	6.68	12.47
	2P	9.36	4.75	5.18	8.50	8.28
	3P	10.63	5.02	5.18	7.40	6.13
	4P	10.14	3.80	8.36	8.73	11.07
	5P	9.77			8.18	
Average		9.96	5.15	5.47	7.90	9.49

* See Table 3-9, under same Ref. No. and Test Condition, for identification of specimen.

Table 3-4

Tensile Test Results

Inconel X-750, Type 1

Property Measured	Ref. No.*	C	A1	C1	B	B1	D_C	D_{C1}	E_C	E_{C1}
UTS (ksi)	1P	212.1	208.0	212.5	172.1	169.3	153.3	143.5	212.1	212.9
	2P	212.7	213.7	216.2	166.5	167.2	148.3	148.4	207.6	203.5
	3P	208.8	206.0	218.6	168.5	163.9	153.3	150.0	207.2	204.7
	4P	208.6		207.9					205.9	212.0
	5P								217.1	
	6P									
Average		210.5	209.2	213.8	169.1	166.8	151.6	147.3	210.0	208.3
TYS (ksi)	1P	120.3	167.2	152.9	106.9	131.1	93.8	91.3	120.7	122.6
	2P	121.2	169.2	151.7	103.5	130.5	92.0	96.2	118.7	116.6
	3P	119.1	163.1	153.3	105.9	131.3	94.2	92.9	118.7	119.1
	4P	118.4		148.4					119.8	121.5
	5P								126.3	
	6P									
Average		119.7	166.5	151.6	105.4	131.0	93.3	93.5	120.9	120.0
NTS (ksi)	1N	247.2	301.8	273.6	216.3	240.9	187.3	180.2	243.2	240.7
	2N	238.9	294.9	282.8	216.3	244.0	183.0	175.4	236.2	236.1
	3N	246.9	301.3	285.1	220.2	245.7	182.0	184.3	247.3	242.9
	4N			279.6		235.5				
	5N									
	6N									
	7N									
	8N									
Average		244.3	299.3	280.3	217.6	241.8	184.1	180.0	242.3	240.0
NTS/UTS	Max	1.19	1.47	1.37	1.32	1.51	1.26	1.28	1.20	1.19
	Min	1.12	1.38	1.25	1.26	1.39	1.19	1.17	1.09	1.11
Average		1.16	1.43	1.31	1.29	1.45	1.21	1.22	1.15	1.15
Percent Elongation	1P	25.0	17.1	22.1	17.7	15.5	11.3	8.80	24.5	21.0
	2P	25.7	21.4	20.2	15.8	16.3	11.0	8.97	21.5	18.4
	3P	23.7	18.9	23.8	15.5	16.5	11.0	10.0	22.7	21.8
	4P	25.4		18.1					19.1	24.2
	5P								22.5	
	6P									
Average		24.9	19.1	21.1	16.3	16.1	11.1	9.26	22.05	21.4
Percent Reduction in Area	1P	34.7	33.4	33.4	36.0	33.6	16.8	13.9	33.4	32.4
	2P	33.1	37.2	36.0	30.6	30.8	17.0	19.8	32.1	41.0
	3P	28.1	32.1	36.0	33.2	30.8	21.2	15.3	38.5	41.0
	4P	38.3		36.0					31.5	32.8
	5P								33.6	
	6P									
Average		33.5	34.2	35.4	33.3	31.7	18.3	16.3	33.8	36.8

Inconel X-750, Type 3

Property Measured	Ref. No.*	C	A1	C1	B	B1	D_C	D_{C1}	E_C	E_{C1}
UTS (ksi)	1P	213.1	211.8	213.8	165.5	163.6	146.0	127.8	206.7	207.3
	2P	210.8	210.8	213.0	166.3	163.8	140.4	137.4	208.8	207.7
	3P	210.3	216.3	212.9	167.3	165.4	141.5	140.1	207.8	209.2
	4P	206.0				165.1		142.7		
	5P					166.8		142.9		
	6P							138.7		
Average		210.1	213.0	213.2	166.4	164.9	142.7	138.3	207.8	208.1
TYS (ksi)	1P	127.3	169.7	153.6	107.9	129.7	98.1	95.1	122.6	123.4
	2P	125.2	168.2	152.2	106.1	129.0	93.6	97.1	124.1	123.1
	3P	125.2	172.5	153.7	109.2	130.1	96.6	97.2	124.0	124.7
	4P	122.5				127.4		98.2		
	5P					130.5		99.6		
	6P							95.2		
Average		125.1	170.1	153.2	107.7	129.4	96.1	97.1	123.6	123.7
NTS (ksi)	1N	187.0	217.0	204.6	159.4	174.2	122.1	119.3	171.4	179.6
	2N	183.4	218.4	205.5	147.0	165.1	131.1	127.8	179.6	175.6
	3N	177.8	217.8	205.2	162.8	171.2	130.4	126.9	166.8	180.6
	4N	182.7			152.5	174.5	125.9	124.5	176.9	
	5N							129.1		
	6N							124.0		
	7N							118.5		
	8N							128.7		
Average		182.7	217.8	205.1	155.4	171.3	127.4	124.9	173.7	178.6
NTS/UTS	Max	0.91	1.04	0.97	0.98	1.07	0.93	1.01	0.87	0.87
	Min	0.83	1.00	0.96	0.88	0.99	0.84	0.83	0.80	0.84
Average		0.87	1.02	0.96	0.93	1.04	0.89	0.90	0.84	0.86
Percent Elongation	1P	27.3	22.1	23.8	18.8	16.8	7.4	5.0	25.6	25.8
	2P	25.8	21.2	24.4	18.7	18.1	7.2	7.2	27.0	25.6
	3P	27.7	22.5	23.3	18.9	17.7	7.2	7.6	27.6	25.8
	4P	27.1				18.7		8.0		
	5P					19.0		8.3		
	6P							8.1		
Average		27.0	21.9	23.9	18.8	18.1	7.3	7.4	26.7	25.7
Percent Reduction in Area	1P	32.5	34.7	31.4	37.4	33.1	14.4	13.5	30.8	32.5
	2P	33.9	32.8	33.7	32.7	36.1	13.1	13.3	37.2	34.1
	3P	37.6	32.1	34.0	37.3	32.5	16.2	13.7	35.0	35.1
	4P	36.3				36.6		13.7		
	5P					41.6		12.2		
	6P							14.6		
Average		35.1	33.2	33.0	35.8	36.0	14.6	13.5	34.3	33.9

* See Table 3-9, under same Ref. No. and Test Condition, for identification of specimen.

Table 3-5

Tensile Test Results

AISI 301-CW, Type 3

Property Measured	Ref. No.*	Test Condition								
		C	A1	C1	B	B1	D_A	D_{A1}	E_A	E_{A1}
UTS (ksi)	1P	293.8	290.5	292.9	184.1	189.8	146.1	147.0	291.2	300.4
	2P	295.2	288.1	294.1	185.5	185.5	144.5	148.1	291.6	289.7
	3P	292.1	292.5	292.5	186.6	189.6	145.4	148.6	291.2	291.7
	4P	290.3		297.6	191.4	190.3	147.0			292.8
	5P									
Average		292.8	290.4	294.3	186.9	188.8	145.8	147.9	291.4	293.7
TYS (ksi)	1P	163.8	177.8	172.0	149.5	156.2	134.1	137.1	192.0	194.5
	2P	167.0	173.4	175.5	153.0	156.2	132.3	133.6	190.2	189.0
	3P	165.1	177.1	172.0	148.6	155.8	130.8	137.3	189.5	194.5
	4P	165.1		175.4	153.1	156.8	135.0			195.2
	5P									
Average		165.2	176.1	173.7	151.0	156.3	133.0	136.0	190.6	193.3
NTS (ksi)	1N	208.7	214.4	217.5	191.9	194.5	159.1	158.4	228.3	230.2
	2N	208.6	216.4	216.7	191.4	193.9	158.7	160.5	226.2	231.3
	3N	202.4	212.1	214.5	191.0	194.5	158.2	163.3	226.8	232.6
	4N	209.2		217.9	190.5	192.2	155.6		228.4	233.7
	5N									
Average		207.3	214.3	216.7	191.2	193.8	157.9	160.7	227.4	232.0
NTS/UTS	Max	0.72	0.75	0.74	1.03	1.05	1.10	1.11	0.784	0.80
	Min	0.69	0.73	0.72	1.00	1.01	1.06	1.07	0.775	0.77
Average		0.71	0.74	0.74	1.02	1.03	1.08	1.09	0.780	0.79
Percent Elongation	1P	21.7	20.1	20.5	18.8	16.2	4.10	3.33	22.7	20.6
	2P	19.9	21.0	19.4	18.7	18.9	4.36	4.86	22.4	21.0
	3P	20.5	19.6	20.4	19.1	16.2	4.01	3.83	23.7	21.6
	4P	19.5		19.8	20.3	18.3	4.09			21.9
	5P									
Average		20.4	20.2	20.0	19.2	17.4	4.14	4.01	22.9	21.3
Percent Reduction in Area	1P	35.7	29.0	26.7	37.0	26.2	19.6	18.9	32.8	70.8
	2P	32.6	35.4	31.6	35.6	37.6	21.2	19.5	33.5	41.5
	3P	30.7	31.9	34.5	41.4	37.3	18.9	19.2	30.5	38.5
	4P	46.4		36.2	46.0	43.7	25.2			36.0
	5P									
Average		36.3	32.1	32.3	40.0	36.2	21.3	19.2	32.2	46.7

AISI 303-Se, Type 1

Property Measured	Ref. No.*	Test Condition								
		C	A1	C1	B	B1	D_A	D_{A1}	E_A	E_{A1}
UTS (ksi)	1P	165.6	168.8	172.1	93.8	96.0	72.6	73.6	170.1	171.2
	2P	157.4	175.5	176.2	92.2	97.1	74.2	73.1	166.0	166.4
	3P	173.3	174.6	166.4	92.2	96.7	72.7	69.7	169.7	
	4P			171.9		94.7	70.9	72.3		
	5P			175.6		95.7				
Average		165.4	173.0	172.4	92.7	96.0	72.6	72.2	168.6	168.8
TYS (ksi)	1P	83.6	112.6	106.0	49.8	61.1	31.6	36.8	90.5	92.5
	2P	79.5	116.2	112.2	49.8	67.3	39.1	36.3	80.9	87.3
	3P	93.0	116.2	99.6	47.7	61.0	30.6	34.5	91.4	
	4P			102.7		57.3	31.8	34.8		
	5P			101.5		57.6				
Average		85.4	115.0	104.4	49.1	60.8	33.3	35.6	87.6	89.9
NTS (ksi)	1N	192.7	230.1	208.2	124.1	134.6	98.0	101.2	176.4	190.2
	2N	190.6	217.7	209.0	121.1	130.9	97.9	104.1	181.1	198.6
	3N	185.8	236.6	207.1	119.1	132.0	98.9	98.4	193.4	182.6
	4N	194.9		209.9	121.9	130.5	94.0		185.6	193.4
	5N					129.0				195.0
Average		191.0	228.2	208.5	121.6	131.4	97.2	101.2	184.2	191.9
NTS/UTS	Max	1.24	1.40	1.26	1.35	1.42	1.39	1.49	1.17	1.19
	Min	1.07	1.24	1.18	1.27	1.33	1.27	1.34	1.04	1.07
Average		1.15	1.32	1.21	1.31	1.37	1.34	1.40	1.09	1.14
Percent Elongation	1P	49.0	29.0	41.7	31.0	22.6	24.6	24.9	42.3	40.3
	2P	33.8	37.0	39.7	30.9	25.4	22.9	21.5	51.3	50.0
	3P	46.5	37.0	33.3	31.8	26.7	25.0	17.8	50.7	
	4P			35.5		26.5	22.0	23.7		
	5P			43.3		28.6				
Average		43.1	34.3	38.7	31.2	26.0	23.6	22.0	48.1	45.2
Percent Reduction in Area	1P	49.3	45.8	45.8	43.2	37.8	35.2	40.1	53.0	44.9
	2P	44.9	44.9	47.0	41.0	42.2	36.3	37.5	50.7	45.3
	3P	50.4	42.2	38.8	50.4	43.7	40.1	30.8	49.3	
	4P			41.3		67.6	66.8	21.3		
	5P			49.6		69.9				
Average		48.2	44.3	44.5	44.9	52.2	44.6	32.4	51.0	45.1

* See Table 3-9, under same Ref. No. and Test Condition, for identification of specimen.

Table 3-6

Tensile Test Results

Al 2219-T6, Type 3

Property Measured	Ref. No.*	Test Condition								
		C	Ai	Ci	B	Bi	D_A	D_{Ai}	E_A	E_{Ai}
UTS (ksi)	1P	75.1	74.7	74.1	57.8	58.8	21.8	21.5	67.1	68.1
	2P	71.1	75.0	74.8	60.2	59.4	21.6	21.8	68.8	68.0
	3P		75.5	73.7	61.0	56.6		22.1	68.3	65.7
	4P					59.0				66.8
	5P									
Average		73.1	75.1	74.2	59.7	58.4	21.7	21.8	68.1	67.1
TYS (ksi)	1P	51.5	62.6	51.7	41.0	41.8	20.4	20.3	40.4	41.3
	2P	46.9	63.1	52.4	42.8	42.3	20.4	20.3	41.0	40.4
	3P		63.6	51.3	42.3	40.3		20.8	40.6	37.8
	4P					41.6				38.1
	5P									
Average		49.2	63.1	51.8	42.0	41.5	20.4	20.5	40.7	39.4
NTS (ksi)	1N	67.9	75.9	68.0	55.6	54.6	26.6	27.4	58.6	56.4
	2N	67.2	74.6	69.3	56.0	50.7	27.0	26.8	60.0	60.2
	3N		75.7	65.9	57.8	55.6	26.6	27.3	57.2	58.9
	4N			68.3		53.2				54.2
	5N									
Average		67.5	75.4	67.9	56.5	53.5	26.7	27.2	58.6	57.4
NTS/UTS	Max	0.95	1.02	0.94	1.00	0.98	1.25	1.27	0.89	0.92
	Min	0.89	0.99	0.88	0.91	0.85	1.22	1.21	0.83	0.80
Average		0.92	1.00	0.91	0.95	0.92	1.23	1.24	0.86	0.86
Percent Elongation	1P	9.52	8.80	10.4	6.54	6.97	7.60	7.91	13.5	11.0
	2P	8.62	7.82	9.43	7.64	6.84	7.59	6.84	12.2	10.2
	3P		7.28	10.4	6.80	6.09		7.82	13.2	10.8
	4P					7.11				13.4
	5P									
Average		9.1	7.97	10.1	6.99	6.75	7.60	7.52	13.0	11.3
Percent Reduction in Area	1P	18.5	23.6	18.0	13.0	16.4	23.7	37.6	22.5	25.1
	2P	11.1	23.6	21.7	10.5	22.7	20.6	31.5	19.2	18.0
	3P		23.4	17.7	10.4	19.4		38.5	18.9	23.6
	4P					26.9				24.8
	5P									
Average		14.8	23.5	19.1	11.3	21.3	22.2	35.9	20.2	22.9

* See Table 3-9 under same Ref. No. and Test Condition, for identification of specimen.

Table 3-7

Tensile Test Results

Al 2219-T6-Transverse, Type 2

Property Measured	Ref. No.*	Test Condition C	Test Condition A1	Test Condition C1	Test Condition B	Test Condition B1
UTS (ksi)	1P	71.0	81.1	71.6	62.7	61.5
	2P	73.9	81.2	72.0	63.1	61.3
	3P	72.6	79.8	74.0	62.1	61.3
	4P	71.6		72.1	61.4	60.8
	5P			73.2		61.5
	6P			69.7		62.0
Average		72.3	80.7	72.1	62.1	61.4
TYS (ksi)	1P	53.5	79.5	55.5	47.1	48.1
	2P	54.1	79.6	55.7	48.3	48.1
	3P	53.5	78.0	55.7	48.1	48.6
	4P	53.1		55.2	46.2	47.8
	5P			52.9	46.6	45.9
	6P			52.5		44.7
Average		53.6	79.0	54.6	47.3	47.2
NTS (ksi)	1N	84.1	85.0	92.0	76.5	74.0
	2N	90.3	92.6	91.1	73.4	73.5
	3N	84.1	96.5	91.5	78.3	74.3
	4N	86.3		82.3	73.8	64.9
	5N	96.1		84.5		74.4
	6N			87.1		
Average		88.2	91.4	88.1	75.5	72.2
NTS/UTS	Max	1.35	1.21	1.32	1.28	1.22
	Min	1.14	1.05	1.11	1.16	1.05
Average		1.22	1.13	1.22	1.22	1.18
Percent Elongation	1P	7.00	2.14	6.27	10.33	7.40
	2P	8.27	1.95	6.87	8.13	7.87
	3P	8.13	2.71	8.07	7.27	6.53
	4P	7.00		6.87	8.07	6.20
	5P			7.73	7.53	7.53
	6P			4.20		12.60
Average		7.60	2.27	6.67	8.27	8.02
Percent Reduction in Area	1P	7.01	2.96	5.92	15.36	8.80
	2P	7.96	2.96	6.88	7.86	10.70
	3P	7.01	6.88	5.92	7.84	7.84
	4P	4.95		4.95	7.83	5.92
	5P			6.88	7.88	7.83
	6P			7.83		13.07
Average		5.73	4.27	6.40	9.35	9.03

Al 2219-T6-Radial, Type 2

Property Measured	Test Condition C	Test Condition A1	Test Condition C1	Test Condition B	Test Condition B1
UTS (ksi)	75.1 72.1	80.4 80.6 80.4	73.7 75.6	62.4 61.9 61.1	62.1 61.5 61.5
Average	73.6	80.5	74.7	61.8	61.7
TYS (ksi)	51.3 52.3	79.0 77.4 78.5	52.8 54.3	46.2 47.5 45.4	47.3 47.0 46.2
Average	51.7	78.3	53.5	46.3	46.3
NTS (ksi)	95.0 91.0	111.5 105.9 98.7	94.9 89.7	75.9 78.6	78.1 77.2 77.9
Average	93.0	105.4	92.3	77.3	77.7
NTS/UTS Max	1.32	1.39	1.29	1.29	1.27
NTS/UTS Min	1.21	1.23	1.19	1.22	1.24
Average	1.26	1.31	1.24	1.25	1.26
Percent Elongation	16.7 9.27	5.54 6.65 4.68	13.2 14.4	11.7 9.40 11.7	11.5 12.3 10.3
Average	12.98	5.62	13.8	10.9	11.4
Percent Reduction in Area	14.51 8.85	10.7 7.83 6.89	9.8 11.6	10.7 12.1 15.4	10.7 14.4 7.84
Average	11.7	8.47	10.7	12.7	11.0

* See Table 3-9, under same Ref. No. and Test Condition, for identification of specimen.

Table 3-8

Tensile Test Results

Beryllium, Type 4

Property Measured	Ref. No.*	Test Condition C	A1	C1	B	B1
UTS (ksi)	1P	23.2	12.7	40.2	49.4	49.4
	2P	31.7	9.76	45.1	51.9	51.1
	3P	29.6	10.3	43.4	50.7	50.9
	4P	38.7	10.3	26.5	52.4	48.2
	5P	47.0		28.0		
	6P	46.7		36.4		
	7P			41.8		
Average		36.2	10.8	37.3	51.1	49.9
TYS (ksi)	1P	23.2	12.7	40.2	41.4	43.7
	2P	31.7	9.76	45.1	42.1	42.8
	3P	29.6	10.3	43.4	41.0	42.6
	4P	38.7	10.3	26.5	41.1	42.5
	5P	47.0		28.0		
	6P	46.7		36.4		
	7P			41.8		
Average		36.2	10.8	37.3	41.4	42.9
NTS (ksi)	1N	7.8	6.45	8.3	36.1	29.6
	2N	4.1	4.32	6.3	29.6	31.0
	3N	6.4	6.76	10.1	31.2	32.6
	4N	7.9	7.62	9.7	27.7	32.4
	5N	6.8		8.6		
	6N	8.3		7.9		
Average		6.9	6.29	8.5	31.2	31.4
NTS/UTS	Max	0.36	0.78	0.38	0.73	0.68
	Min	0.09	0.34	0.14	0.53	0.58
Average		0.19	0.58	0.23	0.61	0.63
Percent Elongation	1P	0.0	0.0	0.0	0.2	0.48
	2P	0.0	0.0	0.0	0.56	0.88
	3P	0.0	0.0	0.0	0.36	0.64
	4P	0.0	0.0	0.0	0.44	0.48
	5P	0.0	0.0	0.0		
	6P	0.0		0.0		
	7P	0.0		0.0		
Average		0.0	0.0	0.0	0.39	0.62
Percent Reduction in Area	1P	0.0	0.0	0.0	1.45	0.0
	2P	0.0	0.0	0.0	2.17	0.72
	3P	0.0	0.0	0.0	1.44	0.0
	4P	0.0	0.0	0.0	2.16	0.72
	5P	0.0	0.0	0.0		
	6P	0.0		0.0		
	7P	0.0		0.0		
Average		0.0	0.0	0.0	1.80	

Ti A-110-AT-Eli, Type 2

Property Measured	Test Condition C	A1	C1	B	B1
UTS (ksi)	184.1	199.5	191.4	121.6	128.7
	182.8	197.1	190.1	121.0	129.0
	183.1	195.9	193.7	120.7	129.3
Average	183.3	197.5	191.8	121.1	129.0
TYS (ksi)	178.3	196.9	187.9	119.4	128.1
	177.7	194.3	187.3	119.1	128.7
	176.8	193.6	191.1	119.1	129.0
Average	177.6	195.0	188.8	119.2	128.6
NTS (ksi)	240.3	223.8	225.5	188.3	189.7
	248.7	235.0	235.1	188.0	194.3
	245.9	222.4	224.8	191.5	195.5
Average	245.0	227.1	228.5	189.3	193.2
NTS/UTS Max	1.36	1.20	1.24	1.59	1.52
NTS/UTS Min	1.31	1.11	1.16	1.55	1.47
Average	1.34	1.15	1.19	1.56	1.50
Percent Elongation	17.5	4.6	17.0	15.9	13.1
	22.3	4.6	9.3	17.3	12.4
	15.1	4.5	9.7	16.4	12.9
Average	18.3	4.6	12.0	16.5	12.8
Percent Reduction in Area	27.8	31.3	33.7	36.9	29.6
	31.9	25.2	23.4	39.2	40.9
	14.4	26.9	32.1	35.2	42.4
Average	24.7	27.8	29.7	37.1	37.6

* See Table 3-9, under same Ref. No. and Test Condition, for identification of specimen.

NPC 23,262

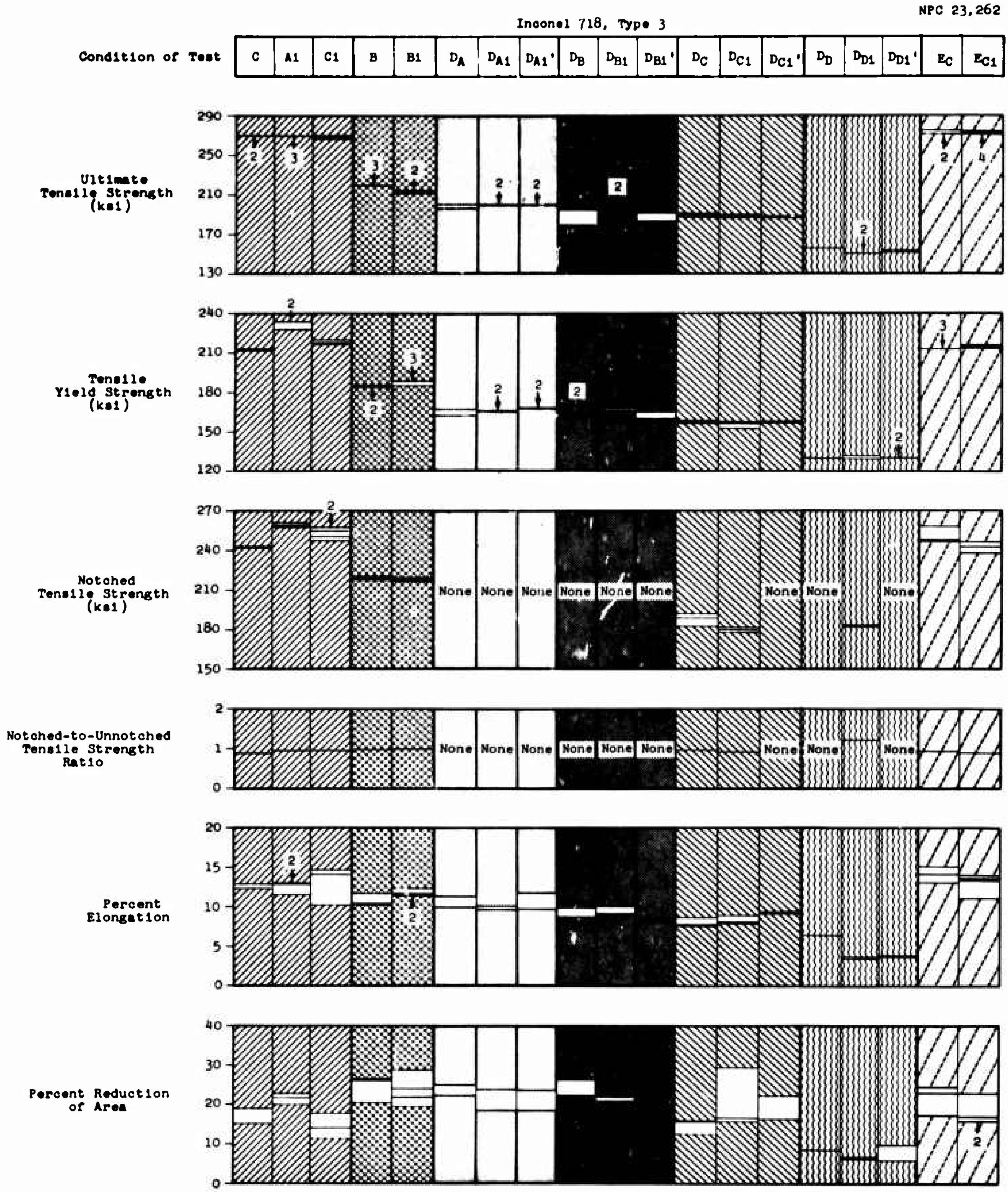


Figure 3-1 Summary of Tensile Test Results: Inconel 718, Type 3

NPC 23,273

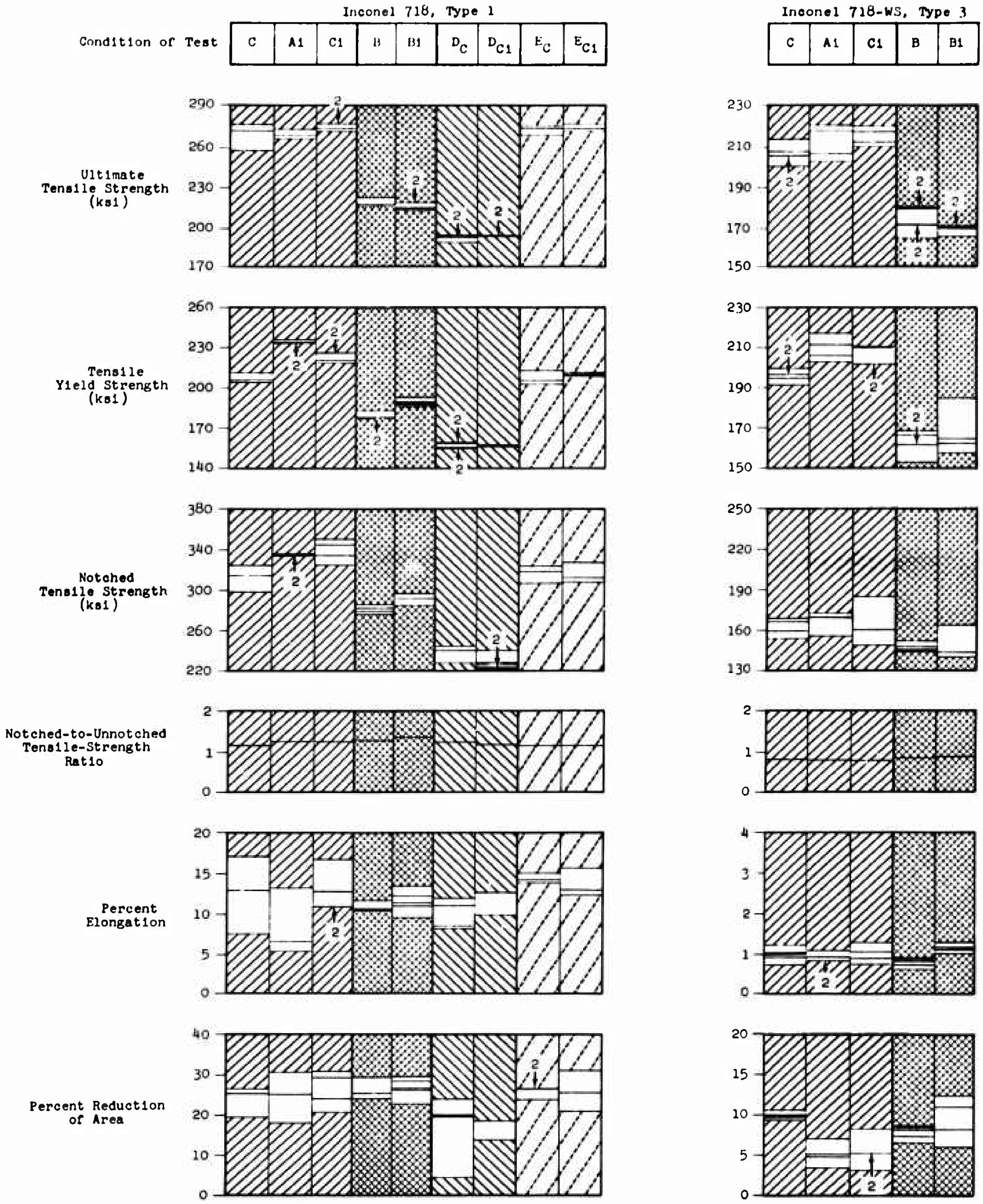


Figure 3-2 Summary of Tensile Test Results: Inconel 718, Type 1, and Inconel 718-WS, Type 3

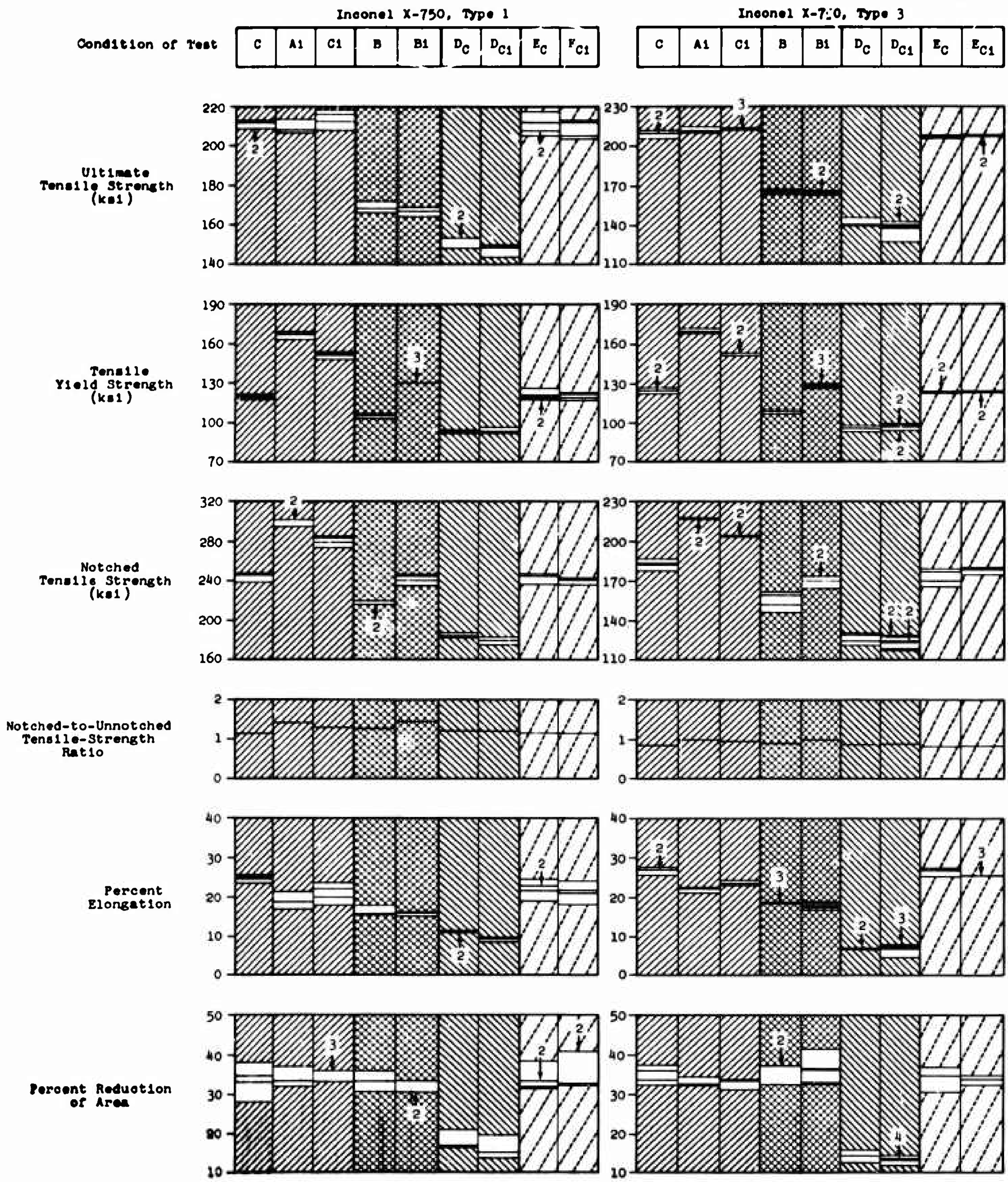


Figure 3-3 Summary of Tensile Test Results: Inconel X-750, Types 1 and 3

NPC 23,264

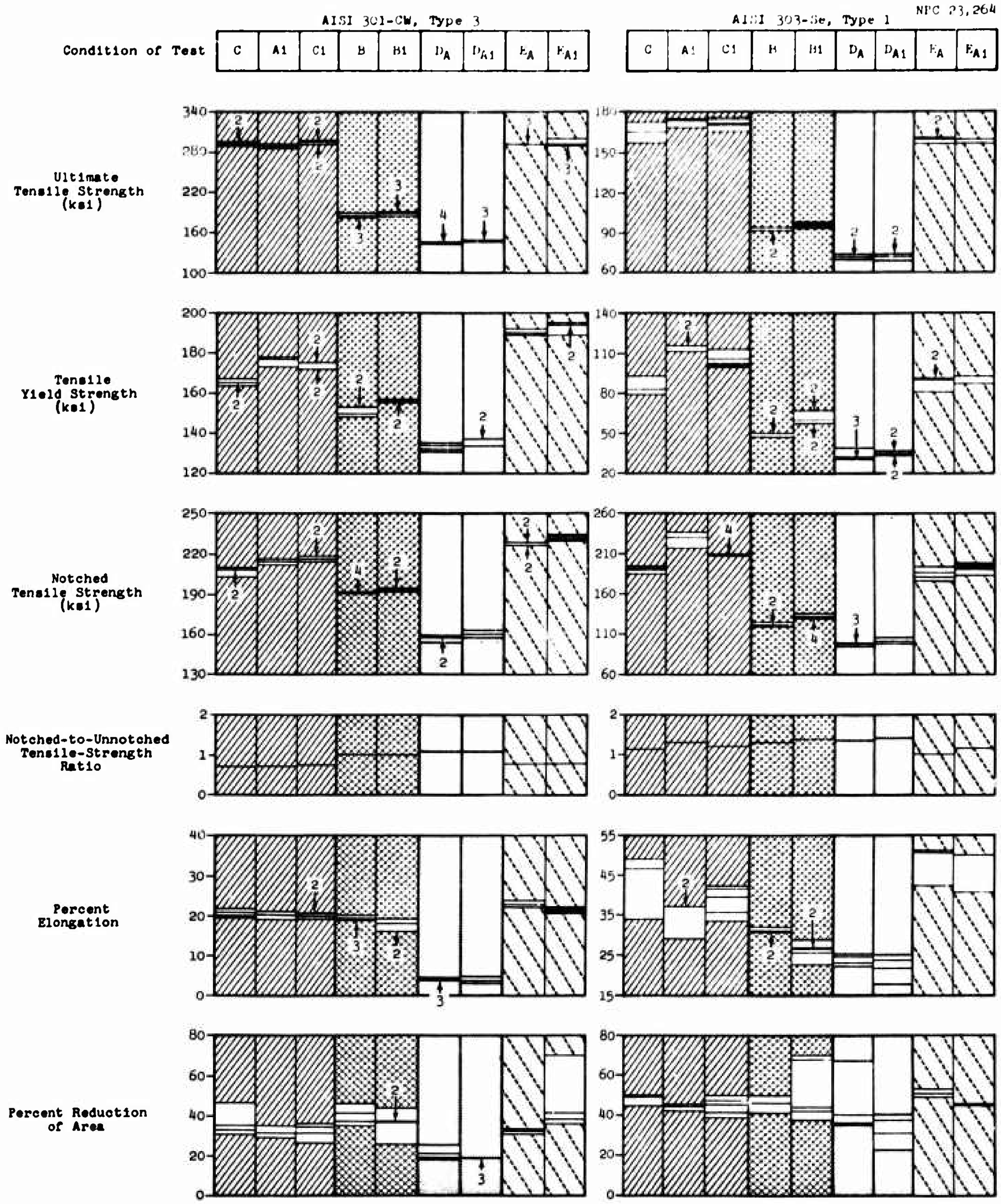


Figure 3-4 Summary of Tensile Test Results: AISI 301-CW, Type 3, and AISI 303-Se, Type 1

NPC 23,266

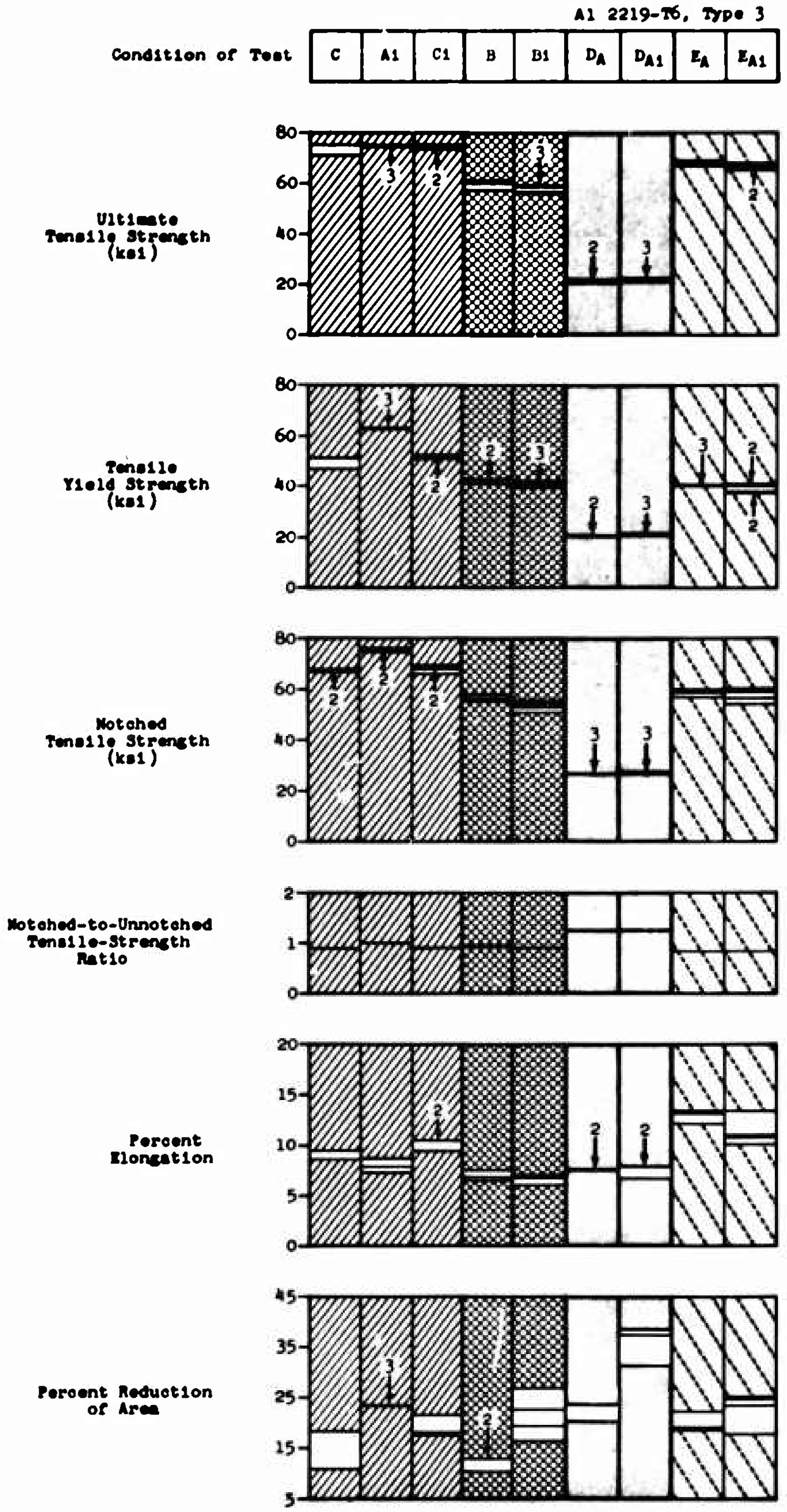


Figure 3-5 Summary of Tensile Test Results: Al 2219-T6, Type 3

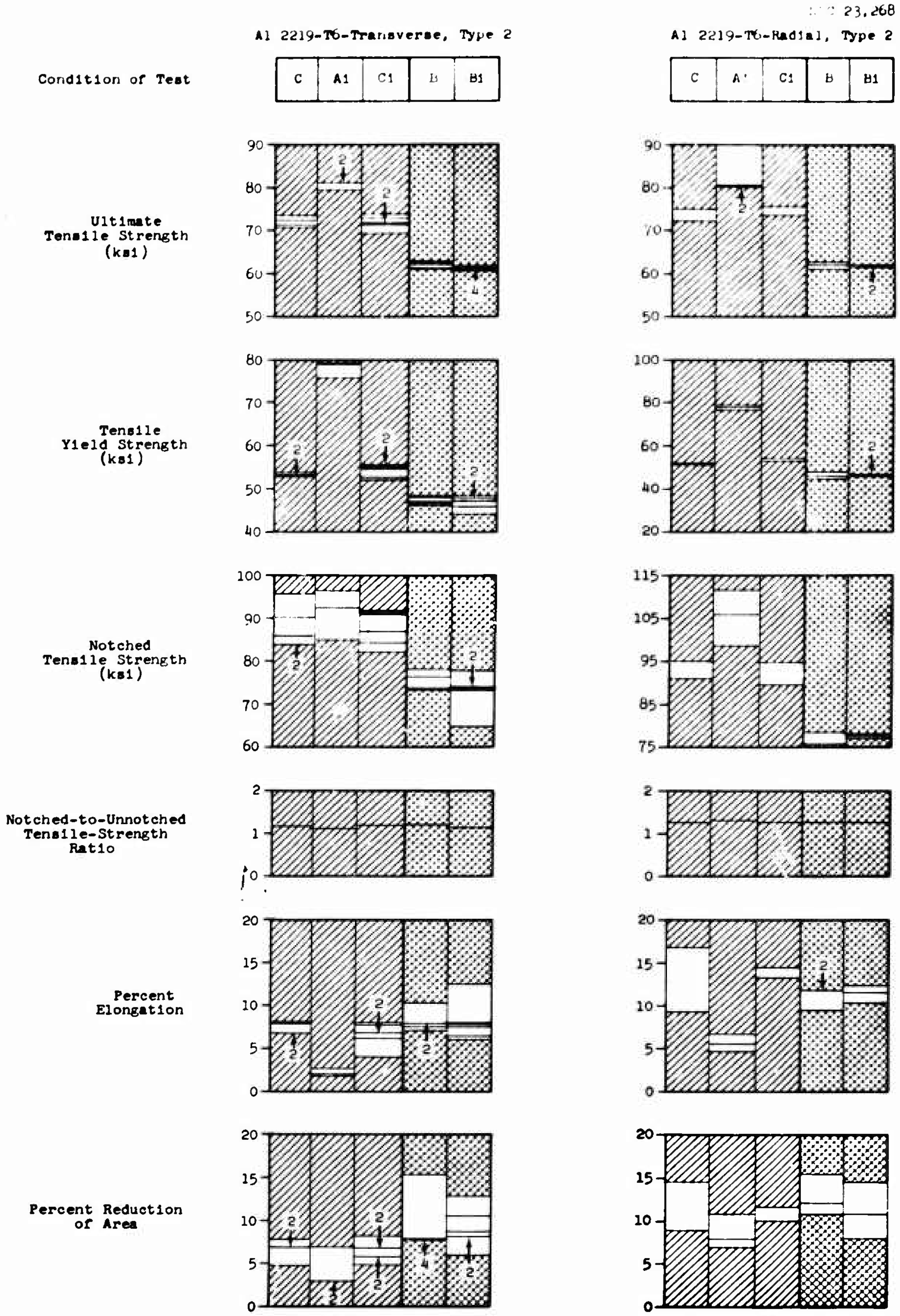


Figure 3-6 Summary of Tensile Test Results: Aluminum 2219-T6, Type 2, Transverse and Radial

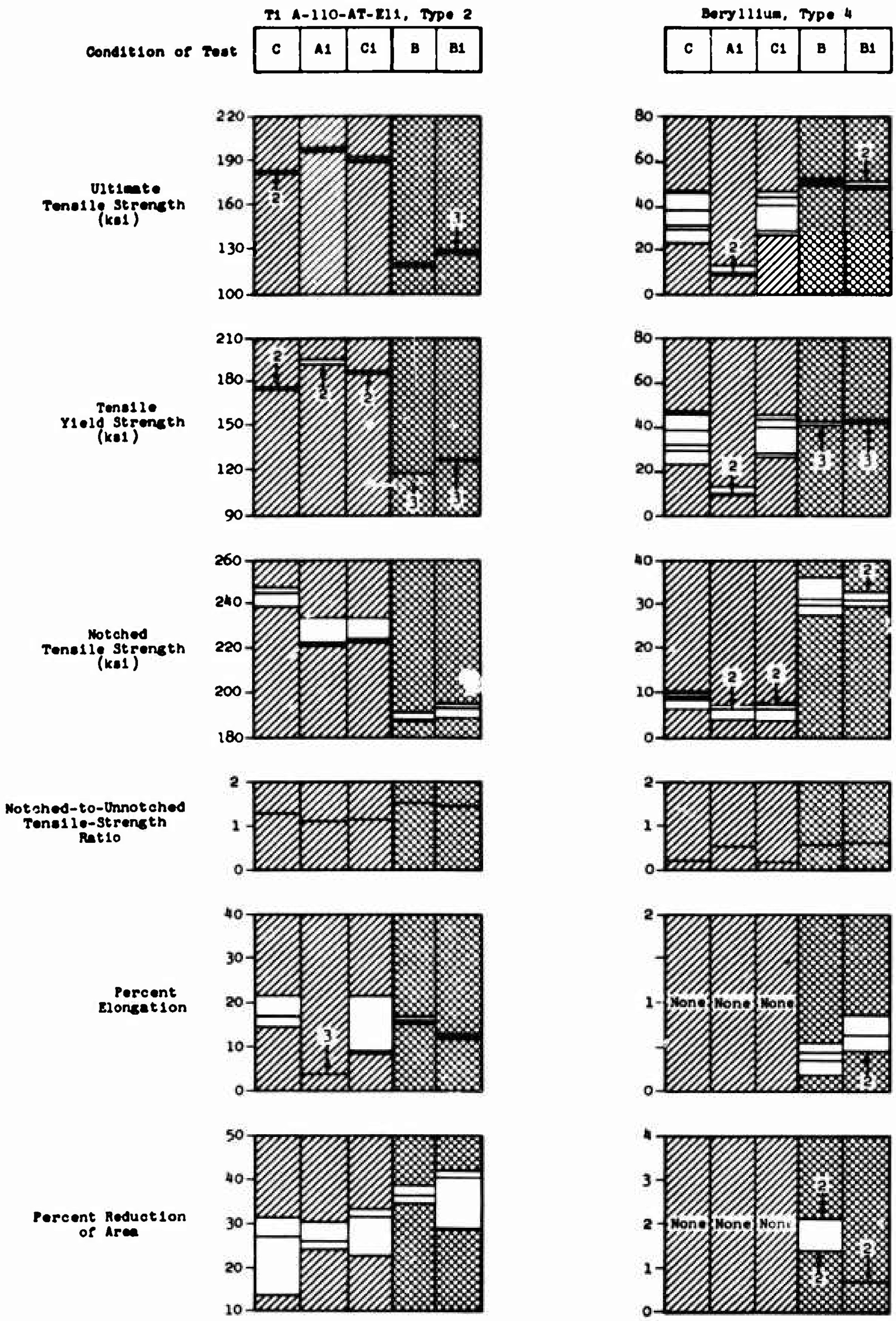


Figure 3-7 Summary of Tensile Test Results: Titanium A-110-AT-Eli, Type 2, and Beryllium, Type 4

Table 3-9

Identification of Individual Tensile Specimens as to Material, Type, and Test Condition

Specimen Material	Ref No.*	Test Condition C	A1	C1	N	N1	D_A	D_{A1}	D_{A1}'	D_B	D_{B1}	D_{B1}'	D_C	D_{C1}	D_{C1}'	D_D	D_{D1}	D_{D1}'	E_A	E_{A1}	E_C	E_{C1}
Inconel 718 Type 3	1P	61C	255	321	49C	245	123C	473	471	126C	477	475	73C	269	483	129C	481	479			89C	281
	2P	63C	251	325	51C	247	125C	474	472	127C	478	476	75C	271	484		482	480			87C	283
	3P		253	327	53C	249							77C	273							85C	285
	4P					237																235
	1N	62C	250	322	50C	244							74C	268			234				86C	282
	2N	64C	252	324	52C	246							76C	270			236				88C	284
	3N		254	326	54C	248							78C	272							90C	280
	4N			232																		
	5N			233																		
Inconel 718 Type 1	1P	175C	49	43	169C	61							181C	69							464C	39
	2P	177C	47	59	171C	63							183C	37							189C	41
	3P	179C	45	67	173C	65							185C								191C	53
	4P			51		57							465C									
	5P					55																
	1N	176C	44	42	170C	60							182C	54							467C	40
	2N	178C	46	66	172C	62							184C	70							190C	52
	3N	180C		50	174C	64							186C	38							192C	56
	4N			36	468C									68								
	5N													58								
Inconel 718-WS Type 3	1P	67C	261	227	55C	265																
	2P	69C	259	229	57C	267																
	3P	71C	257	231	59C	243																
	4P	81C	263	241	79C	239																
	5P	83C			91C																	
	1N	68C	260	226	56C	262																
	2N	70C	258	228	58C	264																
	3N	72C	256	230	60C	266																
	4N	82C			80C																	
Inconel X-750 Type 1	1P	151C	7	13	145C	25							157C	1							163C	17
	2P	153C	9	31	147C	27							159C	19							165C	33
	3P	155C	11	23	149C	29							161C	35							167C	5
	4P	318C		21																	315C	3
	5P																				320C	
	1N	152C	8	14	146C	26							158C	2							164C	32
	2N	154C	12	6	148C	28							160C	18							166C	4
	3N	156C	10	24	150C	30							162C	34							168C	22
	4N			16		20																
Inconel X-750 Type 3	1P	109C	383	329	97C	377							121C	341							133C	287
	2P	111C	385	331	99C	379							123C	343							135C	289
	3P	113C	387	333	101C	381							125C	355							137C	291
	4P	313C				295								293								
	5P					297								467								
	6P													469								
	1N	110C	382	328	98C	376							122C	340							134C	286
	2N	112C	384	330	100C	378							124C	342							136C	288
	3N	114C	386	332	102C	380							126C	344							138C	290
	4N	142C			140C	294							144C	466							310C	
	5N													296								
	6N													292								
	7N													468								
	8N													470								
AISI 301-CW Type 3	1P	265C	311	299	259C	305	271C	293											277C	335		
	2P	267C	313	301	261C	307	273C	295											281C	337		
	3P	269C	315	303	263C	309	275C	297											279C	339		
	4P	287C		355	283C	351	289C													357		
	1N	268C	310	298	260C	304	272C	292											280C	334		
	2N	266C	312	300	262C	306	274C	294											278C	336		
	3N	270C	314	302	264C	308	276C	296											282C	338		
	4N	288C		356	284C	354	290C												292C	352		
AISI 303-Se Type 1	1P	199C	89	79	193C	83	205C	97											211C	73		
	2P	201C	87	81	195C	91	207C	99											213C	101		
	3P	203C	85	95	197C	93	209C	77											215C			
	4P			911		103	119C	75X														
	5P			389		391																
	1N	200C	88	80	194C	82	206C	78											216C	74		
	2N	202C	90	94	196C	84	208C	98											214C	76		
	3N	204C	86	96	198C	92	210C	392											212C	100		
	4N	118C		388	128C	104	120C												130C	102		
	5N					390														921		
Al 2219-T6 Type 3	1P	3C	427	209	13C	191	25C	197											37C	203		
	2P	1C	429	211	15C	193	27C	199											39C	205		
	3P		431	213	17C	195		201											41C	207		
	4P					189														187		
	1N	4C	428	208	14C	190	26C	196											38C	202		
	2N	2C	430	210	16C	192	28C	198											40C	204		
	3N		432	212	18C	194	30C	200											42C	206		
	4N			188		186														418		
Al 2219-T6 Transverse Type 2	1P	223C	109	107	229C	121																
	2P	225C	111	115	219C	123																
	3P	227C	113	119	221C	125																
	4P	235C		105	231C	127																
	5P			117	233C	131																
	6P			133		135																
	1N	224C	108	114	232C	120																
	2N	226C	110	118	220C	122																
	3N	228C	112	126	222C	124																
	4N	230C		130	234C	106																
	5N	236C		132		116																
	6N			134																		
Al 2219-T6 Radial Type 2	1P		433	215	7C	421																
	2P	21C	435	217	9C	423																
	3P	23C	437		11C	425																
	1N	22C	426	214	8C	422																
	2N	24C	436	216	10C	424																
	3N		438			434																
Beryllium Type 4	1P	405C	505	519	397C	511																
	2P	407C	509	521	399C	513																
	3P	409C	503	523	401C	515																
	4P	411C	507	525	403C	517																
	5P	413C		527																		
	6P	415C		531																		
	7P			529																		
	1N	404C	504	520	396C	512																
	2N	406C	506	522	398C	514																
	3N	408C	508	524	400C	516																
	4N	410C	510	526	402C	518																
	5N	414C		528																		
	6N	416C		530																		
Ti A-110-AT-ELI Type 2	1P	247C	149	155	241C	141																
	2P	249C	145	157	243C	143																
	3P	251C	147	159	245C	151																
	1N	248C	148	156	242C	142																
	2N	250C	146	158	244C	150																
	3N	252C	144	140	246C	152																

*P - plain specimens; N - notched specimens

Table 3-10

Tensile Test Results:
Inconel 718 Strain-Rate Study

Property Measured	Ref. No.*	Test Condition						
		Fi	F_{1i}	Gi	G_{1i}	Hi	H_{1i}	H_{2i}**
UTS (ksi)	1P 2P 3P	276.1 277.9	273.0 268.9 269.7	236.3 233.1 238.0	232.3 233.9 229.8	219.2 219.5	211.9 212.7 208.6	
Average		277.0	270.5	235.8	232.0	219.4	211.1	
TYS (ksi)	1P 2P 3P	218.9 222.5	216.0 214.3 214.3	198.9 198.9 200.5	194.8 194.8 189.5	189.9 189.7	182.6 183.4 183.4	
Average		220.7	214.9	199.4	193.0	189.8	183.1	
Percent Elongation	1P 2P 3P	10.9 14.2	13.9 12.5 16.3	13.8 10.9 11.6	13.7 13.4 13.2	13.3 13.5	14.3 11.2 7.26	
Average		12.6	14.2	12.1	13.4	13.4	10.9	
Percent Reduction in Area	1P 2P 3P	14.9 29.5	29.4 25.1 33.8	29.4 32.8 31.5	29.4 32.8 36.0	26.1 22.1	30.8 28.8 18.3	
Average		22.2	29.4	31.2	32.7	24.4	26.0	

* See table below.
** Raw data on these specimen sent to WANL for analysis.

Table 3-11

Identification of Specimens Used
in Strain-Rate Study

Reference Number	Test Condition						
	Fi	F_{1i}	Gi	G_{1i}	Hi	H_{1i}	H_{2i}*
1P 2P 3P	448 451	444 445 446	455 456 457	453 454 458	449 450	441 442 443	459 460

*Raw data on these specimen sent to WANL for analysis

3.1.2 Statistical Analysis of Data (by J. B. Wattier)

3.1.2.1 Methods

Analysis of variance, combined with "t" and "F" tests, has been used to evaluate, on a probability basis, the observed effects of radiation, "annealing temperatures," and test temperatures on the measurements of ultimate tensile strength (UTS), tensile yield strength (TYS), notched tensile strength (NTS), percent elongation, and percent reduction in area for various metals.

As in other situations in which mathematics is used as a tool, assumptions are required. The statistical significance tests used in the analysis of the tensile-specimen data are valid only within the framework of the assumed structure of the variation present in the observations. The assumption of random and normally distributed errors has been made. Any unknown biases introduced into the experiment would invalidate the conclusions, because the standard methods of statistical analysis give no warning of the presence of bias. These techniques assume, in fact, that no bias is present.

In a few instances, when seemingly extreme observations were noted, the question arose whether the observation should be considered discrepant and, therefore, be rejected. One discrepant value in a group might give pertinent information with regard to difficulties in the testing method, but it could also bias the analytical results if included in the calculations. Therefore, an observation that was found to lie a very long way from its fellows in a series of replicate observations was subjected to a ratio test for extreme values and rejected if the ratio exceeded the tabulated critical value. In some instances the analysis was performed with and without the rejected "outlier."

The analysis methods used as the basis for making inferences about the observed effects determine only the statistical significance of the observed variations or differences in the data; an effect may be statistically significant and yet so small as to be of no engineering importance. In making the statistical tests of significance, probability levels of $\alpha = 0.10, 0.05$, and 0.01 were used [α is type I error, or what is perhaps more commonly known as a $(1-\alpha)\%$ test]. When an observed difference in the averages being compared is determined to be not-significant (probability < 0.90) it does not necessarily mean that there is no effect; it might be that the experiment was not sensitive enough to detect an effect when in fact such an effect does exist.

3.1.2.2 Statistical Results

Tables 3-12 through 3-23 summarize the results of the statistical analysis. The main body of the tables (arranged in 2 x 2 and 2 x 3 arrays) contains the average values, standard deviations (by range method), and the number, n, of specimens tested for the conditions in each category. The observed differences and the statistical significance of the observed differences between the averages being compared are listed in the margins of the arrays. An observed difference between the row averages within a given column is a measure of the radiation effects after the "annealing temperature" treatment specified and at the test temperature specified. An observed difference between the column averages within a given row, for the left-hand arrays, is a measure of the "annealing temperature" effects at the -320°F test temperature and the radiation conditions specified. In the right-hand arrays, the observed difference between the column averages within a given row is a measure of the test temperature effects after an 80°F "annealing temperature" treatment and the radiation conditions specified.

3.1.2.3 Discussion of Results

The interpretation of these data is based on the significance level of the observed differences between the averages being analyzed as compared with the sampling error and the number of specimens tested. All data are not listed in the tables because they do not fit into the pattern of the 2 x 2 and 2 x 3 arrays; however, pertinent statistical aspects of these data are discussed later in this section.

The materials were subjected to various temperature conditions before testing to determine the extent that radiation-induced changes could be annealed out as a result of these "annealing temperature" treatments. Analysis of test results indicate that these "annealing temperature" treatments resulted in both an annealing-out of radiation-induced changes and, for some materials, a permanent change in the measured properties - even in the absence of radiation (control specimens). In addition, test temperature effects are quite evident, apart from any statistical analysis, so that these effects are not discussed except when

Table 3-12

Statistical Analysis of Test Data: Inconel 718, Type 3

Significance Probability	
	a < 0.90
0.90 ≤	b < 0.95
0.95 ≤	c < 0.99
0.99 ≤	d

Data Summary

Test Condition
Avg of n Values
(σ/n)

Test Temperature, -320°F				Annealing Temperature, 80°F		
Annealing Temperature			Difference	Test Temperature		Difference
-320°F	80°F	1040°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)						
"C" "270.0"	C 270.0 (0.3/2)	E_C 272.2 (1.4/3)	E_C - C + 2.2^a	C 270.0	B 218.9 (0.9/3)	B - C -51.1^d
A_I 269.6 (1.4/3)	C_I 267.4 (2.5/3)	E_{CI} 272.6 (0.9/4)	E_{CI} - C_I + 5.2^d	C_I 267.4	B_I 213.7 (2.0/4)	B_I - C_I -53.7^d
A_I - C - 0.4^a	C_I - C -2.6^a	E_{CI} - E_C +0.4^a	C_I - A_I - 2.2^a		B_I - B - 5.2^d	
Tensile Yield Strength (ksi)						
"C" "212.4"	C 212.4 (1.2/2)	E_C 212.2 (0.0/3)	E_C - C - 0.2^a	C 212.4	B 184.9 (1.0/3)	B - C -27.5^d
A_I 232.1 (3.6/3)	C_I 217.6 (1.9/3)	E_{CI} 213.5 (1.6/4)	E_{CI} - C_I - 4.1^c	C_I 217.6	B_I 188.2 (1.9/5)	B_I - C_I -29.4^d
A_I - C +19.7^d	C_I - C +5.2^d	E_{CI} - E_C +1.3^a	C_I - A_I -14.5^d		B_I - B + 3.3^c	
Notched Tensile Strength (ksi)						
"C" "242.6"	C 242.6 (1.6/2)	E_C 250.9 (7.0/3)	E_C - C - 8.3^c	C 242.6	B 219.2 (1.5/3)	B - C -23.4^d
A_I 259.9 (1.8/3)	C_I 252.4 (4.3/5)	E_{CI} 242.1 (5.0/3)	E_{CI} - C_I -10.3^c	C_I 252.4	B_I 218.7 (1.4/3)	B_I - C_I -33.7^d
A_I - C +17.3^d	C_I - C +9.8^c	E_{CI} - E_C +8.8^c	C_I - A_I - 7.5^b		B_I - B - 0.5^a	
Percent Elongation						
"C" "12.6"	C 12.6 (0.4/2)	E_C 14.1 (1.2/3)	E_C - C + 1.5^a	C 12.6	B 10.8 (0.9/3)	B - C - 1.6^a
A_I 12.6 (0.9/3)	C_I 13.0 (2.7/3)	E_{CI} 13.0 (1.3/4)	E_{CI} - C_I 0	C_I 13.0	B_I 11.8 (0.5/4)	B_I - C_I - 1.2^a
A_I - C 0	C_I - C +0.4^a	E_{CI} - E_C -0.9^a	C_I - A_I - 0.4^a		B_I - B + 1.0^a	C
Percent Reduction in Area						
"C" "17.1"	C 17.1	E_C 21.3	E_C - C + 4.2^a	C 17.1	B 24.4 ([illegible].5/3)	B - C 7.3^c
A_I 21.5 (1.4/3)	C_I 14.2 (3.8/3)	E_{CI} 17.5 (3.[illegible]/4)	E_{CI} - C_I + 3.4^a	C_I 14.2	B_I 23.6 (4.6/4)	B_I - C_I 9.4^d
A_I - C + 4.4^a	C_I - C -2.9^a	E_{CI} - E_C -3.7^a	C_I - A_I - 7.3^c		B_I - B - 0.8^a	

Table 3-13

Statistical Analysis of Test Data: Inconel 718, Type 1

Significance Probability
a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary
Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F				Annealing Temperature, 80°F		
Annealing Temperature			Difference	Test Temperature		Difference
-320°F	80°F	1040°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)						
"C" "267.9"	C 267.9 (11.2/3)	E_C 271.9 (4.3/3)	E_C - C + 4.0^a	C 267.9	B 217.8 (3.7/3)	B - C -50.1^d
AI 268.3 (4.3/3)	CI 273.6 (3.1/4)	E_{CI} 273.2 (3.2/3)	E_{CI} - CI - 0.4^a	CI 273.6	BI 214.4 (2.9/5)	BI - CI -59.6^d
AI - C - 0.4^a	CI - C + 5.7^a	E_{CI} - E_C +1.3^a	CI - AI + 5.3^d		BI - B -4.4^a	
Tensile Yield Strength (ksi)						
"C" "206.7"	C 206.7 (4.4/3)	E_C 207.0 (5.8/3)	E_C - C + 0.3^a	C 206.7	B 179.5 (3.3/3)	B - C -27.2^d
AI 235.2 (1.4/3)	CI 222.5 (3.5/4)	E_{CI} 210.2 (1.7/3)	E_{CI} - CI -12.3^c	CI 222.5	BI 188.5 (3.1/5)	BI - CI +34.0^d
AI - C +28.5^d	CI - C +15.8^d	E_{CI} - E_C +3.2^a	CI - AI -12.7^d		BI - B +9.0^d	
Notched Tensile Strength (ksi)						
"C" "312.6"	C 312.6 (15.2/3)	E_C 316.5 (10.5/3)	E_C - C + 3.9^a	C 312.6	B 280.9 (4.6/4)	B - C -31.7^d
AI 342 (22.4/2)	CI 338.2 (11.6/4)	E_{CI} 315.8 (11.8/3)	E_{CI} - CI -22.4^c	CI 338.2	BI 290.5 (7.2/3)	BI - CI -47.7^d
AI - C +29.4^c	CI - C +25.6^c	E_{CI} - E_C -0.7^a	CI - AI - 3.8^a		BI - B +9.6^a	
Percent Elongation						
"C" "12.5"	C 12.5 (5.7/3)	E_C 14.4 (0.7/3)	E_C - C + 1.9^a	C 12.5	B 10.9 (0.6/3)	B - C - 1.6^a
AI 8.4 (4.7/3)	CI 12.7 (3.3/4)	E_{CI} 13.7 (2.0/3)	E_{CI} - CI + 1.0^a	CI 12.7	BI 11.4 (1.7/5)	BI - CI - 1.3^a
AI - C - 4.1^a	CI - C + 0.2^a	E_{CI} - E_C -0.7^a	CI - AI + 4.3^a		BI - B +0.5^a	C
Percent Reduction in Area						
"C" 24.0	C 24.0	E_C 25.8	E_C - C 1.8^a	C 24.0	B 26.4 (3.1/3)	B - C + 2.4^a
AI 24.7 (7.4/3)	CI 26.2 (6.0/4)	E_{CI} 25.8 (5.8/3)	E_{CI} - CI - 0.4^a	CI 26.2	BI 26.7 (3.0/5)	BI - CI + 1.5^a
AI - C + 0.7^a	CI - C + 2.2^a	E_{CI} - E_C 0	CI - AI + 1.5^a		BI - B +0.3^a	

Table 5-14

Statistical Analysis of Test Data: Inconel 718-WS, Type 3

Significance Probability
a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary
Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F			Annealing Temperature, 80°F		
Annealing Temperature		Difference	Test Temperature		Difference
-320°F	80°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)					
"C" "206.3"	C 206.3 (5.8/5)		C 206.3	B 173.3 (6.5/5)	B - C -33.0^d
A' 211.6 (8.6/4)	C' 214.2 (5.0/4)	C' - A' +2.6^a	C' 214.2	B' 168.9 (2.6/4)	B' - C' -45.3^d
A' - C +5.3^a	C' - C +7.9^b			B' - B -4.4^a	
Tensile Yield Strength (ksi)					
"C" "195.7"	C 195.7 (3.5/5)		C 195.7	B 162.6 (7.0/5)	B - C -33.1^d
A' 211.6 (8.6/4)	C' 205.8 (4.0/4)	C' - A' -5.8^a	C' 205.8	B' 167.8 (13.3/4)	B' - C' -38.0^d
A' - C +15.9^c	C' - C +10.1^b			B' - B +5.2^a	
Notched Tensile Strength (ksi)					
"C" "162.0"	C 162.0 (7.3/4)		C 162.0	B 148.2 (3.3/4)	B - C -13.8^b
A' 165.8 (10.4/3)	C' 165.0 (21.2/3)	C' - A' -0.8^a	C' 165.0	B' 149.6 (11.6/3)	B' - C' -15.4^b
A' - C +3.8^a	C' - C 3.0^a			B' - B +0.6^a	
Percent Elongation					
"C" "0.96"	C 0.96 (0.21/5)		C 0.96	B 0.80 (0.13/5)	B - C - 0.16^a
A' 0.89 (0.12/4)	C' 0.96 (0.26/4)	C' - A' +0.07^a	C' 0.96	B' 1.15 (0.13/4)	B' - C' + 0.19^a
A' - C -0.07^a	C' - C 0			B' - B +0.35^c	
Percent Reduction in Area					
"C" "10.0"	C 10.0		C 10.0	B 7.9 (0.9/5)	B - C - 2.1^a
A' 5.2 (1.6/4)	C' 5.5	C' - A' 0.3^a	C' 5.5	B' 9.5 (3.1/4)	B' - C' + 4.0^d
A' - C -4.8^d	C' - C -4.5^d			B' - B +1.6^a	

Table 3-15

Statistical Analysis of Test Data: Inconel X-750, Type 1

Significance Probability
a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary
Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F				Annealing Temperature, 80°F		
Annealing Temperature			Difference	Test Temperature		Difference
-320°F	80°F	1040°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)						
"C" "210.5"	C 210.5 (2.0/4)	E_C 210.0 (4.8/5)	E_C - C - 0.5^a	C 210.5	B 169.1 (3.3/3)	B - C -41.4^d
AI 209.2 (4.5/3)	CI 213.8 (5.2/4)	E_{CI} 208.3 (4.6/4)	E_{CI} - CI - 5.5^a	CI 213.8	BI 166.8 (3.2/3)	BI - CI -47.0^d
AI - C - 1.3^a	CI - C + 3.3^a	E_{CI} - E_C -1.7^a	CI - AI + 4.6^a		BI - B - 2.3^a	
Tensile Yield Strength (ksi)						
"C" "119.7"	C 119.7 (1.4/4)	E_C 120.9 (3.3/5)	E_C - C + 1.2^a	C 119.7	B 105.4 (2.0/3)	B - C -14.3^d
AI 166.5 (3.6/3)	CI 151.6 (2.4/4)	E_{CI} 120 (2.9/4)	E_{CI} - CI -31.6^d	CI 151.6	BI 131.0 (0.5/3)	BI - CI -20.6^d
AI - C +46.8^d	CI - C +31.9^d	E_{CI} - E_C -0.9^a	CI - AI -14.9^d		BI - B +25.6^d	
Notched Tensile Strength (ksi)						
"C" "244.3"	C 244.3 (4.9/3)	E_C 242.3 (6.6/3)	E_C - C - 1^a	C 244.3	B 217.6 (2.3/3)	B - C -26.7^d
AI 299.3 (4.1/3)	CI 280.3 (5.6/4)	E_{CI} 240.0 (4.0/3)	E_{CI} - CI -40.3^d	CI 280.3	BI 241.8 (5.4/4)	BI - CI -38.5^d
AI - C +55.0^d	CI - C +36.0^d	E_{CI} - E_C -2.3^a	CI - AI -19.0^d		BI - B +24.2^d	
Percent Elongation						
"C" "24.9"	C 24.9 (1.0/4)	E_C 22.0 (2.3/5)	E_C - C - 2.9^b	C 24.9	B 16.3 (1.3/3)	B - C - 8.6^d
AI 19.1 (2.5/3)	CI 21.1 (2.8/4)	E_{CI} 21.4 (2.8/4)	E_{CI} - CI + 0.3^a	CI 21.1	BI 16.1 (0.6/3)	BI - CI - 5.0^d
AI - C - 5.8^d	CI - C - 3.8^c	E_{CI} - E_C - 0.6^a	CI - AI + 2.0^a		BI - B - 0.2^a	C
Percent Reduction in Area						
"C" "33.5"	C 33.5	E_C 33.8	E_C - C + 0.3^a	C 33.5	B 33.3 (3.2/3)	B - C - 0.2^a
AI 34.2 (3.0/3)	CI 35.4 (1.5/4)	E_{CI} 36.8 (4.2/4)	E_{CI} - CI + 1.4^a	CI 35.4	BI 31.7 (3.2/3)	BI - CI - 3.7^a
AI - C + 0.7^a	CI - C + 1.9^a	E_{CI} - E_C + 3.0^a	CI - AI 1.2^a		BI - B - 1.6^a	

Table 3-16

Statistical Analysis of Test Data: Inconel X-750, Type 3

Significance Probability
a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary
Test Condition Avg of n Values (s/n)

Test Temperature, -320°F				Annealing Temperature, 80°F		
Annealing Temperature			Difference	Test Temperature		Difference
-320°F	80°F	1040°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)						
"C" "210.1"	C 210.1 (3.4/4)	E_C 207.8 (1.2/3)	E_C - C - 2.3[a]	C 210.1	B 166.4 (1.1/3)	B - C -43.7[d]
AI 213.0 (3.2/3)	CI 213.2 (0.5/3	E_{CI} 208.1 (1.1/3)	E_{CI} - CI - 5.1[d]	CI 213.2	BI 164.9 (1.4/5)	BI - CI -48.3[d]
AI - C + 2.9[b]	CI - C + 3.1[b]	E_{CI} - E_C +0.3[a]	CI - AI + 0.2[a]		BI - B - 1.5	
Tensile Yield Strength (ksi)						
"C" "125.1"	C 125.1 (2.3/4)	E_C 123.6 (0.9/3)	E_C - C - 1.5	C 125.1	B 107.7 (1.8/3)	B - C -17.4[d]
AI 170.1 (2.5/3)	CI 153.2 (0.9/3)	E_{CI} 123.7 (1.0/3)	E_{CI} - CI -29.5[d]	CI 153.2	BI 129.4 (1.3/5)	BI - CI -23.8[d]
AI - C +45.0[d]	CI - C +28.1[d]	E_{CI} - E_C +0.1[a]	CI - AI -16.9[d]		BI - B +21.7[d]	
Notched Tensile Strength (ksi)						
"C" "182.7"	C 182.7 (4.5/4)	E_C 173.4 (6.2/4)	E_C - C - 9.3[c]	C 182.7	B 155.4 (7.7/4)	B - C -27.3[d]
AI 217.8 (0.8/3)	CI 205.1 (0.5/3)	E_{CI} 178.6 (3.0/3)	E_{CI} - CI -26.5[d]	CI 205.1	BI 171.3 (4.6/4)	BI - CI -33.8[d]
AI - C +35.1[d]	CI - C +22.4[d]	E_{CI} - E_C +5.2[a]	CI - AI -12.7[d]		BI - B +15.9[d]	
Percent Elongation						
"C" "27.0"	C 27.0 (0.9/4)	E_C 26.7 (1.2/3)	E_C - C - 0.3[a]	C 27.0	B 18.8 (0.1/3)	B - C - 8.2[d]
AI 21.9 (0.8/3)	CI 23.9 (0.6/3)	E_{CI} 25.7 (0.1/3)	E_{CI} - CI + 1.8[c]	CI 23.9	BI 18.1 (0.9/5)	BI - CI - 5.8[d]
AI - C - 5.1[d]	CI - C - 3.1[d]	E_{CI} - E_C -1.0[a]	CI - AI + 2.0[d]		BI - B - 0.7[a]	C
Percent Reduction in Area						
"C" "35.1"	C 35.1 (2.5/4)	E_C 34.3 (3.8/3)	E_C - C - 0.8[a]	C 35.1	B 35.8 (2.8/3)	B - C 0.7[a]
AI 33.2 (1.5/3)	CI 33.0 (1.5/3)	E_{CI} 33.9 (1.5/3)	E_{CI} - CI + 0.9[a]	CI 33.0	BI 36.0 (3.9/5)	BI - CI 3.0[a]
AI - C - 1.9[a]	CI - C - 2.1[a]	E_{CI} - E_C -0.4[a]	CI - AI - 0.2[a]		BI - B 0.2[a]	

Table 4-17

Statistical Analysis of Test Data: AISI 301-CW, Type 3

Significance Probability

a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary

Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F				Annealing Temperature, 80°F		
Annealing Temperature			Difference	Test Temperature		Difference
-320°F	80°F	540°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)						
"C" "292.8"	C 292.8 (2.4/4)	E_A 291.4 (0.2/3)	E_A - C - 1.4^a	C 292.8	B 186.9 (3.5/4)	B - C - 5.9^c
Ai 290.4 (2.6/3)	Ci 294.3 (2.5/4)	E_{Ai} 293.7 (5.2/4)	E_{Ai} - Ci - 1.6^a	Ci 294.3	Bi 188.8 (2.3/4)	Bi - Ci - 5.5^c
Ai - C - 2.4^a	Ci - C +1.5^a	E_{Ai} - E_A +2.3^b	Ci - Ai 3.9^a		Bi - B +1.9^a	
Tensile Yield Strength (ksi)						
"C" "165.2"	C 165.2 (1.6/4)	E_A 190.6 (1.5/3)	E_A - C +25.4^d	C 165.2	B 151.0 (2.2/4)	B - C -14.2^c
Ai 176.1 (2.6/3)	Ci 173.7 (1.7/4)	E_{Ai} 193.3 (3.0/4)	E_{Ai} - Ci +19.6^d	Ci 173.7	Bi 156.3 (0.5/4)	Bi - Ci -17.4^c
Ai - C +10.9^d	Ci - C +8.5^d	E_{Ai} - E_A +2.7^b	Ci - Ai - 2.4^a		Bi - B +5.3^d	
Notched Tensile Strength (ksi)						
"C" "207.3"	C 207.3 (3.3/4)	E_A 227.4 (1.1/4)	E_A - C +20.1^d	C 207.3	B 191.2 (0.7/4)	B - C -15.3^d
Ai 214.3 (2.5/3)	Ci 216.7 (1.5/4)	E_{Ai} 232 (1.7/4)	E_{Ai} - Ci +15.3^d	Ci 216.7	Bi 193.8 (1.1/4)	Bi - Ci -22.9^d
Ai - C 7.0^d	Ci - C 9.4^d	E_{Ai} - E_A 4.6^d	Ci - Ai 2.4^a		Bi - B 2.6^b	
Percent Elongation						
"C" "20.4"	C 20.4 (1.1/4)	E_A 22.9 (0.8/3)	E_A - C + 2.5^d	C 20.4	B 19.2 (0.8/4)	B - C - 1.2^b
Ai 20.2 (0.3/3)	Ci 20.0 (0.5/4)	E_{Ai} 21.3 (0.9/4)	E_{Ai} - Ci + 1.3^b	Ci 20.0	Bi 17.4 (1.3/4)	Bi - Ci - 2.6^d
Ai - C - 0.2^a	Ci - C -0.4^a	E_{Ai} - E_A -1.6^c	Ci - Ai - 0.2^a		Bi - B -1.8^c	C
Percent Reduction in Area						
"C" 36.3	C 36.3 (6.7/4)	E_A 32.2 (1.8/3)	E_A - C - 4.1^a	C 36.3	B 40.0 (5.0/4)	B - C + 3.7^a
Ai 32.1 (3.8/3)	Ci 32.3 (5.6/4)	E_{Ai} 46.7 (3.2/3)	E_{Ai} - Ci +14.4^a	Ci 32.3	Bi 36.2 (8.5/4)	Bi - Ci + 3.9^a
Ai - C - 4.2^a	Ci - C -[illegible].0^a	E_{Ai} - E_A -14.5^a	Ci - Ai 0.2^a		Bi - B -3.8^a	

Table 3-18

Statistical Analysis of Test Data: AISI 303-Se, Type 1

Significance Probability

a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary

Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F				Annealing Temperature, 80°F		
Annealing Temperature			Difference	Test Temperature		Difference
-320°F	80°F	540°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)						
"C" "165.4"	C 165.4 (9.4/3)	E_A 168.6 (2.4/3)	E_A - C $+3.2^{a}$	C 165.4	B 92.7 (0.9/3)	B - C -72.7^{d}
AI 173.0 (4.0/3)	CI 172.4 (4.2/5)	E_{AI} 168.8 (4.3/2)	E_{AI} - CI -3.6^{a}	CI 172.4	BI 96.0 (1.0/5)	BI - CI -76.4^{d}
AI - C $+7.6^{c}$	CI - C $+7.0^{c}$	E_{AI} - E_A $+0.2^{a}$	CI - AI -0.6^{a}		BI - B $+3.3^{a}$	
Tensile Yield Strength (ksi)						
"C" "85.4"	C 85.4 (8.0/3)	E_A 87.6 (6.2/3)	E_A - C $+2.2^{a}$	C 85.4	B 49.1 (1.2/3)	B - C -36.3^{d}
AI 115.0 (2.1/3)	CI 104.4 (5.4/5)	E_{AI} 89.9 (4.6/2)	E_{AI} - CI -14.5^{d}	CI 104.4	BI 60.8 (4.3/5)	BI - CI -43.6^{d}
AI - C $+29.6^{d}$	CI - C $+19.0^{d}$	E_{AI} - E_A $+2.3^{a}$	CI - AI -10.6^{d}		BI - B $+11.7^{d}$	
Notched Tensile Strength (ksi)						
"C" "191.0"	C 191.0 (4.4/4)	E_A 184.2 (8.3/4)	E_A - C -6.8^{a}	C 191.0	B 121.6 (2.4/4)	B - C -69.4^{d}
AI 228.2 (11.2/3)	CI 208.5 (1.4/4)	E_{AI} 191.9 (6.9/5)	E_{AI} - CI -16.6^{d}	CI 208.5	BI 131.4 (2.4/5)	BI - CI -77.1^{d}
AI - C $+37.2^{d}$	CI - C $+17.5^{d}$	E_{AI} - E_A $+7.7^{b}$	CI - AI -19.7^{d}		BI - B $+9.8^{c}$	
Percent Elongation						
"C" "43.1"	C 43.1 (9.0/3)	E_A 48.1 (5.3/3)	E_A - C $+5.0^{a}$	C 43.1 (9.0/3)	B 31.2 (0.5/3)	B - C -11.9^{c}
AI 34.3 (4.7/3)	CI 38.7 (4.3/5)	E_{AI} 45.2 (8.6/2)	E_{AI} - CI $+6.5^{a}$	CI 38.7 (4.3/5)	BI 26.0 (2.6/5)	BI - CI -12.7^{d}
AI - C -8.8^{c}	CI - C -4.4^{a}	E_{AI} - E_A -2.9^{a}	CI - AI $+4.4^{a}$		BI - B -5.2^{a}	C
Percent Reduction in Area						
"C" 48.2	C 48.2 (3.2/3)	E_A 51.0 (2.2/3)	E_A - C $+2.8^{a}$	C 48.2	B 44.9 (5.6/3)	B - C -3.3^{a}
AI 44.3 (2.1/3)	CI 44.5 (4.6/5)	E_{AI} 45.1 (0.4/2)	E_{AI} - CI $+0.6^{a}$	CI 44.5	BI 52.2	BI - CI $+7.7^{a}$
AI - C -3.9^{a}	CI - C -3.7^{a}	E_{AI} - E_A -5.9^{a}	CI - AI $+0.2^{a}$		BI - B $+7.3^{a}$	

Table [illegible]

Statistical Analysis of Test Data: [illegible]

Significance Probability

a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary

Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F				Annealing Temperature, 80°F		
Annealing Temperature			Difference	Test Temperature		Difference
-320°F	80°F	540°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)						
"C" "73.1"	C 73.1 (3.5/2)	E_A 68.1 (1.0/3)	E_A - C -5.0^{d}	C 73.1	B 59.7 (1.9/3)	B - C -13.4^{d}
AI 75.1 (0.5/3)	CI 74.2 (0.6/3)	E_{AI} 67.1 (1.2/4)	E_{AI} - CI -7.1^{d}	CI 74.2	BI 58.4 (1.4/4)	BI - CI -15.8^{d}
AI - C $+2.0^{a}$	CI - C $+1.1^{a}$	E_{AI} - E_A -1.0^{a}	CI - AI -0.9^{a}		BI - B -1.3	
Tensile Yield Strength (ksi)						
"C" "49.2"	C 49.2 (4.1/2)	E_A 40.7 (0.4/3)	E_A - C -8.5^{d}	C 49.2	B 42.0 (1.1/3)	B - C -7.2^{c}
AI 63.1 (0.6/3)	CI 51.8 (0.6/3)	E_{AI} 39.4 (1.7/4)	E_{AI} - CI -12.4^{d}	CI 51.8	BI 41.5 (1.0/4)	BI - CI -10.3^{c}
AI - C $+13.9^{d}$	CI - C $+2.0^{a}$	E_{AI} - E_A -1.3^{a}	CI - AI -11.3^{d}		BI - B -0.5^{a}	
Notched Tensile Strength (ksi)						
"C" "67.5"	C 67.5 (0.6/2)	E_A 58.6 (1.7/3)	E_A - C -8.9^{d}	C 67.5	B 56.5 (1.3/3)	B - C -11.0^{c}
AI 75.4 (0.8/3)	CI 67.9 (1.7/4)	E_{AI} 57.4 (2.9/4)	E_{AI} - CI -10.5^{d}	CI 67.9	BI 53.5 (2.4/4)	BI - CI -14.4^{d}
AI - C $+7.9^{d}$	CI - C $+0.4^{a}$	E_{AI} - E_A -1.2^{a}	CI - AI -7.5^{d}		BI - B -3.0^{c}	
Percent Elongation						
"C" "9.1"	C 9.1 (0.5/2)	E_A 13.0 (0.8/3)	E_A - C $+3.9^{d}$	C 9.1	B 7.0 (0.6/3)	B - C -2.1^{c}
AI 8.0 (0.9/3)	CI 10.1 (0.6/3)	E_{AI} 11.3 (1.6/4)	E_{AI} - CI $+1.2^{a}$	CI 10.1	BI 6.8 (0.5/4)	BI - CI -3.3^{d}
AI - C -1.1^{a}	CI - C $+1.0^{a}$	E_{AI} - E_A -1.7^{b}	CI - AI $+2.1^{c}$		BI - B -0.2^{a}	C
Percent Reduction in Area						
"C" 14.8	C 14.8 (0.6/2)	E_A 20.2 (2.1/3)	E_A - C $+5.4^{a}$	C 14.8	B 11.3 (1.5/3)	B - C -3.5^{a}
AI 23.5 (0.1/3)	CI 19.1 (2.4/3)	E_{AI} 22.9 (3.4/4)	E_{AI} - CI $+3.8^{a}$	CI 19.1	BI 21.3 (5.1/4)	BI - CI $+2.2^{a}$
AI - C $+8.7^{b}$	CI - C $+4.3^{a}$	E_{AI} - E_A $+2.7^{a}$	CI - AI -4.4^{a}		BI - B $+10.0^{d}$	

Table 5-20

Statistical Analysis of Test Data: Al 2219-T6-Transverse, Type 2

Significance Probability
a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary
Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F			Annealing Temperature, 80°F		
Annealing Temperature		Difference	Test Temperature		Difference
-320°F	80°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)					
"C" "72.3"	C 72.3 (1.4/4)		C 72.3	B 62.1 (0.8/5)	B - C -10.2[d]
AI 80.7 (0.8/3)	CI 72.1 (1.7/6)	CI - AI - 8.6[d]	CI 72.1	BI 61.4 (0.5/6)	BI - CI -10.7[d]
AI - C + 8.4[d]	CI - C -0.2[a]			BI - B -0.7[a]	
Tensile Yield Strength (ksi)					
"C" "53.6"	C 53.6 (0.5/4)		C 53.6	B 47.3 (0.9/5)	B - C - 6.3[d]
AI 79.0 (0.9/3)	CI 54.6 (1.1/6)	CI - AI -24.4[d]	CI 54.6	BI [illegible] (1.5/6)	BI - CI - 7.4[d]
AI - C +25.4[d]	CI - C +1.0[a]			BI - B -0.1[a]	
Notched Tensile Strength (ksi)					
"C" "88.2"	C 88.2 (5.2/5)		C 88.2	B 75.5 (2.4/4)	B - C -12.1[d]
AI 91.4 (6.8/3)	CI 88.1 (3.8/6)	CI - AI - 3.3[d]	CI 88.1	BI 72.2 (4.1/5)	BI - CI -15.9[d]
AI - C + 3.2[a]	CI - C - 0.1[a]			BI - B -3.2[a]	
Percent Elongation					
"C" "7.6"	C 7.6 (0.6/4)		C 7.6	B 8.27 (1.3/5)	B - C + 0.7[a]
AI 2.27 (0.4/3)	CI 6.67 (1.5/6)	CI - AI + 4.4[d]	CI 6.67	BI 8.02 (2.5/6)	BI - CI + 1.4[a]
AI - C - 5.3[d]	CI - C -0.9[a]			BI - B -0.025[a]	
Percent Reduction in Area					
"C" 6.7	C 6.7 (1.5/4)		C 6.7	B 9.4 (3.3/5)	B - C + 2.7[a]
AI 4.3 (2.3/3)	CI 6.4 (1.1/6)	CI - AI + 2.1[a]	CI 6.4	BI 9.0 (2.8/6)	BI - CI + 2.6[b]
AI - C - 2.4[a]	CI - C +0.3[a]			BI - B -0.4[a]	

Table 3-21

Statistical Analysis of Test Data: Al 2219-T6-Radial, Type 2

Significance Probability
$a < 0.90$
$0.90 \le b < 0.95$
$0.95 \le c < 0.99$
$0.99 \le d$

Data Summary
Test Condition Avg of n Values (s/n)

Test Temperature, -320°F			Annealing Temperature, 80°F		
Annealing Temperature		Difference	Test Temperature		Difference
-320°F	80°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)					
"C" "73.0"	C 73.6 (2.7/2)		C 73.6	B 61.8 (0.8/3)	B - C -11.8^{d}
AI 80.5 (0.1/3)	CI 74.7 (1.7/2)	CI - AI -5.8^{d}	CI 74.4	BI 61.7 (0.4/3)	BI - CI -12.7^{d}
AI - C $+6.9^{d}$	CI - C $+0.8^{a}$			BI - B -0.1^{a}	
Tensile Yield Strength (ksi)					
"C" "51.7"	C 51.7 (0.9/2)		C 51.7	B 46.3 (1.2/3)	B - C -5.4^{d}
AI 78.3 (0.9/3)	CI 53.5 (1.3/2)	CI - AI -24.8^{d}	CI 53.5	BI 46.8 (0.6/3)	BI - CI -6.7^{d}
AI - C $+26.6^{d}$	CI - C $+1.8^{a}$			BI - B $+0.5^{a}$	
Notched Tensile Strength (ksi)					
"C" "93.0"	C 93.0 (3.5/2)		C 93.0	B 77.3 (2.4/2)	B - C -15.7^{d}
AI 105.4 (7.6/3)	CI 92.3 (4.6/2)	CI - AI -13.1^{c}	CI 92.3	BI 77.7 (0.5/3)	BI - CI -14.6^{d}
AI - C $+12.4^{c}$	CI - C -0.7^{a}			BI - B $+0.4^{a}$	
Percent Elongation					
"C" "13.0"	C 13.0 (6.6/2)		C 13.0	B 10.9 (1.4/3)	B - C -2.1^{a}
AI 5.62 (1.2/3)	CI 13.8 (1.1/2)	CI - AI $+8.2^{d}$	CI 13.8	BI 11.4 (1.2/3)	BI - CI -2.4^{a}
AI - C -7.4^{c}	CI - C $+0.8^{a}$			BI - B $+0.5^{a}$	
Percent Reduction in Area					
"C" 11.7	C 11. (5.0/2)		C 11.7	B 12.7 (2.8/3)	B - C $+1.0^{a}$
AI 8.5 (2.2/3)	CI 10.7 (1.6/2)	CI - AI $+2.2^{a}$	CI 10.7	BI 11.0 (3.9/3)	BI - CI $+0.3^{a}$
AI - C -3.2^{a}	CI - C -1.0^{a}			BI - B -1.7^{a}	

Table 3-22

Statistical Analysis of Test Data: Beryllium, Type 4

Significance Probability

a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary

Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F			Annealing Temperature, 80°F		
Annealing Temperature		Difference	Test Temperature		Difference
-320°F	80°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)					
"C" "36.2	C 36.2 (9.4/6)		C 36.2	B 51.1 (1.5/4)	B - C $+14.9^{d}$
A' 10.8 (1.4/4)	C' 37.3 (6.9/7)	C' - A' $+26.5^{d}$	C' 37.3	B' 49.9 (1.4/4)	B' - C' $+12.6^{d}$
A' - C -25.4^{d}	C' - C $+1.1^{a}$			B' - B -1.2^{a}	
Tensile Yield Strength (ksi)					
"C" "36.2"	C 36.2 (9.4/6)		C 36.2 (9.4/6)	B 41.4 (0.5/4)	B - C $+ 5.2^{a}$
A' 10.8 (1.4/4)	C' 37.3 (6.9/7)	C' - A' $+26.5^{d}$	C' 37.3 (6.9/7)	B' 42.9 (0.6/4)	B' - C' $+ 5.6^{a}$
A' - C -25.4^{d}	C' - C $+1.1^{a}$		$+1.1^{a}$	B' - B $+1.5^{a}$	
Notched Tensile Strength (ksi)					
"C" "6.9"	C 6.9 (1.7/6)		C 6.9	B 31.2 (4.1/4)	B - C $+24.3^{d}$
A' 6.3 (1.6/4)	C' 8.5 (2.5/6)	C' - A' $+ 2.2^{a}$	C' 8.5	B' 31.4 (1.5/4)	B' - C' $+22.9^{d}$
A' - C	C' - C			B' - B	
Percent Elongation					
"C"	C		C	B 0.39 (0.17/4)	B - C
A'	C'	C' - A' Insufficient Data	C'	B' 0.62 (0.19/4)	B' - C'
A' - C Insufficient Data	C' - C Insufficient Data			B' - B $+0.23^{a}$	
Percent Reduction in Area					
"C"	C		C	B	B - C
A'	C'	C' - A' Insufficient Data	C'	B'	B' - C'
A' - C Insufficient Data	C' - C Insufficient Data			B' - B Insufficient Data	

Table 3-21

Statistical Analysis of Test Data: Ti A-110-AT-Ell, Type 2

Significance Probability
a < 0.90
0.90 ≤ b < 0.95
0.95 ≤ c < 0.99
0.99 ≤ d

Data Summary
Test Condition Avg of n Values (σ/n)

Test Temperature, -320°F			Annealing Temperature, 80°F		
Annealing Temperature		Difference	Test Temperature		Difference
-320°F	80°F		-320°F	80°F	
Ultimate Tensile Strength (ksi)					
"C" "183.3"	C 183.3 (0.8/3)		C 183.3	B 121.1 (0.5/3)	B - C -62.2^{d}
AI 197.5 (2.1/3)	CI 191.8 (2.1/3)	CI - AI -5.7^{d}	CI 191.8	BI 129.0 (0.4/3)	BI - CI -62.8^{d}
AI - C +14.2^{d}	CI - C + 8.5^{d}			BI - B +7.9^{d}	
Tensile Yield Strength (ksi)					
"C" "177.6"	C 177.6 (0.9/3)		C 177.6	B 119.2 (0.2/3)	B - C -58.4^{d}
AI 195.0 (1.9/3)	CI 188.8 (2.2/3)	CI - AI -6.2^{d}	CI 188.8	BI 128.6 (0.5/3)	BI - CI -60.2^{d}
AI - C +17.4^{d}	CI - C +11.2^{d}			BI - B +9.4^{d}	
Notched Tensile Strength (ksi)					
"C" "245.0"	C 245.0 (5.0/3)		C 245.0	B 189.3 (2.1/3)	B - C -55.7^{d}
AI 227.1 (7.4/3)	CI 228.5 (6.1/3)	CI - AI +1.4^{a}	CI 228.5	BI 193.2 (3.4/3)	BI - CI -35.3^{d}
AI - C -17.9^{d}	CI - C -16.5^{d}			BI - B +3.9^{a}	
Percent Elongation					
"C" "18.3"	C 18.3 (4.3/3)		C 18.3	B 16.5 (0.8/3)	B - C - 1.8^{a}
AI 4.6 (0.07/3)	CI 12.0 (4.5/3)	CI - AI +7.4^{c}	CI 12.0	BI 12.8 (0.4/3)	BI - CI + 0.8^{a}
AI - C -13.7^{d}	CI - C - 6.3^{c}			BI - B +3.7^{a}	
Percent Reduction in Area					
"C" 24.7	C 24.7 (10.3/3)		C 24.7	B 37.1 (2.4/3)	B - C +12.4^{c}
AI 27.8 (3.6/3)	CI 29.7 (6.1/3)	CI - AI +1.9^{a}	CI 29.7	BI 37.6 (11.7/3)	BI - CI + 7.9^{a}
AI - C + 3.1^{a}	CI - C + 5.0^{a}			BI - B +0.5^{a}	

there is a possible interaction between test temperature and radiation. Without going into detail, an estimate of the "annealing temperature" x radiation interaction and of the test temperature x radiation interaction terms is, respectively,

$$1/2 \left[(C + Ei) - (E + Ci) \right]$$

and

$$1/2 \left[(C + Bi) - (B + Ci) \right]$$

The latter interaction term, evaluated for NTS of Inconel 718, Type 3 (Table 3-12), is

$$1/2 \left[(242.6 + 218.7) - (219.2 + 252.4) \right] = -5.2 \text{ ksi}$$

This interaction term is significant. It means that there is an interaction between the test temperature and radiation such that the effects are not additive (independent). This can be observed by noting the different response to the test temperature for the radiation condition (Bi - Ci) as compared with the no-radiation condition (B - C). In other words, the -33.7-ksi value is a significantly larger change than the -23.4-ksi value.

The tensile properties of materials tested at the same temperature after being subjected to different "annealing temperature" treatments (e.g., E_{Ai}, Ci, and E_A, C) at times experienced changes resulting from an interaction between permanent changes in the material due to a temperature effect and recovery due to annealing-out of radiation-induced changes. This is referred to above as an "annealing temperature" x radiation interaction. If the difference between the control specimen averages (E_A - C) is insignificant (no temperature effects), then a difference in the irradiated specimen averages (E_{Ai} - Ci) can generally be interpreted as an annealing-out of radiation-induced changes in the property. On the other hand, if a significant change (temperature effect) is evident between the control specimen averages, then the interpretation of changes between the irradiated specimen averages is not clear. Part of the observed change could be attributed to a permanent change in the property due to a temperature effect and part could be attributed to annealing as a result of the "annealing temperature" treatments.

To supplement Tables 3-12 through 3-23 and the previous general statements, the following interpretation of the statistical results for each material type is presented.

<u>Inconel 718, Type 3 (Ref. Table 3-12)</u>

<u>Ultimate Tensile Strength</u>

The significant +5.2 and -5.2 ksi values for (E_{Ci} - Ci) and (Bi - B), respectively, are difficult to interpret.

<u>Tensile Yield Strength</u>

There are significant radiation and annealing effects, with the radiation effects annealed out at 1040°F.

<u>Notched Tensile Strength</u>

Except for a suspected "outlier" in the data at E_C, the interpretation is similar to that for TYS. Analyzing the data as is, there is a significant interaction between "annealing temperature" and radiation. If the "outlier" is deleted from the analysis, the "annealing temperature" x radiation interaction is not significant.

Percent Elongation

There are no significant radiation or annealing effects.

Percent Reduction in Area

The (Ci - Ai) difference is significant.

D, D_1, D_1' Series

There are no significant radiation effects. Although some of the observed differences are as large as some of the significant results in the tables, the discrimination of the observed differences is less sensitive because the sample size, n, was smaller for this D series.

Inconel 718, Type 1 (Ref. Table 3-13)

Ultimate Tensile Strength

There are no significant radiation or annealing effects.

Tensile Yield Strength

There are significant radiation and annealing effects, with the radiation effects still evident at 80°F and annealed out at 1040°F.

Notched Tensile Strength

The interpretation is similar to that for TYS except that there is no significant annealing effect between Ci and Ai and the significance level is lower because of the larger variability in the data.

Percent Elongation

There are no significant radiation or annealing effects.

Percent Reduction in Area

There are no significant radiation or annealing effects.

D_C, D_{C1} Series

There are no significant radiation effects.

Inconel 718-WS, Type 3 (Ref. Table 3-14)

Ultimate Tensile Strength

There are significant radiation effects.

Tensile Yield Strength

There are significant radiation effects.

Notched Tensile Strength

There are no significant radiation or annealing effects.

Percent Elongation

There are no significant radiation or annealing effects.

Percent Reduction in Area

There are significant radiation effects as well as a significant test temperature x radiation interaction.

Inconel X-750, Type 1 (Ref. Table 3-15)

Ultimate Tensile Strength

There are no radiation or annealing effects.

Tensile Yield Strength

There are radiation and annealing effects, with the radiation effects annealed out at 1040°F.

Notched Tensile Strength

There are radiation and annealing effects, with the radiation effects annealed out at 1040°F. The test temperature x radiation interaction is significant.

Percent Elongation

There are significant radiation effects.

Percent Reduction in Area

There are no significant radiation effects.

D_C, D_{Ci} Series

There are no significant radiation effects.

Inconel X-750, Type 3 (Ref. Table 3-16)

Ultimate Tensile Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 1040°F.

Tensile Yield Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 1040°F.

Notched Tensile Strength

There are significant radiation and annealing effects. A significant "annealing temperature" effect of -9.3 ksi for condition E_C - C and a significant "annealing temperature" x radiation reaction of -26.5 ksi for (E_{Ci} - Ci) are apparent.

Percent Elongation

There are significant radiation and annealing effects, with the radiation effects annealed out at 1040°F.

Percent Reduction in Area

There are no significant radiation or annealing effects.

D_C, D_{Ci} Series

There are no significant radiation effects.

AISI 301-CW, Type 3 (Ref. Table 3-17)

Ultimate Tensile Strength

There are no significant radiation or annealing effects.

Tensile Yield Strength

There are significant radiation effects. The 540°F "annealing temperature" resulted in a significant increase in the TYS of irradiated specimens, indicating a significant interaction between "annealing temperature" and radiation. The radiation effects are not completely annealed out, as evidenced by the significant radiation effects still remaining after the 540°F anneal.

Notched Tensile Strength

The interpretation is similar to that given for TYS.

Percent Elongation

There are significant radiation and "annealing temperature" effects.

Percent Reduction in Area

There are no significant radiation or annealing effects. A 70.8-ksi datum point was deleted from the analysis.

D_A, D_{A1} Series

There are significant radiation effects for TYS (3.0[b] ksi) and NTS (2.8[b] ksi).

AISI 303-Se, Type 1 (Ref. Table 3-18)

Ultimate Tensile Strength

There are significant radiation effects and an "annealing temperature" x radiation interaction. The radiation effects are annealed out at 540°F.

Tensile Yield Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 540°F.

Notched Tensile Strength

There are significant radiation and annealing effects, with an "annealing temperature" x radiation interaction indicated. The radiation effects are still evident after the 540°F anneal.

Percent Elongation

There are significant radiation effects for the (Ai - C) condition. Generally, annealing effects are not significant; however, radiation effects decrease as the annealing temperature increases.

Percent Reduction in Area

The apparent grouping of the data at Bi suggests that some sort of bias may have been introduced into the data. No conclusions are made because the grouping is difficult to interpret.

D_A, D_{A1} Series

There are no significant radiation effects. The 66.8-ksi value was deleted from the analysis.

Aluminum 2219-T6, Type 3 (Ref. Table 3-19)

Ultimate Tensile Strength

There are significant "annealing temperature" effects.

Tensile Yield Strength

There are significant radiation and annealing effects with the radiation effects annealed out at 80°F. "Annealing temperature" effects occur between 80°F and 540°F.

Notched Tensile Strength

Same interpretation as TYS.

Percent Elongation

The significant effects observed are such that interpretation is difficult.

Percent Reduction in Area

There are significant radiation effects.

D_A, D_{Ai} Series

There are significant radiation effects at the 540°F (13.7^d) test temperature for percent reduction in area and a significant test temperature x radiation interaction.

Aluminum 2219-T6-Transverse, Type 2 (Ref. Table 3-20)

Ultimate Tensile Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 80°F.

Tensile Yield Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 80°F.

Notched Tensile Strength

There are no significant radiation or annealing effects.

Percent Elongation

There are no significant radiation or annealing effects.

Percent Reduction in Area

There are no significant radiation or annealing effects.

Aluminum 2219-T6-Radial, Type 2 (Ref. Table 3-21)

Ultimate Tensile Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 80°F.

Tensile Yield Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 80°F.

Notched Tensile Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 80°F.

Percent Elongation

There are significant radiation and annealing effects, with the radiation effects annealed out at 80°F.

Percent Reduction in Area

There are no significant radiation or annealing effects.

Beryllium, Type 4 (Ref. Table 3-22)

Ultimate Tensile Strength

There are significant radiation and annealing effects, with the radiation effects annealed out at 80°F. Test temperature effects are significant.

Tensile Yield Strength

Interpretation similar to UTS except the observed test temperature effects are not significant.

Notched Tensile Strength

There are no significant radiation or annealing effects.

Percent Elongation

Limited data (not significant).

Percent Reduction in Area

Insufficient data for any comparisons.

Titanium A-110-AT-E11, Type 2 (Ref. Table 3-23)

Ultimate Tensile Strength

There are significant radiation and annealing effects. The radiation effect is partially annealed out at 80°F.

Tensile Yield Strength

There are significant radiation and annealing effects. The radiation effects are partially annealed out at 80°F.

Notched Tensile Strength

There are significant radiation effects. No annealing is evident at 80°F.

Percent Elongation

There are significant radiation and annealing effects. The radiation effects are partially annealed out at 80°F.

Percent Reduction in Area

There are no significant radiation or annealing effects.

3.1.3 Discussion and Analysis of Results

Tables 3-24 through 3-29 summarize the test results by giving the percent change, from control to irradiated, in the six types of physical-property measurements: UTS, TYS, NTS, NTS/UTS, percent elongation, and percent reduction in area. In each table, the percent change in the property, as determined from the average control and irradiation values, is presented for each material and test condition. The statistical significance probability of the data was taken from the statistical analysis of Section 3.1.2.

The amount of change that should be considered significant or insignificant is arbitrary; however, for the purpose of this discussion, which is to indicate the magnitude of change in property values experienced by materials as a result of this irradiation, the following assignments of significance are used. Percent changes of less than 5% will be considered insignificant, even though the observed differences between the averages of the control and irradiated values are statistically significant. Percent changes of greater than 5% but less than 10% that are statistically significant will be considered as of slight significance. Percent changes of greater than 10% that are statistically significant will be considered as significant changes.

No effort has been made to analyze the results of this test for the purpose of determining the mechanisms of material damage associated with the apparent changes due to the environmental conditions imposed. The analysis of results appearing in

Table 3-24

Percent Change: Ultimate Tensile Strength

Material	Test Condition (Control - Irradiated)												
	C - A1	C - C1	B - B1	$D_A - D_{A1}$	$D_A - D_{A1}'$	$D_B - D_{B1}$	$D_B - D_{B1}'$	$D_C - D_{C1}$	$D_C - D_{C1}'$	$D_D - D_{D1}$	$D_D - D_{D1}'$	$E_A - E_{A1}$	$E_C - E_{C1}$
Inconel 718 Type 3	- 0.15[a]	- 0.96[a]	- 2.38[d]	+ 0.91[a]	+ 1.0[a]	+ 3.14[a]	+ 1.38[a]	- 0.42[a]	- 1.05[a]	- 3.10[a]	- 1.94[a]	-	+ 0.15[a]
Inconel 718 Type 1	+ 0.15[a]	+ 2.12[a]	- 1.56[a]	-	-	-	-	+ 0.94[a]	-	-	-	-	+ 0.43[a]
Inconel 718-WS Type 3	+ 2.57[a]	+ 3.83[b]	- 2.54[a]	-	-	-	-	-	-	-	-	-	-
Inconel X-750 Type 1	- 0.02[a]	+ 1.57[a]	- 1.35[a]	-	-	-	-	- 2.84[a]	-	-	-	-	- 0.81[a]
Inconel X-750 Type 3	+ 1.38[b]	+ 1.47[b]	- 0.90[a]	-	-	-	-	- 3.08[a]	-	-	-	-	+ 0.14[a]
AISI 301-CW Type 3	- 0.82[a]	+ 0.51[a]	+ 1.02[a]	+ 1.44[a]	-	-	-	-	-	-	-	+ 0.79[a]	-
AISI 303-Se Type 1	+ 4.59[c]	+ 4.23[c]	+ 3.56[a]	- 0.55[a]	-	-	-	-	-	-	-	+ 0.12[a]	-
Al 2219-T6 Type 3	+ 2.73[a]	+ 1.50[a]	- 2.18[a]	+ 0.46[a]	-	-	-	-	-	-	-	- 1.4[illegible]	-
Al 2219-T6 Type 2, Trans.	+11.6[d]	NC	- 1.13[a]	-	-	-	-	-	-	-	-	-	-
Al 2219-T6 Type 2, Radial	+ 9.37[d]	+ 1.49[a]	NC	-	-	-	-	-	-	-	-	-	-
Beryllium Type 4	-70.16[d]	+ 3.04[a]	- 2.35[a]	-	-	-	-	-	-	-	-	-	-
Ti A-110-AT-Eli Type 2	+ 7.75[d]	+ 4.54[d]	+ 0.52[d]	-	-	-	-	-	-	-	-	-	-
Statistical Significance Probability: $a \leq 0.90$ $0.90 \leq b \leq 0.95$ $0.95 \leq c \leq 0.99$ $0.99 \leq d$													

Table 3-25

Percent Change: Tensile Yield Strength

Material	Test Condition (Control - Irradiated)												
	C - A1	C - C1	B - B1	D_A - D_{A1}	D_A - A1'	D_B - D_{B1}	D_B - D_{B1}'	D_C - D_{C1}	D_C - D_{C1}'	D_D - D_{D1}	D_D - D_{D1}'	E_A - E_{A1}	E_C - E_{C1}
Inconel 718 Type 3	+ 9.27[d]	+ 2.45[d]	+ 1.78[c]	+ 1.03[a]	+ 2.18[a]	+ 2.70[a]	+ 0.12[a]	- 1.7[illegible]	- 0.13[a]	- 0.78[a]	- 1.0[illegible][a]	-	+ [illegible]1[a]
Inconel 718 Type 1	+13.8[d]	+ 7.69[d]	+ 5.01[d]	-	-	-	-	- 0.95[a]	-	-	-	-	+ 1.55[a]
Inconel 718-WS Type 3	+ 7.00[c]	+ 5.16[b]	+ 3.20[a]	-	-	-	-	-	-	-	-	-	-
Inconel X-750 Type 1	+39.1[d]	+26.6[d]	+24.3[d]	-	-	-	-	+ 0.21[a]	-	-	-	-	- 0.[illegible][a]
Inconel X-750 Type 3	+35.9[d]	+22.5[d]	+20.1[d]	-	-	-	-	+ 1.04[a]	-	-	-	-	NC
AISI 301-CW Type 3	+ 6.60[d]	+ 5.14[d]	+ 3.51[d]	+ 2.26[b]	-	-	-	-	-	-	-	+ 1.42[b]	-
AISI 303-Se Type 1	+34.7[d]	+22.2[d]	+23.8[d]	+ 6.91[a]	-	-	-	-	-	-	-	+ 2.02[a]	-
Al 2219-T6 Type 3	+28.3[d]	+ 5.28[a]	- 1.19[a]	+ 0.49[a]	-	-	-	-	-	-	-	- 3.20[a]	-
Al 2219-T6 Type 2, Trans.	+47.4[d]	+ 1.86[a]	NC	-	-	-	-	-	-	-	-	-	-
Al 2219-T6 Type 2, Radial	+51.5[d]	+ 3.48[a]	+ 1.08[a]	-	-	-	-	-	-	-	-	-	-
Beryllium Type 4	-70.2[d]	+ 3.04[a]	+ 3.02[a]	-	-	-	-	-	-	-	-	-	-
Ti A-110-AT-Eli Type 2	+ 9.80[d]	+ 6.31[d]	+ 7.89[d]	-	-	-	-	-	-	-	-	-	-

Statistical Significance Probability: a ≤ 0.90   0.90 ≤ b ≤ 0.95   0.95 ≤ c ≤ 0.99   0.99 ≤ d

Table 3-26

Percent Change: Notched Tensile Strength

Material	Test Condition (Control - Irradiated)												
	C - A1	C - C1	B - B1	$D_A - D_{A1}$	$D_A - D_{A1}'$	$D_B - D_{B1}$	$D_B - D_{B1}'$	$D_C - D_{C1}$	$D_C - D_{C1}'$	$D_D - D_{D1}$	$D_D - D_{D1}'$	$E_A - E_{A1}$	$E_C - E_{C1}$
Inconel 718 Type 3	+ 7.13[d]	+ 4.04[c]	- 0.23[a]	-	-	-	-	- 4.54[a]	-	-	-	-	- 3.51[a]
Inconel 718 Type 1	+ 9.40[c]	+ 8.19[c]	+ 3.42[a]	-	-	-	-	- 3.70[a]	-	-	-	-	- 0.22[a]
Inconel 718-WS Type 3	+ 2.34[a]	+ 1.85[a]	+ 0.94[a]	-	-	-	-	-	-	-	-	-	-
Inconel X-750 Type 1	+22.5[d]	+14.7[d]	+11.1[d]	-	-	-	-	- 2.22[a]	-	-	-	-	- 0.95[a]
Inconel X-750 Type 3	+19.2[d]	+12.3[d]	+10.2[d]	-	-	-	-	- 1.96[a]	-	-	-	-	+ 2.82[a]
AISI 301-CW Type 3	+ 3.38[d]	+ 4.53[d]	+ 1.36[b]	+ 1.77[b]	-	-	-	-	-	-	-	+ 2.02[d]	-
AISI 303-Se Type 1	+19.5[d]	+ 9.16[d]	+ 8.06[c]	+ 4.11[a]	-	-	-	-	-	-	-	+ 4.18[b]	-
Al 2219-T6 Type 3	+11.7[d]	+ 0.59[a]	- 5.31[c]	+ 1.87[a]	-	-	-	-	-	-	-	- 2.05[a]	-
Al 2219-T6 Type 2, Trans.	+ 3.63[a]	NC	- 4.37[a]	-	-	-	-	-	-	-	-	-	-
Al 2219-T6 Type 2, Radial	+13.3[c]	- 0.75[a]	+ 0.52[a]	-	-	-	-	-	-	-	-	-	-
Beryllium Type 4	- 8.84[a]	+23.2[a]	+ 0.64[a]	-	-	-	-	-	-	-	-	-	-
Ti A-110-AT-Eli Type 2	- 7.31[d]	- 6.73[d]	+ 2.06[a]	-	-	-	-	-	-	-	-	-	-

Statistical Significance Probability: a ≤ 0.90   0.90 ≤ b ≤ 0.95   0.95 ≤ c ≤ 0.99   0.99 ≤ d

Table 3-27

Percent Change: Notched-to-Unnotched Tensile Strength Ratio*

Material	Test Condition (Control - Irradiated)												
	C - A1	C - C1	B - B1	$D_A - D_{A1}$	$D_A - D_{A1}'$	$D_B - D_{B1}$	$D_B - D_{B1}'$	$D_C - D_{C1}$	$D_C - D_{C1}'$	$D_D - D_{D1}$	$D_D - D_{D1}'$	$E_A - E_{A1}$	$E_C - E_{C1}$
Inconel 718 Type 3	+ 5.67	+ 4.44	+ 2.00	-	-	-	-	- 5.0	-	-	-	-	- 4.35
Inconel 718 Type 1	+ 8.55	+ 5.98	+ 4.65	-	-	-	-	- 4.84	-	-	-	-	-
Inconel 718-WS Type 3	- 1.26	- 2.53	+ 3.49	-	-	-	-	-	-	-	-	-	-
Inconel X-750 Type 1	+23.3	+12.9	+12.4	-	-	-	-	+ 0.83	-	-	-	-	-
Inconel X-750 Type 3	+17.2	+10.3	+11.8	-	-	-	-	+ 1.12	-	-	-	-	+ 2.35
AISI 301-CW Type 3	+ 4.23	+ 4.23	+ 0.98	+ 0.93	-	-	-	-	-	-	-	+ 1.28	-
AISI 303-Se Type 1	+14.80	+ 5.21	+ 4.58	+ 4.48	-	-	-	-	-	-	-	+ 4.59	-
Al 2219-T6 Type 3	+ 8.70	- 1.09	- 3.16	+ 0.81	-	-	-	-	-	-	-	-	-
Al 2219-T6 Type 2, Trans.	- 7.38	-	- 3.28	-	-	-	-	-	-	-	-	-	-
Al 2219-T6 Type 2, Radial	+ 3.97	- 1.59	+ 0.80	-	-	-	-	-	-	-	-	-	-
Beryllium Type 4	+205.0	+21.05	+ 3.28	-	-	-	-	-	-	-	-	-	-
Ti A-110-AT-Eli Type 2	-14.2	-11.9	- 3.85	-	-	-	-	-	-	-	-	-	-

*No statistical analysis was performed on these ratios.

Table 3-28

Percent Change: Percent Elongation

Material	Test Condition (Control - Irradiated)												
	C - A1	C - C1	B - B1	$D_A - D_{A1}$	$D_A - D_{A1}'$	$D_B - D_{B1}$	$D_B - D_{B1}'$	$D_C - D_{C1}$	$D_C - D_{C1}'$	$D_D - D_{D1}$	$D_D - D_{D1}'$	$E_A - E_{A1}$	$E_C - E_{C1}$
Inconel 718 Type 3	NC	+ 3.17[a]	+ 9.26[a]	-7.48[a]	+0.09[a]	+3.20[a]	-10.40[a]	+ 4.70[a]	+15.5[a]	-44.6[a]	-40.80[a]	-	- 7.82[a]
Inconel 718 Type 1	-33.12[a]	+ 1.60[a]	+ 4.59[a]	-	-	-	-	+14.05[a]	-	-	-	-	- 4.86[a]
Inconel 718-WS Type 3	- 7.29[a]	NC	+43.7[c]	-	-	-	-	-	-	-	-	-	-
Inconel X-750 Type 1	-23.3[d]	-15.3[c]	-1.22[a]	-	-	-	-	-16.6[a]	-	-	-	-	- 3.17[a]
Inconel X-750 Type 3	-18.9[d]	-11.5[d]	-3.72[a]	-	-	-	-	+ 1.37[a]	-	-	-	-	- 3.74[a]
AISI 301-CW Type 3	- 0.98[a]	- 1.96[a]	- 9.37[c]	-3.14[a]	-	-	-	-	-	-	-	- 6.99[c]	-
AISI 303-Se Type 1	-20.4[c]	-10.2[a]	-16.7[a]	-6.78[a]	-	-	-	-	-	-	-	- 6.03[a]	-
Al 2219-T6 Type 3	-12.4[a]	+11.0[a]	- 3.43[a]	-1.05[a]	-	-	-	-	-	-	-	-13.08[b]	-
Al 2219-T6 Type 2, Trans.	-70.1[d]	-12.2[a]	- 3.02[a]	-	-	-	-	-	-	-	-	-	-
Al 2219-T6 Type 2, Radial	-56.7[c]	+ 6.32[a]	+ 4.59[a]	-	-	-	-	-	-	-	-	-	-
Beryllium Type 4	*	*	+59.0[a]*	-	-	-	-	-	-	-	-	-	-
Ti A-110-AT-Eli Type 2	-74.9[d]	-34.4[c]	-22.4[a]	-	-	-	-	-	-	-	-	-	-

Statistical Significance Probability: $a \leq 0.90$ $0.90 \leq b \leq 0.95$ $0.95 \leq c \leq 0.99$ $0.99 \leq d$

*See specimen data in Table 3-8

Table 3 29

Percent Change: Reduction i. Area

Material	Test Condition (Control - Irradiated)													
	C - A1	C - C1	B - B1	$D_A - D_{A1}$	$D_A - D'_{A1}$	$D_B - D_{B1}$	$D_B - D'_{B1}$	$D_C - D_{C1}$	$D_C - D'_{C1}$	$D_D - D_{D1}$	$D_D - D'_{D1}$	$E_A - E_{A1}$	$E_C - E_{C1}$
Inconel 718 Type 3	+25.73[a]	-16.96[a]	- 3.28[d]	- 9.75[a]	-10.42[a]	-11.48[a]	-10.45[a]	+38.67[a]	+15.5[a]	-26.3[a]	-40.77[a]	-	-17.3[a]
Inconel 718 Type 1	+ 2.92[a]	+ 9.17[a]	+ 1.14[a]	-	-	-	-	- 5.26[a]	-	-	-	-	NC
Inconel 718-WS Type 3	-48.3[d]	-45.1[d]	+20.1[a]	-	-	-	-	-	-	-	-	-	-
Inconel X-750 Type 1	+ 2.09[a]	+ 5.67[a]	- 4.80[a]	-	-	-	-	-10.9[a]	-	-	-	-	+ 8.87[a]
Inconel X-750 Type 3	- 5.40[a]	- 6.0[a]	+ 0.56[a]	-	-	-	-	- 7.53[a]	-	-	-	-	- 1.17[a]
AISI 301-CW Type 3	-11.0[a]	-11.0[a]	- 9.50[a]	- 9.80[a]	-	-	-	-	-	-	+45.0[a]	-	-
AISI 303-Se Type 1	- 8.09[a]	- 7.68[a]	+16.3[a]	-27.3[a]	-	-	-	-	-	-	-11.0[a]	-	-
Al 2219-T6 Type 3	+58.8[b]	+29.1[a]	+88.5[d]	+01.7[d]	-	-	-	-	-	-	+13.40[a]	-	-
Al 2219-T6 Type 2, Trans.	-36.6[a]	- 4.90[a]	- 3.42[a]	-	-	-	-	-	-	-	-	-	-
Al 2219-T6 Type 2, Radial	-27.6[a]	- 8.55[a]	-13.4[a]	-	-	-	-	-	-	-	-	-	-
Beryllium Type 4	*	*	*	-	-	-	-	-	-	-	-	-	-
Ti A-110-AT-Eli Type 2	+12.6[a]	+20.2[a]	+ 1.35[a]	-	-	-	-	-	-	-	-	-	-
Statistical Significance Probability: a ≤ 0.90 0.90 ≤ b ≤ 0.95 0.95 ≤ c ≤ 0.99 0.99 ≤ d													

*See specimen data in Table 3-8

this section and the statistical analysis of Section 3.1.2 assume that all specimens received the same incident radiation, when in reality they did not. The integrated neutron flux received by the specimens, as tabulated in Table 3-1, ranged from 4×10^{17} to 10×10^{17} n/cm^2 (E > 1 Mev) for all materials, with a worst-case condition for any material group being a factor of 2 between the lowest flux received by any specimen and the highest flux received by any specimen of the same material type. It is probable that some of the scatter evident in the material data is a result of the difference in incident radiation received by the specimens; however, it is not believed to have a significant effect on the interpretation of the results.

In the following discussion, the apparent changes in each of the tensile properties measured are discussed for each material irradiated. No effort was made to analyze the results on a basis of specimen type, that is, 1, 2, or 3. The purpose of the discussion is to indicate the general trends established by changes in the tensile properties of each material, regardless of specimen type. When a statement is made concerning some material, it will be the general trend experienced by all specimens as a group, regardless of type, unless specifically called out otherwise.

3.1.3.1 Ultimate Tensile Strength

Apparent changes in ultimate tensile strength, presented in tabular form in Table 3-24, were generally insignificant

($<$ 5%). Tests performed in LN_2 without warmup indicated that slight (5-10%) to significant ($>$ 10%) changes had occurred in this property for titanium, aluminum, and beryllium; however, appreciable to complete recovery was evident after a room-temperature anneal.

For test condition A1, slight to significant increases were noted for titanium ($\sim$8.0%) and for both transverse (12%) and radial (9%) aluminum specimens. A significant decrease ($\approx$70%) was noted for beryllium. Tests performed on specimens after a room-temperature anneal indicated complete recovery in this property for all specimens except titanium, which still exhibited a slight increase of approximately 7%. Tests performed on specimens after an elevated-temperature anneal ($>80^\circ F$) indicated that only insignificant changes in UTS had occurred for those specimens tested.

3.1.3.2 <u>Tensile Yield Strength</u>

Apparent changes in tensile yield strength, presented in tabular form in Table 3-25, were generally significant ($>$ 10%). Materials tested at LN_2 temperature without warmup exhibited slight (5-10%) to significant changes in this property. Some recovery was apparent in the materials after warmup to room temperature, and only insignificant changes ($<$ 5%) were noted for materials annealed at elevated temperatures.

For test condition A1, increases of from 25% to 50% were evident for Inconel X-750, AISI 303-Se, and Al 2219 specimens. Except for beryllium, where a significant decrease of $\approx$70%

was noted, the remaining materials experienced increases of from 6% to 15% in this property. Tests performed after the specimens were allowed to warm up to room temperature (test conditions Ci and Bi) indicated that appreciable recovery had occurred; however, slight to significant increases in the property were still evident for Inconel 718, Inconel X-750, AISI 303-Se, and titanium. Specimens subjected to elevated annealing temperatures ($>80^{\circ}F$) exhibited only insignificant changes in the property.

3.1.3.3 Notched Tensile Strength

Apparent changes in notched tensile strength, as presented in Table 3-26, indicate that slight (5-10%) to significant ($>10\%$) changes occurred in this property for specimens tested at LN_2 temperature without warmup. Appreciable recovery was apparent in all materials after a room-temperature anneal, and only insignificant changes ($<5\%$) were apparent after elevated-temperature ($>80^{\circ}$) annealing.

Most of the materials subjected to test condition Ai experienced slight to significant increases; however, AISI 301-Cw and Al 2219-T6-transverse showed increases of less than 4%, and beryllium and titanium experienced decreases of 8% and 7%, respectively. Appreciable recovery was evident in specimens subjected to a room-temperature anneal; however, significant increases ($\approx 10\%$) were still apparent in this property for Inconel X-750, along with a slight ($\approx 8\%$) increase in the property for AISI 303-Se. Specimens tested after annealing treatments at elevated temperatures

($>$80°F) experienced only insignificant changes in this property.

3.1.3.4 Notched-to-Unnotched Tensile Strength Ratio

Most materials tested experienced slight (5-10%) to significant ($>$10%) changes in this property, as evident in Table 3-27. No statistical analysis was performed on these data; therefore, significance probability is not included in the data. A recovery trend was established after specimen warmup to room temperature, and only significant ($<$5%) to slight changes in this property were experienced by the materials after annealing treatments at elevated temperatures ($>$80°F).

For test condition A1, significant increases were noted for Inconel X-750 and AISI 303-Se. All other materials exhibited only slight changes except beryllium and titanium, which showed an increase of 205% and a decrease of 14.2%, respectively. The materials experienced appreciable recovery in this property after room-temperature anneal; however, Inconel X-750 specimens still exhibited increases of approximately 12%. Only insignificant to slight changes were apparent in this property for materials subjected to an elevated-temperature ($>$80°F) anneal.

3.1.3.5 Percent Elongation and Reduction in Area

As discussed previously, dimensional measurements were taken with a special test jig and micrometers. The two halves of each broken specimen were fitted together in the jig and elongation measurements made. Other measurements were made with vernier and dial micrometers. Since the specimens were radioactive (some as high as 20 r/hr) plexiglass body shielding was used. In addition, several operators were used to minimize the exposure to any one operator. Measurements were made only once, and questionable data were not checked to the extent desired because of the personnel exposure required to separate particular specimens from the group.

Percent Elongation. Measured elongation values were checked against Instron chart elongation indication and the trends established by one were in general agreement with the other. Apparent changes in measured elongation, presented in Table 3-28, were generally significant (> 10%). All materials tested at LN_2 temperature without warmup experienced slight (5-10%) to significant decreases in ductility with the exception of beryllium, where no change was discernable. Appreciable recovery was evident after a room-temperature anneal.

For test condition A1, all materials with the exception of AISI 301-CW and beryllium experienced significant decreases in ductility of from 20% to 70%. The percent elongation of the beryllium specimens at LN_2 temperature was nil for both control and irradiated specimens. The AISI 301-CW specimens exhibited only insignificant decreases in the property. Appreciable recovery was evident after a room-temperature anneal; however, the titanium specimens still exhibited a significant decrease of 22.4% in this property. Although statistically significant, the 43.7% increase in percent elongation for Inconel 718-WS specimens is questionable because the percent elongation itself was small (< 1.0%) and any error in the dimensional measurements appears quite large in the calculations for percent change from control to irradiated values.

Percent Reduction in Area. The percent changes in percent reduction in area are tabulated in Table 3-29. Slight errors made in the measurement of specimen diameters, widths, or thicknesses can result in large errors in the final calculations for percent change in the percent reduction in area of specimens. Because of the difficulties encountered in making dimensional measurements on irradiated specimens, the data are questionable and will not be discussed further.

3.1.4 Evaluation of Materials Tested

To supplement the general statements previously made, a summary of the results for each material is given below.

Inconel 718, Type 3

Test Conditions

Ai, Bi, Ci, D_{Ai}, D_{Ai}', D_{Bi}, D_{Bi}', D_{Ci}, D_{Ci}', D_{Di}, D_{Di}', E_{Ci}

Ultimate Tensile Strength

Insignificant changes (< 5%).

Tensile Yield Strength

Insignificant changes for all test conditions except Ai, where an increase of 9.3% was evident.

Notched Tensile Strength

Insignificant changes for all test conditions except Ai, where an increase of 7.1% was noted.

Notched-to-Unnotched Tensile Strength Ratio

Insignificant changes for all test conditions except Ai, where an increase of 6.7% was noted.

Percent Elongation

Insignificant changes.

Inconel 718, Type 1

Test Conditions

A1, B1, C1, D_{C1}, E_{C1}

Ultimate Tensile Strength

Insignificant changes (< 5%).

Tensile Yield Strength

Increase of 13.8% for test condition A1; increases of 7.7% and 5.0%, respectively, for test conditions C1 and B1; and insignificant changes for test conditions D_{C1} and E_{C1}, indicating recovery.

Notched Tensile Strength

Increases of 9.4% and 8.2%, respectively, for test conditions A1 and C1; insignificant changes for test conditions B1, D_{C1}, and E_{C1}, indicating recovery.

Notched-to-Unnotched Tensile Strength Ratio

Increases of 8.6% and 6.0%, respectively, for test conditions A1 and C1; insignificant changes for test conditions B1, D_{C1}, and E_{C1}, indicating recovery.

Percent Elongation

Insignificant changes.

Inconel 718-WS, Type 3

Test Conditions

A1, B1, C1

Ultimate Tensile Strength

Insignificant changes (< 5%).

Tensile Yield Strength

Increases of 7% and 5.2% for test conditions A1 and C1, respectively.

Notched Tensile Strength

Insignificant increases.

Notched-to-Unnotched Tensile Strength Ratio

Insignificant changes.

Percent Elongation

Insignificant changes.

Inconel X-750, Type 1

Test Conditions

A1, B1, C1, D_{C1}, E_{C1}

Ultimate Tensile Strength

Insignificant changes (< 5%).

Tensile Yield Strength

Increase of 39.1% for test condition A1. Considerable recovery was evident for test conditions C1 and B1; however, increases of 26.6% and 24.3%, respectively, were still evident. Insignificant changes for test conditions D_{C1} and E_{C1}.

Notched Tensile Strength

Increase of 22.5% for test condition A1. Considerable recovery for test conditions C1 and B1; however, increases of 14.7% and 11.1%, respectively, were still evident. Insignificant changes for test conditions D_{C1} and E_{C1}.

Notched-to-Unnotched Tensile Strength Ratio

Increase of 23.3% for test condition A1. Considerable recovery for test conditions C1 and B1; however, increases of 12.9% and 12.4%, respectively, were still evident. Insignificant changes for test conditions D_{C1} and E_{C1}.

Percent Elongation

Decrease of 23.3% for test condition A1. Appreciable recovery for test condition C1, although a decrease of 15.3% was still evident. Complete recovery for test condition B1. Insignificant changes for test conditions D_{C1} and E_{C1}.

Inconel X-750, Type 3

Test Conditions

A1, B1, C1, D_{C1}, E_{C1}

Ultimate Tensile Strength

Insignificant changes ($<$ 5%).

Tensile Yield Strength

Increase of 35.9% for test condition A1. Some recovery evident for test conditions C1 and B1; however, increases of 22.5% and 20.1%, respectively, were still evident. Insignificant changes for test conditions D_{C1} and E_{C1}.

Notched Tensile Strength

Increase of 19.2% for test condition A1. Some recovery evident for test conditions C1 and B1; however, increases of 12.3% and 10.2%, respectively, were still evident. Insignificant changes for test conditions D_{C1} and E_{C1}.

Notched-to-Unnotched Tensile Strength Ratio

Increase of 17.2% for test condition A1. Appreciable recovery evident for test conditions C1 and B1, although increases of 10.3% and 11.8%, respectively, were still evident. Insignificant changes for test conditions D_{C1} and E_{C1}.

Percent Elongation

Decrease of 18.9% evident for test condition A1. Considerable recovery for test condition C1, where a decrease of 11.5% was noted. Complete recovery evident for test condition B1. Insignificant changes for test condition D_{C1} and E_{C1}.

AISI 301-CW, Type 3

Test Conditions

A1, B1, C1, D_{A1}, E_{A1}

Ultimate Tensile Strength

Insignificant changes ($<$ 5%).

Tensile Yield Strength

Increases of 6.6% and 5.1% for test conditions A1 and C1, respectively. Insignificant increases for all other test conditions.

Notched Tensile Strength

Insignificant increases.

Notched-to-Unnotched Tensile Strength Ratio

Insignificant increases.

Percent Elongation

Insignificant decreases for all test conditions except Bi and E_{Ai}, where decreases of 9.4% and 7.0%, respectively, were noted.

AISI 303-Se, Type 1

Test Conditions

Ai, Bi, Ci, D_{Ai}, E_{Ai}

Ultimate Tensile Strength

Insignificant changes (< 5%).

Tensile Yield Strength

Increases of 34.7%, 22.2%, and 23.8%, respectively, for test conditions Ai, Ci, and Bi. Increase of 6.9% and insignificant increase of 2.6% for test conditions D_{Ai} and E_{Ai}, respectively, indicating recovery.

Notched Tensile Strength

Increase of 19.5% for test condition Ai; increases of 9.2% and 8.1% for test conditions Ci and Bi, respectively. Insignificant increases for test conditions D_{Ai} and E_{Ai}, indicating recovery.

Notched-to-Unnotched Tensile Strength Ratio

Increase of 14.8% for test condition Ai; increase of 5.2% for test condition Ci. Insignificant increases of 4.6%, 4.5%, and 4.6% for test conditions Bi, D_{Ai}, and E_{Ai}, respectively, indicating considerable recovery.

Percent Elongation

Decrease of 20.4% for test condition Ai. Considerable recovery evident after room-temperature anneal; only insignificant changes noted for test conditions Ci, Bi, D_{Ai}, and E_{Ai}.

Aluminum 2219-T6, Type 3

Test Conditions

A1, B1, C1, D_{A1}, E_{A1}

Ultimate Tensile Strength

Insignificant changes (< 5%).

Tensile Yield Strength

Increase of 28.3% for test condition A1. Increase of 5.3% for test condition C1, indicating appreciable recovery. Insignificant changes for test conditions B1, D_{A1}, and E_{A1}.

Notched Tensile Strength

Increase of 11.7% for test condition A1. Appreciable recovery evident for test conditions B1, C1, D_{A1}, and E_{A1}, with only a slight decrease of 5.3% noted in test condition B1; all other changes were insignificant.

Notched-to-Unnotched Tensile Strength Ratio

Increase of 8.7% for test condition A1. Insignificant changes for all other test conditions.

Percent Elongation

Insignificant changes.

Aluminum 2219-T6-Transverse, Type 2

Test Conditions

A1, B1, C1

Ultimate Tensile Strength

Increase of 11.6% for test condition A1. Insignificant changes (< 5%) for test conditions B1 and C1, indicating recovery.

Tensile Yield Strength

Increase of 47.4% for test condition A1. Recovery evident for test conditions C1 and B1, where changes of less than 2% were noted.

Notched Tensile Strength

Insignificant changes.

Notched-to-Unnotched Tensile Strength Ratio

Decrease of 7.4% for test condition A1; insignificant changes for test conditions C1 and B1.

Percent Elongation

Decrease of 70.1% noted for test condition A1. Recovery evident for test conditions C1 and B1, where only insignificant decreases were noted.

Aluminum 2219-T6-Radial, Type 2

Test Conditions

A1, B1, C1

Ultimate Tensile Strength

Increase of 9.4% for test condition A1. Insignificant changes (< 5%) for test conditions C1 and B1.

Tensile Yield Strength

Increase of 51.5% for test condition A1. Recovery is evident for test conditions C1 and B1, where only slight increases of 3.5% and 1.1%, respectively, were noted.

Notched Tensile Strength

Increase of 13.3% for test condition A1. Recovery is evident for test conditions C1 and B1, where insignificant changes of less than 1% were noted.

Notched-to-Unnotched Tensile Strength Ratio

Insignificant changes.

Percent Elongation

Decrease of 56.7% for test condition A1. Recovery is evident for test condition C1 and B1, where only insignificant changes were noted.

Beryllium, Type 4

Test Conditions

A1, B1, C1

Ultimate Tensile Strength

Decrease of 70.2% for test condition A1. Appreciable recovery for test conditions C1 and B1, where insignificant changes of less than 4% were noted.

Tensile Yield Strength

Decrease of 70.2% for test condition A1. Appreciable recovery for test conditions C1 and B1, which indicated insignificant increases of less than 4%.

Notched Tensile Strength

Large changes were noted in these data for test conditions A1 and C1; however, the statistical analysis of Section 3.1.2 established the significance probability of these changes to be less than 0.90.

Notched-to-Unnotched Tensile Strength Ratio

Large changes evident for test conditions A1 and C1; however, these would probably be statistically insignificant because of the significance probability assigned to changes in notched tensile strength.

Percent Elongation

The percent elongation of these specimens at LN_2 temperature was nil for both control and irradiated specimens. An increase of 59% was noted for test condition B1; however, its significance probability was less than 0.90.

Titanium A-110-AT-Eli, Type 2

Test Conditions

A1, B1, C1

Ultimate Tensile Strength

Increases of 7.8% and 6.5% for test conditions A1 and B1, respectively. Insignificant increase of 4.6% for test condition C1.

Tensile Yield Strength

Increases of 9.8%, 6.3%, and 7.89% for test conditions A1, C1, and B1, respectively.

Notched Tensile Strength

Decreases of 7.3% and 6.7% for test conditions A1 and C1, respectively. Insignificant increase ($<$5%) for test condition B1.

Notched-to-Unnotched Tensile Strength Ratio

Decrease of 14.2% and 11.2% for test conditions A1 and C1, respectively. Insignificant decrease (< 5%) for test condition B1.

Percent Elongation

Decrease of 75% evident for test condition A1. Some recovery evident for test conditions C1 and B1, where decreases of 34.4% and 22.4%, respectively, were noted.

3.1.5 High-Temperature Effects on Inconel Steel Specimens

Inconel X-750 and Inconel 718 tensile specimens, both control and irradiated, exhibited marked serrations in their load-deflection curves (Figs. 3-8 and 3-9) when pulled in tension to break at temperatures above 540°F. All equipment was completely checked out and it was decided that these serrations were a specimen characteristic and not due to the test equipment. As a final check several specimens were returned to WANL for testing in their laboratory. These tests showed conclusively that the serrations were definitely a specimen characteristic for both Inconel X-750 and Inconel 718 specimens at temperatures above 540°F.

3.1.6 Conclusions

As a result of the radiation environment of this test, all materials tested at LN_2 temperatures without warmup experienced statistically significant changes in their tensile properties. Generally speaking, strength increased and ductility decreased for all materials except beryllium, which exhibited a highly significant decrease in strength. Subsequent recovery was apparent for all materials after annealing treatments. In general, the recovery was complete; however,

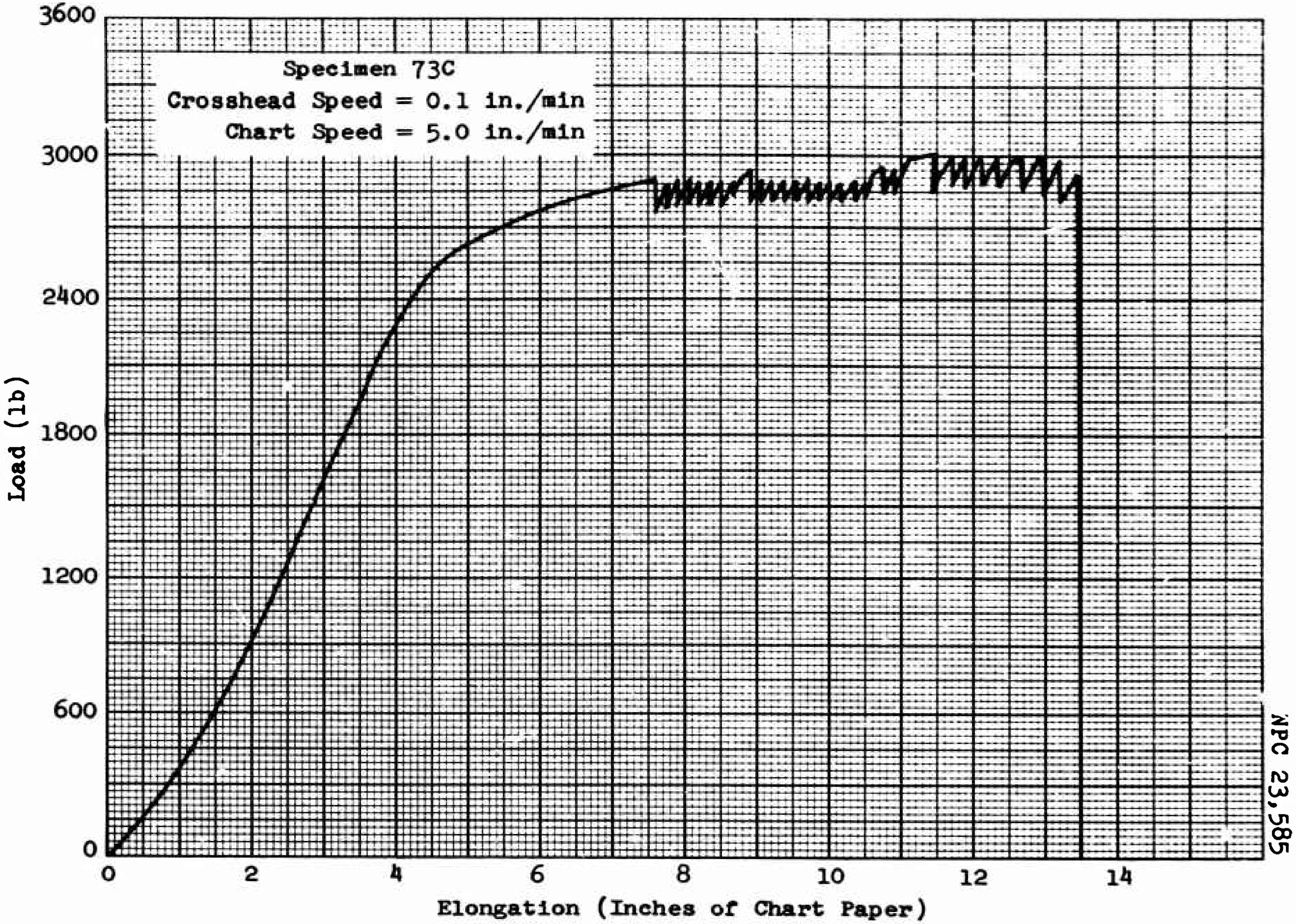


Figure 3-8 Illustration of Serrations in Inconel 718 Control Specimens at Elevated Temperatures

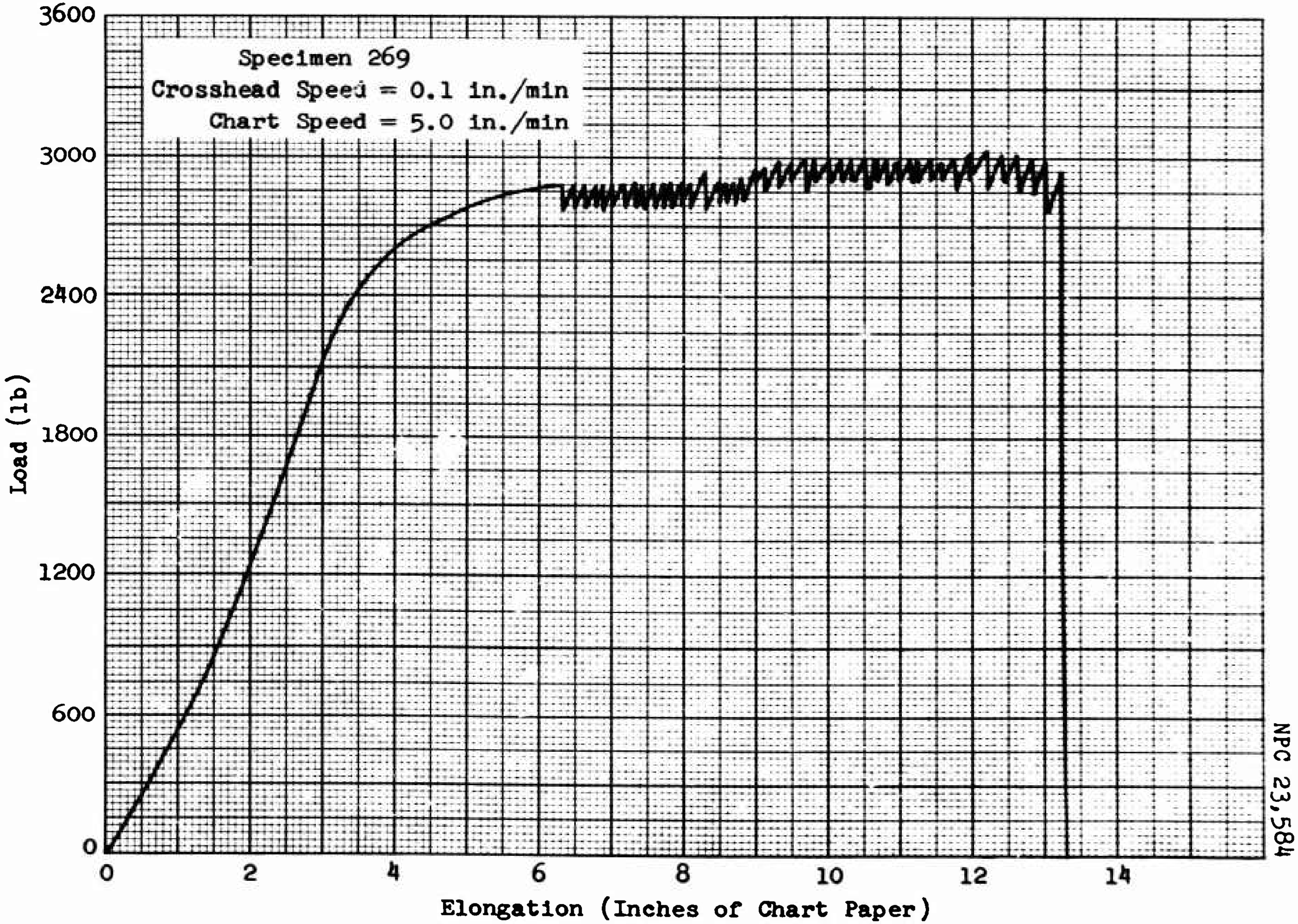


Figure 3-9 Illustration of Serrations in Inconel 718 Irradiated Specimens at Elevated Temperatures

statistically significant changes were still evident for some materials. From the results of this test alone, it would appear that these materials could be ranked, in order of their decreasing resistance to the effects of radiation, as follows; AISI 301-CW, Inconel 718, AISI 303-Se, Inconel X-750, Al 2219-T6, titanium, and beryllium, with AISI 301-CW being the most resistant and beryllium the least resistant.

3.2 Resistivity Tests

3.2.1 Data Presentation

The resistivity specimens received an average integrated neutron flux of 4.5×10^{17} n/cm^2 (E > 1 Mev). Detailed dosimetry data are presented in Appendix B.

Data taken on the resistivity specimens during irradiation are presented in Table 3-30. Only resistivity specimen No. 1 was monitored during the irradiation. The bridge output voltage became erratic approximately 6 hr after termination of the first irradiation period and remained unstable until the experiment was removed from the area. The data recorded after the readings became erratic are not included in the table. A plot of representative data taken from Table 3-30 is presented in Figure 3-10. The postirradiation test data and results of measurements taken on the other three resistivity specimens are presented in Tables 3-31 and 3-32.

3.2.2 Discussion and Analysis of Results

The bridge output voltage increased by approximately 3150 µv as the reactor was brought to a power level of 3 Mw and traversed

Table 3-30

History of Resistivity Specimen During Irradiation

Date (March 1965)	12	12	12	12	12	12	12	12
Time	1400	1430	1500	1600	1720	1805	1838	1847
Power Level (Mw)	0	0	0	0	0	0	0	0
Irradiation Time	0	0	0	0	0	0	0	0
Resistivity Input Current	0.100009	0.100061	0.099999	0.099999	0.099997	0.099989	0.099982	0.099980
Voltage Across 2.2525 Ω (mv)	225.271	225.388	225.248	225.249	225.245	225.226	225.210	225.205
Bridge Voltage (E_o) (μv)	-1.6	+3.1	5.5	107.0	106.0	70.5	57.0	56.0
Cable Current (amp)	0.100899	0.100882	0.100826	0.100745	0.100779	0.100781	0.100815	0.100806
Voltage Across 2.2525 Ω (mv)	227.275	227.238	227.112	226.930	227.006	227.010	227.086	227.067
Cable Voltage (v)	0.136514	0.136694	0.136710	0.136570	0.136560	0.136100	0.134620	0.133620
Cable Resistance (ohms)	1.352976	1.354988	1.355900	1.355600	1.355044	1.350452	1.335317	1.325516

Date (March 1965)	12	12	12	12	12	12	12	12
Time	1900	1916	1940	2010	2100	2200	2300	2347
Power Level (Mw)	0	3	3	3	3	3	3	Retracted
Irradiation Time	0	.05	1.25	2.75	5.25	8.25	11.25	13.4
Resistivity Input Current	0.099992	0.099994	0.099889	0.100003	0.100015	0.099997	0.099994	0.099999
Voltage Across 2.2525 Ω (mv)	225.232	225.238	225.00	225.258	225.285	225.244	225.237	225.248
Bridge Voltage (E_o) (μv)	40.05	1310.0	3150.0	3212.0	3242.0	3249.0	3315.0	327.0
Cable Current (amp)	0.100792	0.100792	0.100776	0.100810	0.100838	0.100802	0.100695	0.100807
Voltage Across 2.2525 Ω (mv)	227.034	227.034	227.00	227.075	227.139	227.058	226.817	227.070
Cable Voltage (v)	0.133960	0.134020	0.133940	0.134110	0.134500	0.134660	0.134620	0.134700
Cable Resistance (ohms)	1.329073	1.329669	1.329086	1.330324	1.333822	1.335886	1.336908	1.336216

Date (March 1965)	12	13	13	13	13	13	13	13
Time	2354	0007	0019	0100	0200	0300	0440	0600
Power Level (Mw)	Retracted	3	3	3	3	0	0	3
Irradiation Time	13.4	13.65	14.25	16.3	19.3	21.1	21.1	21.55
Resistivity Input Current	0.099999	0.099996	0.099987	0.100005	0.099996	0.100003	0.099978	0.100007
Voltage Across 2.2525 Ω (mv)	225.249	225.242	225.221	225.262	225.242	225.259	225.202	225.267
Bridge Voltage (E_o) (μv)	247.0	3240.0	3231.0	3335.9	3274.5	250.5	198.2	3162.5
Cable Current (amp)	0.100763	0.100596	0.100825	0.100823	0.100788	0.100867	0.100828	0.10[illegible]766
Voltage Across 2.2525 Ω (mv)	226.969	226.593	227.109	227.105	227.025	227.203	227.117	226.976
Cable Voltage (v)	0.134660	0.134400	0.134150	0.134410	0.134225	0.133600	0.133465	0.133615
Cable Resistance (ohms)	1.336403	1.336037	1.330523	1.333128	1.331755	1.324516	1.323689	1.325992

Table 3-30 (Cont'd)

Date (March 1965)	13	13	13	13	13	[illegible]	13	13
Time	0700	0800	0900	1015	1100	[illegible]	1400	1500
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	24.55	27.55	30.55	34.3	36.55	39.55	45.55	48.55
Resistivity Input Current	0.099988	0.100001	0.100000	0.100007	0.100000	0.100006	0.100000	0.100001
Voltage Across 2.2525 Ω (mv)	225.225	225.253	225.251	225.266	225.252	225.265	225.250	225.253
Bridge Voltage (E_o) (μv)	3236.5	3272.6	3273.0	3269.5	3315.0	3339.0	3355.6	3398.0
Cable Current (amp)	0.100859	0.100860	0.100755	0.100761	0.100820	0.100868	0.100811	0.100850
Voltage Across 2.2525 Ω (mv)	227.186	227.188	226.951	226.966	227.099	227.206	227.078	227.165
Cable Voltage (v)	0.133315	0.133770	0.133950	0.133995	0.134094	0.134295	0.134590	0.134701
Cable Resistance (ohms)	1.321795	1.326293	1.329462	1.329829	1.330033	1.331393	1.335072	1.335656

Date (March 1965)	13	13	13	13	13	13	14	14
Time	1608	1700	1800	1900	2100	2300	0100	0300
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	48.95	54.55	57.55	60.55	66.55	72.55	78.55	84.55
Resistivity Input Current	0.100001	0.100004	0.100008	0.100008	0.099995	0.099995	0.099993	0.100018
Voltage Across 2.2525 Ω (mv)	225.253	225.260	225.270	225.270	225.240	225.240	225.235	225.292
Bridge Voltage (E_o) (μv)	3403.7	3414.3	3427.5	3442.3	3435.2	3461.3	3525.0	3542.3
Cable Current (amp)	0.100956	0.100851	0.101096	0.100870	0.100901	0.100874	0.100797	0.100862
Voltage Across 2.2525 Ω (mv)	227.[illegible]05	227.169	227.720	227.210	227.280	227.220	227.047	227.193
Cable Voltage (v)	0.134765	0.134898	0.134964	0.134860	0.134742	0.134680	0.134990	0.135102
Cable Resistance (ohms)	1.334888	1.337597	1.335008	1.336968	1.335388	1.335130	1.339226	1.339473

Date (March 1965)	14	14	14	14	14	14	14	14
Time	0500	0700	0900	1100	1300	1500	1700	1900
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	90.55	96.55	102.55	108.55	114.55	120.55	126.55	132.55
Resistivity Input Current	0.100010	0.099990	0.099994	0.099999	0.100002	0.099990	0.099986	0.099995
Voltage Across 2.2525 Ω (mv)	225.27[illegible]	225.228	225.238	225.249	225.255	225.229	225.220	225.240
Bridge Voltage (E_o) (μv)	3531.1	3523.0	3571.5	3641.0	3780.5	3902.5	3938.2	3861.3
Cable Current (amp)	0.101053	0.100764	0.100790	0.100841	0.100820	0.100805	0.100807	0.100812
Voltage Across 2.2525 Ω (mv)	227.622	226.972	227.031	227.146	227.098	227.065	227.070	227.081
Cable Voltage (v)	0.134681	0.134662	0.135081	0.135195	0.137256	0.137640	0.137802	0.136570
Cable Resistance (ohms)	1.332775	1.336409	1.340222	1.340674	1.361396	1.365408	1.366988	1.354699

Table 3-30 (Cont'd)

Date (March 1965)	14	14	15	15	15	15	15	15
Time	2100	2300	0100	0300	0500	0700	0900	1100
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	138.55	144.55	150.55	156.55	162.55	168.55	174.55	180.55
Resistivity Input Current	0.099982	0.100004	0.100001	0.100010	0.100010	0.099987	0.099998	0.100009
Voltage Across 2.2525 Ω (mv)	225.210	225.260	225.254	225.273	225.273	225.222	225.247	225.272
Bridge Voltage (E_o) (μv)	3799.4	3773.2	3673.0	3628.6	3654.5	3621.0	3667.5	3767.1
Cable Current (amp)	0.100867	0.100868	0.100931	0.100899	0.100823	0.100835	0.100841	0.100904
Voltage Across 2.2525 Ω (mv)	227.205	227.206	227.348	227.275	227.105	227.132	227.146	227.287
Cable Voltage (v)	0.136241	0.135757	0.135350	0.135140	0.135060	0.134980	0.135254	0.136651
Cable Resistance (ohms)	1.350699	1.345887	1.341015	1.339359	1.339575	1.338622	1.341260	1.354267

Date (March 1965)	15	15	15	15	15	15	16	16
Time	1300	1500	1700	1900	2100	2300	0100	0300
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	186.55	192.55	198.55	204.55	210.55	216.55	222.55	228.55
Resistivity Input Current	0.099996	0.099997	0.100006	0.100017	0.099991	0.099997	0.100002	0.099990
Voltage Across 2.2525 Ω (mv)	225.243	225.245	225.265	225.290	225.230	225.245	225.255	225.228
Bridge Voltage (E_o) (μv)	3716.0	3678.6	3664.2	3606.0	3615.6	3632.0	3751.6	3797.2
Cable Current (amp)	0.100964	0.100836	0.100925	0.100419	0.101185	0.100792	0.100868	0.100720
Voltage Across 2.2525 Ω (mv)	227.422	227.134	227.334	226.195	227.921	227.036	227.206	226.872
Cable Voltage (v)	0.136455	0.136321	0.136936	0.136700	0.137381	0.137063	0.137259	0.136138
Cable Resistance (ohms)	1.351521	1.351908	1.356809	1.361296	1.357721	1.359859	1.360775	1.351648

Date (March 1965)	16	16	16	16	16	16	16	16
Time	0500	0700	0900	1200	1400	1600	1800	2000
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	234.55	240.55	246.55	255.55	261.55	267.55	273.55	279.55
Resistivity Input Current	0.099991	0.099989	0.099999	0.099982	0.100000	0.099986	0.099998	0.100013
Voltage Across 2.2525 Ω (mv)	225.231	225.226	225.248	225.211	225.251	225.220	225.246	225.280
Bridge Voltage (E_o) (μv)	3702.1	3844.4	3833.6	3802.4	3778.0	4043.2	4103.8	4131.6
Cable Current (amp)	0.100831	0.100784	0.101469	0.100783	0.101176	0.100863	0.101164	0.101045
Voltage Across 2.2525 Ω (mv)	227.123	227.016	228.561	227.015	227.899	227.195	227.873	227.606
Cable Voltage (v)	0.136256	0.136338	0.136320	0.135165	0.135650	0.135941	0.136252	0.137061
Cable Resistance (ohms)	1.351330	1.352774	1.343464	1.341148	1.340732	1.347778	1.346869	1.356435

Table 3-30 (Cont'd)

Date (March 1965)	16	16	17	17	17	17	17	17
Time	2200	2356	0050	0200	0400	0500	0700	0900
Power Level (Mw)	3	0	0	0	3	3	3	3
Irradiation Time	285.55	291.2	291.2	291.2	293.45	296.45	302.45	308.45
Resistivity Input Current	0.100000	0.099964	0.099989	0.100011	0.099979	0.100000	0.100001	0.099979
Voltage Across 2.2525 Ω (mv)	225.250	225.170	225.226	225.277	225.204	225.252	225.253	225.203
Bridge Voltage (E_o) (μv)	3942.2	1770.0	574.2	561.5	4558.2	3750.0	3909.1	3926.0
Cable Current (amp)	0.098095	0.100683	0.100722	0.100783	0.100839	0.100839	0.100843	0.100778
Voltage Across 2.2525 Ω (mv)	229.061	226.790	226.877	227.015	227.142	227.142	227.150	227.004
Cable Voltage (v)	0.137388	0.137212	0.136377	0.136185	0.134363	0.135335	0.135640	0.136000
Cable Resistance (ohms)	1.400560	1.362811	1.353994	1.351269	1.332450	1.342089	1.345061	1.349500

Date (March 1965)	17	17	17	17	17	17	17	18
Time	1100	1300	1500	1700	1900	2100	2300	0100
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	314.45	320.45	326.45	332.45	338.45	344.45	350.45	356.45
Resistivity Input Current	0.100002	0.099994	0.099993	0.099995	0.100017	0.100000	0.099995	0.100005
Voltage Across 2.2525 Ω (mv)	225.256	225.238	225.236	225.240	225.290	225.250	225.240	225.262
Bridge Voltage (E_o) (μv)	3951.8	3926.1	3926.2	4030.5	4085.3	4163.6	4137.2	4105.0
Cable Current (amp)	0.100815	0.100829	0.100815	0.100508	0.100819	0.100727	0.100795	0.100769
Voltage Across 2.2525 Ω (mv)	227.086	227.118	227.088	226.396	227.097	226.889	227.041	[illegible]
Cable Voltage (v)	0.136388	0.135825	0.136196	0.135267	0.135492	0.135247	0.135130	0.134787
Cable Resistance (ohms)	1.352854	1.347082	1.350949	1.345833	1.343913	1.342708	1.340641	1.337583

Date (March 1965)	18	18	18	18	18	18	18	18
Time	0300	0700	0900	1100	1300	1500	1700	1900
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	362.45	373.8	379.8	385.8	391.8	397.8	403.8	409.8
Resistivity Input Current	0.100007	0.100005	0.100000	0.100000	0.100000	[illegible]	0.099991	0.100004
Voltage Across 2.2525 Ω (mv)	225.266	225.263	225.250	225.250	225.250	225.240	225.232	225.258
Bridge Voltage (E_o) (μv)	4107.6	4222.2	4256.8	4365.6	4313.3	4479.7	4509.5	4504.5
Cable Current (amp)	0.100729	0.100825	0.100852	0.100573	0.100799	0.100764	0.100785	0.100915
Voltage Across 2.2525 Ω (mv)	226.893	227.109	227.171	226.541	227.050	226.972	227.019	227.313
Cable Voltage (v)	0.134420	0.133912	0.132568	0.134200	0.134004	0.134948	0.135001	0.134894
Cable Resistance (ohms)	1.334471	1.328162	1.314480	1.334354	1.329417	1.339248	1.339494	1.336709

Table 3-30 (Cont'd)

Date (March 1965)	18	18	19	19	19	19	19	19
Time	2100	2300	0100	0200	0300	0400	0600	0800
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	415.8	421.8	427.8	433.8	436.8	439.8	445.8	451.8
Resistivity Input Current	0.100004	0.099997	0.100001	0.100003	0.099996	0.099998	0.100010	0.100000
Voltage Across 2.2525 Ω (mv)	225.261	225.244	225.254	225.259	225.241	225.247	225.273	225.250
Bridge Voltage (E_o) (μv)	4486.5	4522.2	1160.0	1488.2	4683.6	4734.3	4689.0	4814.5
Cable Current (amp)	0.100765	0.100751	0.100805	0.100782	0.100787	0.100735	0.100768	0.100668
Voltage Across 2.2525 Ω (mv)	226.975	226.942	227.065	227.012	227.024	226.907	226.981	226.756
Cable Voltage (v)	0.134350	0.134687	0.132980	0.134260	0.134330	0.134225	0.134392	0.134302
Cable Resistance (ohms)	1.333300	1.336830	1.319180	1.332182	1.332810	1.332456	1.333677	1.334108

Date (March 1965)	19	19	19	19	19	19	19	19
Time	1000	1200	1400	1600	1800	2000	2200	2400
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	457.8	463.8	469.8	475.8	481.8	487.8	493.8	499.8
Resistivity Input Current	0.099998	0.100004	0.100003	0.100007	0.099993	0.100000	0.099988	0.100003
Voltage Across 2.2525 Ω (mv)	225.246	225.261	225.258	225.268	225.235	225.250	225.225	225.258
Bridge Voltage (E_o) (μv)	4753.2	4775.5	4768.5	4803.2	4970.5	4871.6	4943.6	4972.2
Cable Current (amp)	0.101021	0.100868	0.101405	0.100775	0.101365	0.100772	0.100895	0.100740
Voltage Across 2.2525 Ω (mv)	227.551	227.207	228.416	226.997	228.326	226.991	227.266	226.918
Cable Voltage (v)	0.133940	0.133810	0.134140	0.134524	0.134395	0.133230	0.133566	0.133461
Cable Resistance (ohms)	1.325862	1.326585	1.322814	1.334894	1.325852	1.322093	1.323811	1.324806

Date (March 1965)	20	20	20	20	20	20	20	20
Time	0204	0410	0600	0800	1000	1200	1400	1600
Power Level (Mw)	3	3	3	3	3	3	3	3
Irradiation Time	506.0	512.3	517.8	523.8	529.3	535.3	541.3	547.3
Resistivity Input Current								
Voltage Across 2.2525 Ω (mv)	225.283	225.227	225.266	225.240	225.26	225.27	225.26	225.222
Bridge Voltage (E_o) (μv)	4978.9	5039.1	5006.7	5048.1	5030.0	4963.2	5036.3	5146.9
Cable Current (amp)								
Voltage Across 2.2525 Ω (mv)	227.039	226.973	226.954	229.542	227.324	226.562	226.92	227.243
Cable Voltage (v)	0.133484	0.133701	0.13368	0.133575	0.133015	0.132064	0.133207	0.13380
Cable Resistance (ohms)								

Table 3-30 (Cont'd)

Date (March 1965)	20	20	20	20	21	21	21	21
Time	1800	2000	2210	2400	0115	0200	0400	0600
Power Level (Mw)	3	3	3	3	0	0	0	0
Irradiation Time	553.3	559.3	565.8	571.3	573.25	--	--	--
Resistivity Input Current							0.099984	0.99956
Voltage Across 2.2525 Ω (mv)	225.254	225.257	225.253	225.254	225.2[illegible]	225.230	225.215	225.220
Bridge Voltage (E_o) (μv)	5177.4	5175.6	5160.3	5105.2	[illegible]	1808.1	1835.[illegible]	1863.0
Cable Current (amp)							0.100796	0.1008[illegible]
Voltage Across 2.2525 Ω (mv)	227.128	227.031	227.004	227.046	227.089	227.055	227.[illegible]	227.[illegible]
Cable Voltage (v)	0.133895	0.13406	0.133715	0.133805	0.13315	0.132691	0.132718	0.132[illegible]
Cable Resistance (ohms)							1.316699	1.315259

Date (March 1965)	21	21	21	21	21	21	22	22
Time	0815	1050	1110	1400	1620	2330	0400	0600
Power Level (Mw)	0	0	0	0	0	0	0	0
Irradiation Time	--	--	--	--	--	--	--	--
Resistivity Input Current	0.099995	0.099995	0.100195	0.099973	0.099987	0.099979	[illegible]	0.099989
Voltage Across 2.2525 Ω (mv)	225.240	225.240	225.690	225.190	225.222	225.204	225.250	225.227
Bridge Voltage (E_o) (μv)	726.6	*2985.0	*2667.5	*	*1393.3	*8390.0	*1135.0	*1225.0
Cable Current (amp)	0.100843	0.100947	0.100821	0.100890	0.100790	0.10068[illegible]	0.100790	0.100764
Voltage Across 2.2525 Ω (mv)	227.150	227.385	227.100	227.255	227.031	226.8[illegible]	227.031	226.972
Cable Voltage (v)	0.132578	0.131320	0.130250	0.130915	0.131430	0.131960	0.131805	0.131951
Cable Resistance (ohms)	1.314697	1.300880	1.291893	1.297601	1.303998	1.310570	1.307719	1.309505

Date (March 1965)	22	24	27	27
Time	1645	1730	1045	1200
Power Level (Mw)	0	0	0	0
Irradiation Time	--	--	--	--
Resistivity Input Current	0.100153		0.099932	0.099931
Voltage Across 2.2525 Ω (mv)	225.596		225.098	225.095
Bridge Voltage (E_o) (μv)	*3510.0	*	**-0.3735	**-0.2[illegible]
Cable Current (amp)	0.100710		0.100699	0.100517
Voltage Across 2.2525 Ω (mv)	226.851		226.826	226.415
Cable Voltage (v)	0.131300		0.131510	0.134750
Cable Resistance (ohms)	1.303743		1.305971	1.340569

*Unstable and intermittent. **Reading drifts. Readout in volts.

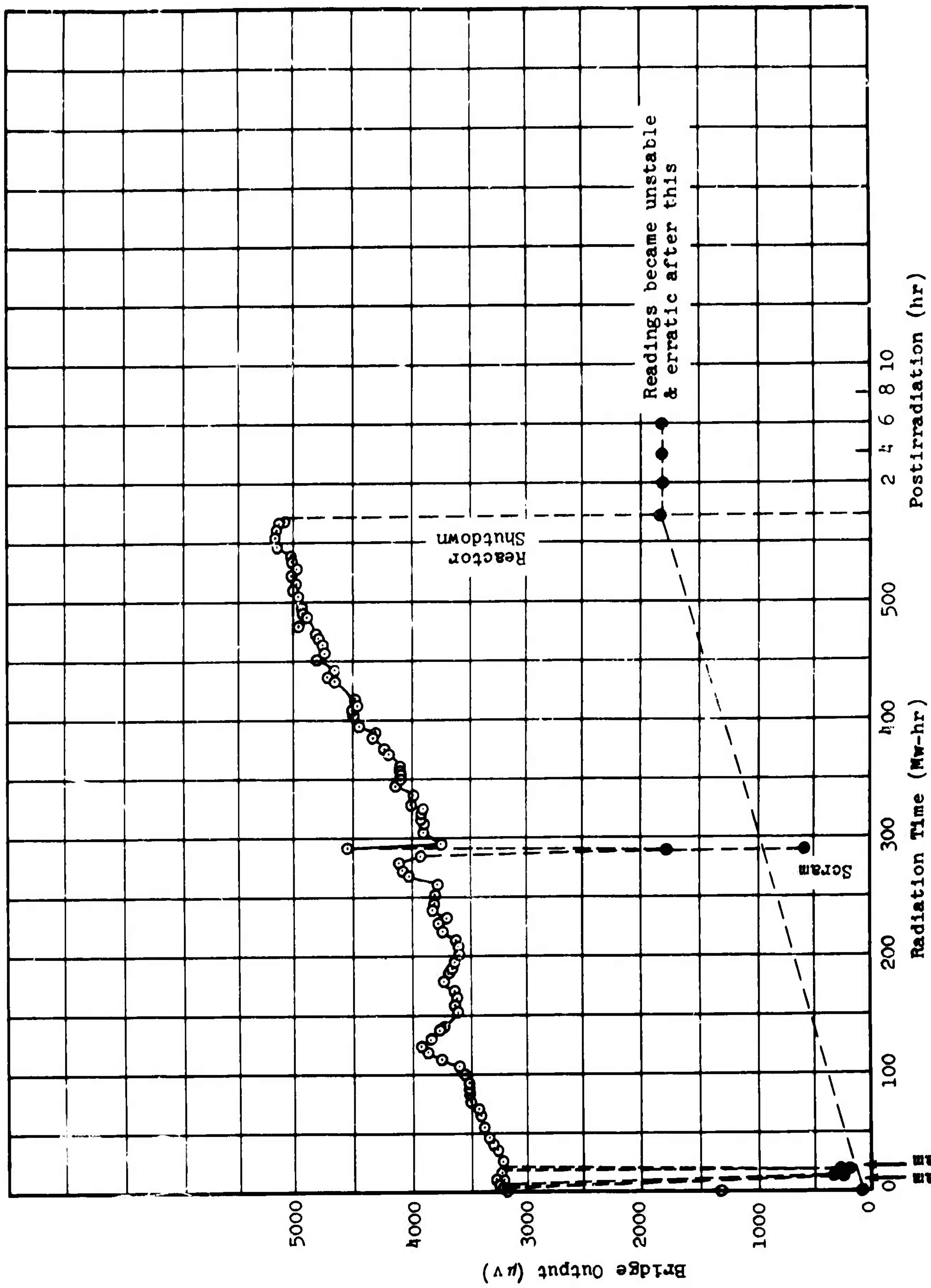


Figure 3-10 Bridge Voltage Output During Irradiation

Table 3-31

Postirradiation Resistivity Data

Annealing Condition		Sample No. 2 Inconel 718		Sample No. 3 Inconel X-750		Sample No. 4 Inconel X-750	
Time (min)	Temperature (^{o}F)	Bridge Voltage (10^{-6} v)	Resistance Change ($10^{-3}\,\Omega$)	Bridge Voltage (10^{-6} v)	Resistance Change ($10^{-3}\,\Omega$)	Bridge Voltage (10^{-6} v)	Resistance Change ($10^{-3}\,\Omega$)
--	-320	--	--	0	0	0	0
10	-270	--	--	624	6.79	751	8.17
10	-220	--	--	629	6.84	803	8.74
10	-180	--	--	702	7.64	859	9.35
10	-130	--	--	790	8.60	854	9.29
10	- 80	--	--	932	10.1	847	9.22
10	- 30	--	--	1176	12.8	846	9.20
10	+ 70	--	--	--	--	854	9.29
30	+ 78	--	--	--	--	861	9.37
--	-320	0	0				
5	-320 to -215	43	0.47				
5	-320 to -215	36	0.39				
10	-320 to -125	99	1.08				
30	-320 to + 37	765	8.32				
60	-320 to + 67	935	10.2				
60	-320 to + 67	932	10.1				

Table 3-32

Percent Recovery of Resistivity Samples

Annealing Condition		Percent Recovery		
Time (min)	Temperature (°F)	Sample No. 2 Inconel 718	Sample No. 3 Inconel X-750	Sample No. 4 Inconel X-750
-	-320	0	0	0
10	-270	-	53	87
10	-220	-	53	93
10	-180	-	60	99
10	-130	-	67	99
10	- 80	-	79	98
10	- 30	-	100	98
10	+ 70	-	-	99
30	+ 78	-	-	100
5	-320 to -215	4	-	-
5	-320 to -215	4	-	-
10	-320 to -125	11	-	-
30	-320 to + 37	82	-	-
60	-320 to 67	100	-	-
60	-320 to 67	100	-	-

into the closet. This transient effect was also apparent during reactor scrams, when the output voltage decreased by approximately 3000 μv as the reactor power fell off. The output voltage increased by 2000 μv during the irradiation to a value of approximately 5150 μv. This 2000-μv increase represents an increase in resistance of approximately 0.020 ohm. At the termination of the first irradiation period, the bridge voltage decreased to approximately 1850 μv as the power level decreased to zero. The voltage remained at this value for approximately 6 hr, at which time the readings became erratic. The 1850-μv output is of the same magnitude as the 2000-μv increase during irradiation, indicating an apparent permanent change in the resistance in the order of 0.018 to 0.020 ohm. Details of the resistance bridge circuit and a sample calculation are presented in Appendix C.

Postirradiation data taken several weeks after the irradiation still indicated erratic readings for specimen No. 1. The other specimens experienced apparent decreases in resistance of approximately 0.010 ohm after the annealing treatments discussed in Section 2.1.2. These data indicate that the resistivity specimens increased in resistance by some amount greater than 0.010 ohm during the irradiation.

3.3 Steel-Spring Specimen Tests

3.3.1 Data Presentation

The spring specimens received an average integrated neutron flux of 4.5×10^{17} n/cm^2 (E > 1 Mev). Detailed dosimetry data on all specimens may be found in Appendix B.

The results of the tests on the spring specimens are tabulated in Table 3-33.

3.3.2 Discussion and Analysis of Results

Any changes in the specimens as a result of radiation are not discernable from the data. There appears to be a slight increase in the amount of permanent set (after load removal) in the irradiated specimens as compared to the control specimens. The control specimens and the irradiated specimens were kept under load for the same period of time. The control specimens were stored in LN_2 during the storage of irradiated specimens for radioactivity decay. Upon removal of the loads, the measurements indicated that the free length of the irradiated specimens had decreased by an average of 3.89%, while the free length of the control specimens had decreased by 1.59%. This apparent difference of 2.3% is so small as to possibly be a result of measuring technique; however, it could be an effect of radiation. In any case the change is of such small magnitude as to probably be insignificant.

3.4 O-Ring Seal Tests

3.4.1 Data Presentation

The O-Ring specimens received an average integrated neutron flux of 4.0×10^{16} n/cm^2 (E> 2.9 Mev) and an average gamma dose of 2.6×10^{10} ergs/gm(C).

The temperature, during the irradiation period, of the fixture mounted on the outside of the LH_2 dewar is tabulated in Table 3-34.

Table 3-33

Results of Spring Test

Spring Identification		Free Length									Spring Rate		
		Before Irrad. (in.)	After Irradiation		After Deformation*		After Anneal**		After Deformation & Anneal		Before Irrad. (lb/in.)	After Irrad. (lb/in.)	% Change
Control	Irradiated		Length (in.)	% Change	Length (in.)	% Change	Length (in.)	% Change	Length (in.)	% Change			
X		2.6990	2.6545	-1.65	2.6525	-1.75					127.0	128.5	+1.18
B_1		2.6824	2.6720	-0.39	2.6725	-0.37					125.7	128.0	+1.83
B_2		2.6960	2.6400	-2.08			2.6710	-0.93	2.6610	-1.30	125.9	127.2	+1.03
B_3		2.6870	2.6270	-2.23			2.6575	-1.09	2.6480	-1.45	125.9	128.9	+2.38
	R_1	2.6994	2.6170	-3.05	2.6185	-3.00					125.7	128.0	+1.83
	R_4	2.6992	2.5835	-4.29	2.5830	-4.30					125.7	128.4	+2.15
	R_5	2.7037	2.5895	-4.22			2.6410	-2.32	2.6365	-2.48	126.6	131.4	+3.79
	R_6	2.6787	2.5720	-3.98			2.6195	-2.21	2.6115	-2.51	127.5	128.0	+0.39

*Deformation to 130 lb at 1.0 in./min.
**Anneal at 540°F for 1 hr.

Table 3-34

Representative Temperatures for the Orifice Cement
and the O-Ring Fixture

Date	Time	Power Level (Mw)	Exposure (Mw-hr)	Temperature (°F)	
				Orifice	O-Ring
3-12-65	1805	0	0	- 50	+ 48
	1904	3	1.25	+ 39	+ 64
	2300	3	11.25	+151	+ 88
	2347	0	13.4	+124	+ 68
	2354	0	13.4	+110	+ 60
3-13-65	0100	3	16.3	+145	+ 96
	0300	0	21.1	+ 97	+ 58
	0440	0	21.1	+ 28	+ 40
	0600	3	21.55	+ 51	+ 52
	0700	3	24.55	+128	+ 82
	1100	3	30.55	+150	+ 81
	1700	3	54.55	+162	+ 88
	2300	3	72.55	+161	+ 88
3-14-65	0700	3	96.55	+162	+ 97
	1100	3	108.55	+165	+ 92
	1700	3	126.55	+167	+100
	2300	3	144.55	+164	+ 98
3-15-65	0700	3	168.55	+164	+ 99
	1100	3	180.55	+163	+ 95
	1700	3	198.55	+168	+ 98
	2300	3	216.55	+168	+ 98
3-16-65	0700	3	240.55	+171	+ 99
	1100	3	252.55	+176	+ 99
	1800	3	273.55	+174	+ 98
	2356	0	291.2	+155	+ 80
3-17-65	0200	0	291.2	+ 32	+ 37
	0700	3	302.45	+162	+ 97
	1100	3	314.45	+166	+ 97
	1700	3	332.45	+171	+ 91
	2300	3	350.45	+166	+ 84
3-18-65	0700	3	373.8	+148	+ 92
	1100	3	385.8	+158	+ 96
	1700	3	403.8	+160	+ 91
	2300	3	421.8	+158	+ 85
3-19-65	0600	3	442.8	+157	+ 82
	1200	3	460.8	+158	+ 82
	1800	3	478.8	+158	+ 82
	2400	3	496.8	+154	+ 80
3-20-65	0600	3	514.8	+157	+ 78
	1200	3	532.55	+156	+ 84
	1800	3	550.55	+156	+ 84
	2400	3	568.55	+152	+ 83
3-21-65	0200	0	571.1	+ 28	+ 18
	1400	0	571.1	+ 11	+ 31
3-22-65	0400	0	571.1	- 9	+ 28
	1645	0	571.1	- 10	+ 28
3-26-65	1200	0	571.1	-100	
3-27-65	0007	3	571.45	- 40	
	0100	3	574.1	+ 40	
	0400	3	583.1	+146	
	1200	3	607.1	+150	
	2200	3	637.1	+155	
3-28-65	0900	3	670.1	+155	
	2300	3	710.8	+142	
3-29-65	0300	3	722.8	+151	
	1800	3	767.8	+151	
3-30-65	1200	3	821.8	+163	
	2300	3	854.8	+166	
3-31-65	0900	3	884.8	+154	
	2300	3	926.8	+159	
4-1-65	0930	3	955.3	+150	
	2115	3	994.3	+164	
4-2-65	0900	3	1028.8	+163	
	2000	3	1060.43		
4-3-65	0500	3	1087.43	+168	
	1100	0	1104.18	+ 72	
	1700	0		+ 20	
4-4-65	0730	0		- 12	
	2100	0		- 21	

3.4.2 Discussion and Analysis of Results

The data presented in Table 3-34 were picked at random to illustrate the temperature excursions inside the container during the irradiation and shutdown periods. All testing of these specimens was performed at WANL by Westinghouse personnel and no results are available for this report.

3.5 Cemented-Orifice Tests

3.5.1 Data Presentation

The cemented orifice specimens inside the north dewar received an average integrated neutron flux of 2.5×10^{17} n/cm^2 (E > 1 Mev) and an average gamma dose of 1.0×10^{11} ergs/gm(C). The specimens mounted outside the north dewar received an average integrated neutron flux of 4.0×10^{17} n/cm^2 (E > 1 Mev) and an average gamma dose of 2.0×10^{11} ergs/gm(C).

The temperature, during irradiation, of the container mounted outside the LN_2 dewar is tabulated in Table 3-34.

3.5.2 Discussion and Analysis of Results

The data in Table 3-34 were picked at random to illustrate temperature excursions during the irradiation period. All testing of these specimens was conducted by Westinghouse personnel at their facilities and the results are not available for this report.

APPENDIX A

GTR RADIATION EFFECTS TESTING SYSTEM

APPENDIX A

GTR RADIATION EFFECTS TESTING SYSTEM

The GTR Radiation Effects Testing System is located in the Reactor Operations Area at the north end of the NARF complex. Figure A-1 is a plan view and Figure A-2 is a cutaway view of the system. A closeup of the irradiation test cell and the reactor tank is pictured in Figure A-3. During operation, the reactor is moved into the closet-like structure built into the north wall of the GTR tank. Items to be irradiated can be located on the north, east, or west sides of the closet, as indicated in the figures.

The reactor closet is constructed of 1-in. aluminum plate and is partially covered by 1/4-in.-thick boral to attenuate thermal neutrons. The boral extends 36 in. east and west from the closet along the tank wall and 36 in. up and down from the horizontal centerline of the reactor core. The centerline is 57 in. above the test-cell floor.

The Ground Test Reactor (GTR) is a heterogeneous, highly enriched, thermal reactor that utilizes water as neutron moderator and reflector, as radiation shielding, and as coolant. Maximum power generation is 3 Mw. The GTR, in an aluminum enclosure to facilitate cooling-water flow, is suspended by an open framework that is carried on a horizontal positioning mechanism at the top of the reactor tank. This mechanism permits the reactor to be positioned at distances ranging from

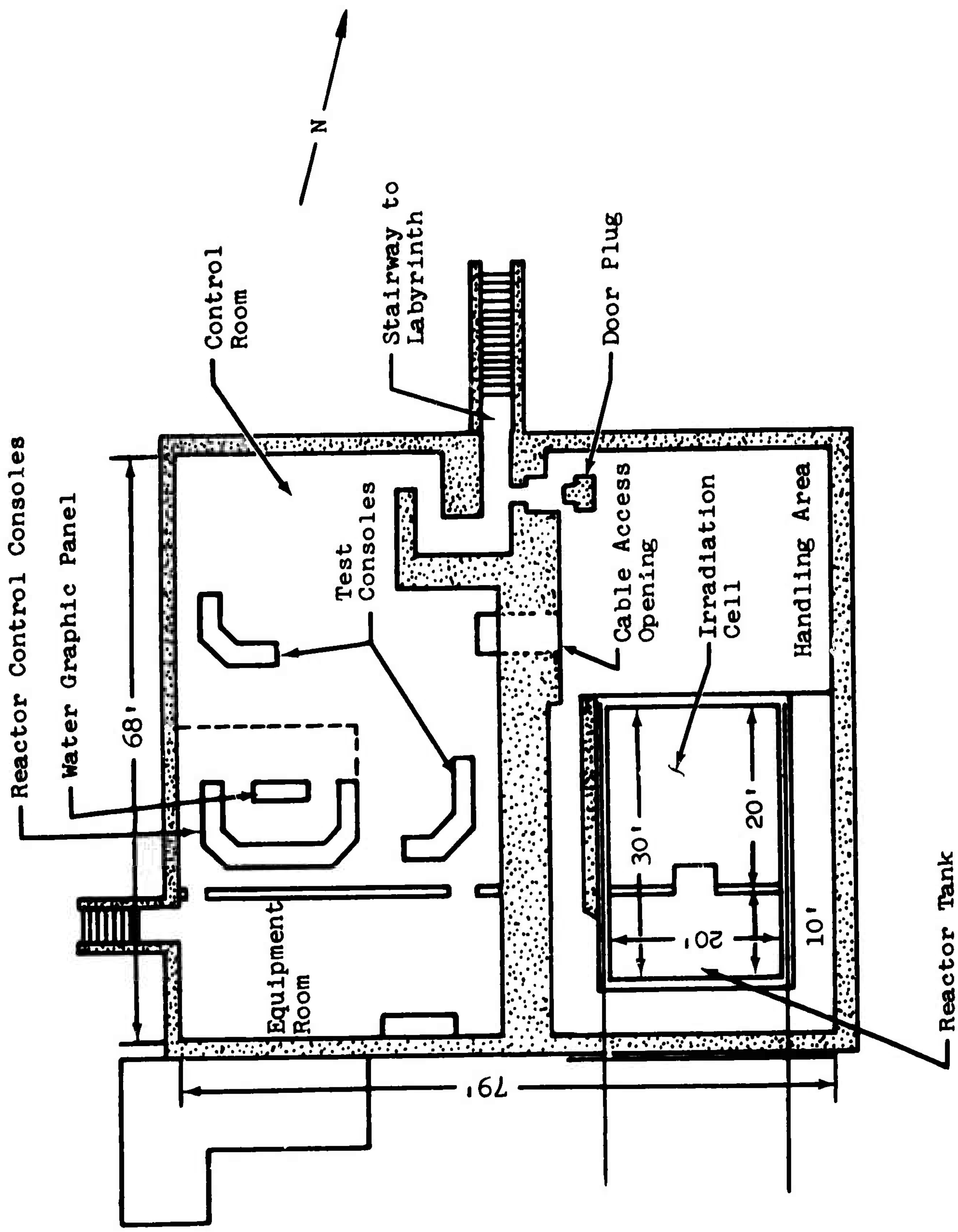
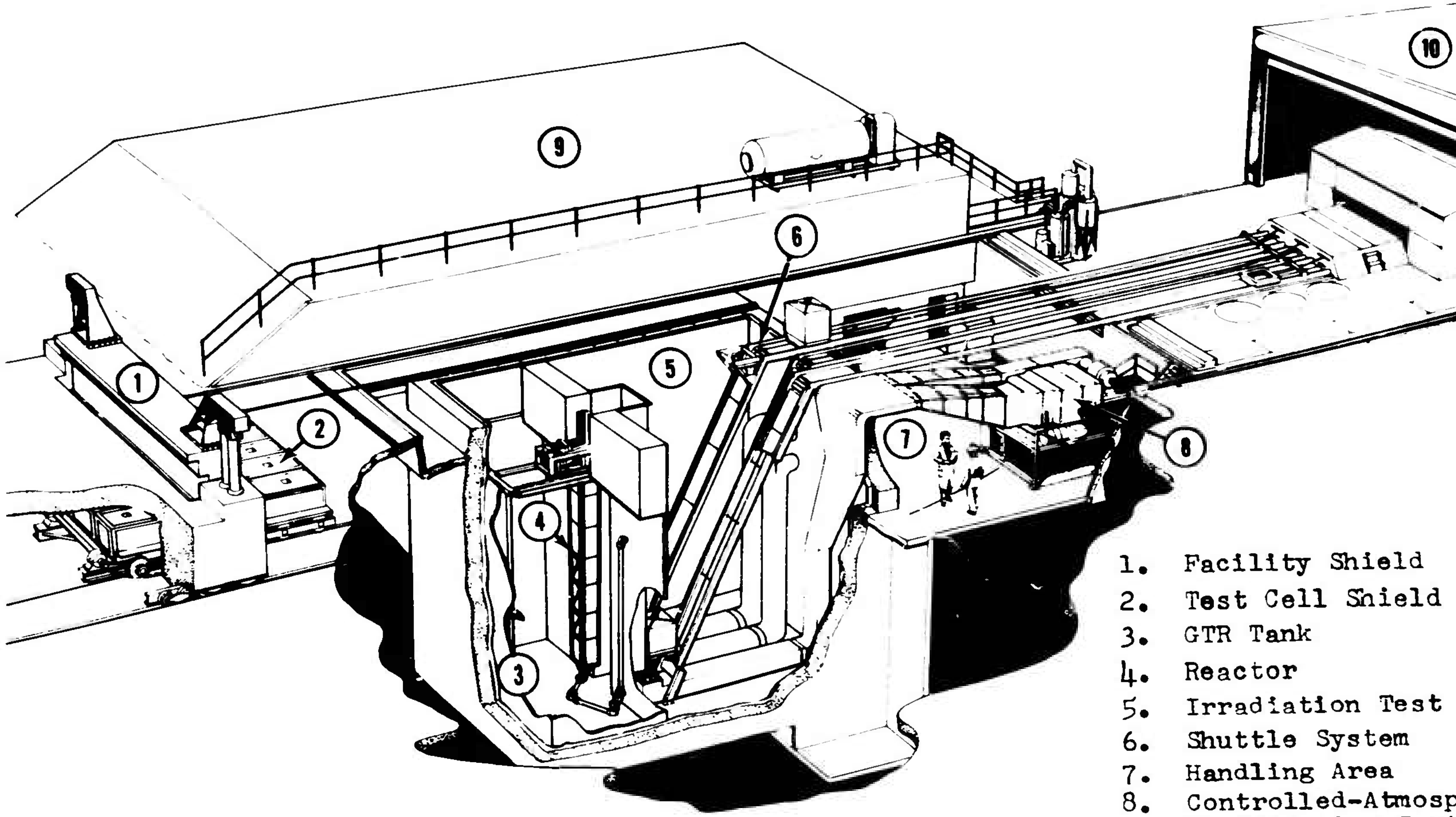


Figure A-1 Operations Building and GTR Facility



1. Facility Shield
2. Test Cell Shield
3. GTR Tank
4. Reactor
5. Irradiation Test Cell
6. Shuttle System
7. Handling Area
8. Controlled-Atmosphere Conditioning System
9. Operations Building
10. Weather Cover

Figure A-2 Cutaway View of GTR Radiation Effects System

NPC 20,669
31-7909

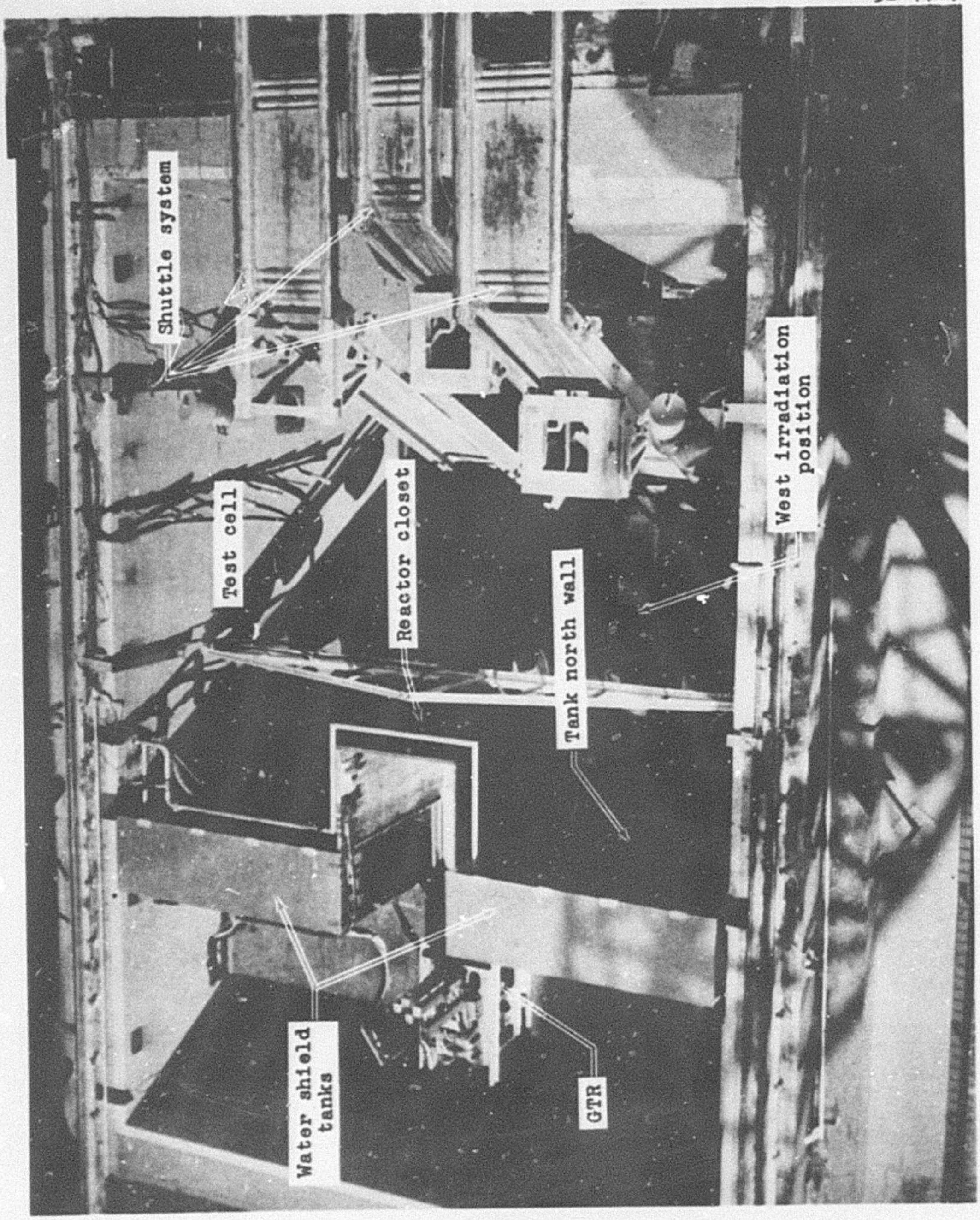


Figure A-3 Irradiation Test Cell and Reactor Tank

2 to 87 in. from the north face of the closet.

Adjacent to the north wall of the irradiation cell is the handling area. In this area, various connections are made for cryogenic, hydraulic, and pneumatic equipment.

An integral part of the GTR testing facility is the shuttle system, which is used to move test assemblies into irradiation position. This system consists of cable-driven dollies mounted on three sets of parallel tracks. The tracks extend from the irradiation positions adjacent to the reactor closet, up an incline to the north wall of the irradiation cell, and to a loading area on the ramp just north of the handling area. The system can be operated from either the control room or the dolly motor-drive shed on the north ramp. Full-coverage televiewing of the entire shuttle system is provided by means of a closed-circuit television in the control room.

The control room (Fig. A-1) is a below-grade, reinforced concrete structure adjacent to the GTR system. The control room provides a shielded area for reactor instrumentation, control consoles, and test systems as well as special test equipment needed to conduct radiation experiments.

APPENDIX B

DOSIMETRY

APPENDIX B

DOSIMETRY

Extensive nuclear measurements, performed prior to and during GTR Test 16, were required to provide data sufficient for a reliable characterization of the radiation incident on the test materials. The purpose of this discussion is to detail the procedures used for obtaining the incident-fast-neutron fluxes and the incident-gamma dose rates. All gamma dose values are based on the results obtained in the two mapping runs described in Section B.2.

B.1 GTR-16 Irradiations

B.1.1 Tensile Tests

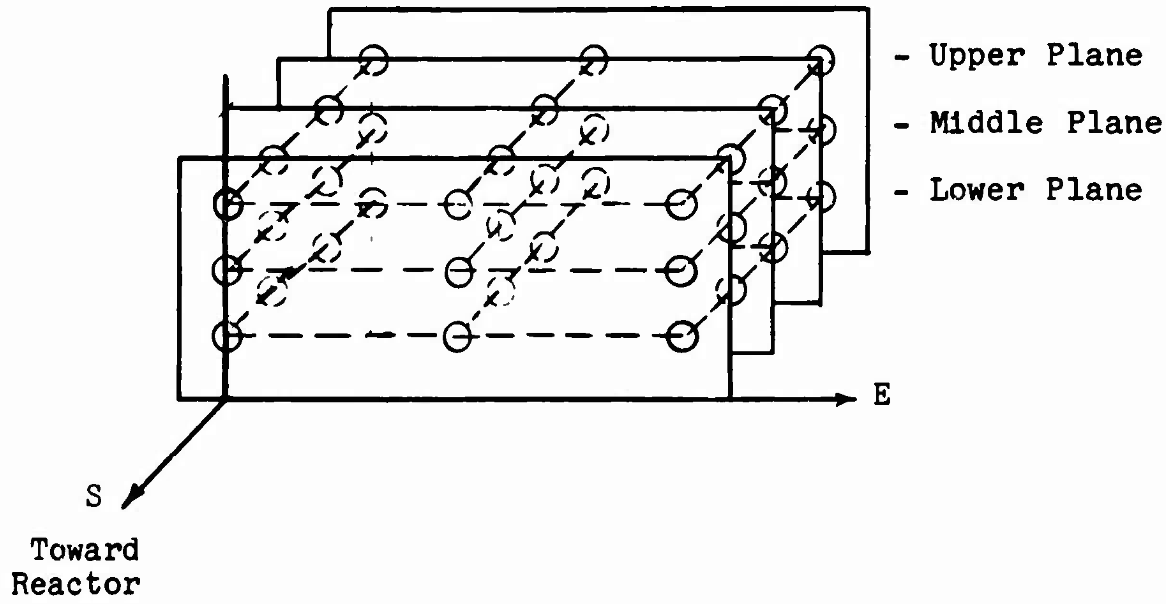
Measurements of the neutron flux were made with standard dosimetry packets attached to each rack of material specimens. Each packet contained a nickel foil for measurement of the fast-neutron flux ($E > 2.9$ Mev) and two phosphorous pellets (one bare and one cadmium-shielded) for measurement of the thermal-neutron flux. Standard foil techniques were used specifying the neutron flux field. The activated foils were counted in the GD/FW Nuclear Radiation Effects Foil Counting Facility, and the data reduced using an IBM 7090 digital computer program.

From neutron spectral measurements (Ref. 2) made previously in the north position of the GTR irradiation facility, the following neutron flux ratios were obtained:

$$\frac{\Phi(E > 1.0 \text{ Mev})}{\Phi(E > 2.9 \text{ Mev})} = 2.82 \qquad \frac{\Phi(E > 0.1 \text{ Mev})}{\Phi(E > 2.9 \text{ Mev})} = 4.9$$

Preliminary analysis of the mapping experiment made prior to GTR-16 indicates no significant variation in the shape of the neutron spectrum between 0.1 and 2.9 Mev, regardless of position inside the dewar. Further, the neutron flux ($E > 2.9$ Mev) measured during GTR-16 with nickel foils was virtually identical to that measured during the mapping experiment with sulfur pellets. The neutron flux for $E > 1$ Mev was obtained by multiplying the neutron flux for $E > 2.9$ Mev (measured with nickel foils) by the factor 2.82.

Figure B-1 is a sketch showing the position of dosimetry packets within the north dewar. Basically, the dosimetry packets were located on three horizontal planes - Upper, Middle, and Lower - corresponding to imaginary planes through the center of the upper, middle, and lower tensile specimen trays. The packets were, in general, in the same locations as those shown in the photographs in Section B.2.2. On each of these three planes, three packets were located longitudinally and four packets transversely, as shown below.



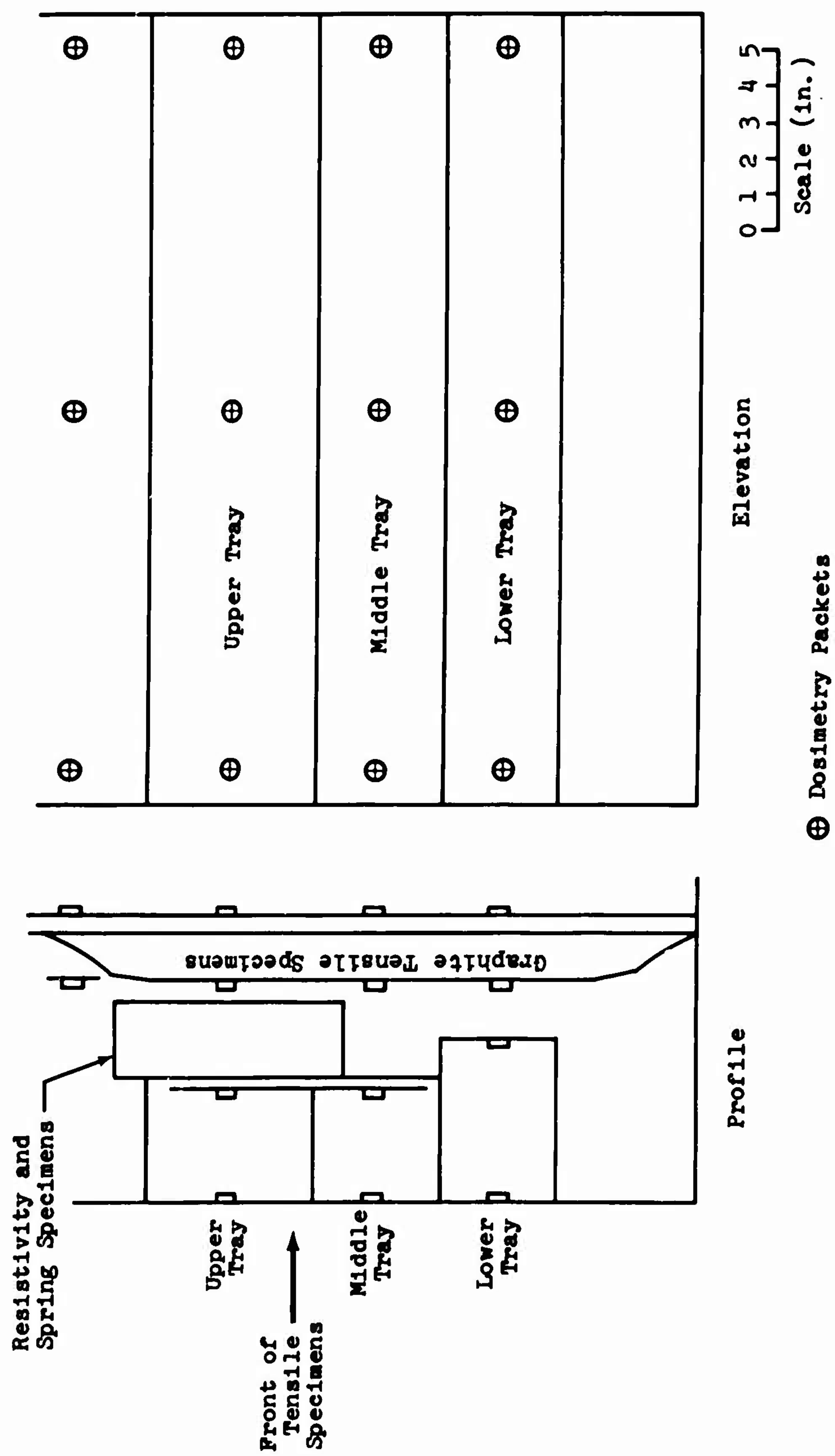


Figure B-1 Dosimetry Locations in North Irradiation Dewar

Plots of the integrated neutron flux ($E > 1$ Mev) vs distance from front to rear through the specimen assembly are shown in Figures B-2, B-3, and B-4 for the Upper, Middle, and Lower planes, respectively. Similarly, Figures B-5, B-6, and B-7 are plots of the gamma dose for these planes. Figures B-8, B-9, B-10, and B-11 are plots of integrated neutron flux ($E > 1$ Mev) in the planes in front of and behind the tensile and the graphite specimens; Figures B-12, B-13, and B-14 are plots of the gamma dose in front of and behind the tensile specimens and behind the graphite specimens. Table B-1 gives the integrated thermal-neutron flux ($E < 0.48$ ev) for the Upper, Middle, and Lower planes.

Table B-1

Integrated Thermal-Neutron Flux in North Specimen Assembly (n/cm^2)

Plane	Column		
	West	Center	East
UPPER			
Row 1	1.35(16)*	1.86(16)	1.02(16)
Row 2	9.30(15)	1.47(16)	1.38(16)
Row 3	1.12(16)	1.88(16)	1.42(16)
Row 4	--	--	1.66(16)
MIDDLE			
Row 1	--	2.20(16)	1.12(16)
Row 2	1.38(16)	2.20(16)	1.38(16)
Row 3	5.0 (15)	1.25(16)	8.70(15)
Row 4	--	--	--
LOWER			
Row 1	7.90(15)	1.31(16)	5.50(15)
Row 2	6.60(15)	--	2.45(15)
Row 3	3.35(15)	2.21(15)	5.50(15)
Row 4	6.85(15)	7.56(15)	1.32(16)

*Read 1.35(16) as 1.35×10^{16}

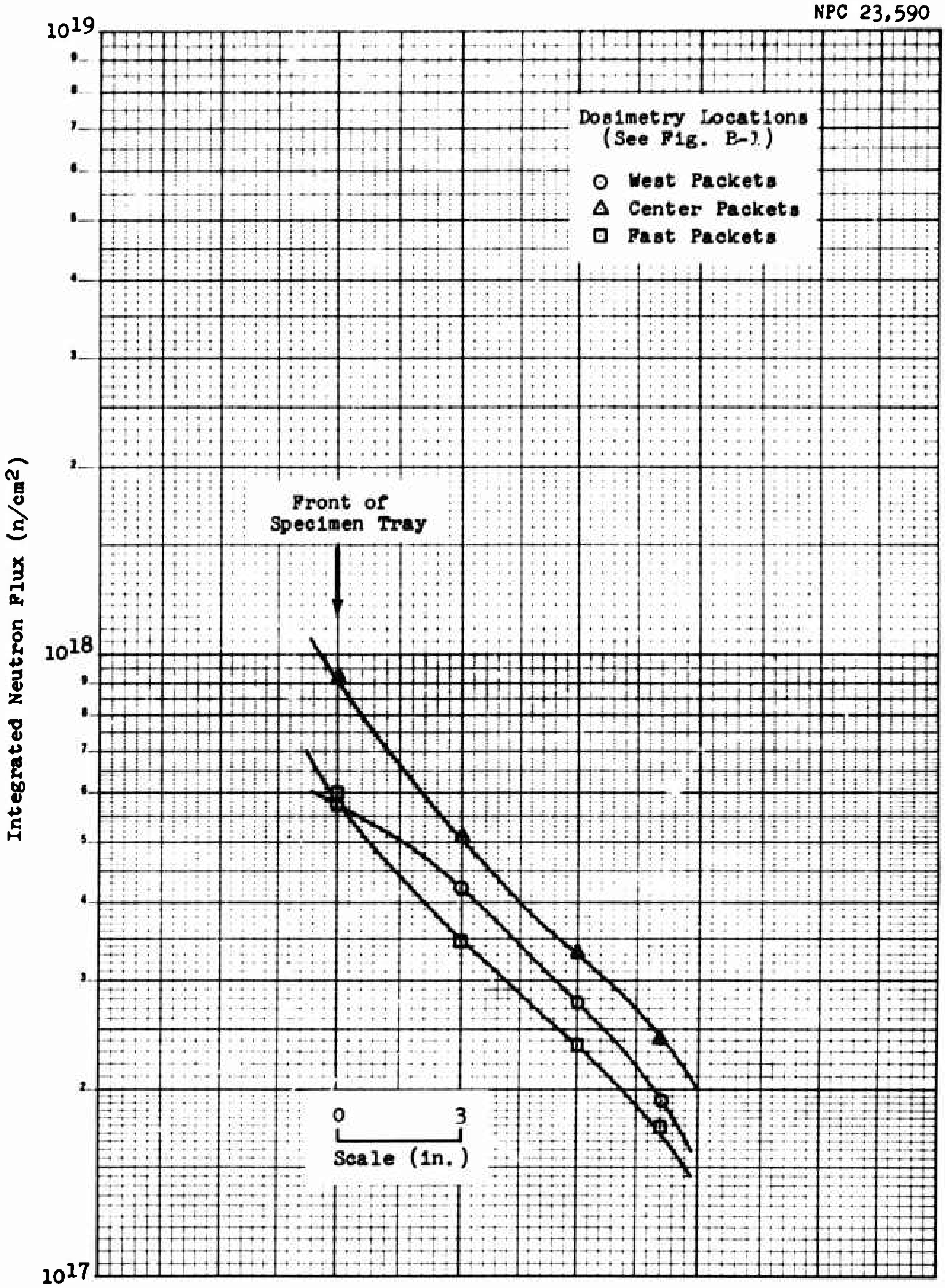


Figure B-2 Integrated Neutron Flux (E > 1 Mev) Profile - North Dewar, Upper Plane

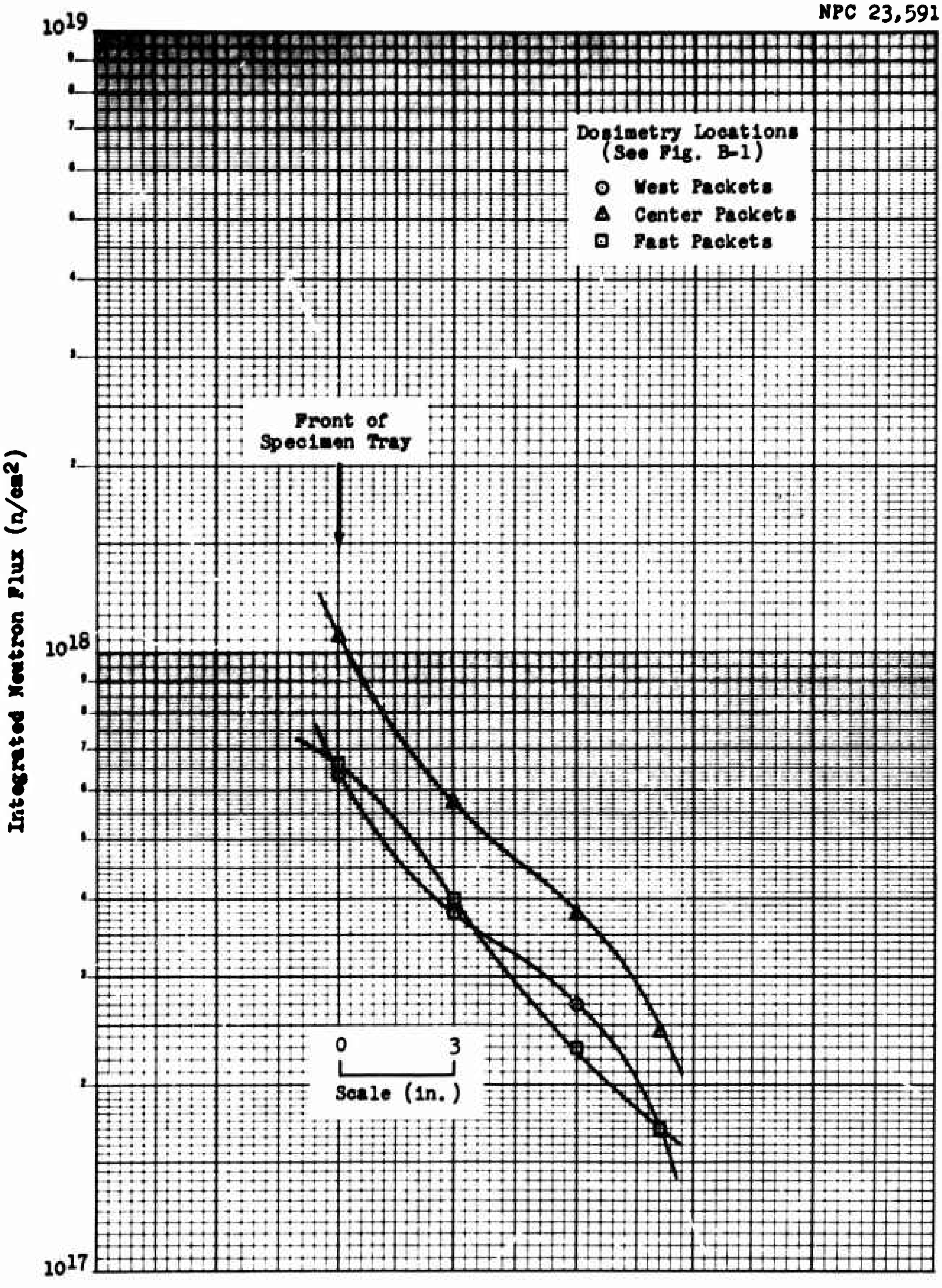


Figure B-3 Integrated Neutron Flux (E > 1 Mev) Profile - North Dewar, Middle Plane

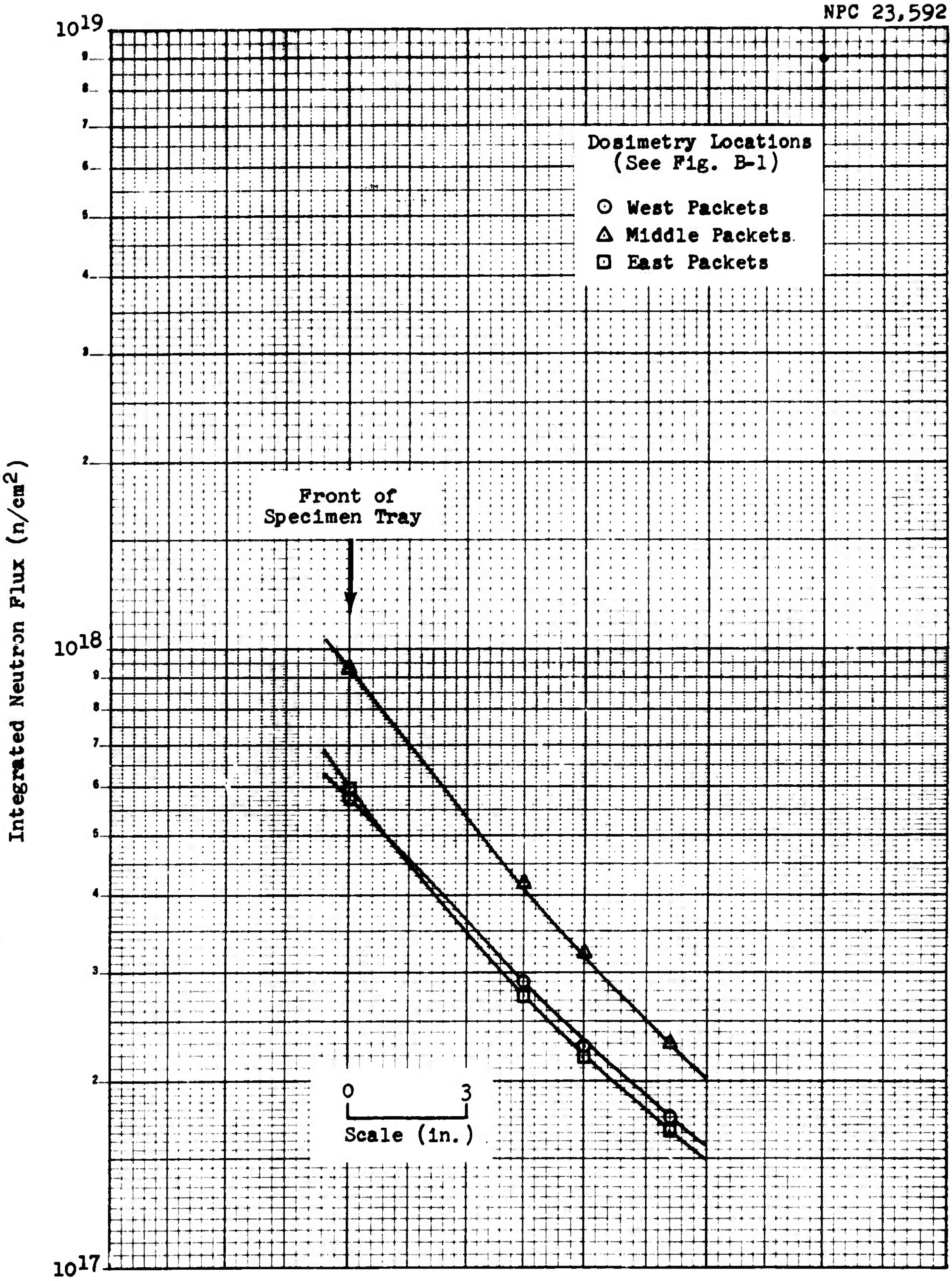


Figure B-4 Integrated Neutron Flux (E > 1 Mev) Profile - North Dewar, Lower Plane

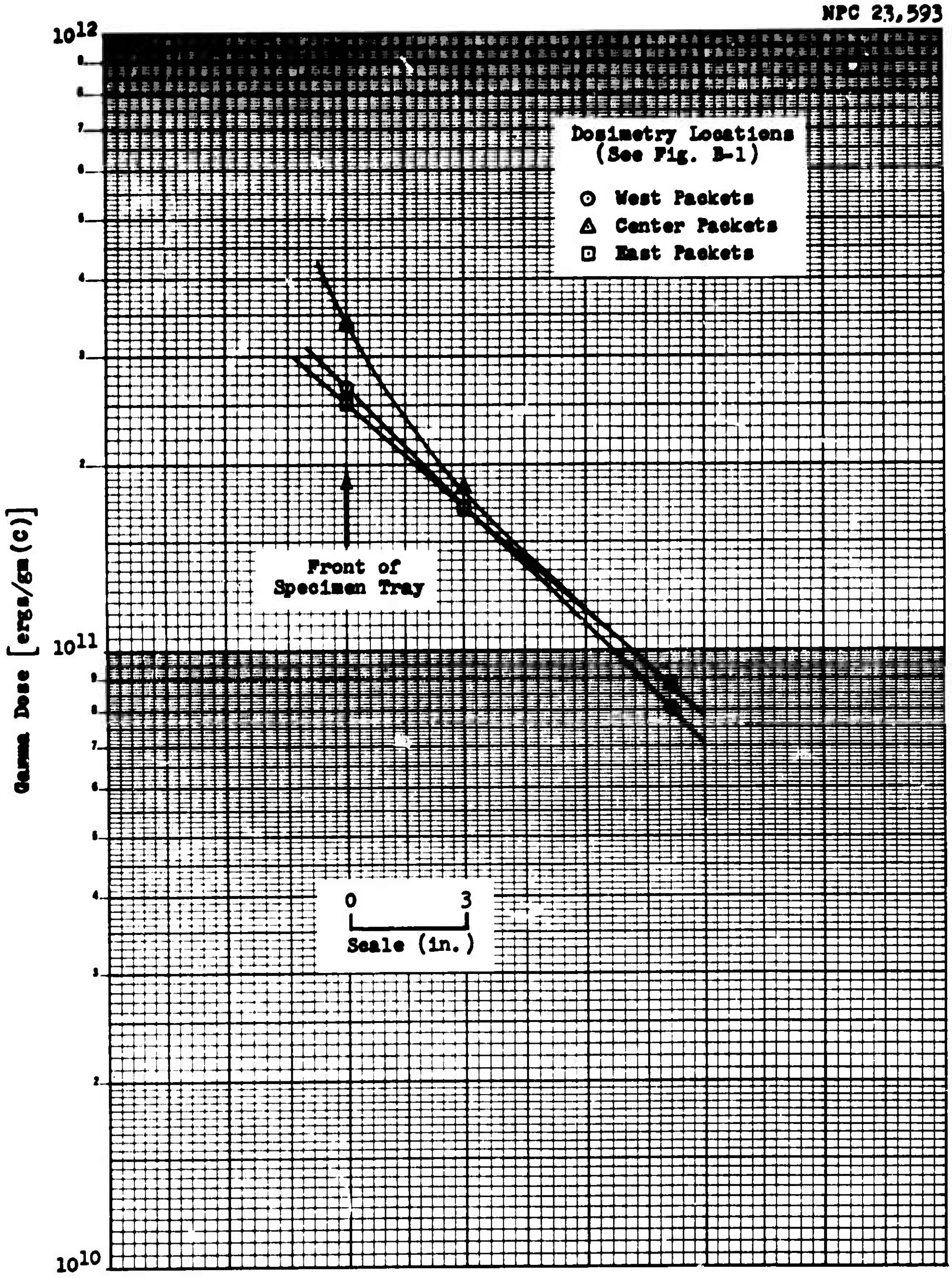


Figure B-5 Gamma Dose Profile - North Dewar, Upper Plane

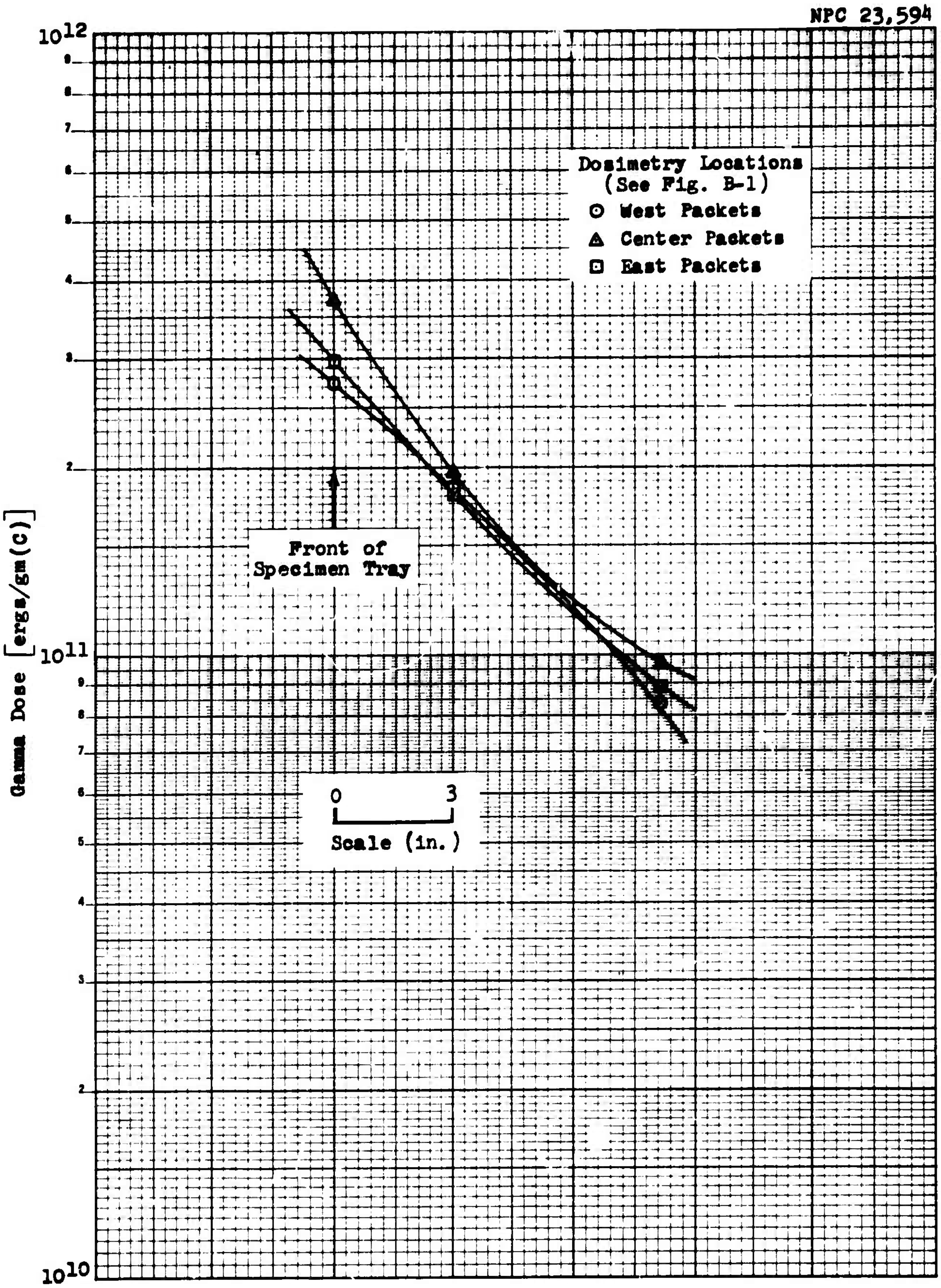


Figure B-6 Gamma Dose Profile - North Dewar, Middle Plane

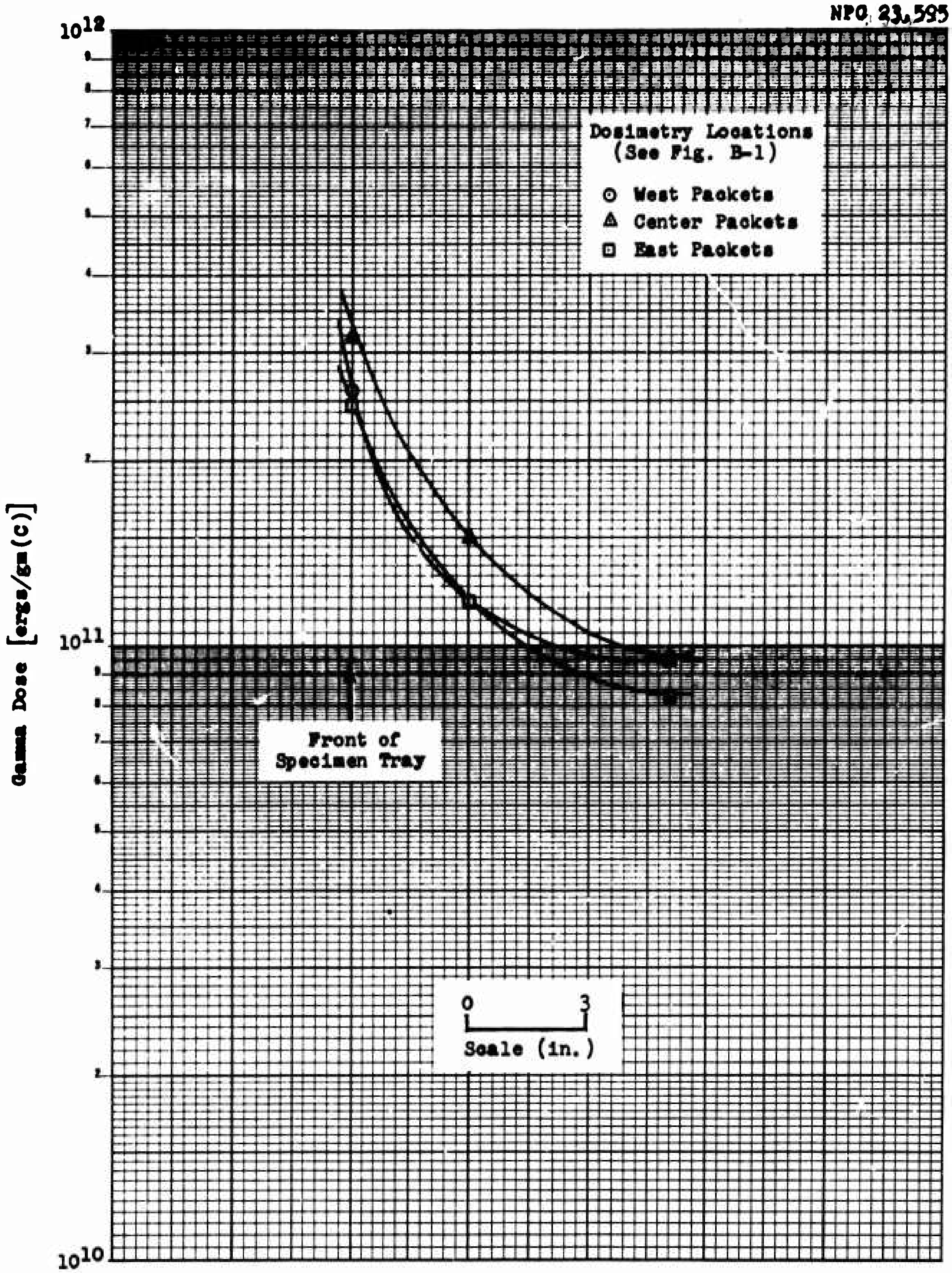


Figure B-7 Gamma Dose Profile - North Dewar, Lower Plane

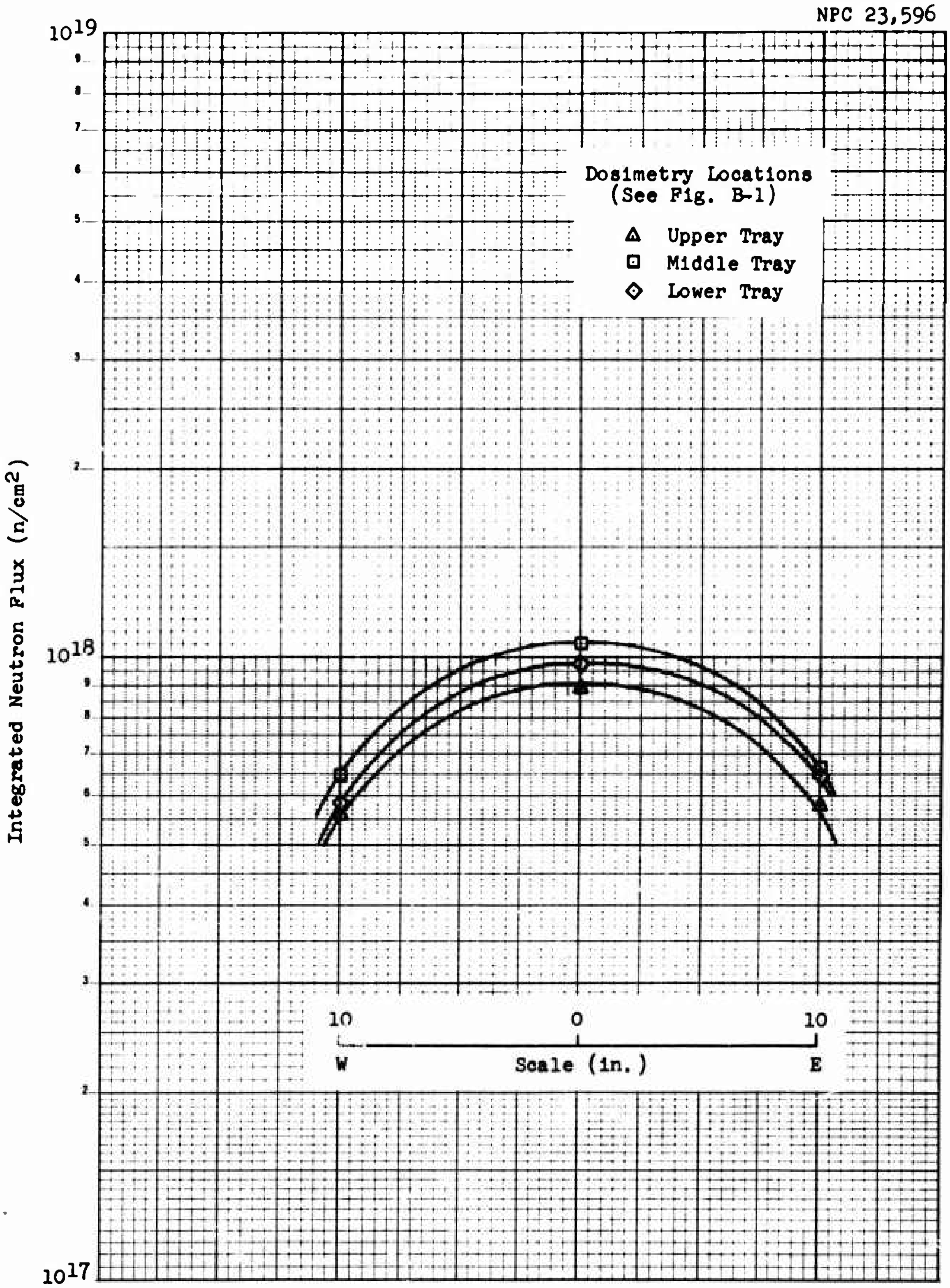


Figure B-8 Integrated Neutron Flux (E > 1 Mev) Profile - North Dewar, Plane in Front of Tensile Specimens

NPC 23,597

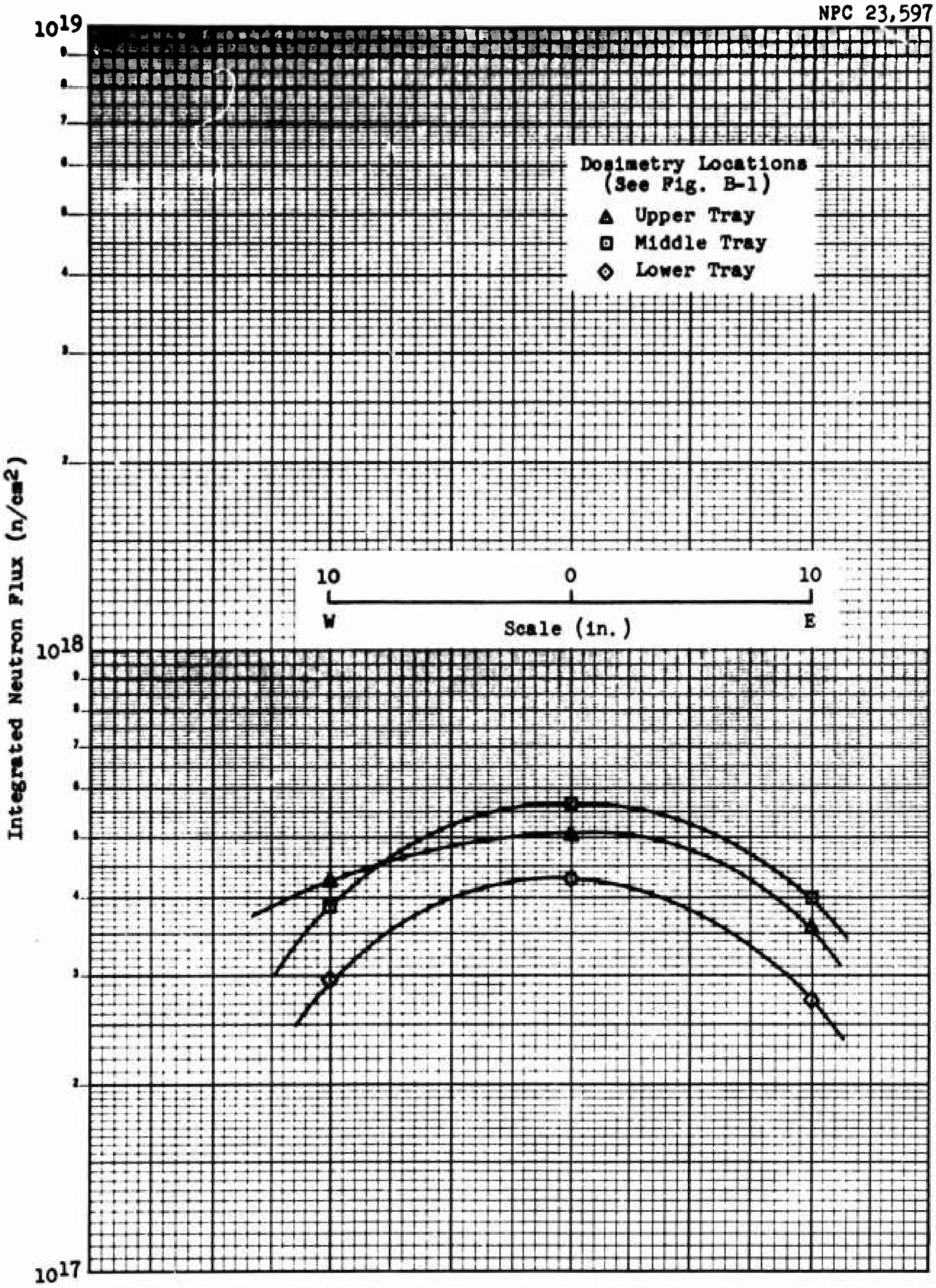


Figure B-9 Integrated Neutron Flux (E > 1 Mev) Profile - North Dewar, Plane Behind Tensile Specimens

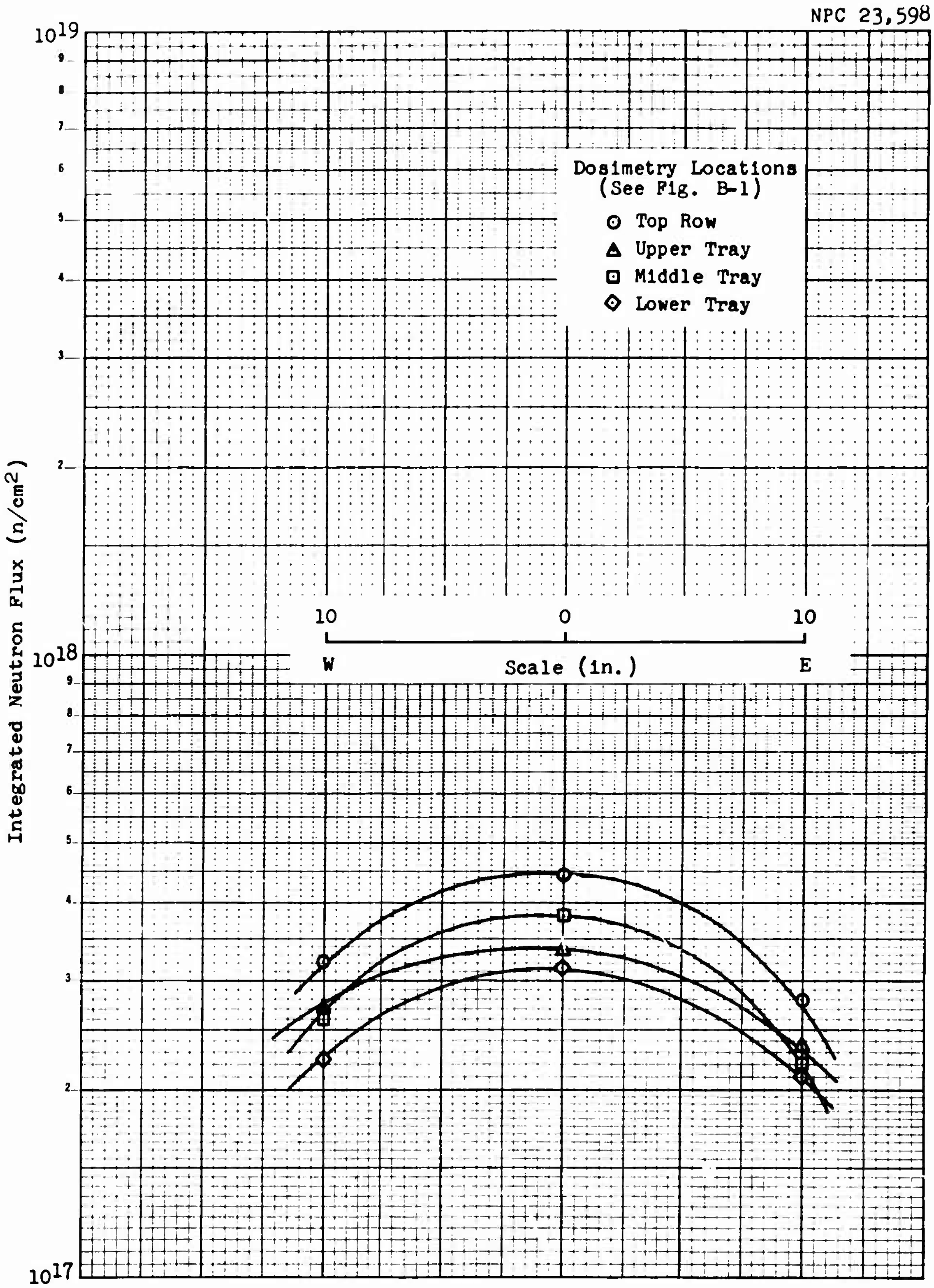


Figure B-10 Integrated Neutron Flux (E > 1 Mev) Profile - North Dewar, Plane in Front of Graphite Specimens

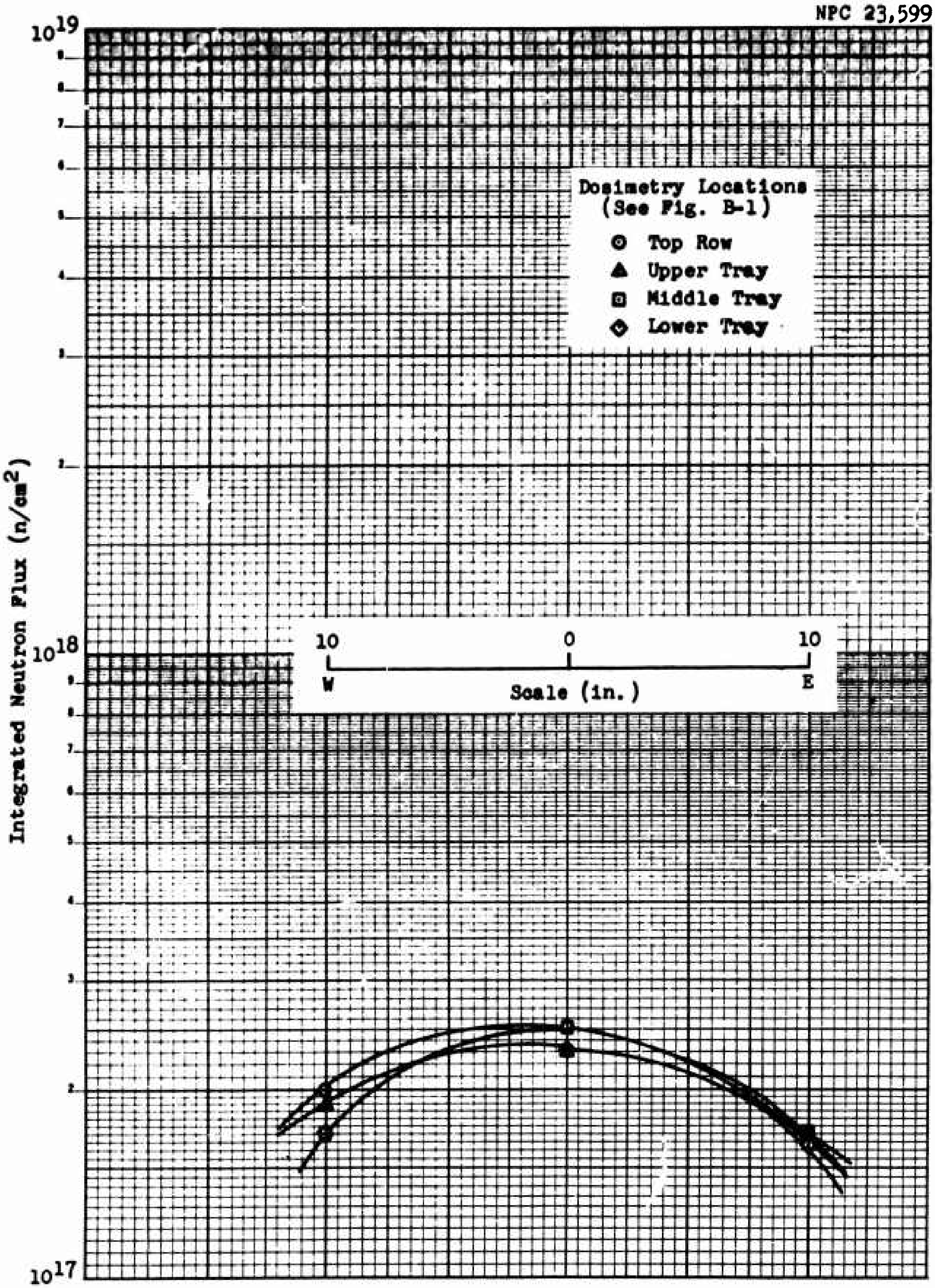


Figure B-11 Integrated Neutron Flux (E > 1 Mev) Profile - North Dewar, Plane Behind Graphite Specimens

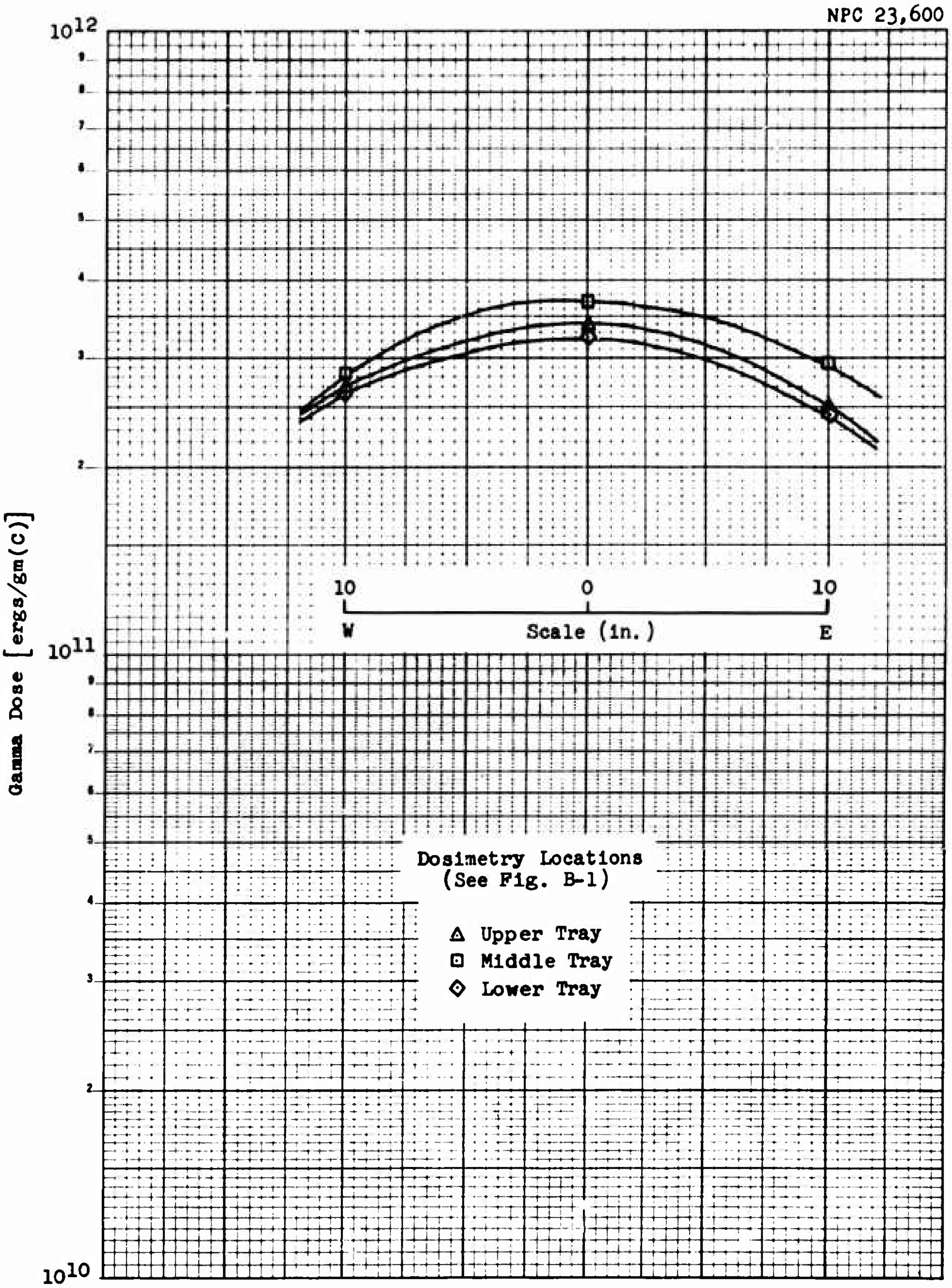


Figure B-12 Gamma Dose Profile - North Dewar, Plane in Front of Tensile Specimens

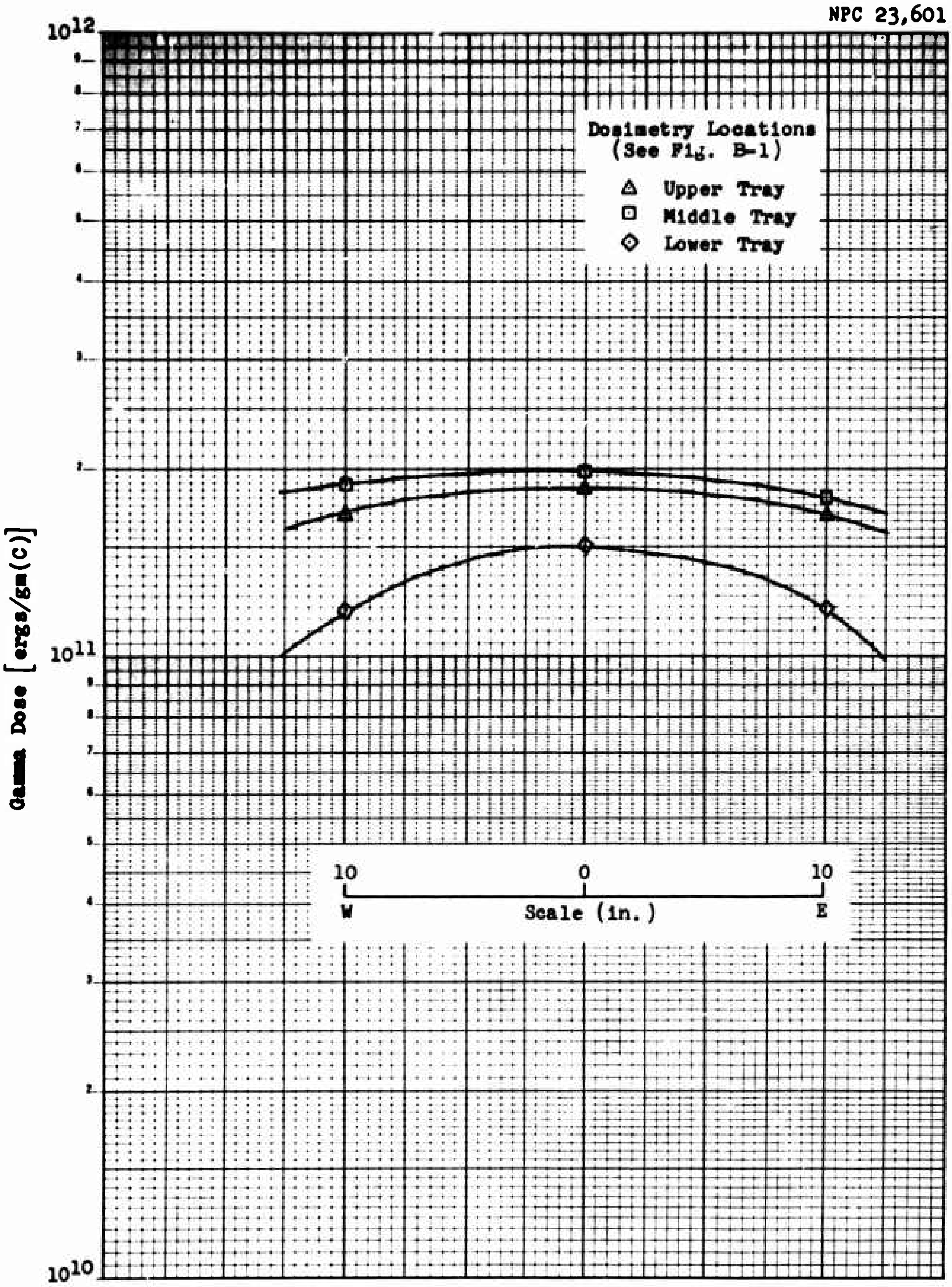


Figure B-13 Gamma Dose Profile - North Dewar, Plane Behind Tensile Specimens

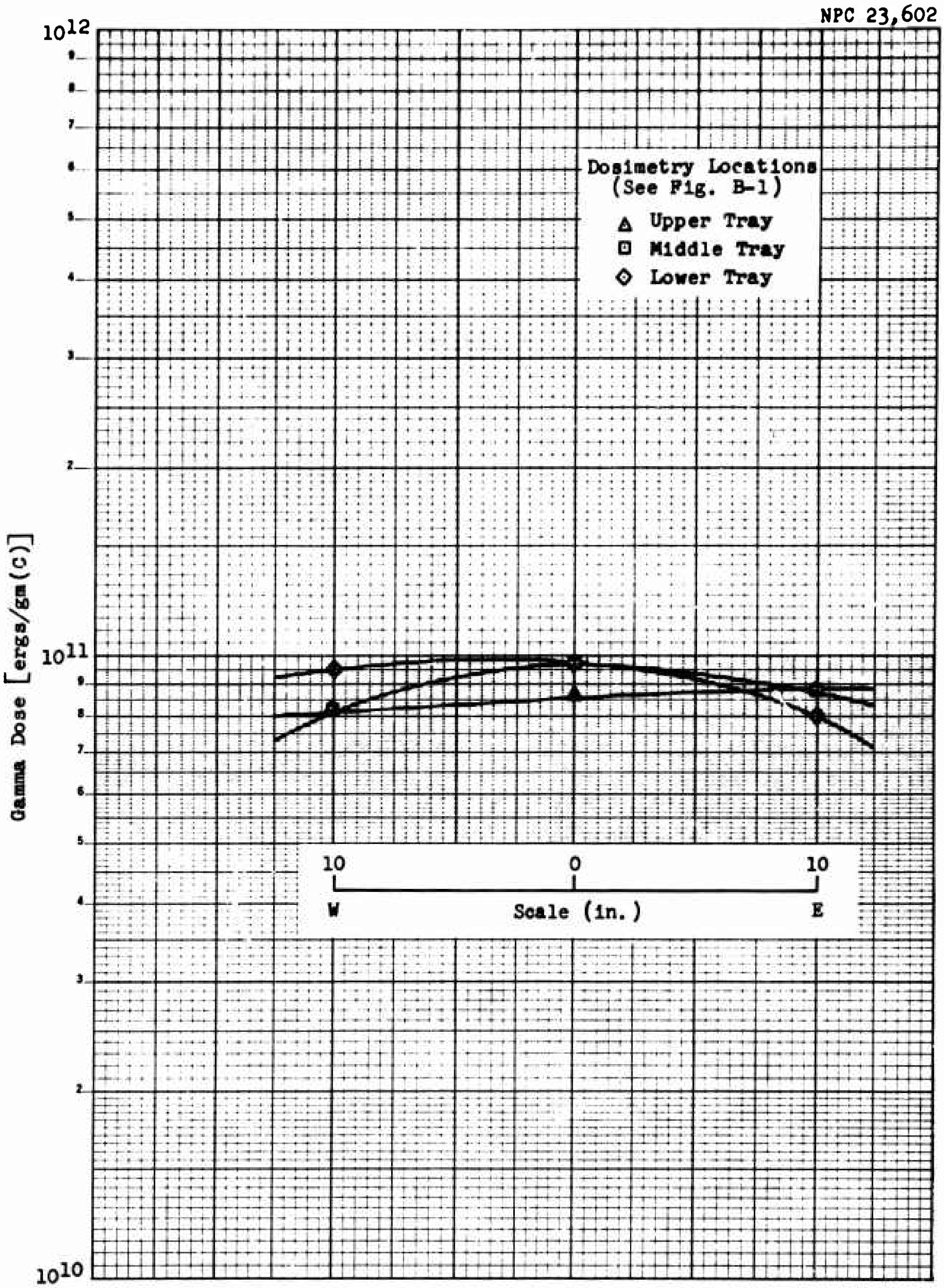


Figure B-14 Gamma Dose Profile - North Dewar, Plane Behind Graphite Specimens

B.1.2 Resistivity Test

These specimens, irradiated in the north position along with the tensile specimens, received an average integrated neutron flux of 4.5×10^{17} n/cm^2 (E > 1 Mev).

B.1.3 Steel Spring Test

These specimens, irradiated in the north position along with the tensile specimens, received an average integrated neutron flux of 9.5×10^{17} n/cm^2 (E > 1 Mev).

B.1.4 C-Ring Seal Test

The two O-ring fixtures were irradiated in the east position. One dosimetry packet containing one nickel foil and two phosphorous foils was attached to each fixture. The test fixtures received an integrated neutron flux of 4×10^{16} n/cm^2 (E > 2.9 Mev) and a gamma dose, based on the results of the mapping runs (see Sec. B.2), of 2.6×10^{10} ergs/gm(C).

B.1.5 Cemented Orifice Test

The dosimetry for these specimens is the same as that described in Section B.1.1. Specimens mounted inside the north dewar received an average integrated neutron flux of 2.5×10^{17} n/cm^2 (E > 1 Mev) and an average gamma dose of 1.0×10^{11} ergs/gm(C). Those mounted outside the north dewar received an average integrated neutron flux of 4.0×10^{17} n/cm^2 (E > 1 Mev) and an average gamma dose of 2.0×10^{11} ergs/gm(C).

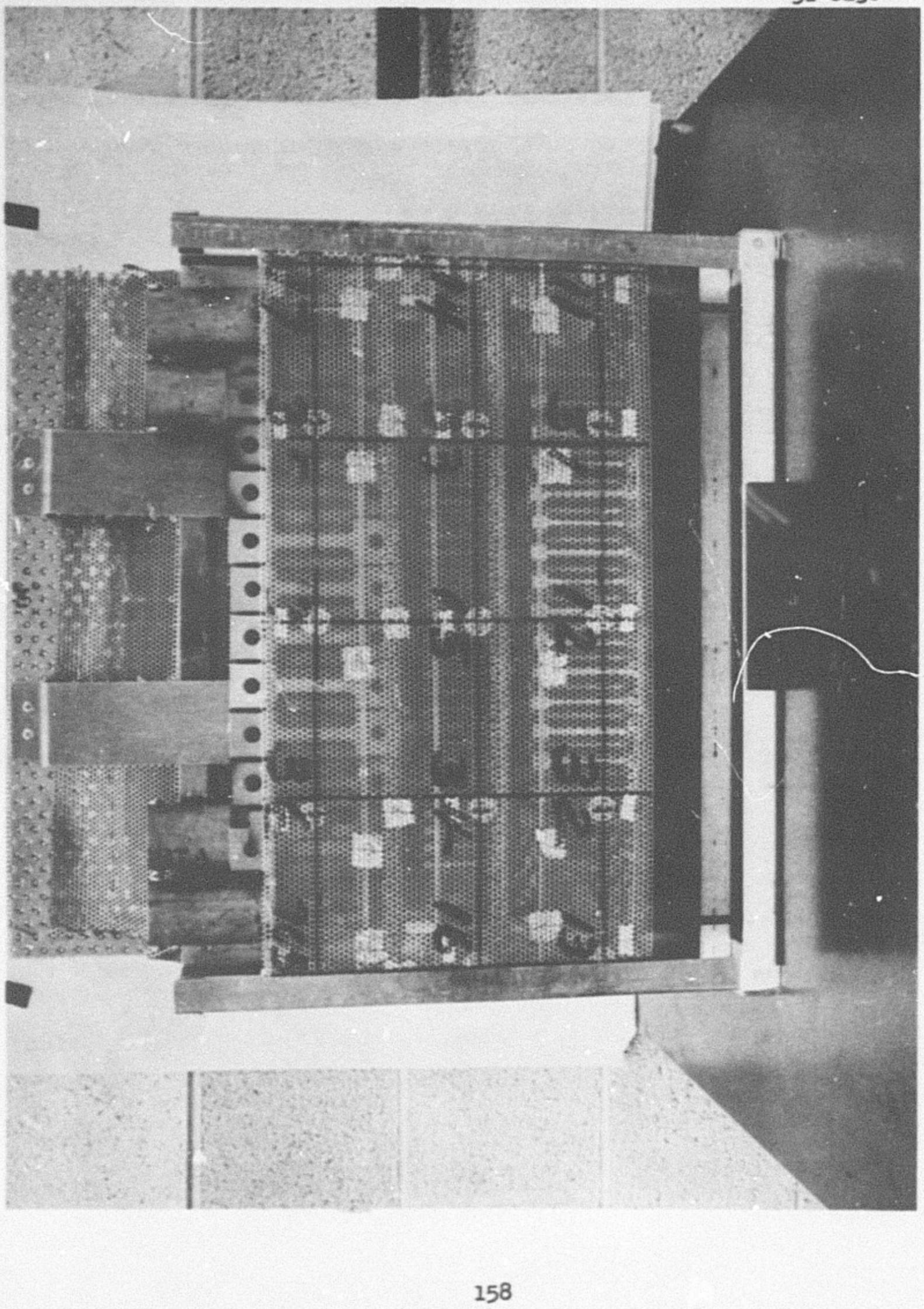
B.2 GTR 16 Mapping Runs - North Dewar

Passive nuclear measuring systems, i.e., neutron-detecting foils and gamma-dose-rate integrators, represent the most practical means for obtaining the desired radiation information. The neutron exposure and gamma-dose range anticipated for GTR-16 exceeded the measuring capability of all neutron detectors except nickel ($E > 2.9$ Mev) and all practical gamma detectors. Therefore, mapping tests at the desired dose levels were made before GTR-16 with foils and cobalt glass. Since the reactor core was relatively unpoisoned prior to GTR-16, and since the 200- and 400-hr planned irradiations at 3 Mw constituted a poisoned condition, two mapping irradiations were performed.

The first mapping run, with unpoisoned core, was made to verify predicted exposure conditions for foils and gamma detectors. The second, with the retracted core poisoned by a 45-Mw-hr exposure immediately preceding the mapping run, was made to establish neutron fluxes and spectral dependence, as well as gamma-dose rates, under simulated GTR-16 conditions. Both mapping runs were made with AGC and WANL cryogen test assemblies in irradiation position and with each containing actual test specimens (or facsimilies) and pertinent cryogen, namely, LH_2 in the AGC dewars and LN_2 in the WANL dewar. The AGC dewar, with pulling assembly and tensile test specimens, was located at the east irradiation cell position; the thermal-conductivity simulator with an AGC dewar was located at the west position; the WANL dewar was located at the north position.

Figures B-15 through B-18 show nuclear detector packet locations within the cryogen volume of the north dewar. In addition to these locations, detectors, placed in vertical planes in a symmetric pattern, were exposed in front and back of the cryogen fluid container to obtain supplementary dose-extrapolation data.

NPC 22,761
31-8230



NPC 22,762
31-8231

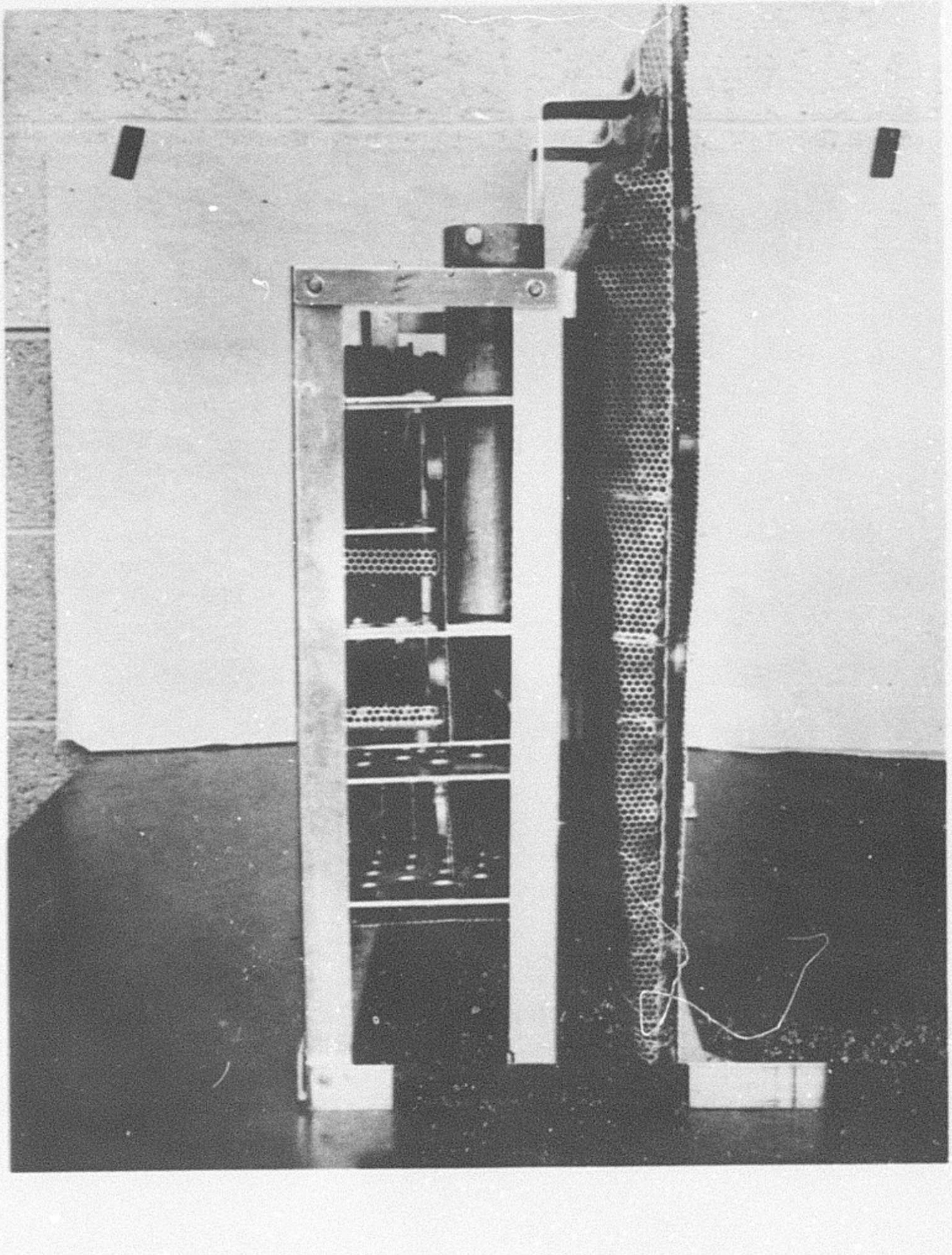


Figure B-16 Side View of Mapping-Run Dosimetry

NPC 22,763
31-8233

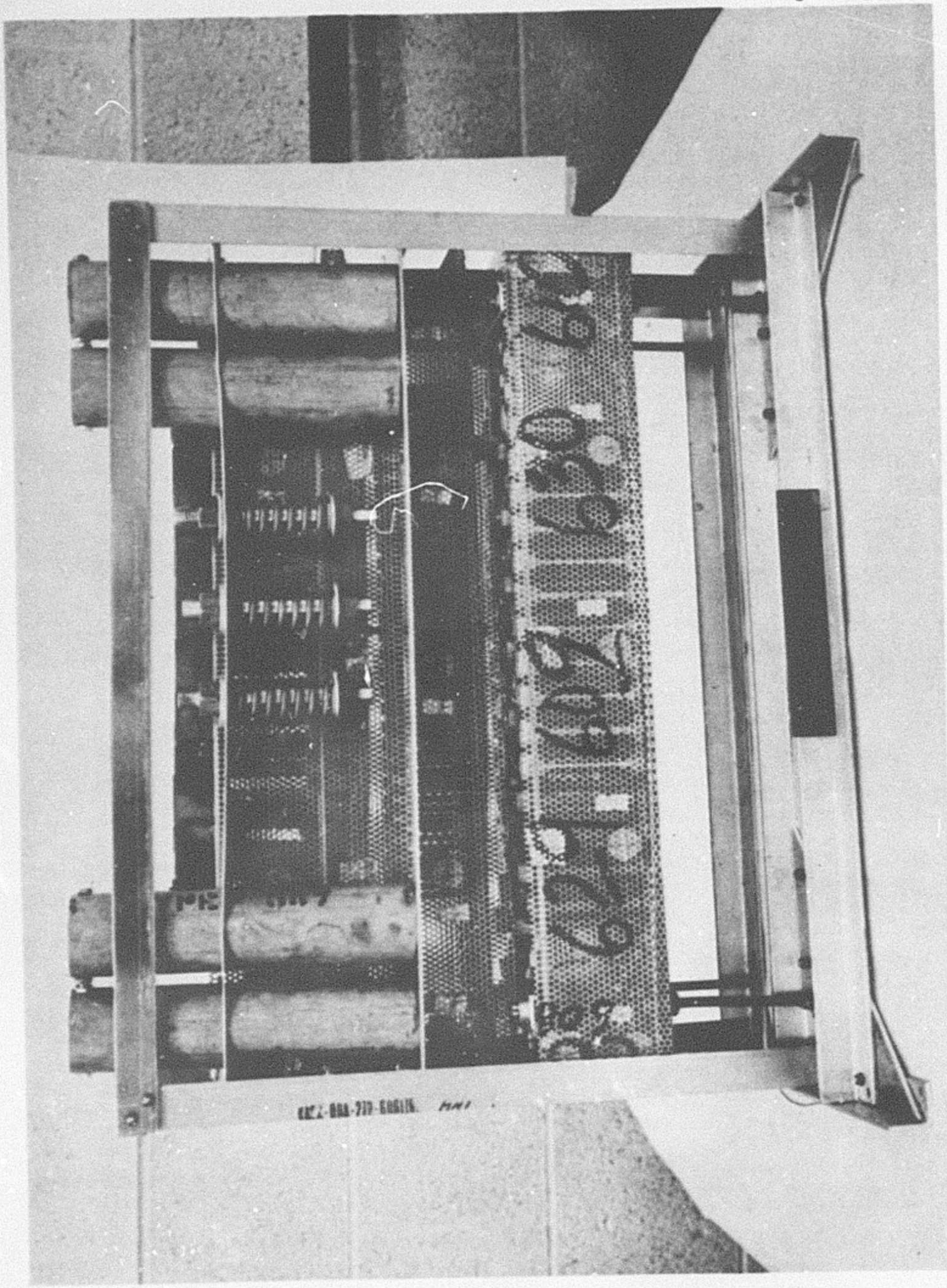


Figure B-17 Internal View of Mapping-Run Dosimetry

NPC 22,764
31-8232

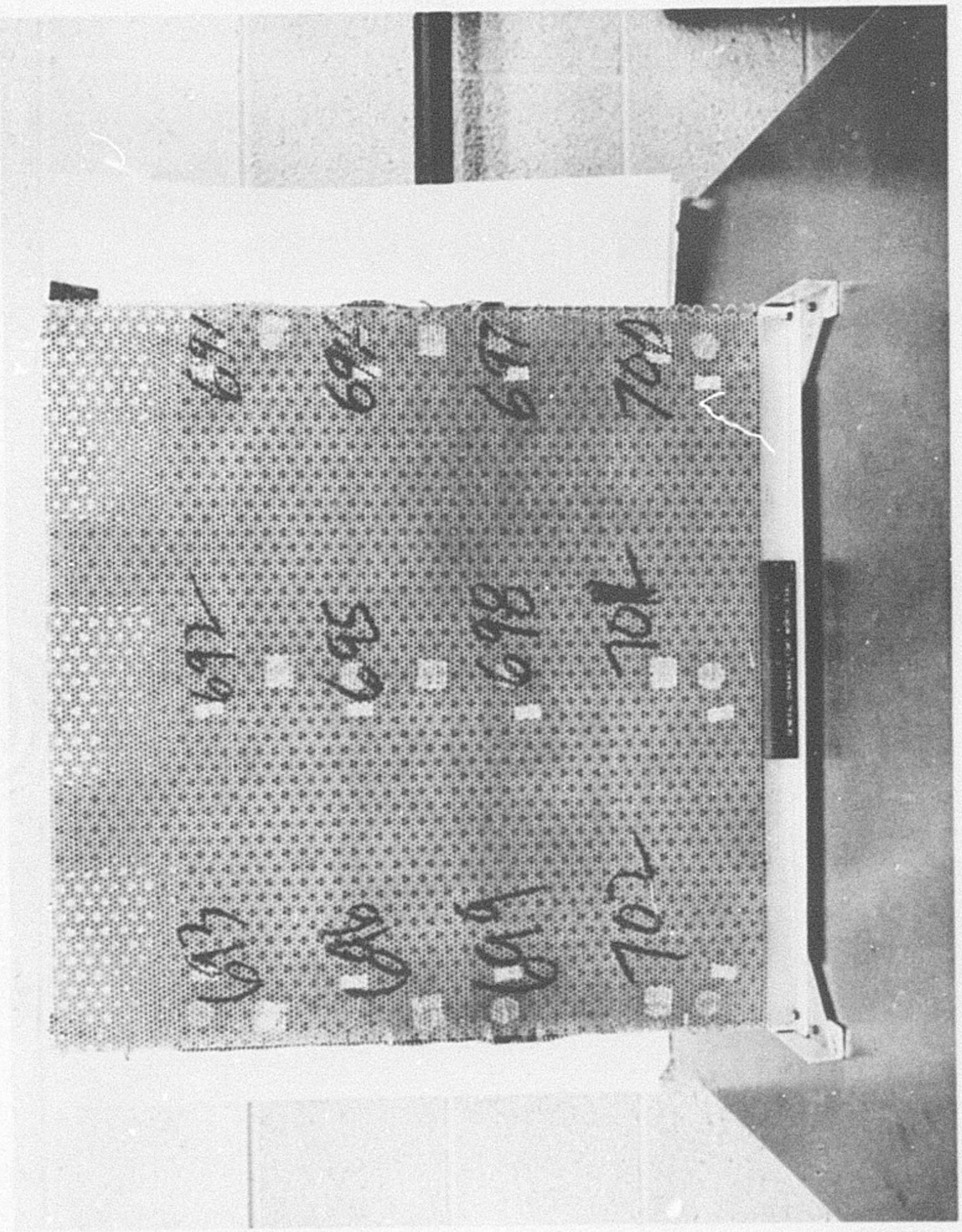


Figure B-18 Rear View of Mapping-Run Dosimetry

Figure B-19 illustrates schematically the overall detector arrangement for the mapping runs.

B.2.1 Detector Packets

Neutron and gamma detector packets for the described mapping locations consisted of indium, sulfur, and aluminum foils (one each per packet) for determining the fast flux of nominal energies greater than 0.85 Mev, 2.9 Mev, and 8.1 Mev, respectively; a pair of bare and cadmium-covered copper foils per packet for thermal-flux monitoring; and an enriched-boron-encapsulated cobalt glass per packet for gamma monitoring. These detectors were mounted on perforated aluminum sheets which, in turn, were wired to the test assembly at the given locations.

In addition to these detector packets, nine special neutron spectral packets were included in each mapping run (3 packets per test assembly) to provide additional data from which confidence in the extrapolation of the fast-neutron fluxes to 0.1 Mev would result. These packets contained resonance detectors for estimating the spectral dependence of the neutron flux between thermal energy and several kilovolts. The detectors, sensitive to (n,γ) reactions, included the common elements indium, gold, tungsten, cadmium, manganese, copper, and phosphorus, as well as the rare earths of lutetium, europium, samarium, and lanthenum. These detectors, in the form of thin, non-flux-perturbing foils, are being developed in the NARF program for intermediate-energy spectral studies of various neutron environments. Activation data are treated differently in that fluxes responsible for the activation are not calculated

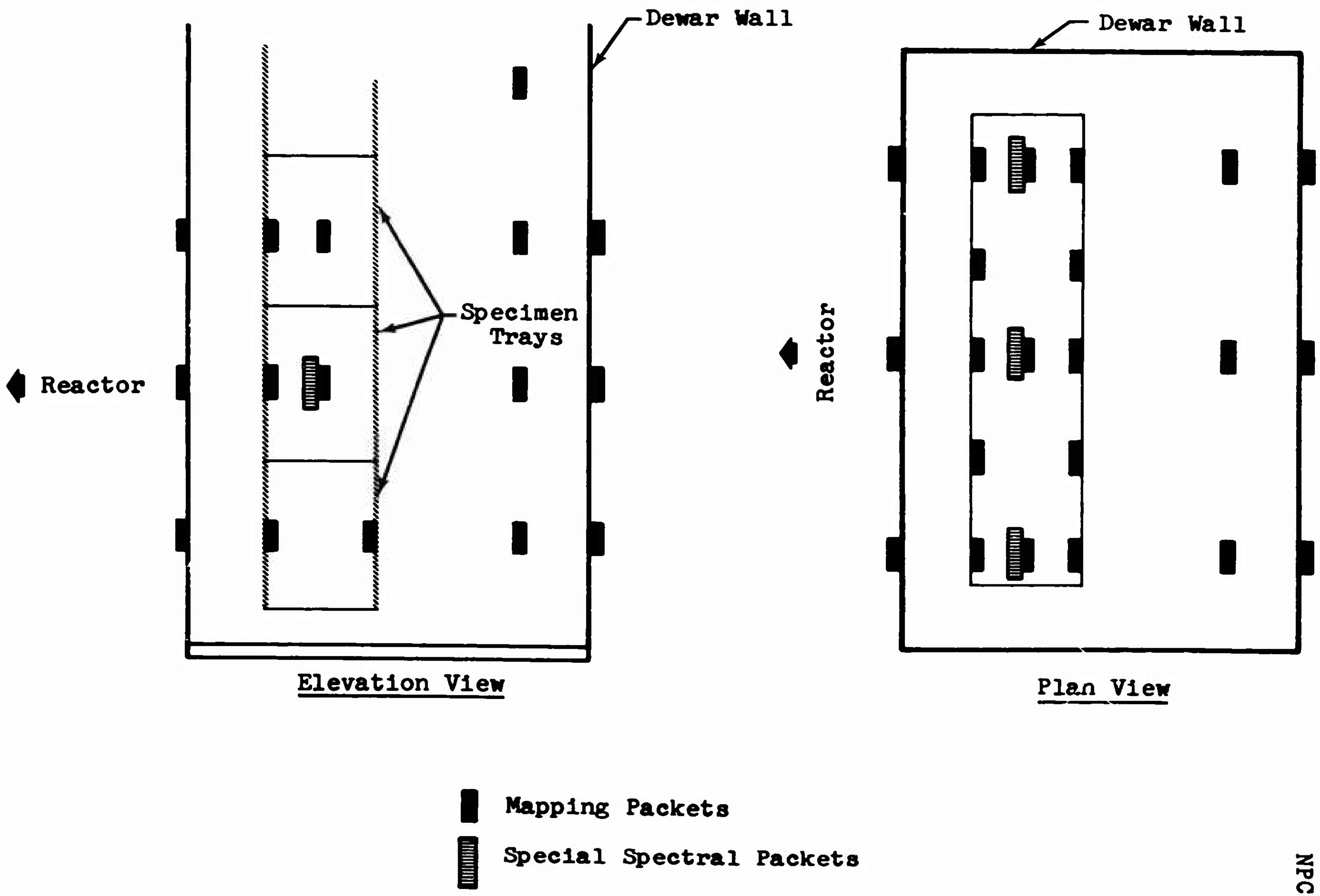


Figure B-19 Dosimetry Packet Arrangement for Mapping Run per se; rather, the data are compared with similar data obtained in more or less known spectral environments, with the result that confidence is gained in the accuracy of fast-flux spectral measurements.

The special spectral packets were mounted, together with additional fast-neutron detectors of indium, sulfur, and aluminum, at selected locations within the cryogen volumes indicated in Figure B-19.

B.2.2 Irradiation Procedure, Foil-Counting, and Data Processing

After all systems had been checked out, the three cryogen chambers were positioned in their respective locations north, east, and west of the reactor closet while the GTR was at zero power in the full south position. The east and west cryogen chambers were then filled with LH_2 and the north with LN_2. The systems were stabilized and the reactor, still in the retracted position, was brought to power, moved into irradiation position within the closet (2 in. of water on north face), and maintained at power for 30 min. The power level was 40 kw for the first mapping run and 120 kw for the second.

Since the purpose of the second mapping run (which was made several days after the first) was to simulate the poisoned core conditions encountered in long, high-power irradiations such as GTR Test 16, the 120-kw irradiation was immediately preceded by a 45-Mw-hr exposure followed by a 12-hr delay.

All foils were retrieved about 4 hr after each exposure and prepared for count-data accumulation. The foils were counted on the GD/FW end-window flow counters at various time intervals until sufficient data were obtained for adequate IBM analysis with a statistical accuracy of 1-2%. All foil data were accumulated on tapes and processed by the K-25 IBM procedure for activity levels and flux information.

Cobalt-glass gamma detectors were also retrieved following the mapping irradiations and processed routinely for gamma exposure levels.

B.2.3 Data Analysis and Results

The data analysis for the two extensive mapping tests required the analysis of over 1500 flux and/or activation data points. The flux and spectral perturbations in all cryogen chambers were analyzed. It is anticipated that an independent report will be published on these data at some later date.

The neutron flux ratios calculated on the basis of all flux data from both runs include Φ_{In}/Φ_S and Φ_S/Φ_{Al}, where Φ_{In} is the fast flux for $E > 0.85$ Mev, Φ_S is that for $E > 2.9$ Mev, and Φ_{Al} is that for $E > 8.1$ Mev. Activation ratios relative to sulfur activation were computed for the foils exposed in the special spectral packets. All flux and activation ratios for the cryogen chambers were compared with similar air data obtained in the normal boral-attenuated GTR irradiation cell. A brief description of the results for the north cryogen chamber follows.

The ratios Φ_{In}/Φ_S and Φ_S/Φ_{Al} calculated for the north chamber ranged from 3.11 to 3.69 and from 28.4 to 35.1, respectively. The averages of these values are within 5-10% of those anticipated for the north irradiation volume when the GTR is operating with 2 in. of water reflector. No correlation of variance with location or between poisoned- and unpoisoned-core maps was obtained in the analysis.

The resonance-activation data indicate a significant depression within the cryogen chamber for the thermal and low-energy ($<$20 ev) epithermal fluxes. However, because of the small difference in the fast-flux ratios to those anticipated, the detailed analysis did not reveal any surprising results. Therefore, use of the GTR neutron spectrum, shown in Figure B-20, with flux monitoring data for the chamber should yield reliable values for the neutron fluxes in excess of 0.1 Mev.

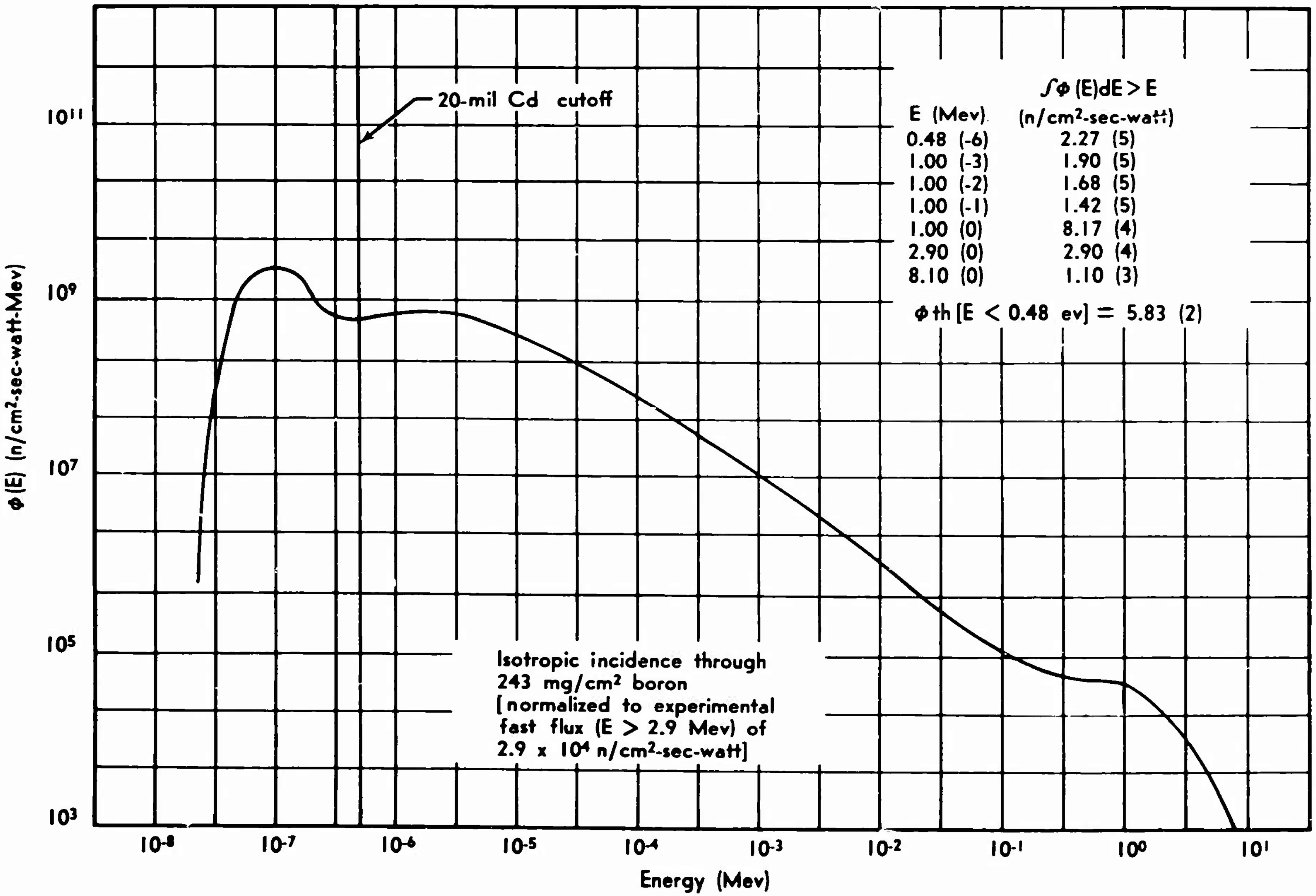


Figure B-20 Analytical GTR Neutron Spectrum

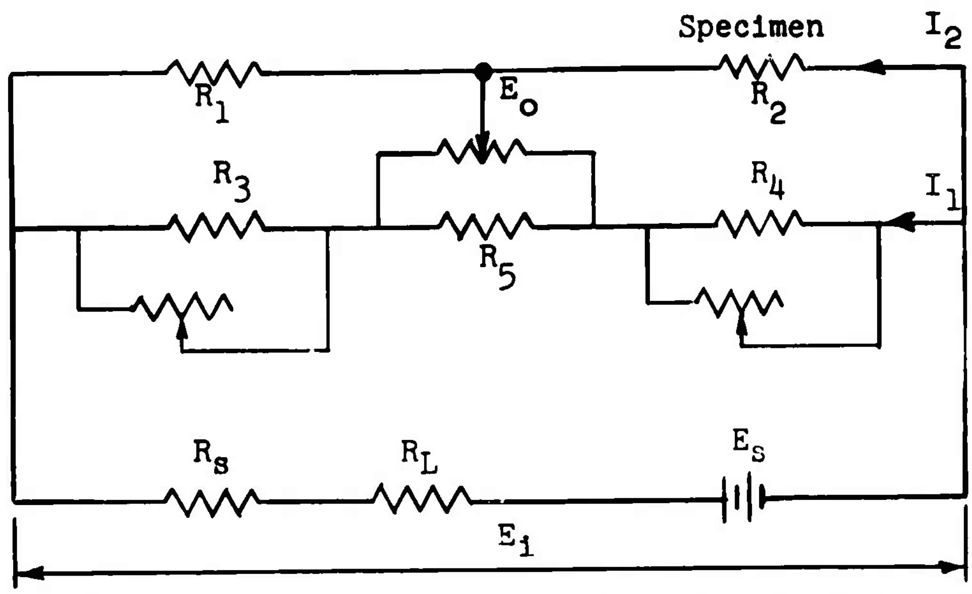
APPENDIX C

RESISTANCE BRIDGE ANALYSIS

APPENDIX C

RESISTANCE BRIDGE ANALYSIS

The following analysis is presented to show the relationship between specimen resistance change (ΔR_2) and bridge unbalance voltage (E_o^1), bridge input voltage (E_1), and dummy resistance plus specimen resistance ($R_1 + R_2$).



When the bridge is balanced, the following relationships exist:

$$I_1R_4^1 = I_2R_2 \quad \text{and} \quad I_1R_3^1 = I_2R_1$$

or

$$\frac{I_1R_4^1}{I_1R_3^1} = \frac{I_2R_2}{I_2R_1}$$

After cancelling and rearranging terms, we have

$$R_2 = \frac{R_4^1R_1}{R_3^1}$$

where

R_3^1 = resistance R_3 plus that portion of R_5 required for balance

R_4^1 = resistance R_4 plus that portion of R_5 necessary for balance

Also in the balanced system, we have

$$I_1 = \frac{E_1}{R_4^1 + R_3^1} \quad \text{and } I_2 = \frac{E_1}{R_1 + R_2}$$

$$E_o = I_1 R_4^1 - I_2 R_2 \quad \text{and}$$

$$E_o = \frac{E_1 R_4^1}{R_4^1 + R_3^1} - \frac{E_1 R_2}{R_1 + R_2} = E_1\left(\frac{R_4^1}{R_4^1 + R_3^1} - \frac{R_2}{R_1 + R_2}\right)$$

$$E_o = 0 \text{ at bridge balance}$$

At bridge unbalance (E_o^1) due to change in specimen resistance, R_2 changes to $(R_2 + \Delta R_2)$, so that

$$E_o^1 = E_1\left(\frac{R_4^1}{R_3^1 + R_4^1} - \frac{R_2 + \Delta R_2}{R_1 + R_2 + \Delta R_2}\right)$$

and since ΔR_2 (approximately 0.01 ohm) is very small compared to $R_1 + R_2$ (approximately 32 ohms), it can be neglected in the denominator above, making

$$E_o^1 = E_1\left(\frac{R_4^1}{R_3^1 + R_4^1} - \frac{R_2}{R_1 + R_2} - \frac{\Delta R_2}{R_1 + R_2}\right)$$

$$\text{Since } R_2 = \frac{R_4^1 R_1}{R_3^1},$$

$$\frac{R_4^1}{R_3^1 + R_4^1} - \frac{R_2}{R_1 + R_2} = 0$$

$$\text{Therefore, } E_o^1 = E_1 \left(- \frac{\Delta R_2}{R_1 + R_2} \right)$$

$$\text{or } \Delta R_2 = - \frac{E_o^1 (R_1 + R_2)}{E_1}$$

Sample Calculations

During irradiation the bridge output voltage changed by approximately -2000 μv. This corresponds to a resistance increase of approximately 0.02 ohm, as shown below:

$$\Delta R_2 = - \frac{E_o^1 (R_1 + R_2)}{E_1} = \frac{2000 \times 10^{-6} (16 + 16)}{3.15}$$

$$\Delta R_2 = 0.0203 \text{ ohm}$$

where

R_1 = 16 ohms

R_2 = 16 ohms

E_1 = 3.15 volts

A typical maximum bridge voltage unbalance during postirradiation annealing treatments was 935 μv. This corresponds to a resistance decrease of approximately 0.01 ohm, as shown below:

$$\Delta R_2 = -\frac{E_o^1 (R_1 + R_2)}{E_1} = -\frac{935 \times 10^{-6} (16 + 16)}{2.94}$$

$$\Delta R_2 = -0.0102 \text{ ohm}$$

REFERENCES

1. Thornton, H. G., NERVA Materials Irradiation Program, Vol. 1, GTR Test 16 - AGC Materials Test, General Dynamics/Fort Worth Report FZK-263-1, October 1965.

2. NARF Facilities Handbook, General Dynamics/Fort Worth Report FZK-185A, March 1964.