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IRRADIATION OF SNAP SYSTEM ELECTRICAL DEVICES
IN A HIGH-TEMPERATURE VACUUM ENVIRONMENT

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ABSTRACT

A series of electrical devices was exposed to an integrated fast-neutron exposure of about 5 to 8×10^{18} n/cm² in a high-vacuum environment ($<10^{-5}$ torr) with specimen temperatures maintained at specified levels in the 650 to 1050 F range to obtain radiation-effects data for the Atomics International SNAP program. Two separate experiments were conducted; 12 specimens were exposed in the first (Experiment HF-6) and 16 in the second (Experiment HF-7). Nuclear environments were measured by extensive dosimetry. The electrical characteristics of the specimens were measured during the irradiation. These data were transmitted to Atomics International for use in SNAP program systems development.

INTRODUCTION

Under the sponsorship of Atomics International, Division of North American Aviation, Inc., Battelle has been conducting a series of radiation-damage experiments at the Battelle Research Reactor (BRR). Part of the program has consisted of the irradiation of selected electronic and mechanical devices and materials under the following conditions:

Temperature - 500 to 1100 F

Integrated fast-neutron exposure - greater than 1×10^{19} n/cm²

Vacuum level - 1×10^{-5} torr or below.

The two experiments described herein constitute part of this support for the SNAP-10A program and are designated HF (high-flux) -6 and -7. Previous experiments in the HF series are described in recent reports designated BMI-X-310 and BMI-X-10109. Another part of the program consists of five in-vacuum irradiations at a nominal 150 F to total integrated fast-neutron exposures of 1×10^{16} n/cm². These experiments are described in Report BMI-X-290.

Generally, each of the two experiments consisted of the following phases:

- (1) Selection by Atomics International of components to be irradiated in each experiment and the specification of experimental conditions

- (2) Reactor flux mapping to determine neutron distribution and gamma exposure rates.
- (3) Experiment design
- (4) Experiment assembly and installation at the reactor in the previously modified high-vacuum system
- (5) Experiment operations including continuous temperature monitoring of the specimens and periodic sampling of the vacuum level and specimen performance to establish damage thresholds and ascertain the degradation rates after these thresholds were exceeded
- (6) Postirradiation evaluation of experiment dosimetry.

This report covers all aspects of the experiment. Typical performance data are presented without interpretation. The irradiated samples were examined at the Battelle Hot Cell Facility, and the results are reported separately.

IRRADIATION SYSTEM

Facility at Reactor

The high-vacuum facility at the BRR employed in these two experiments is illustrated in Figure 1. It consists of a test section (8-in. aluminum pipe), an 8-in. tee section with 6-in. side arm, a lead tube (4-in. aluminum pipe), an ionization-gage housing and lead tube (2-1/2-in. pipe), a 6-in. vacuum line (aluminum) to the pool surface, and a 6-in. oil diffusion pump (with a liquid-nitrogen cold trap) backed by a mechanical fore pump. Ionization gages are located upstream from the test section and downstream from the pump to monitor system vacuum.

The entire facility is mounted on a movable bridge which can be positioned in the back pool or moved to the front face of the reactor core. The pumping unit is mounted in a framework which allows both vertical and sidewise movement of the system to facilitate the insertion and removal of specimen assemblies and the maneuvering required to insert the test section in the core position.

The specimen subassembly is inserted through the upper side of the tee section. The assembly header is the point of exit of thermocouple and measurement leads through hermetic seals. The specimen assembly is suspended from and fully supported by the header. Two large elastomer O-rings were used to form the closures on each side of the water-exposed header flange surfaces.

The specimen lead extensions are brought to an air-conditioned room where the measurement instrumentation is located. Several necessary subsystems are on the movable bridge and include:

- (1) Temperature-recording instrumentation with a capacity of 40 thermocouples.

FIGURE 1. VACUUM IRRADIATION FACILITY AT FRONT CORE FACE OF BRR

- (2) Heater control systems for up to six individual 2-kw heaters (manual control).
- (3) A circulating water system for specimen cooling.

Specimen Assemblies

The two experiments described in this report were alike with respect to general design practice, auxiliary heating, thermocoupling, etc. The following design aspects were basic to each:

- (1) Bare wire Chromel-Alumel thermocouples were spot welded on the specimens at selected locations for in-pile temperature monitoring, with the exceptions noted in the experiment design descriptions. Between the specimen zone and the top seal plate, the thermocouple wires were insulated with 60 per cent Al_2O_3 protection tubing. Mechanical connections were made between the wires and the glass-sealed lead-out pins.
- (2) All specimen monitoring leads were bare 0.045-in. diameter nickel wire insulated with ceramic tubing. In most cases the connections were made in or near the specimen zones. Several cable samples extended to the top of the test chamber and were connected to the lead-outs with short lengths of wire.
- (3) Each experiment assembly included several independently controlled 1/8-in. -OD stainless steel-sheathed auxiliary heaters. The heaters were interposed between either individual specimens or specimen zones and the water-contacting test chamber. The heaters were used during neutron exposure to regulate specimen temperatures by functioning, essentially, as variable-temperature thermal-radiation baffles. The heaters were also employed to maintain specimens at temperature during scheduled reactor-shutdown periods and to heat the specimens to temperature to obtain preirradiation base-line performance data. All gamma and electrical heat was transferred to the chamber wall except as noted below.
- (4) The experiment assemblies were suspended on three 1/4-in. rods attached to the top seal plate. The seal plate contained 19 lead-out sites. Measurement and thermocouple leads emerged from the vacuum chamber through 9-pin hermetic seals. These seals were held in place by an O-ring and threaded brass bushing. The heater leads and water lines were brazed into metal plugs; the plugs were sealed in the header using the O-ring and bushing arrangement.
- (5) Specimen locations were dictated by irradiation-exposure specifications and by heat-transfer considerations.

HF-6 Assembly

The HF-6 experiment is shown in various stages of assembly in Figure 2. The specimens included in this experiment were:

- (1) Two 12-lead cable harnesses each consisting of 4 connectors (19 pin, 6 pin, 4 pin, and 2 pin) with appropriate glass-fiber insulated connecting cable
- (2) Two limit switches (one actuated)
- (3) Two connectors (one 2 pin, D-119, one 4 pin, D-133)
- (4) Six 6-ft metallic sheath cable samples (5 in as-received condition, 1 baked out prior to installation).

The specified operating temperature for all specimens was 700 F. The specimens were mounted in three separately heated zones. Most of the connecting cables and cable samples were strapped to the inner walls of the rectangular baffle boxes which formed the top and bottom zones to achieve uniform temperatures. The other samples were mounted in the open middle zone, except the massive 19-pin connectors. Heat-transfer calculations indicated that the large connector could not be located with the less massive specimens and operate at the same temperature. Calculations also confirmed that the large connector would operate in excess of 700 F if it were completely enclosed in the bottom baffle box. Therefore, it was mounted in conforming slots in the baffle. The 6-ft cable samples were extended from the lower end of the bottom baffle box to the top of the test chamber and consequently passed through all three zones.

Thermocouples could not be attached directly to the glass-fiber insulated cables. Cable-bundle temperatures were monitored by inserting the thermocouple bead in the center of the bundle. Where the cables were strapped to the baffle surface, the thermocouples were spot welded to the baffle surface adjacent to the cables.

HF-7 Assembly

The HF-7 specimen assembly is shown in Figure 3. The following components were included:

- (1) Two resistance temperature detectors (RTD)
- (2) Two electrically actuated band release devices (EABRD)
- (3) Nine deposited-film resistors mounted on ceramic boards
- (4) Two limit switches (one actuated)
- (5) One actuated push-button switch.

The specified operating temperature for the platinum temperature-sensing element in each RTD was $1010\text{ F} \pm 10\text{ F}$. Each element was surrounded by a zinc heat-sink bath contained in a graphite crucible. The crucible was sealed in a 3-1/2-in. -OD x 7-in. -long stainless steel can. Six sheathed thermocouples were inserted in holes in the

6630

6937

7222

FIGURE 2. EXPERIMENT HF-6 IN VARIOUS STAGES OF ASSEMBLY

8784

8786

FIGURE 3. SPECIMEN ASSEMBLY FOR EXPERIMENT HF-7

graphite wall with their beads positioned at several locations along the axial length of the element. The sheaths were welded to the bottom of the container at the point of exit, as was the connector on which the element was mounted. These fixtures were positioned side by side in the test chamber with the axial center of the platinum elements located 21 in. above the bottom of the chamber. A sheathed heater was wrapped on the outside diameter of each fixture for temperature control. The mating half on the connector for the sensor element leads was attached to a sheathed cable which extended to the vacuum seal at the top of the test chamber. The sheathed thermocouple pairs were spot welded to bare Chromel and Alume1 lead-outs.

The resistors and switches were to operate at 700 to 900 F without controlled auxiliary electrical heat. The masses of these components were small and calculations showed that gamma heating alone would not be sufficient to raise their temperature above 500 F. Therefore, they were interposed between the RTD's and the chamber wall to absorb and reradiate the thermal radiation from the RTD's.

The specified operating temperature for the gold-plated separable EABRD links was 500 F. The links were mounted in massive fixtures and the fixtures were located in the highest gamma flux available in the test chamber. The temperature of the link was dependent on its emissivity, the temperature of the loading clevises and case, and the contact conductances from the link to the case. Calculations indicated that the link temperature could be held under 500 F if the case temperature was reduced substantially and if the assumption of high contact conductances from the link to the clevis, and from the clevis to the case, was valid. Cooling lugs were welded to the fixture cases and a water-cooling coil was brazed to the lugs. The lug size was adequate to cool the case but restrictive enough to prevent the loss of additional heat when heaters were employed to control the link temperature at 500 F.

FLUX-LEVEL CONSIDERATIONS AND MEASUREMENTS

Background

The nuclear environments attained in Experiments HF-6 and HF-7 were determined by the following factors:

- (1) The specifications of neutron and gamma-ray exposures for the specimens, as presented in Table 1
- (2) The use of a BRR irradiation facility large enough to house the 8-in. test chamber and its associated shielding
- (3) An irradiation period for each experiment of three normal BRR operating cycles (total irradiation time 864 hr).

Initial examination of the specified exposures indicated the need for adjustment of the thermal-neutron fluxes and gamma exposure rates available in the irradiation site chosen to meet the requested fast neutron fluxes. A 3/8-in. -thick aluminized lead shield was interposed between the reactor core and test section to reduce the gamma exposure rate; a 0.007-in. -thick cadmium shield containing two vertical slots was

placed around the test section to depress the thermal-neutron flux. The center line of the cylindrical test chamber was 5.1 in. from the core face for maximum fast-neutron flux, as illustrated in Figure 4.

TABLE 1. NUCLEAR ENVIRONMENTS SPECIFIED FOR
EXPERIMENTS HF-6 AND HF-7

Experiment	Component	Neutron Flux, n/cm^2		Gamma, R
		Fast	Thermal	
HF-6	All	1.5×10^{19}	1.8×10^{18}	1.5×10^{10}
HF-7	EABRD	1.5×10^{19}	1.8×10^{18}	1.5×10^{10}
HF-7	RTD	5.0×10^{18}	6.0×10^{17}	1.0×10^{10}

Flux-level investigations included measurements performed both in a mock-up of the test section, and in the test-specimen assembly during irradiation. Both neutron and gamma exposures were considered.

Mock-up Measurement Techniques and Data

Preliminary mock-up data were used in arriving at the final design of the test section and its shielding, after which detailed measurements added information on neutron spectra and the distributions of neutron fluxes and gamma exposure rates throughout the volume to be occupied by the test specimens.

The mock-up chamber was fabricated from a 40-in. section of 8-in. -diameter Schedule 40 aluminum pipe. A 1/4-in. -thick plate was welded to the bottom, and the top was fitted with a removable cap attached to a lead tube. Dosimeters were supported by special holders inserted in the chamber. Mock-up operations were conducted at reactor power levels varying from 200 kw to 1 Mw, depending on the activation characteristics of the detectors. Extrapolation to full reactor power of 2 Mw was based on information taken from several power monitors.

The incident neutron field was divided into three energy groups (fast, resonance, and thermal) and investigated by techniques applicable to each of these groups.

Fast neutrons are defined as those with energies greater than 0.1 Mev, resonance neutrons are those ranging in energy from 0.1 Mev to 0.4 ev, while thermal neutrons include those of energies below 0.4 ev.

Neutron measurements consisted of energy-spectrum determinations for the fast and resonance groups, as well as the flux distributions throughout the volume of the test section for fast, resonance, and thermal neutrons. (Fast- and resonance-spectra and resonance-distribution measurements were made prior to Experiments HF-6 and HF-7. The methods used for these measurements are detailed in Report BMI-X-310 covering Experiments HF-1 through HF-4.)

FIGURE 4. THE POSITION OF THE HIGH-FLUX EXPERIMENT SPECIMEN CHAMBER
RELATIVE TO THE BRR CORE

Neutron Spectra

Representations of the fast-neutron spectrum were obtained at two elevations in the mock-up chamber from the integral neutron fluxes measured by six detectors whose reaction cross-section values approximate step increases at threshold energies ranging from 0.1 Mev to several Mev. The data, fitted to the integral Watts fission spectrum, were normalized to an integral fast neutron flux of one at 0.1 Mev as shown in Figure 5.

The resonance neutron spectrum was obtained from the differential neutron fluxes measured by four resonance detectors in combination with the cadmium-difference method of analysis, which may be used only if the differential neutron flux is proportional to the reciprocal neutron energy. Analysis of the detector data confirmed this inverse proportionality over the measured energy range.

The resultant differential spectrum, normalized to unit flux at 0.1 kev, is shown in Figure 6. This spectrum is represented mathematically as

$$\phi(E) = \phi_0/E, \quad (1)$$

where ϕ_0 is a spectral function parameter.

Neutron-Flux Distribution

The fast, thermal, and resonance neutron flux distributions were determined by measurements at five radial positions in the test chamber, as shown in Figure 4, and over a 33-inch axial span in the chamber.

The fast-neutron distribution was measured by nickel wire dosimeters. The resultant threshold flux values were corrected to total fast-neutron fluxes (i.e., energies above 0.1 Mev) by use of the established fast-neutron spectrum. The volume-averaged fast-neutron flux from 1 to 25 in. above the chamber bottom was 2.1×10^{12} n/(cm²)(sec).

The thermal-neutron distribution was measured by cobalt wire dosimeters exposed bare and enclosed in 0.020 to 0.040-in.-thick cadmium covers. Differences in the responses of the bare and cadmium-covered detectors are proportional to the thermal-neutron flux. The volume-averaged thermal-neutron flux from 2 to 30 in. above the chamber bottom was 5.3×10^{11} n/(cm²)(sec).

The resonance-neutron distribution was determined by the cadmium-difference method applied to cobalt wire detectors exposed bare and enclosed in 0.020 to 0.040-in.-thick cadmium, as detailed in Report BMI-X-310. Values of the resonance spectral function parameter (ϕ_0) were actually tabulated, permitting the determination of the total neutron flux in any subgroup within the resonance-neutron energy range by integration of the differential spectrum, Equation (1), between the chosen limits of energy. The volume-averaged value of ϕ_0 from 1 to 19 in. above the chamber bottom was 2.9×10^{11} n/(cm²)(sec), yielding an average total resonance-neutron flux of 3.6×10^{12} n/(cm²)(sec).

For each set of neutron-distribution measurements, the flux values at the five radial positions were averaged at various axial positions. Figure 7 indicates these average radial fluxes as functions of axial position.

FIGURE 5. FAST-NEUTRON-FLUX SPECTRUM

FIGURE 6. RESONANCE-NEUTRON-FLUX SPECTRUM

FIGURE 7. NEUTRON-FLUX DISTRIBUTIONS IN MOCK-UP

Gamma-Exposure-Rate Distribution

Gamma-exposure-rate measurements were made in the mock-up chamber at the same five radial positions as for the neutron distributions (see Figure 4) and over a 28-inch axial span. Measurements were made with 10-cm³ graphite-walled ionization chambers through which was maintained a small flow of carbon dioxide at atmospheric pressure. A regulated power supply applied 500 v to the chambers, and the current outputs were measured by a Keithley Model 610A Electrometer.

The ionization chambers were calibrated at the Battelle Cobalt-60 Irradiation Laboratory using copper-modified ferrous sulfate chemical dosimeters. Gamma measurements were corrected for the presence of fast neutrons, this correction being 9.3×10^{-5} erg/(g)(hr)(carbon) per n/(cm²)(sec). The volume-averaged exposure rate from 1 to 29 in. above the chamber bottom was 2.2×10^7 R/hr. Figure 8 shows the average radial exposure rate as a function of axial position in the mock-up chamber.

IN-PILE OPERATION

Experiment HF-6

Operation

This experiment was irradiated for 802 hr (93 per cent of the specified irradiation period) during BRR Cycles 149 and 150, and during parts of Cycles 151 and 152. The experiment remained out-of-pile for 9 days after the end of Cycle 150 to obtain out-of-pile specimen performance data. Most of the irradiation time which was lost during this 9-day period was regained in Cycle 152.

Temperature Levels

Specimen temperatures are summarized in Table 2. The cable harness designated 106 was installed closer to the reactor core than cable harness designated 100. Temperatures measured in the former were 25 to 50 F higher than those monitored at similar locations on the latter. Temperatures were maintained at constant elevated levels throughout this experiment; temperature distributions were altered during scheduled reactor shutdowns. Occasional temperature variations caused by reactor power changes were subsequently corrected by heater adjustments.

During the out-of-pile period following the second cycle, temperatures were maintained at nominal operating values for 4 days. The top-zone temperature was then raised to 800 F for 5 days to observe the effects of temperature change on specimen performance. When the experiment was repositioned in-pile, temperatures were restored to normal levels.

On the second day of the last cycle, the temperature of the top zone was again increased to 800 F for the remainder of the irradiation (4 days). This increase caused a 10 to 15 F temperature rise in the uncabled connectors and in the limit switches in the middle zone.

FIGURE 8. GAMMA-EXPOSURE-RATE DISTRIBUTION IN MOCK-UP

TABLE 2. SUMMARY OF SPECIMEN TEMPERATURES IN EXPERIMENT HF-6

Sample	Zone	Average Temperature, F, and Limits			
		Cycle 149	Cycle 150	Cycle 151	Cycle 152
Cable Harness 100					
19-pin connector, upper half	3	740 ± 10	745 ± 5	750 ± 10	740 ± 15
19-pin connector, lower half	3	700 ± 10	710 ± 10	720 ± 10	710 ± 15
Cables	3	660 ± 10	660 ± 10	660 ± 10	650 ± 15
6-pin connector	2	725 ± 10	725 ± 10	730 ± 5	725 ± 20
6-pin connector sheath	2	685 ± 10	680 ± 20	680 ± 5	680 ± 20
4-pin connector	2	720 ± 20	735 ± 5	740 ± 5	730 ± 15
4-pin connector sheath	2	680 ± 10	680 ± 5	680 ± 5	675 ± 15
Single conductor lug	2	660 ± 10	660 ± 10	665 ± 5	660 ± 20
Cables	1	710 ± 10	710 ± 10	715 ± 5	810 ± 15 ^(c)
Cable Harness 106					
19-pin connector, upper half	3	765 ± 5	765 ± 15	775 ± 10	775 ± 20 ^(d)
19-pin connector, lower half	3	750 ± 30	745 ± 25	760 ± 10	750 ± 15
Cables	3	685 ± 10	685 ± 5	685 ± 10	675 ± 15
6-pin connector	2	760 ± 20	765 ± 10	770 ± 10	755 ± 15
6-pin connector sheath	2	705 ± 15	700 ± 10	700 ± 10	690 ± 20
4-pin connector ^(a)	2	--	--	--	--
4-pin connector sheath	2	705 ± 20	700 ± 10	695 ± 5	700 ± 25
Single conductor lug	2	685 ± 15	675 ± 10	670 ± 10	670 ± 20
Cable	1	745 ± 5	745 ± 10	750 ± 5	800 ± 10 ^(c)
Limit Switches	2	705 ± 15	705 ± 10	705 ± 10	720 ± 5
D-119 Connector	2	735 ± 10	735 ± 5	735 ± 5	740 ± 5
D-133 Connector	2	740 ± 10	740 ± 5	740 ± 5	750 ± 5
Cable U and Cable B ^(b)	1	725 ± 10	725 ± 10	725 ± 5	800 ± 5 ^(c)
Top Zone	1	730 ± 10	730 ± 10	735 ± 5	800 ± 5 ^(c)
Bottom Zone	3	670 ± 10	670 ± 10	660 ± 10	660 ± 20

(a) This thermocouple was open before the start of the irradiation.

(b) These cables as well as Cable Samples 1, 2, 3, and 4 passed through all the zones. However, the temperatures of sheaths of Cables U and B were monitored in the top zone.

(c) This is the average temperature after the temperature was increased on the second day of the cycle.

(d) Estimated. Recording instrument out of calibration during this period.

Vacuum Levels

The vacuum readings monitored in Experiment HF-6 are presented in Figure 9. After the first week of operation, the vacuum level in the test section was 2×10^{-5} torr; it remained below 1×10^{-5} torr during the last 4 weeks of the irradiation.

The ionization-gage filaments remained in continuous operation throughout this experiment. One of the ion gages located at the test section failed near the end of the third cycle and the alternate gage was used until the completion of the experiment.

Electrical Measurements

This section presents the methods employed to obtain performance data and a summary of the performed measurements. A limited amount of data is presented in the report, but these data were only recorded as part of normal experiment surveillance. The data are not evaluated and cannot be assumed to be a true indication of the component performance under actual operating conditions.

The measurement equipment was located in a temperature- and humidity-controlled room one floor below the reactor pool surface. TV-type multiconductor cables connected the capsule lead-outs to a pool-side terminal box. The cabling between this box and the instrument room had been permanently installed for earlier experiments.

All of the specimen leads were terminated in the instrument room in a crossbar scanner connected as a 6-level, 100-point switch. The six outputs of the crossbar scanner were connected to the measurement control chassis. A mode selector switch was used to select the proper scanner level outputs for either two-wire measurements (insulation resistance and higher resistance measurements) or four-wire measurements (low resistances and contact resistances where the lead resistance would introduce error).

Insulation-resistance measurements were made with the circuit shown in the lower part of Figure 10. Switch S_1 was adjusted to produce at least three significant figures on the digital voltmeter. With Switch S_2 in the "a" position, the power supply was adjusted until the voltage drop across the shunt resistor was 50.00 v. With Switch S_2 in the "b" position, Switch S_3 was closed. After a specified time interval, the digital voltmeter was placed in the hold mode, and Switch S_3 was opened. The insulation resistance of the specimen could then be computed from the DVM reading as follows:

$$IR = \frac{50.00}{(DVM)/R_{sh}} \quad .$$

The resistance and contact-resistance measurements were made with the circuit shown in the upper part of Figure 10. The value of resistance was computed as follows:

$$R = \frac{(DVM \text{ No. } 1)}{(DVM \text{ No. } 2)/R_{sh}}$$

The value of R_{sh} was 1 ohm, and thus the resistance was the ratio of the two DVM readings.

FIGURE 9. VACUUM LEVELS MONITORED IN THE HF-6 EXPERIMENT

RESISTANCE AND CONTACT RESISTANCE
MEASUREMENT CIRCUIT

INSULATION RESISTANCE MEASURING CIRCUIT
PROVIDED BY ATOMICS INTERNATIONAL

FIGURE 10. BASIC MEASURING CIRCUITS EMPLOYED IN EXPERIMENTS HF-6 AND HF-7

All data were recorded directly on punch cards using an IBM 526 summary punch and the punch-control circuitry from the automatic data system developed for the LF-1 experiment (described in BMI-X-290). The punch cards were sorted every week to arrange the data for each specimen in chronological order. The cards were forwarded to Atomics International for data analysis.

The specimen performance measurements are identified by scanner point numbers as shown in Table 3. The notations P1, P2, etc., refer to specified wires in the cable harnesses. The internal test refers to a pair of dummy leads extending down into the specimen region of the capsule. The external test leads terminated at the feedthroughs in the capsule header plate.

Measurements were made prior to the irradiation to obtain base-line data. After the first day of irradiation, when six sets of data were taken, measurements were taken two times a day, 7 days a week for the remainder of the experiment.

Data from selected scanner points are presented in Figures 11 through 17. The scanner points are identified in the figures. The darkened areas along the bottom of the figures indicate the periods at full reactor power.

Experiment HF-7

Operation

The HF-7 experiment was irradiated for 820 hr during BRR Cycles 153, 154, and 155 (95 per cent of specified irradiation period).

Temperature Levels

Selected specimen temperatures are plotted in Figures 18 and 19 and are summarized in Table 4. The RTD element temperatures as monitored by the internal thermocouples were maintained at $1010\text{ F} \pm 15\text{ F}$ throughout the irradiation except as noted in later sections. The internal Chromel-Alumel thermocouples were monitored with a high-precision potentiometer using a compensating distilled-water ice bath. In RTD 119, the six internal thermocouples were usually all within a 6 to 8-degree spread. The thermocouples in RTD 107 were as consistent until the element circuit failed within the device on the fifth day of the second cycle. The internal-thermocouple temperature spread gradually increased from 12 to 30 F. During the course of irradiation, it was necessary to increase the auxiliary heat to RTD 107 frequently to maintain its temperature at 1010 F; at the same time, the heat addition to the other RTD was being reduced frequently to control specimen temperature.

During the initial reactor cycle start-up, it was evident that the EABRD link temperatures would exceed the desired 500 F. The experiment was removed from the core position and the core configuration was altered to reduce the gamma flux. The EABRD link temperatures equilibrated at 640 and 675 F, and it was decided to operate at these temperatures. These temperatures fluctuated throughout each cycle and from cycle to cycle as reactor power was adjusted.

TABLE 3. IDENTIFICATION OF SPECIMEN PERFORMANCE MEASUREMENTS
IN EXPERIMENT HF-6

Scanner Points	Specimen	Insulation Resistance	Resistance
0000	Cable 100	P1 to ground	P1 to P15
0001	Cable 100	P2 to ground	
0002	Cable 100	P3 to ground	P3 to P17
0003	Cable 100	P4 to ground	
0004	Cable 100	P5 to ground	P5 to P36
0005	Cable 100	P8 to ground	P8 to P39
0006	Cable 100	P13 to ground	P13 to P32
0007	Cable 106	P1 to ground	P1 to P15
0008	Cable 106	P2 to ground	
0009	Cable 106	P3 to ground	P3 to P17
0010	Cable 106	P4 to ground	
0011	Cable 106	P5 to ground	P5 to P36
0012	Cable 106	P8 to ground	P8 to P39
0013	Cable 106	P13 to ground	P13 to P32
0014	Actuated switch	Open contact to common	Closed contact to common
0015	Unactuated switch	Open contact to common	Closed contact to common
0016	Internal test	Lead to lead	Shorted leads
0017	External test	Lead to ground	Shorted leads
0018	Cable 100	P1 to P2	
0019	Cable 100	P1 to P3	
0020	Cable 100	P1 to P4	
0021	Cable 100	P2 to P3	
0022	Cable 100	P2 to P4	
0023	Cable 100	P3 to P4	
0024	Cable 100	P5 to P8	
0025	Cable 106	P1 to P2	
0026	Cable 106	P1 to P3	
0027	Cable 106	P1 to P4	
0028	Cable 106	P2 to P3	
0029	Cable 106	P2 to P4	
0030	Cable 106	P3 to P4	
0031	Cable 106	P5 to P8	
0032	Cable B	Lead to ground	
0033	Cable B	Lead to ground	
0034	Cable U	Lead to ground	
0035	Cable U	Lead to ground	
0036	Connector B	Pin A to ground	
0037	Connector B	Pin B to ground	
0038	Connector Y	Pin A to ground	
0039	Connector Y	Pin B to ground	
0040	Cable 1	Lead to ground	
0041	Cable 1	Lead to ground	
0042	Cable 2	Lead to ground	

TABLE 3. (Continued)

Scanner Points	Specimen	Insulation Resistance	Lead Resistance
0043	Cable 2	Lead to ground	
0044	Cable 3	Lead to ground	
0045	Cable 3	Lead to ground	
0046	Cable 4	Lead to ground	
0047	Cable 4	Lead to ground	
0048(a)	Instrumentation cable only	Lead to lead	
0049(a)	Instrumentation cable only	Lead to lead	
0050(a)	Instrumentation cable only	Lead to shield	

(a) Periodic check measurements.

FIGURE 11. INSULATION RESISTANCES OF SELECTED LEADS TO GROUND IN CABLE HARNESS 100 IN EXPERIMENT HF-6

FIGURE 12. INSULATION RESISTANCES BETWEEN SELECTED LEAD PAIRS
IN CABLE HARNESS 100 IN EXPERIMENT HF-6

FIGURE 13. INSULATION RESISTANCES OF SELECTED LEADS TO GROUND
IN CABLE HARNESS 106 IN EXPERIMENT HF-6

FIGURE 14. INSULATION RESISTANCE BETWEEN SELECTED LEAD PAIRS
IN CABLE HARNESS 106 IN EXPERIMENT HF-6

FIGURE 15. INSULATION RESISTANCES OF SELECTED LEADS TO GROUND FOR CABLE SAMPLES IN EXPERIMENT HF-6

FIGURE 16. INSULATION RESISTANCES OF SWITCHES AND CONNECTOR SAMPLES IN EXPERIMENT HF-6

FIGURE 17. INSULATION RESISTANCES OF DUMMY TEST LEADS IN EXPERIMENT HF-6

FIGURE 18. REPRESENTATIVE INTERNAL THERMOCOUPLE TEMPERATURE IN RTD 119 IN EXPERIMENT HF-7

FIGURE 19. TYPICAL SPECIMEN TEMPERATURES IN EXPERIMENT HF-7

TABLE 4. SUMMARY OF SPECIMEN TEMPERATURES IN
EXPERIMENT HF-7

Sample	Average Temperature, F, and Limits		
	Cycle 153	Cycle 154	Cycle 155
RTD 107			
Internal	1005 $\pm$ 10	1005 $\pm$ 15	1000 $\pm$ 15
OD of case	1005 $\pm$ 15	1030 $\pm$ 10	1050 $\pm$ 15
Connector	870 $\pm$ 10	900 $\pm$ 20	915 $\pm$ 10
RTD 119			
Internal	1015 $\pm$ 10	1015 $\pm$ 10	1010 $\pm$ 10
OD of case	965 $\pm$ 5	965 $\pm$ 15	960 $\pm$ 10
Connector	830 $\pm$ 5	835 $\pm$ 15	840 $\pm$ 10
EABRD 1			
Link	640 $\pm$ 5	635 $\pm$ 15	650 $\pm$ 10
Large clevis	645 $\pm$ 5	650 $\pm$ 20	655 $\pm$ 10
Small clevis	680 $\pm$ 5	685 $\pm$ 15	690 $\pm$ 10
Spring	510 $\pm$ 10	510 $\pm$ 10	510 $\pm$ 5
EABRD 2			
Link	670 $\pm$ 5	670 $\pm$ 20	680 $\pm$ 10
Large clevis	680 $\pm$ 10	680 $\pm$ 20	690 $\pm$ 10
Small clevis	715 $\pm$ 10	715 $\pm$ 15	720 $\pm$ 10
Spring	540 $\pm$ 10	535 $\pm$ 10	520 $\pm$ 5
Resistors	865 $\pm$ 10	895 $\pm$ 15	915 $\pm$ 15
Switch 1	800 $\pm$ 10	830 $\pm$ 10	855 $\pm$ 10
Switch 2	855 $\pm$ 10	900 $\pm$ 15	930 $\pm$ 10
Switch 3	645 $\pm$ 5	630 $\pm$ 15	620 $\pm$ 10

The resistor board and limit switches were irradiated at 800 to 900 F. However, during scheduled reactor shutdown periods, the temperatures of these specimens were increased about 100 F when additional electrical heat was needed to maintain the RTD's at temperature.

System Vacuum

During the initial pumpdown, the vacuum levels were in the 10^{-4} torr range. The vacuum level decreased from 10^{-4} torr to 10^{-5} torr during Cycle 153 (the first cycle of operation). The average vacuum level for the last two cycles was 1×10^{-5} torr. The vacuum levels are plotted in Figure 20.

On the second day of Cycle 153, the power cord to the diffusion pump shorted to ground, and instrument and heater power was lost for 1/2 hr. While repairs were being made, the system pressure rose into the micron range. The experiment remained in-pile during this period. After 1-1/2 hr, normal pumping was resumed and temperatures were returned to normal operating levels. The ionization gage at the pump failed and the alternate gage was monitored for the remainder of the experiment.

On the seventh day of the final cycle, building water pressure was interrupted for 15 min. The diffusion pump overheated, as reflected in subsequent increased liquid-nitrogen usage, but ultimate system vacuum was unaffected. Two days later, the main power line to the reactor site failed, with the subsequent interruption of all operations for a period of 12 hr. The manual valve on the roughing pump was closed immediately. When electric service was restored, the forepump would not evacuate the system properly. A replacement forepump was installed but difficulties in attaining good vacuum were still encountered. The diffusion pump was dismantled and cleaned with the associated complete loss of system vacuum. When pumping was resumed and a vacuum of 10^{-4} torr was achieved, the irradiation was resumed and specimen temperatures were restored to operating levels. Liquid-nitrogen consumption also returned to its original rate.

Electrical Measurements

The measurement circuits were the same as those described for the HF-6 experiment. Voltage measurements from the EABRD transducer-translator circuitry were made with the four-wire measuring circuit, using only the potential leads.

The RTD resistance measurements were performed using the four-wire circuit as far as the irradiation capsule header plate. Measurements between Points A and B (see Table 5) included the RTD temperature-sensing element and the lead resistances from the header plate to the RTD unit. Measurements between Points B and C were made to determine the lead resistances. The (AB) measurement minus the (BC) measurement gave the resistance of the temperature-sensing element only.

Measurements were made twice daily, 7 days a week for the entire irradiation, with the exceptions noted in the sections on RTD thermal cycling and EABRD actuation. The irradiation specimen performance measurements are identified by the scanner point number in Table 5.

FIGURE 20. VACUUM LEVELS MONITORED IN EXPERIMENT HF-7

TABLE 5. IDENTIFICATION OF SPECIMEN PERFORMANCE MEASUREMENTS
IN EXPERIMENT HF-7

Scanner Points	Specimen	Insulation Resistance	Resistance
0000	RTD 107	Pt. A to ground	Pts. A to B
0001	RTD 107		Pts. B to C
0002	RTD 119	Pt. A to ground	Pts. A to B
0003	RTD 119		Pts. B to C
0004	EABRD 1 heater	Pt. A to ground	Pts. A to B
0005	EABRD 2 heater	Pt. A to ground	Pts. A to B
0006	Switch 2	Open contact to common	Closed contact to common
0007	Resistor 2	Common to ground	R 2 to common
0008	Resistor 3		R 3 to common
0009	Resistor 4		R 4 to common
0010	Resistor 5		R 5 to common
0011	Resistor 6		R 6 to common
0012	Resistor 7		R 7 to common
0013	Resistor 8		R 8 to common
0014	Resistor 9		R 9 to common
0015	Resistor 10		R 10 to common
0016	Internal test ^(a)	Lead to lead	
0017	External test ^(b)	Feedthrough to ground	
0018	EABRD 1 transducer	Lead to ground	
0019	EABRD 2 transducer	Lead to ground	
0020	External test ^(c)	Lead to ground	
0021	External test ^(c)	Lead to ground	
0022	RTD 107		Pts. A to C
0023	RTD 119		Pts. A to C
0024	Translator 1086	Voltage-output measurement	EABRD 2
0025	Translator 1087	Voltage-output measurement	EABRD 1

(a) Insulation-resistance measurement of a pair of leads extending to the specimen area in the irradiation capsule.

(b) Insulation-resistance measurement of a feedthrough in the capsule header plate.

(c) Insulation-resistance measurement of instrumentation leads down to the header plate, but not connected at the header plate.

During the HF-7 irradiation, selected scanner points were continuously plotted for the purpose of maintaining experiment surveillance. Typical insulation resistance data are plotted in Figure 21.

In Figure 22, three curves are shown, representing the median, and the upper and lower extreme values of resistance for the nine test resistors. The vertical lines show the limits for the seven intermediate resistance values. The two drops in the lower extreme value occurred during reactor shutdowns.

RTD Thermal Cycling

To obtain calibration data from the RTD platinum elements as the irradiation progressed, four periodic thermal-cycling experiments were conducted during each reactor cycle; one of these cycling experiments was conducted during the scheduled cycle shutdown. The following procedure was used when the reactor was at power:

- (1) The sensor resistance and six internal-thermocouple outputs were monitored at the nominal 1010 F operating temperature.
- (2) The temperature was decreased to a nominal 980 F and stabilized before the same measurements were repeated.
- (3) The temperature was subsequently changed to 1010 F, 1040 F, and 1010 F again, and measurements were made at each step when temperatures were stable.

Preirradiation and between cycle, thermal-cycling data were taken as follows:

- (1) Sensor and thermocouple data were obtained at the nominal but stable 1010 F.
- (2) The RTD heaters were turned off. As the zinc bath cooled, its temperature was monitored continually by the internal thermocouples into the isotherm (approximately 787 F). The isotherm was observed for durations of 20 to 30 min and the resistance of the sensor was monitored near the end of the isotherm.
- (3) The heaters were turned on and additional data were obtained as outlined in Items 2 and 3 above.

The cycling procedure was altered slightly during the last cycle; measurements were made at 1010, 980, 1000, 1020, 1040, and 1010 F nominal temperatures. The isotherm was established at the end of the irradiation and the elements were thermally cycled with the same temperature schedule.

The results of the isotherm experiments are presented in Table 6. The isotherm experiment at the end of the irradiation was conducted while the reactor was at 215 kw. The measuring circuit for the RTD 107 element failed in the middle of the second cycle. (Hot-cell examination showed that the graphite crucible had cracked and the zinc had shorted the measurement leads.) During irradiation periods, the RTD element indicated a higher temperature than did the thermocouple, as was expected owing to internal heating from gamma radiation. Between reactor cycles, the thermocouple indicated a higher temperature than did the RTD element.

FIGURE 21. INSULATION RESISTANCES OF SELECTED SPECIMENS IN EXPERIMENT HF-7

FIGURE 22. RESISTANCES MEASURED IN EXPERIMENT HF-7

TABLE 6. SUMMARY OF RESULTS OF PLATINUM
SENSOR-ISOTHERM EXPERIMENTS

Accumulated Time In-Pile, hr	RTD 119		RTD 107	
	Resistance, ohms	Temperature, F	Resistance, ohms	Temperature, F
0	120.5	785	122.6	783
262	119.8	790	122.0	764
553	121.7	787	--	746
820	124.5	785	--	725

EABRD Actuation

Data obtained from the EABRD transducer-translator output was regularly forwarded to Atomics International. At the end of the irradiation, it was specified that one of the EABRD links be actuated while in a specified gamma flux of 1.8×10^6 R/hr (equivalent to 215-kw reactor power) at a link temperature of 500 F. A Moseley recorder was set up to monitor Translator 1087 (EABRD 1). A dual-channel Sanborn recorder was used to measure the power consumed while actuating the link heater. The power was supplied by a 12-v d-c storage battery and the current peaked at 4.95 amp. Both recorders were operated with a fast chart speed and heater power was left on until evidence of link separation was observed. The time of firing monitored by the two recorders agreed within 0.7 per cent.

The power trace was measured by a planimeter and by step integration, and yielded 811.935 w-sec (the time to actuate was 18.57 sec).

POSTIRRADIATION DOSIMETRYIn-pile Measurement Techniques and Data

The neutron and gamma exposures actually received by the specimens were determined from a series of postirradiation analyses involving data obtained during both mock-up and in-pile operations.

The actual neutron exposures were measured by two types of wire dosimeters attached to the test specimens. These wires were recovered at the Battelle hot cell and returned to the research reactor for analysis. Iron wire dosimeters were used for fast-neutron exposures, using the Fe-54 (n, p) Mn-54 threshold reaction. The resultant threshold exposures were corrected to exposures above 0.1 Mev and above 0.5 Mev using the fast-neutron energy-spectrum data obtained in mock-up dosimetry.

Cobalt-aluminum wire dosimeters (0.1 w/o cobalt) were used for thermal-neutron exposures. The total activities of the dosimeters were corrected to thermal-neutron activations by use of the cadmium ratios for cobalt as determined from mock-up measurements.

Resonance neutron exposures were calculated from the fast exposures, applying ratios of resonance- to fast-neutron fluxes as measured simultaneously in the mock-up chamber, at the positions occupied by the test specimens.

Accumulated gamma exposures were found from the mock-up measurements of the gamma exposure rates at the positions of the test specimens and the irradiation time.

The exposures of the principal test specimens of Experiments HF-6 and HF-7 as determined by these methods are given in the Appendix.

Summary of Results

The neutron and gamma exposures specified, anticipated, and actually received for Experiments HF-6 and HF-7 are compared in Table 7. Specified exposures are as stated by Atomics International. Anticipated exposures are results of mock-up dosimetry, based on irradiation-exposure-rate distributions, specimen locations in the test chamber, and maximum expected irradiation times. Received exposures are average values taken over all in-pile dosimeters associated with the specimens reported. Fast-neutron exposures received were generally below the specifications, although the test chamber was positioned in a region of maximum fast flux. Thermal-neutron and gamma exposures received generally exceeded those specified. An additional fuel element would have increased the fast flux, but the resultant gamma exposure rate could not have been tolerated by some of the specimens.

For Experiment HF-6, neutron exposures of individual specimens varied within about ± 40 per cent of the average exposure reported in Table 7. The variations resulted from placement of the specimens over a 16-in. axial span of the test chamber where flux gradients were inherent.

TABLE 7. SUMMARY OF ENVIRONMENTS FOR EXPERIMENTS HF-6 AND HF-7

Experiment, Specimen	Radiation Type	Exposures		
		Specified	Anticipated	Received
HF-6, All	Fast Neutrons, n/cm^2	1.5×10^{19}	7.5×10^{18}	5.7×10^{18}
	Thermal Neutrons, n/cm^2	1.8×10^{18}	2.1×10^{18}	1.8×10^{18}
	Gamma, R	1.5×10^{10}	2.3×10^{10}	2.2×10^{10}
HF-7, EABRD	Fast Neutrons, n/cm^2	1.5×10^{19}	8.8×10^{18}	8.3×10^{18}
	Thermal Neutrons, n/cm^2	1.8×10^{18}	2.2×10^{18}	2.4×10^{18}
	Gamma, R	1.5×10^{10}	2.6×10^{10}	2.1×10^{10}
HF-7, RTD	Fast Neutrons, n/cm^2	5.0×10^{18}	4.0×10^{18}	4.7×10^{18}
	Thermal Neutrons, n/cm^2	6.0×10^{17}	1.2×10^{18}	1.6×10^{18}
	Gamma, R	1.0×10^{10}	1.6×10^{10}	1.6×10^{10}

For Experiment HF-7, neutron exposures of parts in the two electrically actuated band-release devices (EABRD) varied within ± 15 per cent, while components of the two resistance-temperature detectors (RTD) varied within about ± 60 per cent of the exposures reported in Table 7. These variations resulted from flux attenuations in the devices; the RTD was three times more massive than the EABRD. The average fast-neutron exposure received by the two EABRD's was 45 per cent below that requested, and the exposures of the prime components (the links) were 35 per cent low. The average fast-neutron exposure received by the two RTD's was 6 per cent below that requested, though the exposures incident upon the parts facing the BRR core were 25 per cent greater than specified.

APPENDIX

RADIATION EXPOSURES OF INDIVIDUAL COMPONENTS
OF EXPERIMENTS HF-6 AND HF-7

APPENDIX

RADIATION EXPOSURES OF INDIVIDUAL COMPONENTS
OF EXPERIMENTS HF-6 AND HF-7

The neutron and gamma exposures of the individual components are listed in Tables A-1 and A-2. The neutron exposures are broken down into four groups: Group I is the thermal-neutron exposure (0 to 0.4 ev); Group II is the resonance-neutron exposure (0.4 ev to 1 Mev); Group III is the fast-neutron exposure from 0.1 to 0.5 Mev and was obtained by subtracting the fast-neutron exposure above 0.5 Mev from the total fast exposure; and Group IV is the fast-neutron exposure above 0.5 Mev.

TABLE A-1. EXPERIMENT HF-6 NEUTRON AND GAMMA EXPOSURES

Specimen	Zone ^(a)	Group I, 10 ¹⁸ n/cm ²	Group II, 10 ¹⁸ n/cm ²	Group III, 10 ¹⁷ n/cm ²	Group IV, 10 ¹⁸ n/cm ²	Gamma Exposure, 10 ¹⁰ R
Cable Harness 100						
19-pin connector	3-B	1.57	6.5	4.16	3.04	1.52
Cables	3-B	1.78	7.1	5.05	3.69	1.75
Cables	3-A	2.21	7.5	5.96	4.36	2.06
19-pin connector	3-A	1.61	6.8	4.53	3.31	1.71
Cables	2	1.72	7.8	5.80	4.24	1.88
2-pin connector	2	1.64	7.0	5.73	4.19	2.14
4-pin connector	2	2.19	9.2	8.55	6.25	2.92
6-pin connector	2	1.83	7.0	6.08	4.44	2.33
Single conductor lug	2	1.72	7.1	5.82	4.26	2.34
Cables	1-B	1.96	7.3	5.96	4.35	2.36
	1-A	1.94	7.3	5.87	4.29	2.22
Cable Harness 106						
19-pin connector	3-B	1.79	7.4	6.97	5.30	1.98
Cables	3-B	1.56	7.9	6.05	4.42	1.71
Cables	3-A	1.72	8.4	7.11	5.20	2.06
19-pin connector	3-A	2.00	8.7	9.25	6.84	2.33
Cables	2	2.10	9.3	8.97	6.55	2.65
2-pin connector	2	2.00	12.1	10.12	7.40	2.94
4-pin connector	2	1.81	8.3	6.09	4.45	2.17
6-pin connector	2	1.79	10.2	8.01	5.85	2.38
Single connector lug	2	1.91	11.0	9.18	6.71	2.41
Cables	1-B	1.78	9.4	7.55	5.52	2.43
	1-A	1.70	10.0	7.94	5.81	2.27
Limit Switches						
Actuated	2	1.84	8.2	6.87	5.03	1.76
Unactuated	2	2.04	9.8	8.27	6.05	1.76
D-119 Connector	2	2.06	7.8	7.70	5.63	2.82
D-133 Connector	2	1.77	8.8	6.20	4.53	2.10
Cables A, 3, and 4	3-B	1.78	7.1	5.05	3.69	1.75
	3-A	2.21	7.5	5.96	4.36	2.06
	2	1.85	7.4	6.46	4.73	2.05
	1-B	1.96	7.3	5.96	4.36	2.36
	1-A	1.94	7.3	5.87	4.29	2.22
	0-B	1.63	--	3.98	2.91	1.59
	0-A	0.95	--	1.73	1.27	0.83
Cables B (heat treated), 1 and 2	3-B	1.67	7.9	6.05	4.42	1.71
	3-A	1.72	8.4	7.11	5.20	2.06
	2	1.92	10.9	8.55	6.25	2.08
	1-B	1.78	9.4	7.55	5.52	2.43
	1-A	1.70	10.0	7.94	5.81	2.27
	0-B	1.50	--	5.55	4.06	1.57
	0-A	0.89	--	2.47	1.80	0.79

(a) The test region was divided into seven zones as follows, to define the exposures received by various parts of those specimens which traversed several zones

Zone Designation	Distance Above Bottom of Test Chamber, in.	Zone Designation	Distance Above Bottom of Test Chamber, in.
3-B	1 to 4	1-A	14 to 17
3-A	4 to 7	0-B	17 to 23
2	7 to 11	0-A	23 to 29
1-B	11 to 14		

A-3 and A-4

TABLE A-2. EXPERIMENT HF-7 NEUTRON AND GAMMA EXPOSURES

Specimen	Group I, 10^{18} n/cm ²	Group II, 10^{18} n/cm ²	Group III, 10^{17} n/cm ²	Group IV, 10^{18} n/cm ²	Gamma Exposure, 10^{10} R
RTD 107					
Upper Half					1.12
Surface (total)	1.01	4.4	3.9	2.82	
Front (core side)	1.13	6.4	5.6	4.09	
Back (away from core)	1.06	2.9	2.6	1.84	
Lower Half					1.61
Surface (total)	0.98	6.0	5.3	3.86	
Front (core side)	1.52	8.9	7.8	5.69	
Back (away from core)	0.75	3.4	2.9	2.17	
Connector	2.48	10.1	8.8	6.46	2.01
RTD 119					
Upper Half					1.32
Surface (total)	1.28	3.9	3.5	2.51	
Front (core side)	1.90	5.9	5.2	3.75	
Back (away from core)	0.69	2.0	1.7	1.26	
Lower Half					1.62
Surface (total)	1.73	5.5	4.8	3.51	
Front (core side)	2.54	8.4	7.3	5.37	
Back (away from core)	1.02	2.9	2.6	1.84	
Connector	2.21	8.9	7.7	5.69	1.99
EABRD 1					
Link	2.85	13.1	11.3	8.30	2.12
Large clevis	2.36	10.2	8.9	6.49	2.15
Small clevis	2.41	10.7	9.2	6.74	2.09
Spring	2.35	9.5	7.3	5.32	1.80
EABRD 2					
Link	2.44	13.9	12.0	8.79	2.15
Large clevis	2.23	10.4	9.1	6.61	2.19
Small clevis	2.36	11.1	9.5	6.93	2.12
Spring	2.20	9.7	7.5	5.46	1.77
Resistors	1.79	8.2	7.2	5.22	1.84
Limit Switches					
Actuated	1.42	2.3	2.0	1.45	1.11
Unactuated	1.42	2.3	2.0	1.45	1.00
Push-Button Switch	0.85	4.4	3.9	2.79	1.53