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PRELIMINARY REPORT OF TMI-2 IN-CORE INSTRUMENT DAMAGE

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ABSTRACT

In situ tests were performed on the in-core instrumentation at TMI-2 in order to establish the operational conditions and/or failure modes of the in-core thermocouples, self-powered neutron detectors (SPNDs), and background detectors. To determine the extent of possible core damage, a statistical analysis of both the in situ test data and actual in-core instrument data obtained during and following the accident was performed. The results of this investigation indicate that the center area of the core experienced the major change as a result of the accident. In general, the test data indicate that all thermocouples apparently failed and that the majority of the SPNDs and background detectors had moisture in the insulation. Additional in situ testing will be performed to identify the location of instrument failures and to refine the estimates of the length of in-core thermocouples.

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PRELIMINARY REPORT OF TMI-2 IN-CORE INSTRUMENT DAMAGE

INTRODUCTION

In situ tests were performed on all of the in-core instrumentation, including 364 self-powered neutron detectors (SPNDs), 52 background detectors, and 52 thermocouples (Type K). The tests were designed to evaluate the general condition of the in-core detectors, identify possible failure modes, and determine the length of the in-core thermocouples (TCs).

In an effort to better understand the general condition of the core, a resistive model of the in-core instrumentation based on the resistance data is considered in light of possible failure modes. Furthermore, in order to establish discrete classes of instrument damage and to identify the effect of the accident on in-core instruments, the TC and SPND resistance data were subjected to statistical grouping and analysis.

This report presents a summary of in situ test results and correlations between core exit temperatures and the resistive conditions of in-core instrumentations. The correlations are based on postaccident temperature data and various sets of pre- and postaccident resistance measurements on TCs and SPNDs.

This work was accomplished from January through June 1982. Results from this study were presented informally to the Technical Advisory and Assistance Group for Reactor Evaluation at TMI during June and July 1982.

Resistive Model Analysis

Resistance data are from in situ test performed by EG&G Idaho on in-core instrumentation during February and March 1982 and from earlier tests conducted by others. Postinstallation resistance measurements were used to provide a baseline for evaluating the available in situ test data.

Based on estimated preaccident resistance data, it is possible to calculate the amount of change in a TC's total resistance as a result of the accident. The resistance change for each TC, normalized by the ohms per foot value from postinstallation data, may relate to the present location of the TC junction. This analysis assumes that no shunting of actual resistance values has resulted from moisture in the insulation, an assumption validated by actual laboratory tests.

An evaluation of the available test data indicates that additional in situ testing will provide valuable information on the condition of in-core instrument extension cabling, as well as information needed to improve estimates of actual in-core TC length.

Statistical Analysis

Postaccident temperature data and various sets of pre- and postaccident resistance measurements of in-core TCs and SPNDs are used in this analysis. The data sets are statistically grouped and analyzed to establish discrete classes of instrument damage, the basic purpose of which is to identify the effect of the accident on in-core instruments. Determination of specific causes of various failure modes remains for future investigation.

Three statistical groups of damage are identified in Figure 1. Group I consists of locations having experienced highest temperatures and apparently greatest damage. As expected, these locations are in the center of the core. Group II consists of locations having experienced lower temperature and apparently least damage. They are nearer the perimeter of the core. Within these first two groups, measured data and, presumably, damage to the instruments are very consistent and correlate well with temperature. Group III locations present inconsistent data and are poorly correlated with temperature. They seem to be geometrically grouped in two regions of the core, as shown in Figure 1.

The loss of all seven SPNDs and the background detector was mostly in Group I, while being inconsistent in Group III. For the most part, one or

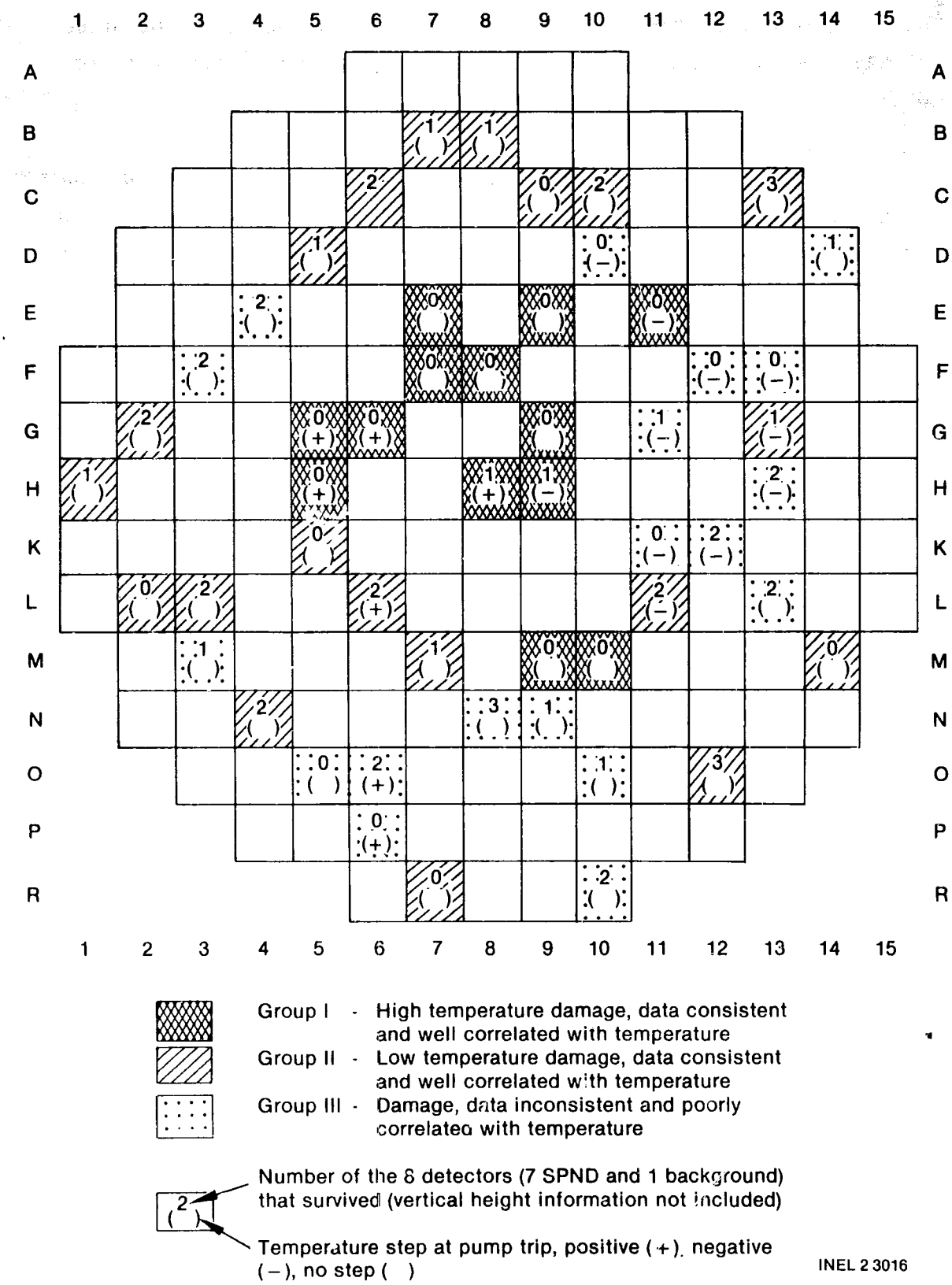


Figure 1. In-core instrument damage map.

more survived in Group II. Also, most of the survivors, 40 out of 50, were at the lower two core levels. None of the other data seems to correlate with vertical height.

The postaccident core temperature indicated by the TCs shows another grouping phenomenon. During the seventh day after the accident, a pump tripped. This resulted in a step increase of temperature at seven locations, a step decrease at 11 locations, and no change at the remainder of the locations. The step increases were generally grouped in Group I, whereas the step decreases were mainly grouped in a region of Group III.

DESCRIPTION OF IN-CORE INSTRUMENTATION

The in-core instrumentation consists of 52 detector assemblies located in instrument tubes distributed throughout the core. Each of the 52 detector assemblies (0.292 in. OD) contains seven SPNDs, one background detector, and one Type K TC. Each SPND consists of a rhodium beta emitter and zircaloy lead wire surrounded by aluminum oxide (Al_2O_3) insulation with a 0.0625 in. OD Inconel sheath. The background detector is a SPND without a rhodium detector. The TC has a 0.0625 in. OD Inconel sheath with Al_2O_3 insulation. The SPNDs are equally spaced at different elevations throughout the area of the active core, while the TCs pass completely through the active core region, their junctions positioned approximately 7 in. above the core. Each detector assembly has a total length of approximately 130 ft.

The in-core instrumentation considered in this study includes the extension cables and containment penetrations, extending from the detectors to the relay racks in the cable room. Access to the instrumentation was available through the relay racks. Figure 2 is a sketch of the in-core instrumentation system showing the range of cable lengths. The in-core monitoring extension cable consists of nine pairs of AWG Number 20 conductors paired and twisted. One pair was Chromel-Alumel TC extension wire; the other eight pairs were tinned copper. The AWG Number 20 conductors are stranded (7 x 0.0126 in.).

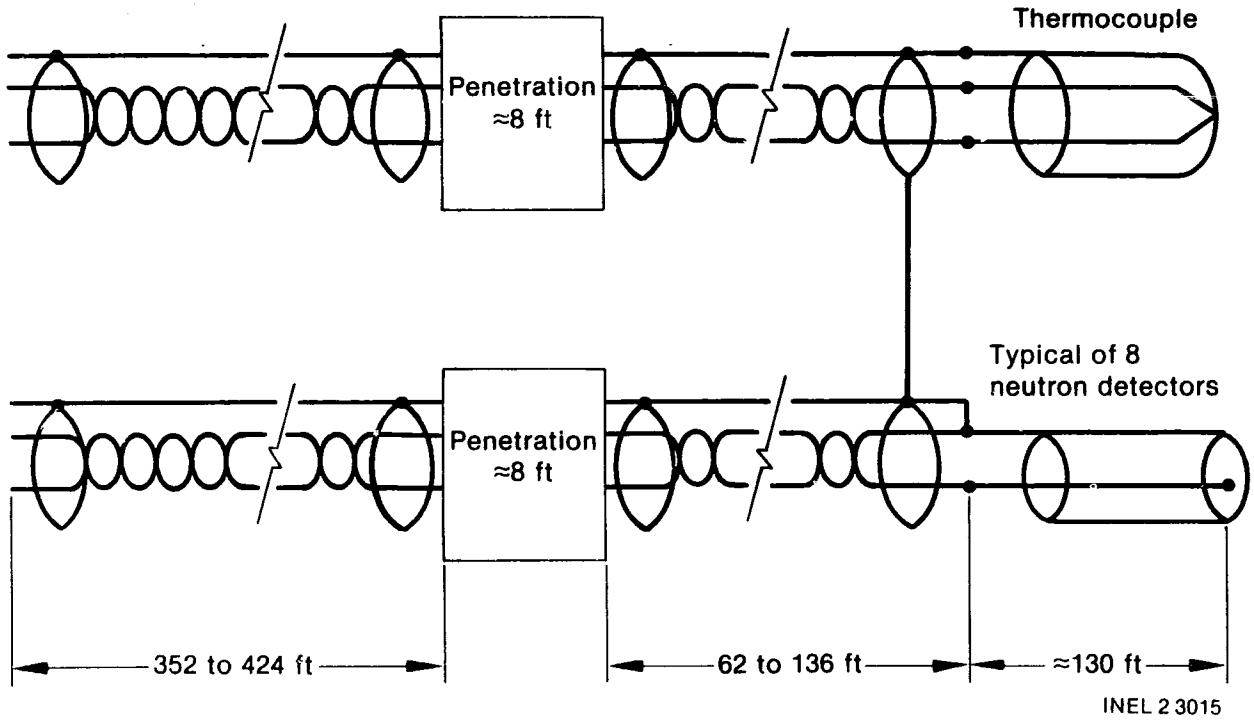


Figure 2. In-core instruments and range of cable lengths.

DATA SOURCES

Since the accident of March 28, 1979, considerable data have been collected on the in-core detectors, including the background detectors, SPNDs, and TCs. H. D. Warren and L. Banda[1,2] provided in situ test data on various in-core instruments shortly after the accident. EG&G Idaho also conducted in situ tests on the in-core instrumentation during February and March 1982. In addition to postaccident test data, various sets of preaccident data were considered, and provide a baseline for the evaluation. Postinstallation measurements of TC resistance and SPND insulation resistance were available. Plan records also included information on in-core monitoring cable lengths and conductor size.

RESISTIVE MODEL ANALYSIS

Potential failure modes for both the in-core TCs and SPNDs were considered in evaluating the in-core instrumentation. The in-core TCs were fabricated with grounded junctions, whereas the SPNDs normally exhibited an insulation resistance greater than 1×10^{10} ohms. The failure mode for each would, therefore, be different. The potential failure modes are

1. Thermocouples

    a. Open junction, no moisture in cable

    b. Open junction, moisture in cable

    c. Normal junction, moisture in cable

    d. Shunting effect due to moisture and corrosion in connector

    e. Failure Modes 1b and 1c occurring at other than the original junction location.

2. SPNDs (including background detectors)

    a. Open, moisture in cable

    b. Conductor to sheath short, no moisture in cable

    c. Conductor to sheath short, moisture in cable

    d. Shunting effect due to moisture and corrosion in connector

    e. Failure Modes 2a, 2b, or 2c occurring other than the normal end of the detector.

In the resistive model for this evaluation, an SPND exhibiting an open circuit condition was assumed to have experienced less damage than a detector exhibiting a sorted condition. Inasmuch as the TCs were normally grounded junction devices, it should be possible to verify the preaccident resistance data using the postaccident resistance data. Assuming that no shunting occurred in the TC's resistance because of moisture in its insulation, it should be possible to calculate any change in the location of the TC's junction, considering reduction in expected TC resistance values. Laboratory tests conducted at INEL verified that no shunting occurred in either the in-core detector cable or the TC as a result of moisture in the insulation.

An initial reiview of the 1982 in situ test results indicated that 22 of the 416 SPNDs had insulation resistances greater than 10^9 ohms and were therefore considered good. Most of these "good" detectors were in the lower levels of the active core area. Of the remaining SPNDs, seven had high resistance readings but were not considered high enough to be operational, while 331 exhibited characteristics of open circuit detectors with moisture in the insulation. This judgment is based on evaluation of in situ test data in the light of laboratory tests. The results indicate that an open junction detector with moisture in the insulation exhibits a charging characteristic while resistance measurements are made. Fifty-six SPNDs located at various elevations, mainly in the center area of the core, indicated a short circuit failure mode. Twenty-six of the TCs also had open junctions, with moisture in their insulation. Two TCs were dry, with open circuit characteristics. The remainder of the TCs had shorted junctions.

A comparison was made between the pre- and postaccident resistance data from the TCs with shorted junctions, and a decrease was observed in every case. The preaccident data lacked a measurement of the total resistance loop as defined in Figure 2. The in-core TC (130 ft) resistance was measured, but the remainder was only recorded as pull length. In this case, the manufacturer's data were used to calculate loop resistance and has an unknown of ±5% plus a potential trim error (approximately 0.5 ohms/ft). The resultant possible error in terms of feet of in-core TC is 3 to 4 ft, but should be a constant bias.

The decrease in resistance occurring in each of the TCs was normalized using the ohm/ft value of the as-installed TC. The normalized value of the resistance change was equivalent to a length in feet and could be indicative of the location of the TC's junction. The change in the length (normalized resistance) ranges between approximately 25 and 10.5 ft. From the available data, two sets of normalized resistance values were considered and averaged. Meaningful resistance data were not available for all the in-core TCs. The delta change that occurred in these averaged values was tabulated. The available data are shown in Table 1. The maximum change in length exceeded the length of the active core, whereas the delta change in the normalized values was more closely related to core length. An unidentified shunting effect, or the preaccident data uncertainties, could account for the additional change in normalized resistance values. Tests are planned to better define the measured data.

The delta change in the normalized resistance for each of the TCs was plotted three-dimensionally. The plot of the logarithm of the normalized resistance is shown in Figure 3 (compare Figure 1). The longest vertical height on the lot corresponds to the TC experiencing the minimum reduction in normalized resistance, thus, the base represents a TC 25 ft shorter than installed length. Grid locations where the vertical height drops below zero represent TCs having open junctions, and no resistance data were available.

A review of the TC data indicate that the center area of the core experienced the major change during the accident. The in-core SPND data also indicate that the majority of the shorted SPNDs were located in the center area of the core.

In assessing the extent of damage to the in-core instruments, TCs exhibiting the maximum change in resistance were considered to have experienced more damage than the others. Since an operating in-core detector exhibits an open circuit condition by design, the open circuit conditions would probably be a less severe failure mode than a shorted condition. The majority of the in-core detectors still have open circuit characteristics. Test data also indicate that a number of SPNDs failed as a result of

TABLE 1. AVERAGE DECREASE IN THERMOCOUPLE LENGTHS AS DETERMINED FROM RESISTANCE DATA

Assembly	Grid Location	Set 1 (ft)	Set 2 (ft)	Average (ft)	Delta (ft)
1	H-8	20.92	22.59	21.75	3.425
2	H-9	12.4	10.87	11.635	13.54
3	G-9	22.77	24.55	23.66	1.515
4	F-8	23.04	26.09	24.565	0.61
5	E-9	21.1	23.14	22.12	3.055
6	F-7	23.94	24.34	24.14	1.035
7	E-7	24.11	24.8	24.455	0.72
8	G-6	24.92	24.89	24.905	0.27
9	G-5	24.55	25.8	25.175	0
10	H-5		21.19	21.19	3.985
11	K-5	13.39	9.9	11.654	13.53
12	L-6	13.7	13.51	13.605	11.57
13	M-7	14.1	16.3	15.2	9.975
14	N-8	--	--	--	--
15	N-9	--	--	--	--
16	M-9	22.96	26.16	24.56	0.615
17	M-10	22.95	23.36	23.155	2.02
18	L-11	12.97	12.05	12.51	12.665
19	K-11	24.18	24.73	24.455	0.72
20	K-12	--	--	--	--
21	H-13	--	--	--	--
22	G-13	--	--	--	--
23	F-13	--	--	--	--
24	F-12	--	--	--	--
25	G-11	--	--	--	--
26	E-11	25.18	24.64	24.91	0.265
27	D-10	24.43	23.24	23.835	1.34
28	C-10	15.8	15.08	15.44	9.735
29	C-9	14.81	14.06	14.435	10.74
30	B-8	13.29	14.89	14.09	11.085
31	B-7	14.42	12.2	13.31	11.865
32	C-6	14.25	12.43	13.34	11.835
33	D-5	15.11	11.02	13.065	12.11
34	E-4	--	--	--	--
35	F-3	--	--	--	--
36	G-2	15.23	13.4	14.315	10.86

TABLE 1. (continued)

Assembly	Grid Location	Set 1 (ft)	Set 2 (ft)	Average (ft)	Delta (ft)
37	H-1	11.78	12.1	11.94	13.235
38	L-2	16.62	--	16.62	8.555
39	L-3	15.85	14.32	15.085	10.09
40	M-3	--	--	--	--
41	N-4	13.65	11.81	12.73	12.445
42	O-5	--	--	--	--
43	O-6	--	--	--	--
44	P-6	--	--	--	--
45	R-7	22.05	21.65	21.85	3.325
46	R-10	11.38	9.6	10.49	14.685
47	O-10	--	--	--	--
48	O-12	13.85	12.45	13.15	12.025
49	M-14	19.97	18.16	19.065	6.11
50	L-13	--	--	--	--
51	D-14	--	--	--	--
52	C-13	14.86	12.39	13.625	11.55

reduced insulation resistance some time after the temperature had returned to lower levels. Data indicate that moisture was absorbed by the insulation. The actual failure mechanism was probably initiate by the earlier high temperatures and possibly thermal shock.

The thermal history of the in-core instruments is not well known. Laboratory tests were conducted in an attempt to reproduce the shorted condition on the SPNDs as a function of temperature, but the test proved inconclusive. Sheath failure, which is indicative of the 331 in-core SPNDs that exhibit open circuits, represents a minimum temperature excursion of 2498 to 2597°F for thermal damage only, or at lower temperatures if rapid quenching is also considered (as determined earlier by Babcock and Wilcox[3]). Additional in situ testing and data reduction will be performed in an effort to better understand failure mechanism and postaccident data.

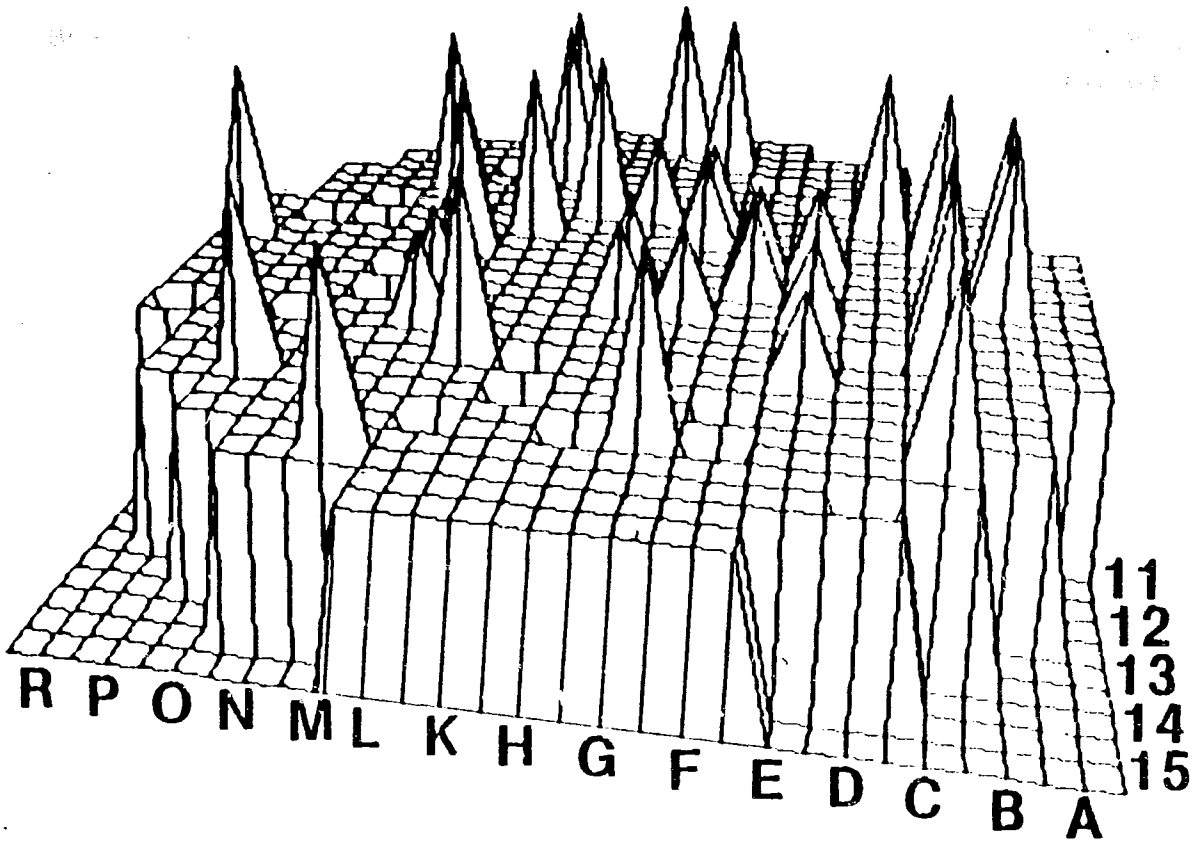


Figure 3. Three-dimensional plot of normalized resistance for each thermocouple.

STATISTICAL ANALYSIS

Data Description

The data, shown in Table 2, were obtained from various sources. The following is a description of the data on the left side of Table 2, by column:

Grid	This column indicates the core grid location of an instrument set. A set consists of nine detectors vertically distributed in the core. Starting at the bottom, there are six SPNDs, a SPND background detector, a seventh SPND, and on top at the outlet is the TC.
Temperature Peak (°F)	Temperatures indicated by the TCs were recorded between 4 and 5 h after the accident scram (0400, 28 March, 1979). For this report, these temperatures are assumed to be the peak temperatures. Although the temperatures may be inaccurate, they are still of value to this statistical analysis because relative grouping is employed. This peak temperature is of interest since some forms of damage, such as melting, are a function of peak temperature. The temperature must exceed some threshold long enough for sufficient energy to cause the damage. The data were obtained by the Metropolatin Edison Instrument Department, 28 March, 1979 between 0800 and 0900. Inlet temperature (RTD) was 250°F; exit temperature (RTD) was off scale (see Reference 4, TMI-0009190). These are essentially the same temperatures given in NUREG-0600, page I-4-63.

TABLE 2. DATA SHEET

	Temperature				Temperature								
					Group I				Group II				
					TC ΔR > 17%		SPND 7 or 8 shorts		TC ΔR < 17%		SPND 6 or less shorts		Group III No ΔR Data or Inconsistent
Grid	Peak	Average[a]	TC ΔR% Decrease	Number of SPNDs: Ok, Shorted	Peak >1200	Average >296	Peak >1200	Average >296	Peak <1200	Average <296	Peak <1200	Average <296	
8-H	1295	410 +	18	1,7	X	X	X	X	--	--	--	--	--
9-H	2176	302 -	9	1,7	--	--	X	X	--	--	--	--	--
9-G	1806	376	19	0,8	X	X	X	X	--	--	--	--	--
8-F	2378	297	20	0,8	X	X	X	X	--	--	--	--	--
9-E	2560	350	19	0,8	X	X	X	X	--	--	--	--	--
7-F	2266	307	20	0,8	X	X	X	X	--	--	--	--	--
7-E	1926	309	20	0,0	X	X	--	--	--	--	--	--	--
6-G	1974	319 +	21	0,0	X	X	--	--	--	--	--	--	--
5-G	2272	343 +	20	0,8	X	X	X	X	--	--	--	--	--
5-H	2452	315 -	18	0,7	X	X	X	X	--	--	--	--	--
5-K	1811	294	10	0,0	--	--	--	--	--	X	--	X	--
6-L	382	360 +	11	2,0	--	--	--	--	X	--	X	--	--
7-M	2171	293	12	1,5	--	--	--	--	--	X	--	X	--
8-M	578	310	--	3,3	--	--	--	--	--	--	--	--	X
9-N	2167	295	--	1,0	--	--	--	--	--	--	--	--	X
9-M	2327	330	20	0,8	X	X	X	X	--	--	--	--	--
10-M	398	314	19	0,8	--	X	--	X	--	--	--	--	--
11-L	296	310 -	11	2,0	--	--	--	--	X	--	X	--	--
11-K	682	343 -	20	0,0		X[b]					X		X
12-K	1760	309 -	--	2,0	--	--	--	--	--	--	--	--	X
13-H	1852	304 -	--	2,0	--	--	--	--	--	--	--	--	X
13-G	234	313 -	14	1,3	--	--	--	--	X	--	X	--	--
13-F	555	297 -	--	0,0	--	--	--	--	--	--	--	--	X
12-F	323	307 -	--	0,0	--	--	--	--	--	--	--	--	X
11-G	1875	400 -	--	1,0	--	--	--	--	--	--	--	--	X
11-E	326	335 -	21	0,8	--	X	--	X	--	--	--	--	--
10-D	500	391 -	20	0,0	--	X[b]					X		X
10-O	325	291	13	2,1	--	--	--	--	X	X	X	X	--
9-C	957	292	11	0,0	--	--	--	--	X	X	X	X	--
8-B	325	291	11	1,7	--	--	--	--	X	X	--	--	--

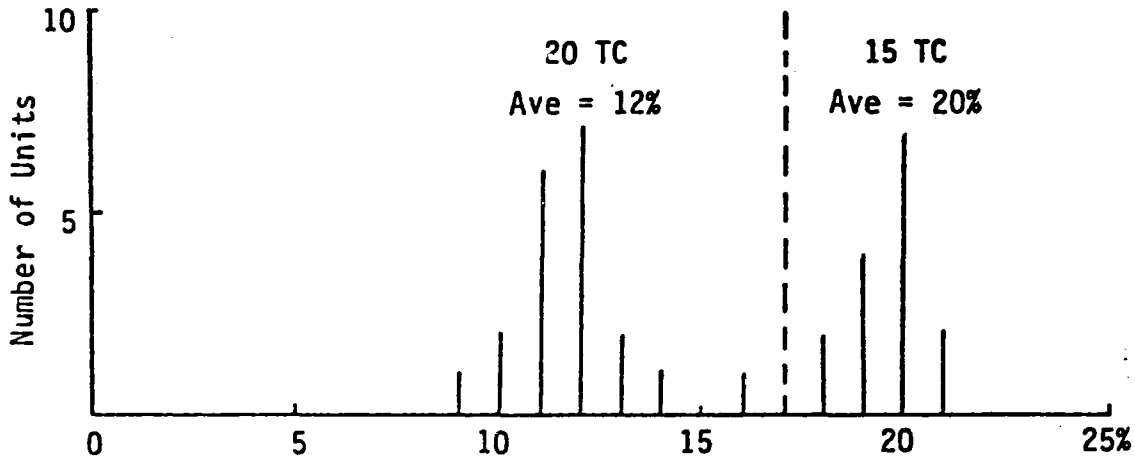
TABLE 2. (continued)

Grid	Temperature Peak	Temperature Average[a]	TC ΔR% Decrease	Number of SPNDs: Ok, Shorted	Temperature: Group I, TC ΔR > 17%: Peak >1200	Group I, TC ΔR > 17%: Average >296	Group I, SPND 7 or 8 shorts: Peak >1200	Group I, SPND 7 or 8 shorts: Average >296	Group II, TC ΔR < 17%: Peak <1200	Group II, TC ΔR < 17%: Average <296	Group II, SPND 6 or less shorts: Peak <1200	Group II, SPND 6 or less shorts: Average <296	Group III No ΔR Data or Inconsistent
7-B	281	289	11	1,3	--	--	--	--	X	X	X	X	--
6-C	469	292	12	2,6	--	--	--	--	X	X	X	X	--
5-D	1196	293	12	1,2	--	--	--	--	X	X	X	X	--
4-E	599	292	--	2,6	--	--	--	--	--	--	--	--	X
3-E	80	292	--	2,4	--	--	--	--	--	--	--	--	X
2-G	375	290	13	2,0	--	--	--	--	X	X	X	X	--
1-H	260	289	12	1,2	--	--	--	--	X	X	X	X	--
2-L	373	289	12	0,6	--	--	--	--	X	X	X	X	--
3-L	1566	290	12	2,0	--	--	--	--	--	X	--	X	--
3-M	325	289	--	1,2	--	--	--	--	--	--	--	--	X
4-N	413	293	10	2,0	--	--	--	--	X	X	X	X	--
5-O	356	291	--	0,0	--	--	--	--	--	--	--	--	X
6-O	462	294 +	--	2,0	--	--	--	--	--	--	--	--	X
6-P	291	292 +	--	0,1	--	--	--	--	--	--	--	--	X
7-R	352	291	19	0,0	--	--	--	--	--	--	X	X	--
10-R	475	288	--	2,6	--	--	--	--	--	--	--	--	X
10-O	1138	293	--	1,0	--	--	--	--	--	--	--	--	X
12-O	309	290	11	3,0	--	--	--	--	X	X	X	X	--
14-M	252	293	16	0,0	--	--	--	--	X	X	X	X	--
13-L	1774	No data	--	2,1	--	--	--	--	--	--	--	--	X
14-D	217	287	--	1,0	--	--	--	--	--	--	--	--	X
13-G	No data	293	12	3,0	—	—	—	—	—	X	—	X	—
			Column Totals		10	14	9	11	15	16	17	16	17
			Group Totals		13				20				19

a. The temperature step at pump trip (when present) is shown as positive (+) or negative (-).

b. Sets at Grid Locations 11-K and 10-D fall into both Group I and II, and because of this inconsistency have been transferred to Group III.

Temperature Average (°F)	The available average temperature was the 10-day average from the 2nd to the 12th day after the accident. It included a pump trip on the 7th day. The direction of the step temperature change due to the pump trip is indicated for the locations that experienced the change. This average temperature is of interest since some forms of damage, such as the change in material characteristics, are a function of accumulated thermal energy over a period of time, which in turn are proportional to average temperature. See Reference 5.
TC ΔR% Decrease	Preaccident resistance measurements were used as a baseline. Postaccident measurements were taken a few days after the accident and again in February 1982. Even though the second set of data was taken 3 yr after the accident, it greatly decreased the statistical uncertainty present in the first postaccident set. The decrease in resistance (ΔR) with respect to the preaccident baseline resistance was calculated. In several cases, the data seemed very inconsistent and a value could not be determined. The ΔRs fell into three distinct groups: (Group I) averaging 20% reduction, (Group II) a 12% reduction group, and (Group III) where ΔR could not be determined due to inconsistent data. Figure 4 tabulates these groupings. The pre- and postaccident (April 1979) data were obtained from Reference 1. The 1982 data were taken during the in situ test by EG&G Idaho.
SPND Number OK-Shorted	This column contains data on a set of eight SPND detectors (seven SPND units and one background detector). Two sets of postaccident resistance measurements are available (April 1979 and February 1982). Once



Grouping	Description	Number
Low resistance decrease	Consistent data	20
High resistance decrease	Consistent data	15
Subtotal	--	35
Unknown resistance change	Inconsistent data	16
Non-Functional	No data	1
Subtotal	--	17
Total	--	52

Figure 4. Distribution of thermocouple resistance decrease.

again, a composite of both sets reduced the statistical variations. The first number in the column indicates the number of units in a set that have a very high normal resistance reading. It is assumed that these are normal (OK). The second number is the number of units that appear to be shorted and are considered non-functional (damaged). The units not accounted for showed a charging characteristic. The ohmmeter indicator drifted upward during the measurement. The "chargers" were more prevalent in Group II. No level information has been included. See References 1 and 2.

Data Analysis

The instrument damage is primarily a result of thermal energy. In simplified form

$$\text{Damage} = f\,(T_{peak}, T_{ave})$$

where

$$T_{ave} = K \int_{2\ \text{days}}^{12\ \text{days}} T(t)\,dt.$$

In other words, temperature is the independent variable and damage is the dependent variable. The data analysis effort, then, consists of a search for a statistical relationship between the independent variable (temperature) and the dependent variable (damage). Due to the nature of the data and lack of a model, a functional relationship was not sought; rather, an attribute relationship was sought. The data were grouped and relationship hypotheses tested with the enumerated data. Many combinations were tested. Combinations that showed a high correlation and still preserved a realistic relationship to the physical world are presented in Figures 5 and 6.

Thermocouples, resistance data available (34)

°F	ΔR > 17%	ΔR < 17%	Total
<1200	10	4	14
<1200	5	15	20
Total	15	19	34

$\chi^2 = 7.20$

Thermocouples, resistance data not available (17)

°F	ΔR > 17%	ΔR < 17%	Total
>1200	—	—	5
<1200	—	—	12
Total			17

$\chi^2 = 2.88$

Total thermocouples

°F	ΔR > 17%	ΔR < 17%	Total
>1200	14	5	19
<1200	20	12	32
Total	34	17	51

$\chi^2 = 0.67$

a. TC ΔR Versus Peak Temperature

Thermocouples, resistance data available (35)

°F	ΔR > 17%	ΔR < 17%	Total
>296	14	4	18
<296	1	16	17
Total	15	20	35

$\chi^2 = 18.45$

Thermocouples, resistance data not available (16)

°F	ΔR > 17%	ΔR < 17%	Total
>296	—	—	6
<296	—	—	10
Total			16

$\chi^2 = 1.00$

Total thermocouples

°F	ΔR > 17%	ΔR < 17%	Total
>296	18	6	24
<296	17	10	27
Total	35	16	51

$\chi^2 = 0.86$

b. TC ΔR Versus Average Temperature

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Figure 5. Chi-square calculations for thermocouple resistance decrease versus temperature correlation.

SPND sets
TC resistance data
available (34)

°F	Shorts ≥7	Shorts ≤6	Total
>1200	9	5	14
<1200	3	17	20
Total	12	22	34

$\chi^2 = 8.76$

SPND sets
TC resistance data
not available (17)

°F	Shorts ≥7	Shorts ≤6	Total
>1200	0	5	5
<1200	0	12	12
Total	0	17	17

$\chi^2 = 2.88$

Total
SPND sets

°F	Shorts ≥7	Shorts ≤6	Total
>1200	9	10	19
<1200	3	29	32
Total	12	39	51

$\chi^2 = 9.56$

a. Number of SPNDs Shorted Versus Peak Temperature

SPND sets
TC resistance data
available (35)

°F	Shorts ≥7	Shorts ≤6	Total
>296	11	7	18
<296	1	16	17
Total	12	23	35

$\chi^2 = 11.84$

SPND sets
TC resistance data
not available (16)

°F	Shorts ≥7	Shorts ≤6	Total
>296	0	6	6
<296	0	10	10
Total	0	16	16

$\chi^2 = 1.00$

Total
SPND sets

°F	Shorts ≥7	Shorts ≤6	Total
>296	11	13	24
<296	1	26	27
Total	12	39	51

$\chi^2 = 12.53$

b. Number of SPNDs Shorted Versus Average Temperature

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Figure 6. Chi-square calculations for SPND damage versus temperature decrease versus temperature correlation.

Figure 5 presents the relationships between TC damage and peak temperature and also average temperature. For purposes of the chi-square (χ^2) analysis, the TCs having a stable measurable resistance were classified "good," whereas the remaining TCs were classified "bad." The chi-square is used as a measure of the relationship between TC resistance and temperature. The higher the value of of χ^2, the higher the probability that the two parameters are related.

The peak temperature was partitioned at the 1200°F level. This value was chosen because previously reported information[6] shows that the TC and SPND cables start to change characteristics at this temperature. The TC resistance was partitioned at 17% (see Figure 4) and the χ^2 calculated. Notice how inclusion of the inconsistent ΔRs mask the relationship between the consistent ΔRs and the peak temperature. The relationship between the ΔRs and the average temperature follows the same pattern. The partitioning at 296°F is based on an apparently natural grouping of the data.

Figure 6 is a repeat of Figure 5, but using the number of SPNDs shorted as a measure of damage. The major difference is that the inclusions of the units that had inconsistent TC ΔR data does not mask the relationship.

Table 3 shows that at the very high confidence level of 99% there is a statistical relationship between

- Peak temperature and TC ΔR
- Peak temperature and number of SPND shorts
- Average temperature and TC ΔR
- Average temperature and number of SPND shorts.

If the calculated chi-square is greater than the value of the chi-square for 1 degree of freedom (DF = 1) at a 1% level of significance, (α = 0.01), then the two variables are statistically associated with a 99% confidence level. Table 3 then shows a "Yes."

TABLE 3. STATISTICAL TEST OF ASSOCIATION

	TC Resistance		SPND Shorts	
Temperature	Data Available (34)	Data Not Available (17)	Data Available (35)	Data Not Available (16)
Peak	$\chi^2 = 7.20$	$\chi^2 = 2.88$	$\chi^2 = 8.72$	$\chi^2 = 2.88$
	Yes	No	Yes	No
Average	$\chi^2 = 18.45$	$\chi^2 = 1.00$	$\chi^2 = 11.84$	$\chi^2 = 1.00$
	Yes	No	Yes	No

Now, χ^2 (DF = 1, α = 0.01) = 6.64. Therefore, if χ^2 (calculated) >6.64, then the two variables are statistically associated at the 99% confidence level. Otherwise, they are considered independent. In other words, if the calculated chi-squared is greater than 6.64, there is only one chance in a hundred that this set of numbers could have occurred by random chance.

The SPND survival data were not used since they so strongly correlate with SPND shorts they do not present new information.

Having established statistical confidence in the grouping and selected partitioning, damage groups can be established (see Table 2).

With the exception of Grid Location 11-K and 10-D, all sets fall into only one of three groupings.

Group	Description
I	Higher temperature, high TC and SPND damage
II	Lower temperature, lower TC and SPND damage
III	Inconsistent data

The two exceptions fall into both Group I and II. Because of this inconsistency, they have been transferred to Group III. The three statistical groups are core mapped in Figure 1.

Correlation Coefficients

The correlation coefficient between a variable (X) and a second variable (Y) has been calculated (see Table 4). If this coefficient is not zero, it suggests that the two variables are functionally related and represented by

$$Y = f(X).$$

The correlation between peak and average temperatures has been included.

TABLE 4. CORRELATION COEFFICIENTS

	Y = f(X) Dependent Variable			
	Temperature			
X	Peak	Average	TC Resistance Decrease	Number of SPNDs Shorted
Peak temperature	1.00	0.31	0.38	0.32
Average temperature	0.31	1.00	0.61	0.22
Number of data points	50	50	35/34	51

The correlation coefficient varies from zero to unity. Zero implies that X and Y are independent variables. Unity implies that Y is completely dependent on X. There are two major points of interest in Table 4. First, the correlation between TC resistance and average temperature is the highest, and is also greater than that between average temperature and peak temperature. Second, the number of SPND shorts is more strongly correlated with peak temperature than average temperature.

CONCLUSIONS

The resistive model analysis indicates that the center area of the core experienced the major changes as a result of the accident. This conclusion is supported by he data from the in-core TCs, as well as by the statistical analysis.

The statistical analysis characterizes instrument damage into three types, which, as shown in Figure 1, tend to group. Group I is primarily in the center of the core where higher temperatures existed. Instrument damage appeared greatest in this region. Statistically, the data, and presumably the damage, were consistent. That is, the data had small variance from location to location, as opposed to random and large variance. Group II is primarily the perimeter of the core, where lower temperatures prevailed. Instrument damage appeared less in this region but was still statistically consistent. Group III is the interesting group, since the data are inconsistent and do not seem to make sense. The group is concentrated in two areas. In Figure 1, these areas are bottom and right. The right area contains most of the negative temperature steps that occurred during the pump trip.

It is hypothesized that core damage strongly correlates with instrument damage. In the Group I and II areas, the thermally induced core damage appears predictable and repeatable. However, Group III areas, and particularly the area with the negative temperature steps, appear to have experienced random core damage of a nature different than, or in addition to, the expected thermally induced, consistent, core damage as seen in the other two areas. It may be possible that severe mechanical deformation with major flow blockage is responsible for this randomness.

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