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The Toledo Edison Company

Final Report

On

Davis-Besse Nuclear Power Station Unit 1

Conduit Separation Test Program

March 30, 1977

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Appendices

LIST OF FIGURES AND TABLES AS THEY APPEAR IN TEST REPORT

Part I: INTRODUCTION

The purpose of this Final Report is to present an overall view of the Conduit Separation Program as undertaken by the Toledo Edison Company, December - 1976 through March - 1977. Highlights of the Interim Test Report (January 12, 1977) and the Summary Test Report (February 17, 1977) will be used to describe the results achieved through the program conducted by the Franklin Institute Research Laboratories (FIRL); correlating these with the concurrent efforts conducted by the field construction forces and the Design Engineering team to provide clear justification to where less than one inch conduit separation can be allowed.

As stated in the previous reports, the purpose of the program was not to prove the adequacy of one inch separation as described in IEEE 384-1974 and Regulatory Guide 1.75, Revision 1, but instead to substantiate where less than one inch is acceptable.

Part II: PROGRAM DESCRIPTION & CRITERIA

IEEE 384-1974 provides a basis for separation of redundant Class IE circuits where external hazards are not limiting. Section 5.1.1.2 further states that (...where the damage potential is limited to failures or faults internal to the electrical equipment or circuits, the minimum separation distance can be established by analysis of the proposed cable installation.) Without this analysis, 1 inch minimum separation would be used between redundant conduits.

Since Davis-Besse Nuclear Power Station Unit 1 was substantially designed and constructed prior to the advent of either IEEE 384 or Regulatory Guide 1.75, the 1 inch separation was not necessarily implemented into the design of the exposed conduit installations. In addressing this issue, it was felt that ample conservatism existed in the present design to warrant entering a test program which would then provide actual data to be used in the analysis approach mentioned in Section 5.1.1.2 of IEEE 384-1974.

To our knowledge, no previous applicant had attempted to conduct such a program, therefore it was first necessary to develop guidelines for conducting the test. Neither IEEE 384 nor Regulatory Guide 1.75 give any guidance on the bases for conducting a test; joint discussions between TECo and the NRC were held to develop a basis for conducting the test program. The conditions established were as follows:

a. The cable or equipment in the circuit develops a fault that is not cleared due to failure of the primary protective device (breaker) and is just below the long-term trip point of the backup device. This causes long-term heating of the cable which may go unnoticed by the operators. For instance, using this requirement on a motor control center circuit would mean that the backup protective device on the load center feeding the motor control center would allow any amount of current up to 600 amps on the circuit for a continuous period of time.

b. After the long-term heating, a fault is developed that would be cleared by the backup device which could introduce EMI.

c. In addition arcing faults are to be considered.

Implementaion of these three conditions into specific worst case criteria resulted in the 15 items listed below:

TEST CRITERIA

The criteria established to define the worst case condition that will be used as a basis for analyzing less than 1 inch conduit separation is defined as follows:

1) A fault occurs in the cable or device and the primary protective device (breaker) fails to clear.

2) The fault has such a resistance associated with it as to produce just enough current to reach, but not exceed, the rating of the backup protective device. A lower level of current is assumed if it generates a greater amount of heating.

3) The resistance of the fault is variable and adjusts itself automatically during rising conductor temperature so as to maintain constant current from the source.

4) There are no other loads running on the motor control centers supplied by the same load center breaker that might prevent the circuit from reaching its full 600 amp capability on the fault.

5) The adjacent circuit less than 1 inch away contains the redundant circuit of the other channel to the faulted circuit itself.

6) Long-term continuous heating in this case is assumed to mean any cable that can last longer than one hour before the conductors melt. Where tests demonstrate that cables fail within one hour, this time period will be taken into consideration in the evaluation process.

7) The overloaded cable can maintain the continuous overheated status without the operator being aware of the condition.

8) That if the redundant circuit is failed by the overloaded cable less than 1 inch away, the operator is unaware of this occurrence also.

9) That the failures of the redundant circuits occur either before a LOCA without the operator's knowledge, or simultaneously with a LOCA.

10) The impedances associated with the cable and circuit devices up-stream of the fault locations are assumed to be negligible, thus not limiting the energy available at the fault location.

11) The overloads installed within the starters on Class IE circuits are assumed not to trigger an alarm that would warn the operator of the overloaded condition.

12) For separation at cross-over points, the fault is assumed to occur in the conduit line at precisely the point of cross-over.

13) Separation is predicated strictly on an internal fault of the conduit affecting an adjacent conduit, not a common external hazard.

14) That the source of faulted conduit is directly underneath the target conduit.

15) That the IEEE 384 and Regulatory Guide 1.75 requirement of 1 inch applies for conduit with any type cable installed, that is they could be conduits with unshielded, untwisted pair instrument wire rated 75°C operation.

It should be noted that these circumstances when evaluated jointly, are very conservative. To implement the above test criteria for this test program, meant taking a typical motor control center circuit and first subjecting it to high current overloads, up to 600 amps current which is the largest backup breaker protection for a motor control center to determine the long-term heating effects. After determining the heating effects, the tests were also to evaluate point faults and electro-magnetic interferences.

Even though the point fault and electro-magnetic interference appeared to be the more conceivable events, the long-term heating proved to be the more limiting case and hence used as the basis for the subsequent evaluations.

BACKGROUND

To provide a meaningful data base on which to make meaningful analysis, a test program was prepared jointly with the Franklin Institute Research Laboratories (FIRL). At the same time, a review of the number of circuits involved at Davis-Besse Unit 1 was made by the design engineering team. It was found that there were about 30-40 circuits fed either from Class IE-4.16 KV buses or 480 volt load centers and that most of these were run as embedded conduits. Since there were so few circuits, and the test program criteria discussed above would have required a testing capability of 2,000 amps, which was far in excess of the capability of FIRL, it was decided to merely rework these conduits where necessary. This decision allowed the test program to be concentrated on power circuits fed from motor control centers or below, control circuits, and instrumentation circuits.

Early in the test program at FIRL, it became readily apparent that with the rigid steel conduit used on Davis-Besse Unit 1, there were no internal faults that could be generated in cable of No. 12 AWG or smaller that could generate enough heat or discharge enough energy to have any detrimental effects on the thick, rigid steel conduit walls thus affecting adjacent circuits. No instances of rupturing, bowing or dislocation of conduits occurred during any of these tests except in one test where a condulet fitting cracked due to excessive heating caused by artifically holding fault current high and creating the high temperature. This fact alone was significant since this represents over 90% of the 3,000 Class IE circuits of Davis-Besse, allowing the program to really concentrate on the power circuits that may conceivably be a greater source of trouble.

At this point in the program, the field had inspected existing installations and had documented 2,100 cases where Class IE conduit of one channel come within 1 inch of the redundant channel or within 1 inch of a non-class IE conduit that may (bridge) the other channel.

Part III: TESTS

The investigation was undertaken to study three safety-related aspects of electrical spacing in a nuclear power generating station, as they pertain to common mode failures among redundant Class IE circuits:

1. Heat transfer from an electrically overloaded (600 amp maximum) conduit (the "source") to an adjacent conduit (the "target") containing a redundant circuit.
2. Energy transfer from a sustained arcing fault in a source conduit to an adjacent target conduit.
3. Electro-magnetic interference between adjacent conduits as a consequence of high power transients in one of them.

Tests were conducted with instrumentation, control and power cables in conduits of different sizes and configurations to determine maximum credible temperature and electro-magnetic effects for adjacent conduits when physically touching, when separated by the thickness of pipe straps and up to 1 inch of separation. The cable and configuration were the same as those used on the Davis-Besse project with the exception of the electro-magnetic inteference tests.

The test program was conducted in three sections. They were:

III-1. Overload Current Test Program

Part A - Phase A	600 A Tests
Part A - Phase B	Less than 600 A Tests
Part B	Heat Transfer Tests

III-2. Sustained Arc Test Program

III-3. Effect of conduit spacing on electro-magnetic coupling from power cable faults.

Each part is described in the following manner:

The test description andprocedures used for the test.

Test data.

Observations.

Results from tests.

III-1.0 OVERLOAD CURRENT TEST PROGRAM

For the overload circuit tests, it was assumed that the primary protective device (breaker) failed to operate and that the current overload was slightly below the long term 600 amp trip level of the backup protective device. Therefore, the tests were conducted with several overload currents, up to values exceeding those that would normally trip the primary circuit breaker; but they were maintained continuously until steady conditions were obtained or a malfunction occurred. Furthermore, although the current overload caused the temperature and therefore the resistance of the conductor to increase, which would normally cause the current to increase, the overload current was kept at a constant level during the test.

1.1 600-A CURRENT SUPPLY

A 3Ø, 600 amp variable current supply was provided using a stack of three 1Ø auto-transformers (480 volt) connected to 3 pairs of 1Ø step-down transformers as illustrated in Figure II-8. The maximum power available, approximately 30 KVA, was sized to provide 600 amp initially in approximately 7 ft of 3/C #12 AWG cable (connected in wye fashion).

The currents were monitored using standard, instrument-type current transformers and ammeters. In addition, two legs of the 3Ø current were instrumented with current transducers (in series with the ammeters), and their output was recorded on a 2-channel continuous strip-chart recorder.

The voltage between the three phases was monitored by means of a 3-position selector switch and a digital multimeter.

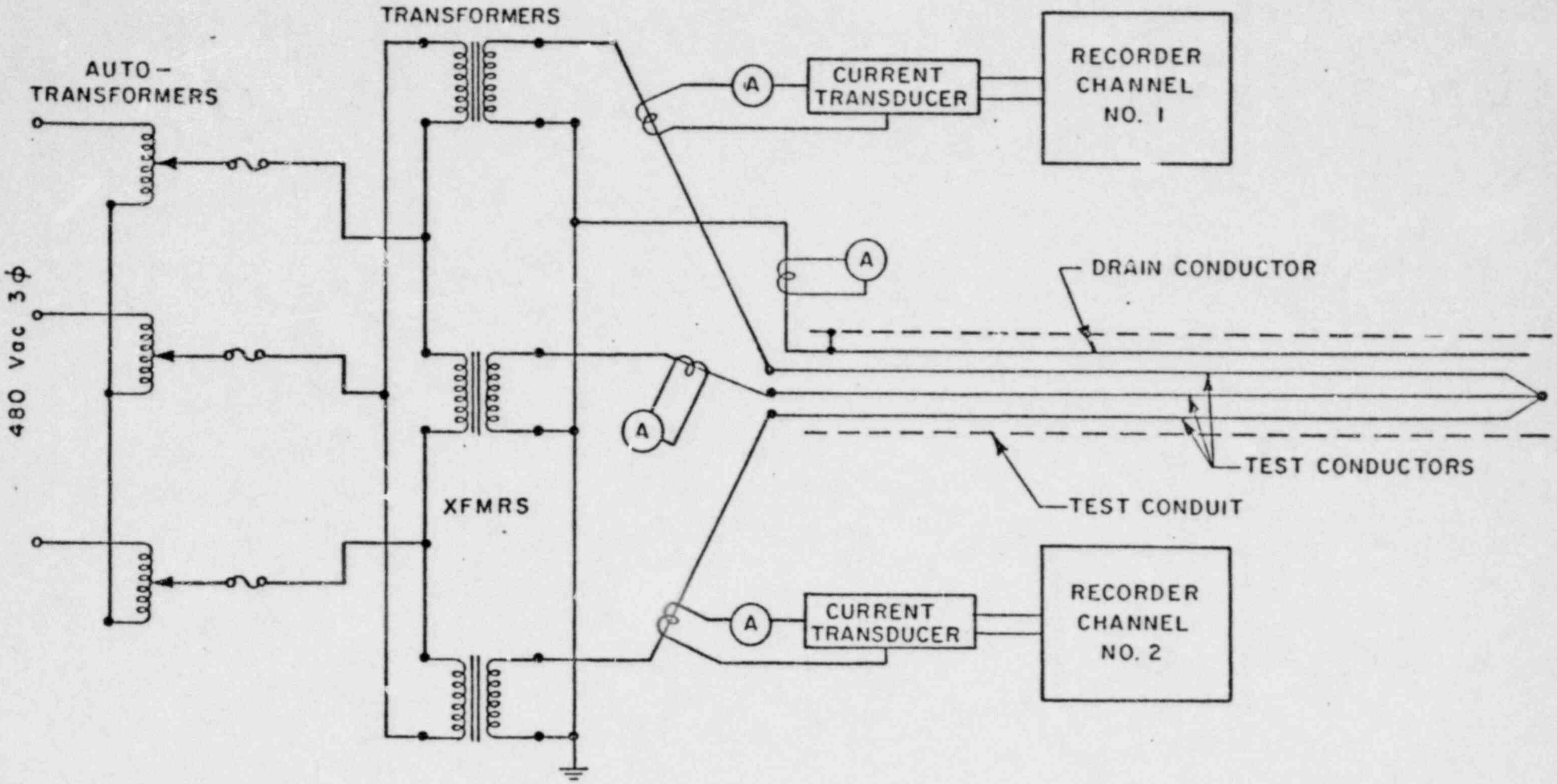

FIGURE II-8

Typical Electrical Schematic of good current supply and control

III-1.2 TEMPERATURE MEASUREMENTS

All temperature measurements were made using type K (chromel/alumel) and type T (copper/constantan) thermocouples. Measurement of conductor temperatures was accomplished using an 0.063 inch diameter Inconel-sheathed ungrounded thermocouple. Measurement of the jacket temperatures was performed using twisted and silver-soldered thermocouple junctions. Measurement of conduit temperatures was accomplished using thermocouple wires electrically welded (for type K) or silver-soldered (for type T) directly to the conduit surface. The galvanized coating was previously removed in the vicinity of the thermocouple.

The output of the thermocouple was recorded.

III-1.3 TEST PROCEDURES

The following general procedures were used to provide results for phases A and B of Part A tests:

a. Thermocouples (usually 11 in number) were attached to the cable conductor, the cable jacket and the conduit. A twelfth thermocouple was usually used to monitor the ambient air temperature in the flame test room.

b. The conduit containing the thermocouples and test cable was positioned in the flame test room.

c. The test cable was attached to the energizing circuit and the voltmeter was attached to the connection by alligator clips.

d. The instrumentation (that is, temperature recorders and current meters were checked to insure proper functioning.)

e. The cable current was quickly brought up to the required level (for example, 600 amps) by manual control of the auto-transformer stack while monitoring the current. Since perfect balance of current between the three phases was not p[illegible]ible with this arrangement, the auto-transformer stack was adjusted manually to provide currents whose average value approximated the required level.

f. Simultaneously with application of the current, an elapsed time clock was started. The strip chart recorders were started before the currents were applied.

g. Periodically during the tests, selected temperatures and observations of special interest were recorded on a data log sheet. The script charts on the recorders were also annotated with chart speeds and elapsed times.

h. The tests were terminated when either the cable failed (as evidenced by loss of cable current) or the temperatures stabilized or started to decrease.

i. The cable conduit was removed from the flame test room and inspected visually.

III-1.4 CONDUIT SUPPORT STRUCTURES

The horizontal portion of the test conduits were supported at heights of 45 to 80 inches above the floor in the flame test room. Pipe stands with a saddle at the top were used to support the conduits for the Part A tests. A double thickness of abestos paper insulated the conduits from the pipe saddles.

Conduits used in Part B heat-transfer tests were supported by standard Unistrut pipe-straps and short sections of Unitstrut channels. The channels, in turn, were fastened either to vertical pipe stands or to a special box-like frame for the crossing conduit configuration.

III-1.5 MEASUREMENT OF CONDUIT TEMPERATURES WITH 600-Amp FAULT CURRENTS TO DETERMINE MAXIMUM CONDUIT TEMPERATURE OF FAULTED CONDUIT (Part A - Phase A Tests)

The cable and conduit sizes listed in Table II-1 (together with summarized results) were assembled into six foot horizontal configurations and L-shaped configurations (horizontal legs). The ends of the conductors located in the conduit pull box (condulet) were connected together; at the other end of the conduit, the three conductors were terminated at a wye-connected, current-transformer bank, which supplied a 600 amp, 3Ø current. The temperatures of the cable conductors, cable jackets and conduit surface were measured using thermocouples and strip chart recorders.

Test No.	Cable Size (AWG)	Conduit Size (in.)	Time to Failure (min)	Maximum Temperatures (°C)			Remarks
				Conduit	Jacket	Conductor	
Horizontal Tests							
A1-1	3/C #12	3/4	~0.5	96 @ 3 min	300 @ 0.5 min	519 @ 0.46 min	Currents peaked @ 610-660 A then decayed to 200-250 A. One phased failed @ ~0.3 min. Another failed @ ~0.45 min. Conductors failed outside of outlet box near energizing connections.
A1-2	3/C #8	1-1/2	~1.0	120	236 @ 2.5 min	662	Decay of current started @ ~0.7 min. Current was 520-540 A @ 0.9 min. Conductor failed outside of outlet box as in Test A1-1 above.
A1-3	3/C #6	1-1/2	~2.2	115 @ 7.4 min	260 @ 2.4 min	726	Currents became erratic and varied between 500 and 630 A. Conductor failed outside of outlet box as in Test A1-1 above.
A1-3C	3/C #6	1-1/2	14.9 (see remarks)	192 @ 13.5 min	775 @ 13.5 min	800 @ 13.3 min	After peaking @ 600 A, currents allowed to decay naturally (i.e., current controls were not readjusted). Time (min): 0, 1, 5, 10, 13, 13.5; Current (A): 600, 450, 350, 250, 310, Erratic. Conductors failed outside of outlet box as in Test A1-1 above.
A1-5	3 1/C #2	1-1/2	~24.7	416 @ 25.5 min	605 @ 22.5 min	880 @ 23.2 min	One phase failed @ 23.5 min and other phase currents decreased to 160-250 A. Test stopped @ ~24.7 min. Conductors failed within conduit.
A1-6	3 1/C #4.0	3	~175	187	266	328 @ 138 to 175 min	Test stopped @ 175 min. No conductor failure. Cable jacket intact but shrunk in length on one conductor leaving a gap of 3/4 in. at the midpoint of the conductor jacket. The insulation was intact. No conductor failure.
L-Shaped Conduit Tests							
A3-1	3/C #12	3/4	1.1	110 @ 2.0 min	197 @ 2.0 min	587 @ 0.7 min	Currents peaked @ 465-505 A then decreased rapidly to 250 A @ 0.25 min. One phase failed @ 0.65 min. Another phase maintained 180 A until 1.1 min. Conductor failure possibly occurred at point of thermocouple insertion into cable jacket (inside the conduit).
A3-2	3/C #8	1-1/2	~1.4	152 @ 1.6 min	240 @ 4.4 min	642 @ 1.5 min	Current decreased starting @ 0.45 min. Current was 410-430 A @ 1.0 min. One phase failed @ ~1.2 min. Another phase failed @ ~1.5 min. Specific point of cable failure was not determined.
A3-3	3/C #6	1-1/2	2.2	141 @ 4.0 min	260 @ 4.0 min	749 @ 2.25 min	Current decreased starting @ 1.75 min. Current 520-540 A @ 2.0 min. One phase failed @ 2.2 min. Another phase failed @ 2.3 min. Cable jacket swollen throughout and ruptured in two locations. Cable failed within conduit.
A3-5	3 1/C #2	1-1/2	20.5	304	480	802	Two phases failed @ 19.7 min. Condulet fitting cracked. Could not remove cable from conduit for inspection. Cable probably failed within conduit.
A3-6	3 1/C #4/0	3	220	142	274	305 @ 165 to 220 min	Test stopped @ 220 min. Cable did not fail. Cable jacket shrunk in length leaving gaps 1/4 to 1/2 in. wide in jacket in several places. The insulation was intact.

TABLE II -1

Summary of maximum temperatures with good fault current temperature vs. time history, for 3/C #8 AWG cable.

III-1.6 RESULTS OF TESTS WITH 600 AMP CURRENTS (Part A - Phase A)

The strip chart records were examined together with manually recorded data logs. Thermocouple channels which indicated the highest temperatures (for the conductors, cable jackets and conduit) were selected for further evaluation. The temperature history of these selected thermocouples were then plotted for each test in the manner of Figures II-11 and 12, with annotations of other observed events such as loss of current (a conductor failure).

The results were resummarized and are presented in Table II-1. The highest conduit temperature observed with 600 amp currents was 416°C, which occurred with a 3/C #2 AWG cable in a 1½ inch conduit (Test No. A1-5).

It should be noted that the temperatures reported are subject to a ± 8°C instrument tolerance.

The ambient air temperatures in the flame test room were usually well below 50°C (120°F).* These temperatures were measured at a horizontal distance greater than 3 ft from the test conduit.

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*Two test results that indicated room temperature of 50°C and 86°C were considered anomalous. It was always possible to step into the flame test room without discomfort from the heat. Part of the heat was generated by 300 to 600 watts of incandescent lighting, contained in the room.

FIGURE II-11

With 600 A fault current temperature vs. time history for 3 1/C #2 AWG cables

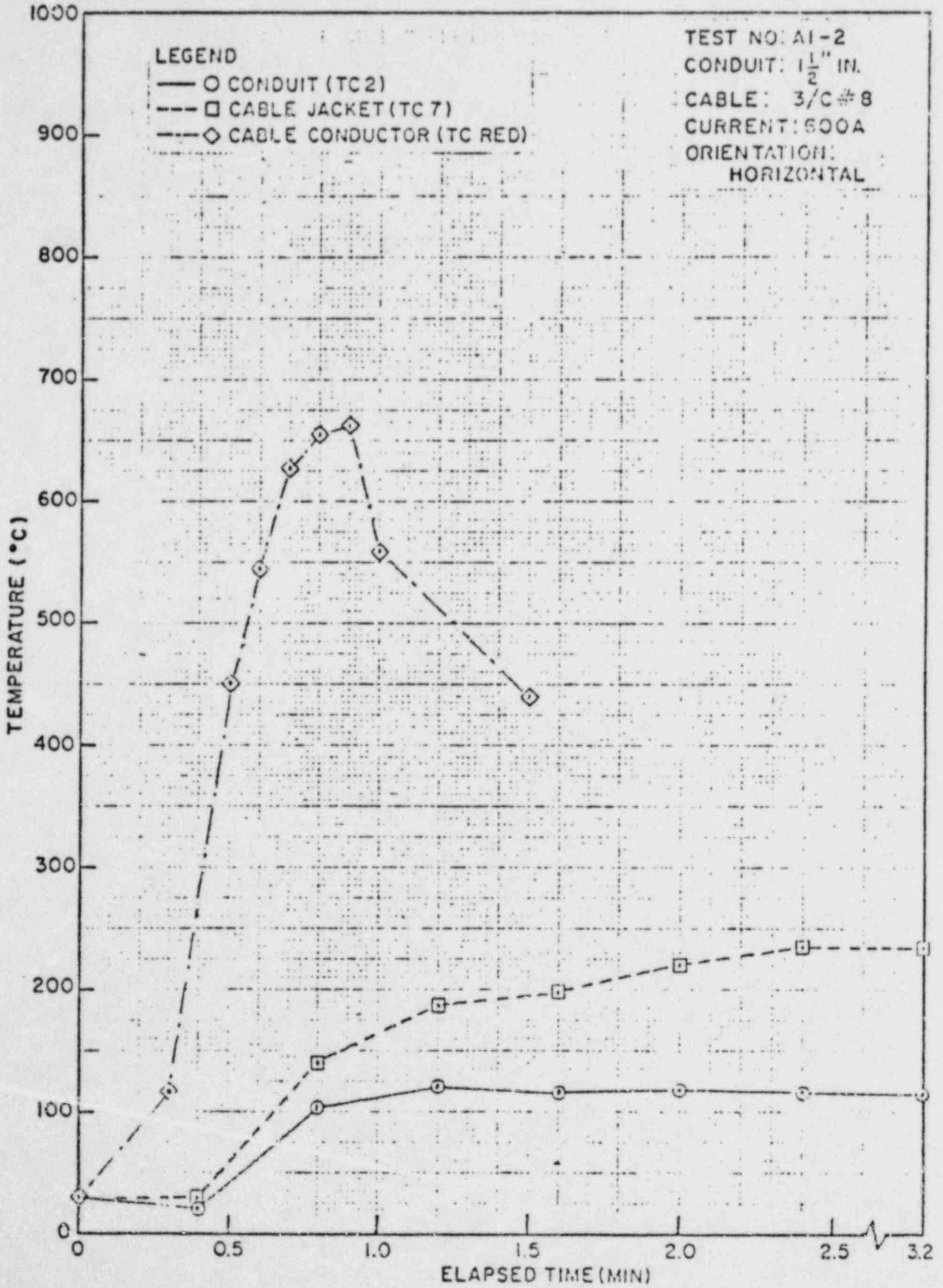
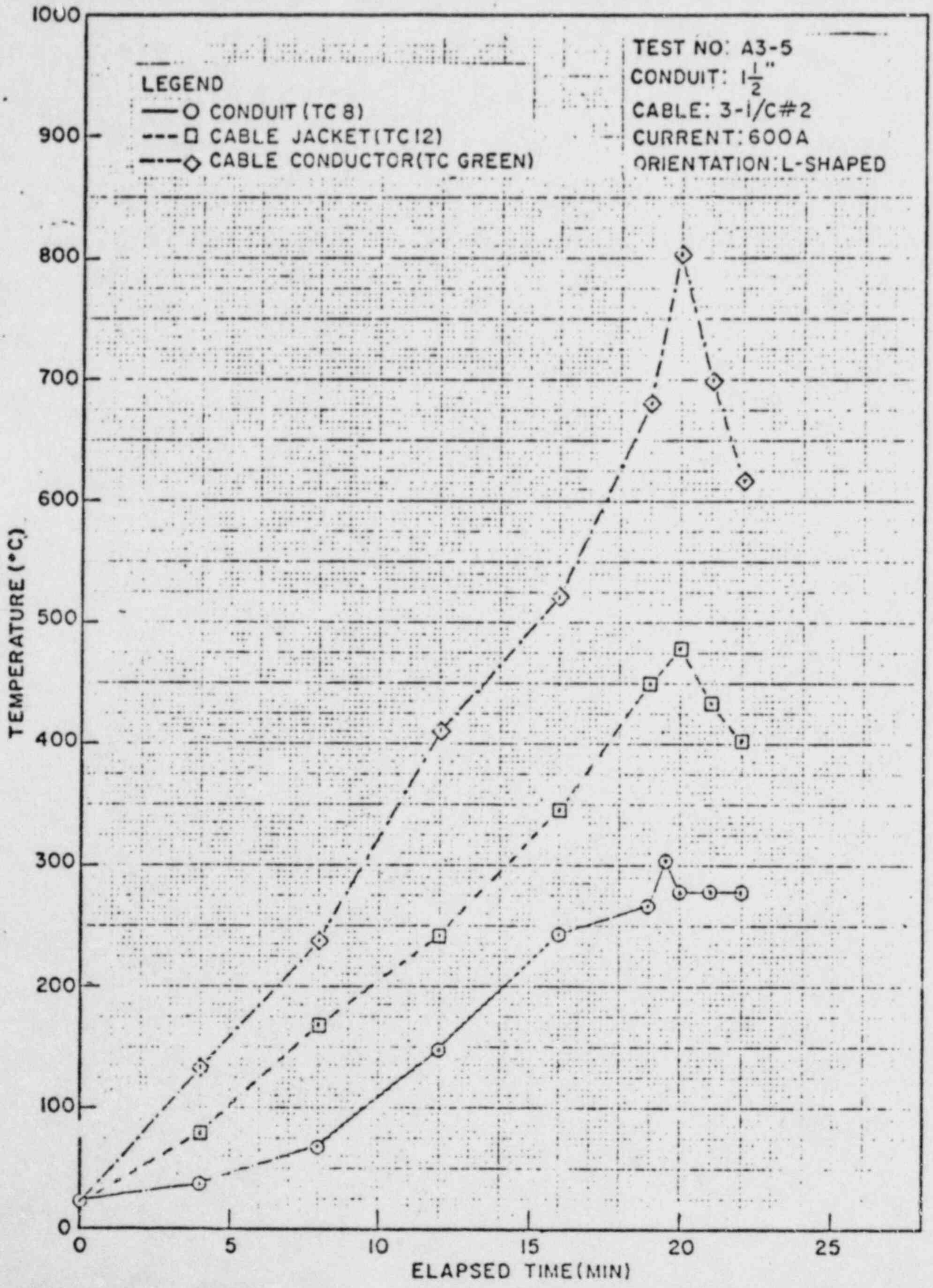


FIGURE 11-12

With 600 A fault current summary of maximum temperatures with fault current of



III-1.7 DISCUSSION OF FAULT-CURRENT TEST

The results of these experiments, which are summarized in Table II-1 are consistent with the hypothesis that the maximum conduit temperature is dependent primarily on the energy dissipated within the conduit. For a steady current through a 3/C cable, the energy dissipated per unit length of cable is $3I^2Rt$, where I is the current through each conductor, and R the resistance per unit length of conductor and t the time that the current is maintained. In the experiments under consideration, R was an increasing function of time because of the heating of the conductor; and it was subject to local variations where a fault developed in the conductor. Therefore, a quantitative correlation of conduit temperature with energy dissipation was not attempted. Qualitatively, however, looking first at the results of experiments with horizontal conduits, we see that the temperature rise of the conduit was relatively low when the experiment was of short duration (approximately 1 minute) because of early cable failure (tests A1-1, A1-2 and A1-3). In Test A1-3C, which lasted about 15 minutes, the maximum conduit temperature was observed was significantly higher (192°C) even though the current was allowed to decay as a consequence of increasing conductor resistance, instead of being kept at the nominal value of 600 Amps by manual circuit adjustment. A comparable conduit temperature (187°C) was attained in Test A1-6, which lasted a longer time (175 minutes), but in which the conductor was larger and, therefore, had a lower resistance per foot. In the aforementioned tests, the conductor either did not fail or failed outside the conduit. In Test A1-5, the conductor failed within the conduit and the maximum conduit temperature observed (416°C) was higher than in any of the other tests in the same series. This implies that the rate of energy dissipation in the vicinity of the fault was greater than the rate along the rest of the cable.

The results obtained with L-shaped conduits were not significantly different from those obtained with horizontal conduits. The small differences that may be noted are probably related to variations in the nature of the faults and their location relative to the thermocouples. Since the conduit thermocouples were approximately 18 to 36 inches apart, a fault within the conduit could be located up to 9 to 18 inches from the nearest thermocouple.

It is interesting to note that the highest conductor temperature observed in the phase B tests was 973°C approaching within 100° C of the melting point of copper, 1,050 °C.

It can also be noted that the cable jacket temperatures were generally intermediate between the conduit and conductor temperatures, as would be expected. However, a quantitative analysis is difficult: for one matter, the method of attaching thermocouples to the conductor and jackets was subject to considerably greater variation than was the case with the conduit thermocouples. Also, after the cables were drawn through the conduit there was no way of knowing the exact location of a thermocouple junction within the cross-section (for example, between the jacket and the bottom of the conduit, near the center of the cross-section or exposed to an air space). Matters such as these, however, were of relatively little importance in terms of the objective of the investigation. It was the conduit temperatures that were of greatest importance, because these determine the rate of heat transfer to adjacent circuits; and these were not subject to the problems associated with the measurement of conductor and jacket temperatures.

The most meaningful outcome of this first series of experiments was the demcnstration that maximum conduit heating was not necessarily accociated with maximum overload current. Conduit heating depends not only on the rate of energy dissipation within it but also on time; consequently, if a circuit is so highly overloaded that the cable fails very quickly, there is less conduit heating than that which occurs when the circuit load is reduced but is maintained for a longer period.

III-1.8 DETERMINATION OF MAXIMUM CREDIBLE CONDUIT TEMPERATURES FROM FAULT CURRENTS OF LESS THAN 600 AMPS. (Part A - Phase B Tests) TO DETERMINE MAXIMUM TEMPERATURE OF FAULTED CONDUIT

Since the Part A - Phase A tests and a few experimental tests with exposed cables (that is, not installed in conduits), indicated that 600 Amp currents in some cases resulted in cable failure before high conduit temperatures were realized, a series of tests were run with fault currents less than 600 Amps to determine whether conduit temperatures higher than those achieved with 600 Amp fault currents could be developed.

The cable/conduit configurations and the test currents that were tried are listed in Table II-2. The test arrangements are illustrated in Figure II-8. The temperatures were recorded using thermocouples and strip chart recorders.

TEST NO.	CABLE SIZE (AWG)	CONDUIT SIZE (in.)	NOMINAL CURRENT (A)	TIME TO FAILURE (min)	MAXIMUM TEMPERATURE (°C) CONDUIT	CABLE JACKET	CONDUCTOR	REMARKS
Horizontal Tests								
Prel. to A1-1B	3/C #12	No Conduit	150	~3	No Conduit	235	Not Measured	Preliminary test to select current for Test A1-1B. Cable coiled on floor. Jacket ruptured ~30 in. from energized end.
A1-1B	3/C #12	3/4	100	14.5	194	290	555 @ 13.5 min	Current was erratic @ 9 & 10 min. One phase failed @ 14.0 min and another phase failed @ 14.7 min. Cable failed in outlet box and conduit.
A1-1C	3/C #12	3/4	70 & 85	114	230	Not Measured	Not Measured	Obtained conduit temperatures of ~150°C with 70 A after 65 min. Current then increased to 85 A. Cable failed @ 114 min outside of conduit.
Prel. to A1-2B	3/C #8	No Conduit	300	~5.3	No Conduit	232	540	Preliminary test to select current for Test A1-2B. Cable coiled on sheet of transite. Jacket ruptured in several places.
A1-2B	3/C #8	1-1/2	200	23.3	137	341 @ 16.5 min	570 @ 16 min	Current was erratic @ 10.6 and 21.5 min. One phase failed @ ~24.0 min. Another failed @ 24.7 min. Cable failed inside and outside the conduit.
A1-2C	3/C #8	1-1/2	150 & 175	95	297	Not Measured	Not Measured	Obtained conduit temperatures of 165°C with 150 A after 65 min. Current then increased to 175 A. Test stopped @ 95 min after temp. levelled off. Cable did not fail.
Prel. to A1-3B	3/C #6	No Conduit	300	16.7	No Conduit	Not Measured	Not Measured	Preliminary test to select current for Test A1-3B. Cable jacket ruptured @ 8.7 min. One phase failed @ 16.1 min. Another phase failed @ 16.5 min.
A1-3B	3/C #6	1-1/2	300	20.5	222 @ 16 min	560 @ 16.5 min	907 @ 16 min	Current was erratic @ ~19.6 min. One phase failed @ 18.5 min. Another failed @ 20.6 min. Conductors melted at location outside of conduit.
A1-3B1	3/C #6	None	450	4.7	No Conduit	255 @ 5.5 min	741 @ 4.3 min	Cable jacket ruptured @ 2.5 min. One phase failed @ ~4.4 min. Another phase failed @ ~4.6 min.
A1-3D	3/C #6	1-1/2	250	~34.5	326	Not Measured	Not Measured	All phases failed @ ~34.5 min. Fire occurred at energized end of cable. Conductors burned away. Cable inside conduit not inspected.
A1-5B	3-1/C #2	1-1/2	500 & 550	125	480	Not Measured	Not Measured	Obtained conduit temperature of 418°C with 500 A after 70 min. Current then increased to 550 A. One phase failed @ 110 min. Test stopped @ 125 min because temperature was falling. One conductor melted at location outside of conduit. Cable not inspected.
Vertical Test								
A2-5	3-1/C #2	1-1/2	500	28.8	275 @ 28 min	385 @ 28 min	555	Test stopped @ 28.8 min due to excessive smoke from cable. Cable not inspected.
L-Shaped Tests								
A3-1B	3/C #12	3/4	100	14.4	130	285 @ 10 min	405 @ 11.2 min	Current was erratic @ 10 min and recovered @ 11 min. One phase failed @ 14.0 min. Another phase failed @ 14.5 min. Conductors failed in outlet box.
A3-2B	3/C #8	1-1/2	200	31.5	110 @ 18.5 min	240 @ 12.5 min	452 @ 20 min	Current peaked at 362-375 A and then steadied @ 200-210 A until 10.7 min when currents became erratic. Erratic also @ 23 and 25 min. Lost one phase at 26 min. Other two phases, currents were 200-120 A @ 31.5 min when test ended. Failure occurred within conduit.
A3-3B	3/C #6	1-1/2	300	14.5	231	270	973	Two conductors failed at 14.5 min. Conductor failed within conduit.

TABLE II-2

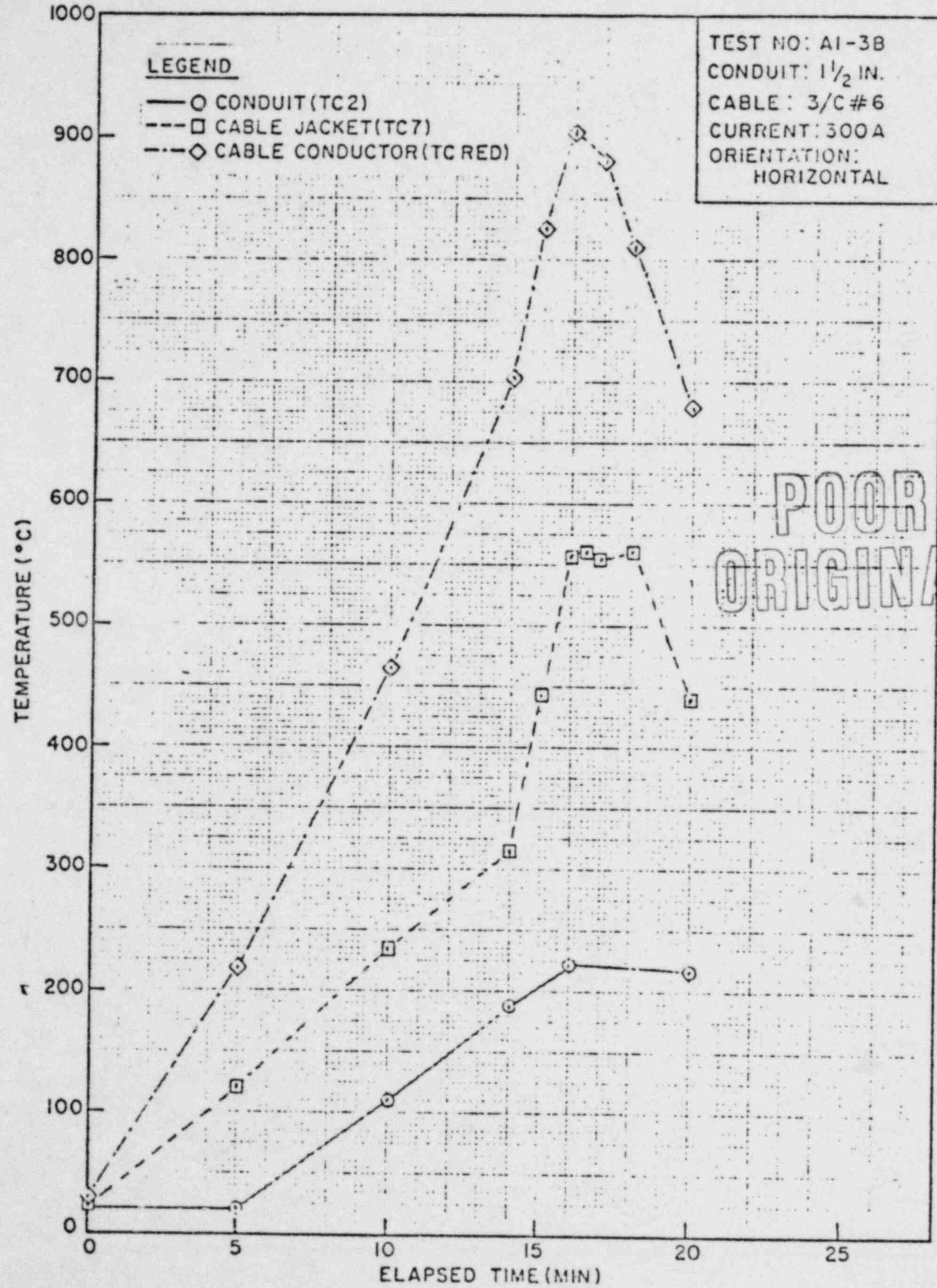
Less than 600 A temperature vs. time history for a 3/C #C AWG cable

III-1.9 RESULTS OF TESTS WITH CURRENTS LESS THAN 600 AMPS (Part A - Phase B)

The tests data were processed in the same manner as for Phase A tests (Section 4.1). The results are summarized in Table II-2 and a typical plot is illustrated in Figure II-13. The highest measured conduit temperature was 480°C and occurred with 3 1/C #2 AWG cables in a 1½ inch conduit carrying 550 Amps (Test A1-5B).

FIGURE 11-13

With 300 A Current



These tests showed that the 4/0 cables were large enough to sustain 600 Amps current loads for several hours without failing, and that the peak conduit tempeature levels reached during this time were less than the peak temperaures reached when smaller cables (conductor sizes 2, 6, 8 and 12 AWG) were tested.

With one exception, the few experiments conducted with L-shaped conduits and the one with a vertical conduit yielded maximum conduit temperatures that were lower than the maximum conduit temperature obtained with a single horizontal section of conduit with the same cable and current overload. This can be seen in Figure II-15. An exception occurred with a test involving conductor size #6, in which the peak conduit temperature was 231°F in the test with an L-shaped conduit and 222°F with the horizontal conduit. The tests with vertical and L-shaped conduits were not pursued further because it seemed that they would not yield conduit temperatures exceeding those observed in tests with horizontal conduits.

This series of tests served to establish the highest conduit temperatures that are likely to occur with the circuits under consideration. The next step in the program was to investigate how the conduits heated by an overloaded cable (that is, the faulted conduit) could affect an adjacent (that is, target) conduit.

The next step in the program was to determine the circuit loading conditions that would lead to the highest conduit temperatures.

The data of tests conducted to determine the current loading that would lead to the highest conduit temperature to each type of cable are summarized in Table II-2 and plotted in Figure II-15.

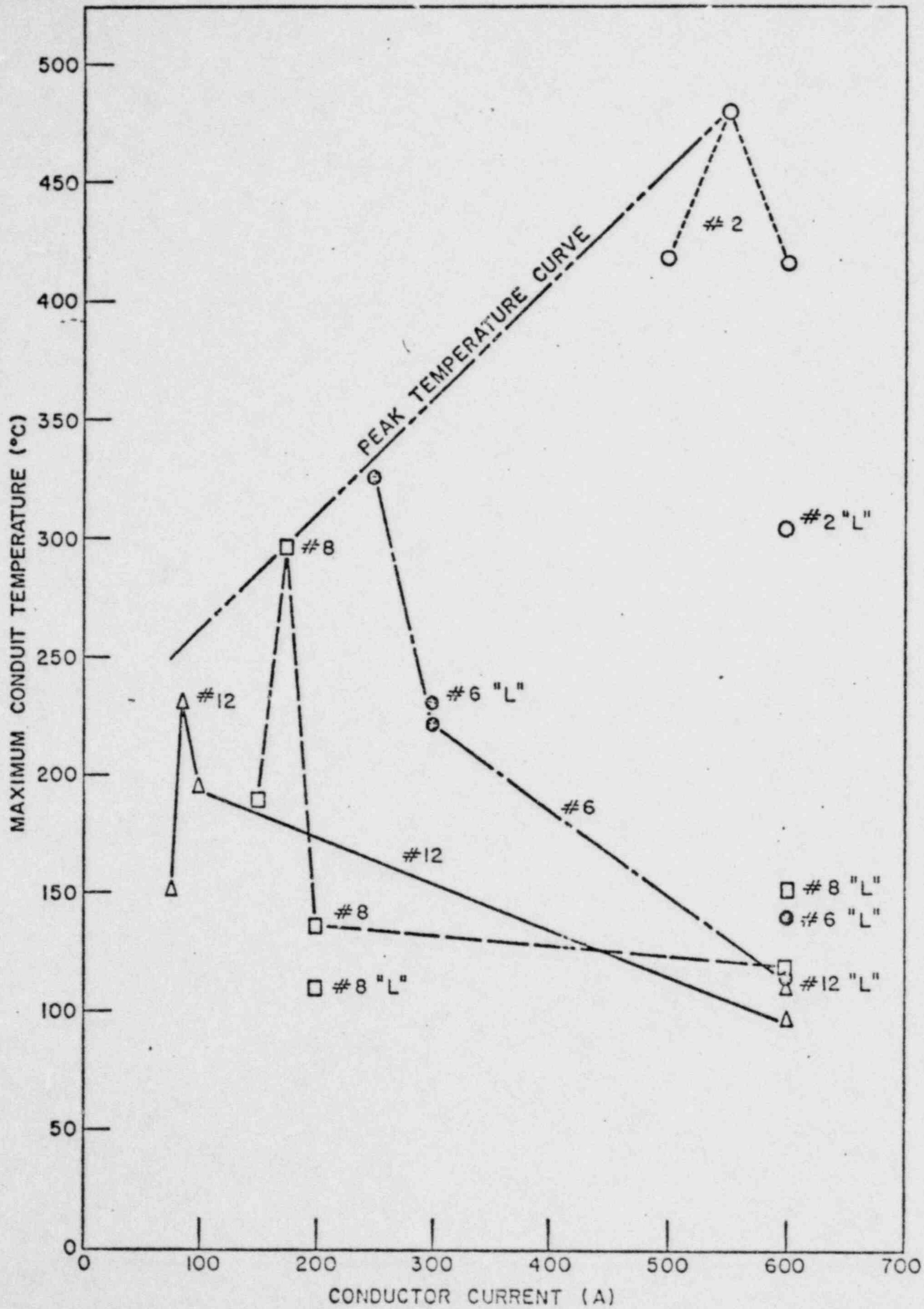


FIGURE 11-15

Maximum conduit temperatures as function of current load

If we look at the curves for conductor sizes 2, 6, 8 and 12 in Figure II-15, we note the following pattern: For a given conductor size, the range of current load within which the peak conduit temperature occurs, is relatively narrow; and the conduit temperature drops substantially when the load current deviates by only 10 to 15 percent from the value that gives the peak conduit temperature. As the conductor size is increased, the peak conduit temperature also increases; similarly, the current load associated with the peak conduit temperature also increases as the conductor size is increased. This pattern is consistent with the hypothesis that the maximum total energy dissipation (I^2Rt) increases as the conductor size increases; although the value of R decreases as the conductor size is increased, the increase in I (current at peak conduit temperature) and t (time to failure) appear to be the dominant factors.

The trend of rising peak conduit temperature with increasing conductor size did not continue beyond the range represented in Figure II-15, that is, conductor sizes 2 through 12 AWG. Two tests with #4/0 cable (Tests A1-6 and A3-6), with sustained 600 Amp fault currents, produced maximum conduit temperatures no higher than 187°C after approximately 3 hours, at which time temperatures had stablizied and there was no outward indication of impending cable failure.

There was some slight smoke and some liquid dripping from the outlet box during the time interval of 45 to 112 minutes elapsed time. This is probably the result of the heat removing the volatile ingredients of the insulation and jacket. (See also the remarks column of Table II-2.)

III-1.10 MEASUREMENT OF HEAT TRANSFER BETWEEN ADJACENT CONDUITS (Part B Tests) TO DETERMINE MAXIMUM TEMPERATURE OF TARGET CONDUIT

The following general procedures were used in the Part B Tests:

a. Thermocouples were attached to the source conduit and the target conduit. Because of the temperatures ranges (up to 500°C on the source conduit and up to 200°C on the target conduit), type K thermocouples were used on the source conduit and type T on the target conduit. (The type T thermocouple systems provided better temperature accuracy at "low" temperatures, but the recorder was limited to 260°C maximum.)

b. The conduits, with thermocouples attached, were assembled in the flame test room into the required configuration. (See Table II-3). The heaters for the source conduit were connected to the energizing and control circuits. Thermocouples were connected to their recorders and tested for proper functioning.

c. Upon application of power to the source conduit heaters, an elapsed time clock was started. Temperature recorders were previously started. The temperature of the source conduit was increased to the first temperature level of 150°C and maintained while monitoring and recording the temperature of the target conduit(s). When the target temperature appeared to be stabilizing (for example, less than a 3°C change in 5 minutes), the source temperature was increased to the next level (for example, 200°C), and so on. The test was performed at source temperatures of 150, 200, 300, 400 and 500°C. The average period of dwell at each temperature level was 20 to 30 minutes.

d. The same conduits and thermocouples were used in tests that differed only in the separation of the conduits. The conduits were allowed to cool well below 100°C before they were readjusted to a different separation distance, and retested.

III-1.11 SOURCE CONDUIT HEATERS

The source conduit for the Part B, heat-transfer test was heated by the following methods:

a. For the 3/4 inch source conduit, resistive heating was achieved by passing a controlled current directly through the steel wall of the conduit.

b. The 1½ inch source conduit was heated by three 3.0-kW Calrod resistance heaters (approximately 6 ft long), which were assembled inside the conduit and in close proximity to the conduit walls. The power input to the heaters was controlled using a stack of three 1Ø auto-transformers* which were wye connected for 3Ø power control of the heaters.

The temperature of the source conduits was monitored by use of thermocouples. The temperature was controlled by manual adjustment of the auto-transformers.*

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*The auto-transformers were the same ones used in Part A tests.

Conduits of 3/4, 1½ and 3 inches sizes were arranged in configurations simulating field installations (that is, side by side, over and under in parallel runs, and over and under in perpendicular crossings) as summarized in Table II-3. The conduits were held in place with "Uni-strut" pipe straps and sections of "Uni-strut" structural channel. The free air space between conduits was varied between 0 and 1 inch in the crossover configuration and 1/8 inch (with pipe straps touching) to 1 1/8 inches in the parallel configurations.

"Touching" is defined as that condition where two adjacent conduits are installed as close as possible using the existing support details for the Davis-Besse project. As shown in Figure II-7, this represents physical contact at support clips only, with an air gap of approximately 1/8 to ¼ inch between the conduits.

To prevent end effects from having a significant effect on the test results, a conduit length to diameter (L/D) ratio of 10 was considered adequate. The conduit length of 6 ft that was used gave (L/D) ratios that considerably exceed this requirement; the L/D ratios were 96, 48 and 24 for the 3/4, 1½ and 3 inch conduits respectively.

In each test, a conduit designated as the source or faulted conduit was heated internally to temperatures of 150, 200, 300, 400 and 500°C and held at each temperature successively while the temperature of the adjacent target conduit(s) was measured. These temperatures were based on the preceding tests.

TEST NO.	CONDUIT SIZES (in.)			CONDUIT SEPARATION (in.)(1)	CONDUIT CONFIGURATION (1,2)	MAXIMUM TARGET TEMPERATURES (°C) WITH FOLLOWING SOURCE TEMPERATURES					NOTES
	SOURCE	[illegible] TARGET	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Over and Under					Unistrut, Pipestrap, Separation, Conduit; T over S						
B-1	3/4	3/4	-	Touching (1)		-	95	-	-	-	
B2-1	1-1/2	3/4	-	Touching		53	72	116	153	209	
B2-4	1-1/2	3/4	-	1/2		-	73	101	137	179	
B2-5	1-1/2	-	3/4	Touching	S over T; Pipe Straps Not Shown	-	57	85	126	171	
B2-6	1-1/2	-	3/4	1/2		-	44	62	90	126	
B2-2	1-1/2	3/4	3/4	1/8	T, S, T; Pipe Straps Not Shown	62	68	112	157	218	(7)
B2-2A	See Note 3					-	84	121	163	208	(7)
B2-3	1-1/2	3/4	3/4	1		49	63	88	116	150	(7)
B3-1	1-1/2	1-1/2	-	Touching	T over S; Pipe Straps Not Shown	60	86	128	176	234	
B3-2A (4)	1-1/2	1-1/2	-	1/8		62	82	119	163	222	
B3-3	1-1/2	1-1/2	-	1/2		52	69	103	146	193	
B3-4	1-1/2	1-1/2	-	1		56	71	101	132	177	
B3-5	1-1/2	1-1/2	1-1/2	1/8	T, S, T; Pipe Straps Not Shown	67	83	122	171	220	(7)
B3-6	1-1/2	1-1/2	1-1/2	1/2		57	72	106	142	190	(7)
B3-7	1-1/2	1-1/2	1-1/2	1		50 (6)	67	97	131	165	(7)
B2-7	3	1-1/2	-	Touching	T over S; Pipe Straps Not Shown	-	68	139	193	252	
B2-7A1 (5)	3	1-1/2	-	1/8 (5)		-	72	107	143	195	
B2-7A2 (5)	3	1-1/2	-	1/8		-	-	-	-	188	
B2-7B	3	1-1/2	-	1/2		-	-	97	127	162	
B2-7C	3	1-1/2	-	1		-	-	-	114	182	

Cont'd

Notes:

(1) Conduit separation is the distance between pipe straps as illustrated in Figure II-7. "Touching" means the straps were in contact with each other. The free air space between conduits (in parallel arrangements) was 1/8" to 1/4" greater than the separation between straps.

(2) "T" designates target conduit.
"S" designates source conduit.

(3) B2-2A was a repeat of Test B2-2 to increase the stabilization time at each source temperature.

(4) B3-2 was aborted after 15 min when it was noted that wrong conduit separation was used. Separation was corrected and test rerun as B3-2A.

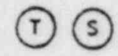
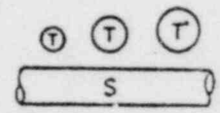
(5) Test B2-7A1 was rerun as B2-7A2 when it was noted that the actual separation distance was suspect.

(6) Average source temperature was 137°C instead of nominal 150°C.

(7) Upper target temperature. Temperature of lower target conduit was lower.

TABLE II-3

Summary of heat transfer tests

TEST NO.	CONDUIT SIZES (in.)		CONDUIT SEPARATION (in.)(1)	CONDUIT CONFIGURATION (1)	[illegible] TEMPERATURES (°C) [illegible]				
	SOURCE	TARGET			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B5-1	1-1/2	1-1/2	Touching		37	47	67	94	136
B5-2	1-1/2	1-1/2	1/8		41	49	68	92	127
B5-3	1-1/2	1-1/2	1/2		33	44	59	84	117
B5-4	1-1/2	1-1/2	1	Pipe Straps Not Shown (Note 2)	-	40	-	-	106
B4-1	1-1/2	3/4	Touching (Note 3)		42	52	76	105	154
		1-1/2			43	54	81	157	218
		3			61	79	120	166	232
B4-2	1-1/2	3/4	1/8 (Note 3)		39	47	69	93	128
		1-1/2			39	48	71	99	138
		3			40	48	68	95	127
B4-3	1-1/2	3/4	1/2 (Note 3)	No Pipe Straps (Note 3)	38	46	65	88	121
		1-1/2			38	48	69	94	131
		3			37	47	67	92	127
B4-4	1-1/2	3/4	1 (Note 3)		37	46	63	83	112
		1-1/2			38	48	67	89	121
		3			36	46	64	86	119

Notes:

(1) "T" designates target conduit.
"S" designates source conduit.

(2) Conduit separation is the distance between pipe straps as illustrated in Figure II-7. "Touching" means the straps were in contact with each other. The free air space between conduits (in parallel arrangements) was 1/8" to 1/4" greater than the separation between straps.

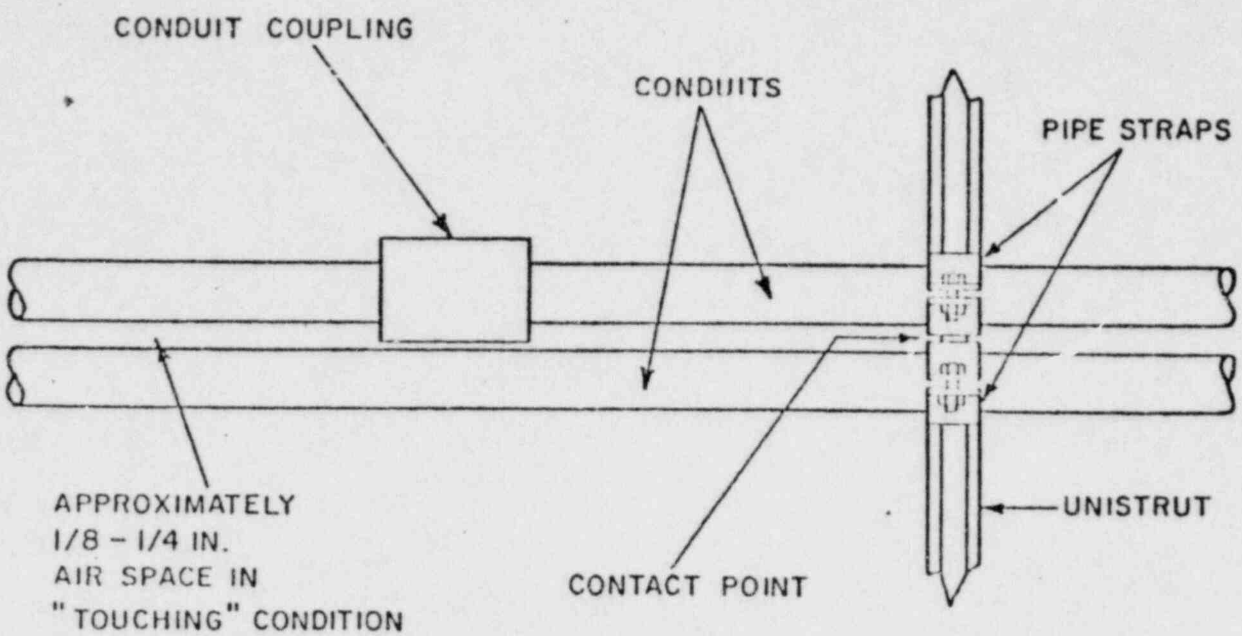
(3) Conduit separation for tests B4-1 through B4-4 is the distance between the lower conduit wall and the upper crossing conduit. Pipe straps do not enter into the main heat transfer mechanism for this configuration.

TABLE II-3(Cont)

Summary of heat transfer test temperature vs. time historices for adjacent 1-1/2 in.

FIGURE 11-7

Conduit support configuration

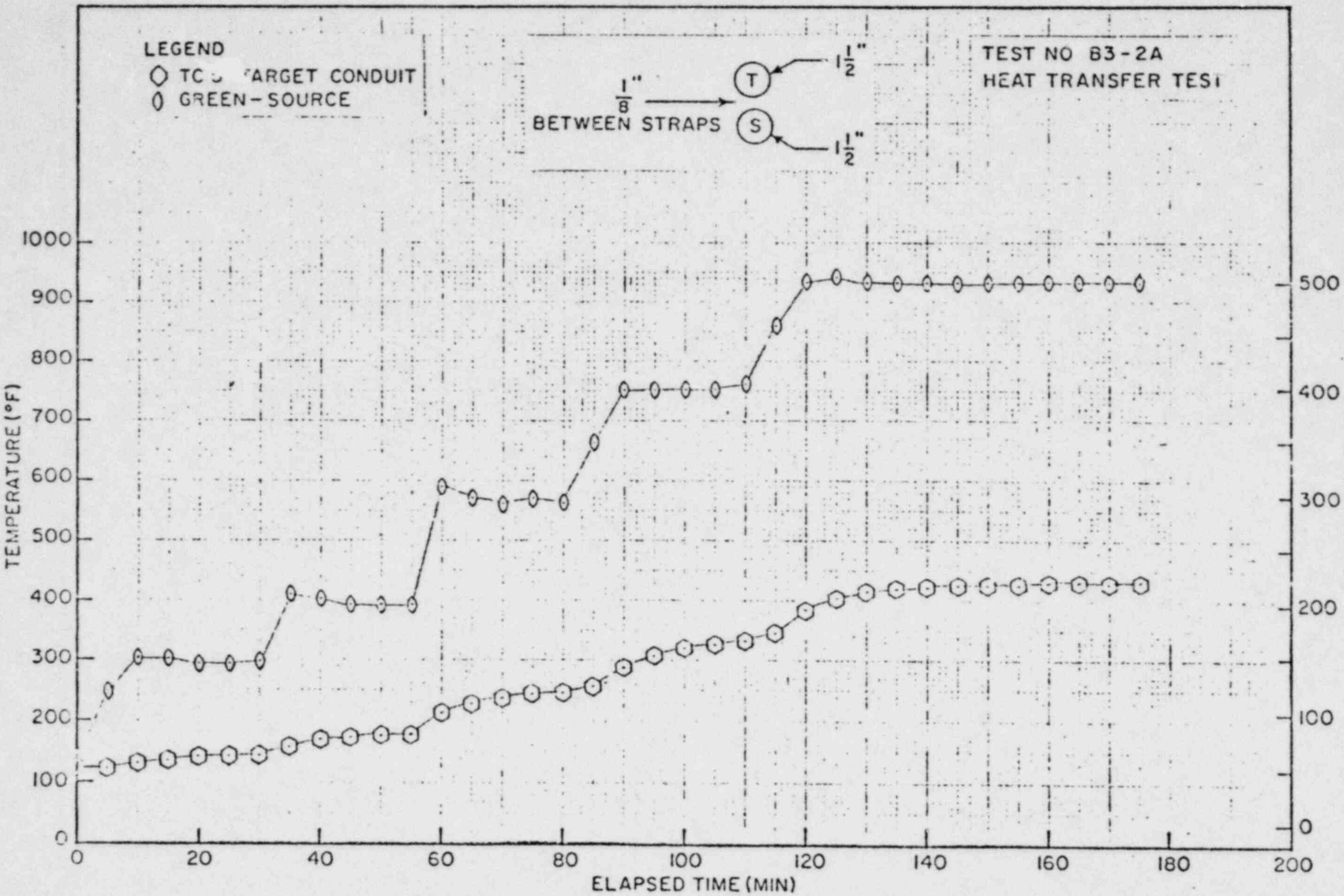


III-1.12 HEAT TRANSFER TEST RESULTS (Part B)

The test data were processed in the same manner as for Phase A tests (Section 4.1) except that the analysis was limited to source-and-target-conduit temperatures only. A typical plot of a temperature history is presented in Figure II-14. The results are further summarized and presented as Table II-3. It should be noted that the source-conduit temperatures are the highest temperatures measured at the thermocouple locations.

FIGURE II-14

CONDUITS WITH ONE CONDUIT HEATED

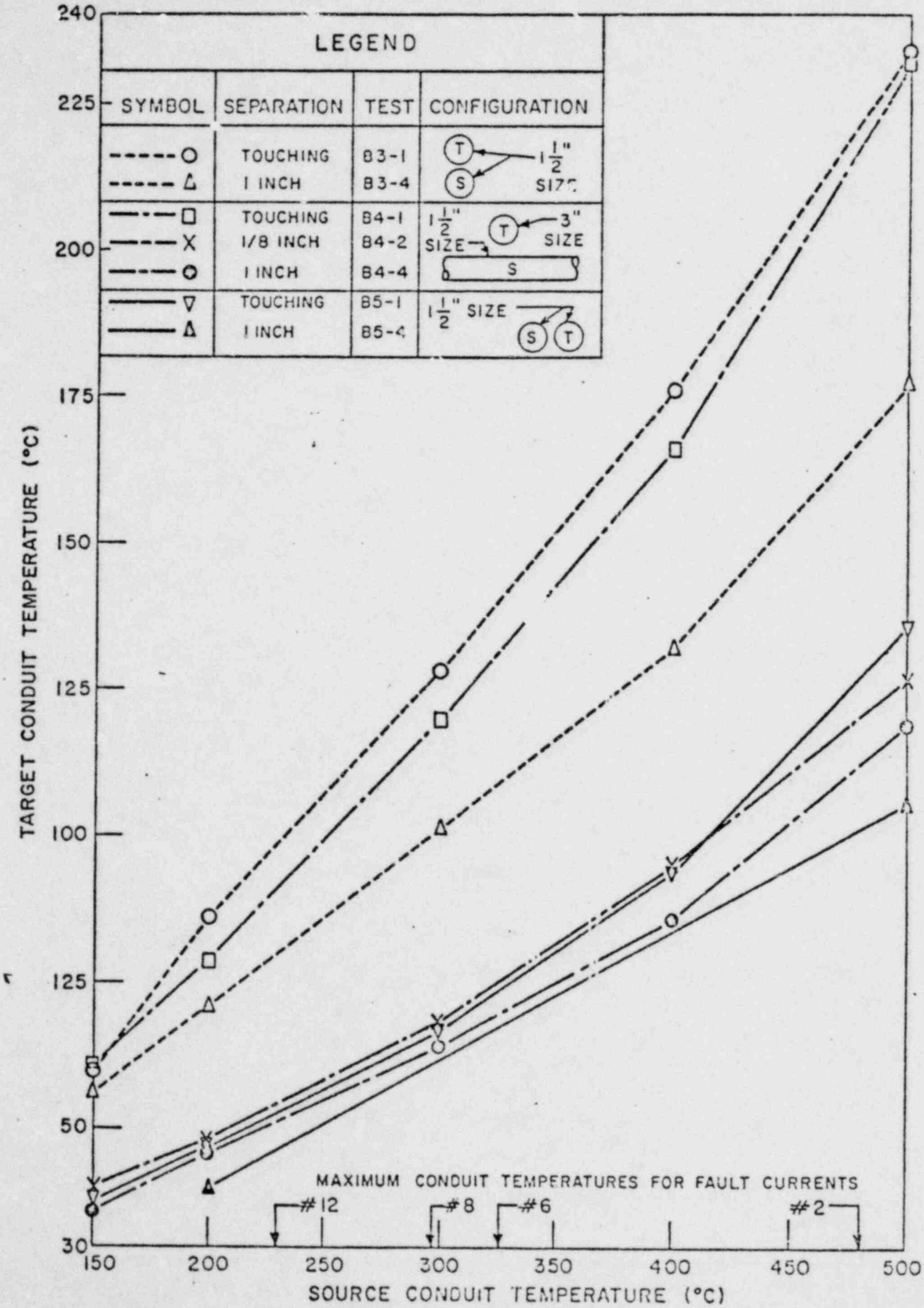


III-1.13 HEAT TRANSFER TESTS

Selected results of tests to investigate the effect of heat transfer from an overheated, source conduit to an adjacent, target conduit are summarized in Table II-3 and plotted in Figure II-16. It is readily apparent from Figure II-16 that the influence of the source conduit on the target conduit is approximately the same in the side-by-side and crossover conduit configuratins as long as there was some free air space between them, while the configuration of a target conduit above the source conduit leads, as had been expected, to significantly greater influence of the source on the target. For a given configuration, the influence decreased with increased separation between the conduits. As can be seen from the curve for the crossover configuration with the conduits in contact, the absence of any free air space greatly enhances the heat transfer between conduits. In the case of parallel conduits, the conduit support straps prevented contact between conduits in the tests conducted.

FIGURE 11-16

Target conduit temperature vs. source conduit temperature



III-1.14 GENERAL OBSERVATIONS

Smoke Generation - Considerable smoking of the cables, accompanied by a noxious odor, was observed when they became heated by overload currents. The smoke was visible from exposed sections of cable, and also noticed leaking out of conduit joints (at the condulet on one end and the junction box at the other end). The smoking usually started well before a fault occurred.

The smoke generated by the heated cables is a potential visual and olfactory indication of malfunction.

Discoloration of the Conduits - The steel conduits became discolored as they were heated by the overloaded cables (or the heater simulating overloaded cables). The surface first turned brown in color and as the temperature continued to increase, it then turned a greyish white. Along with the discoloration, a slight smoking of the surface was sometimes visible. The discoloration and smoking were probably caused by the heating of the galvanized surface or of compounds left on the surface during the manufacturing process.

As with the smoke generated by the cables, the discoloration and slight smoking of the conduits are potential visual indications of malfunction.

Effect of Ventilation - In one test (No. B3-2A), the exhaust blower in the test room was turned off for 20 minutes to check whether the level of ventilation used during the tests had a significant effect. This was conducted while the source conduit temperature was being maintained at 500°C. It was found that the conduit temperatures increased by 2 to 3°C while the blower was off, but this rise appeared to be a continuation of the normal temperature stabilization. Based on this observation, it appears that the low level of ventilation that was necessary to exhaust the smoke generated during the tests did not have a significant influence on the conduit temperatures. Accordingly, the test conditions may be regarded as being representative of those that apply in unventilated areas inside a plant.

III-2.0 SUSTAINED ARC TESTS

To investigate the effects of sustained arcs on a conduit system a test configuration was set up to place an intentional fault internal to a conduit with the conduit wall being part of the fault circuit. Temperature rise of the conduit surface was observed to determine if this test was a bounding condition on separation.

The equipment used and circuit configuration was as shown on Figure IV-8. The test description is regarded as notes to the data sheet Table IV-1.

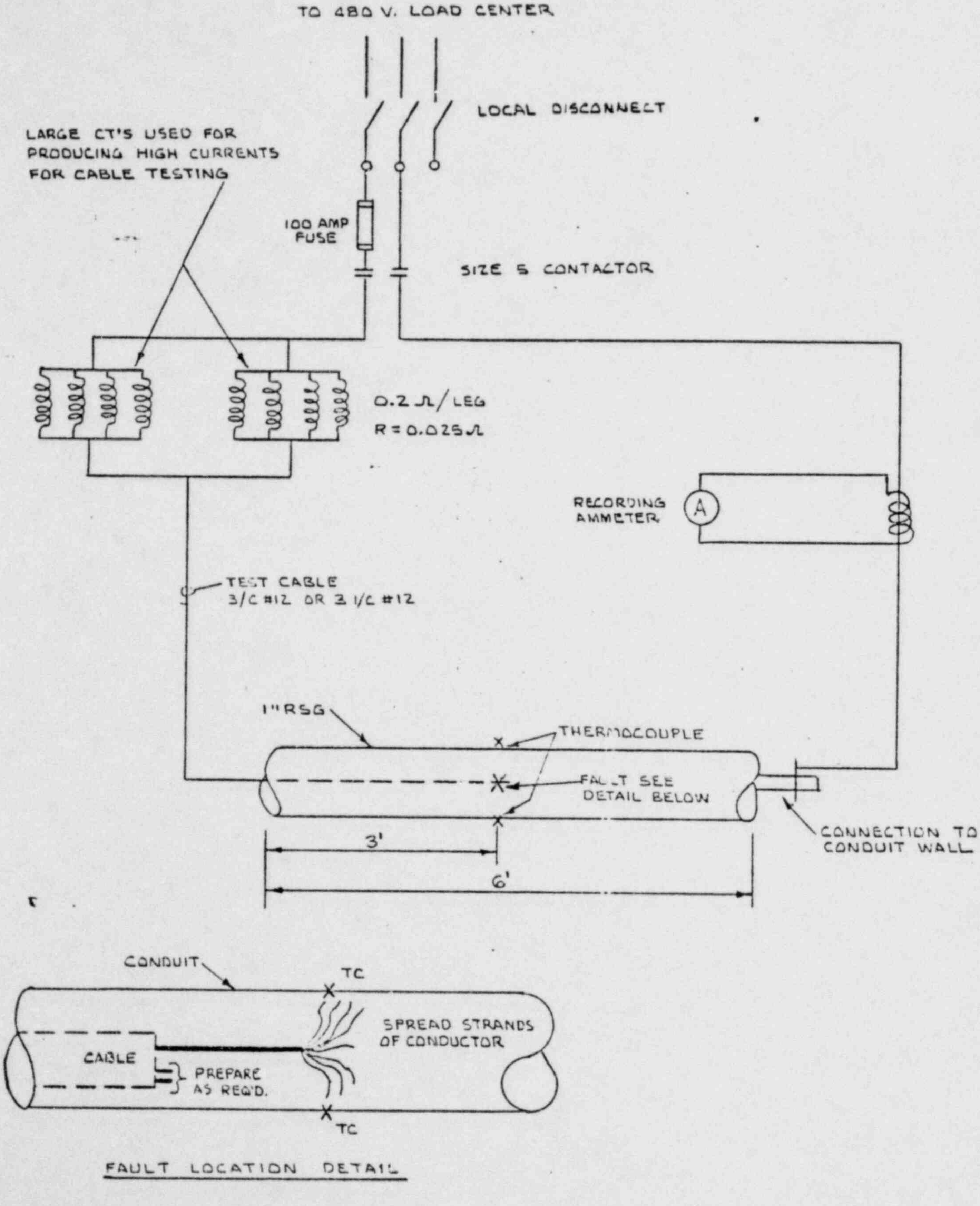
III-2.1 DISCUSSION OF SUSTAINED ARC TEST RESULTS

After repeated attempts it became apparent that sustained arcing faults could not be maintined. Once the arc was established, it vaporized the conductor material at the point of fault. All faults were completely contained within the rigid steel conduit and therefore would not directly affect another conduit.

Temperature rise of the faulted conduit did not exceed 55°C in the worst case recorded and, due to the nature of the test, was a transient effect.

FIGURE IV-8

Arcing fault test serup



FIGURE

TEST NO.	CABLE SIZE AWG	NO. OF CONDUCTORS USED	FUSE TYPE (100 A)	INDUCTOR USED (Note 1)	TEST CONFIGURATION (Note 2)	VISUAL RESULTS (Note 2)	ARC DURATION	MAX. CURRENT (Note 4) (A)	MAX. CU[illegible] TEMP. RISE ([illegible])
1	3/C #12	1	ELS	YES	Conductor touching inside of conduit.	Conductor strands burned off to conductor insulation. 100 A fuse did not open.	Note 3	160	~1[illegible]
2	3/C #12	1	ELS	YES	Same as for Test 1.	Same as for Test 1 except fuse opened.	Note 3	240	~5[illegible]
3	3/C #12	3 in parallel	ELS	YES	Conductors twisted together and bent into U-shape with bottom of U touching the inside of the conduit.	Approximately ½ of conductors burnt off on bend where they were touching the conduit. The fuse opened.	Note 3	520	~4[illegible]
4	3/C #12	1	ELS	NO	Same as for Test 1.	Same as for Test 2.	Note 3	360	~[illegible]
5	3/C #12	3 in parallel	ELS	NO	Conductors twisted together and bent to touch the inside of the conduit.	The tips of the conductors melted. The fuse opened.	Note 3	176	~1[illegible]
6	3/C 12	3 in parallel	ECS	NO	Same as for Test 5.	No arc. Fuse opened too fast.	None	120	~0
7	3/C 12	3 in parallel	ELS	NO	Repeat of Test 6 with ELS fuse.	None reported except fuse opened.	Note 3	304	~12
8	3-1/C #2	1	ELS	YES	One #2 conductor terminated with 3 strands from a #12 conductor. Strands whiskers arranged to touch inside of 1½" conduit.	None reported.	Note 3	~184	~2
9	3-1/C #2	1	ELS	YES	Similar to Test 8	None reported.	Note 3	~240	~9
10	3-1/C #2	1	ELS	YES	Similar to Test 8.	Conductor strands burned ~½ in.	Note 3	~464	~13
11	3-1/C #2	1	ELS	NO	Similar to Test 8.	None reported.	Note 3	~296	~3

NOTES:

1. Inductors were two large special current transformers connected in parallel. There was no information on their impedance, no. of turns, etc. Their dimensions are approximately 21 in. by 21 in. by 14 in. thick with a central hole approximately 6 in. by 6 in.

2. The tests were designed and performed by D. Schieman of Bechtel with FIRL support. The test description and results were provided by Mr. Schieman.

3. The measurement of arc duration was limited by the capability of the current recorder (Item No. 18-266) whose pen response is described as "faster than 0.3 s for full scale response." Because the current traces appeared as instantaneous spikes on the recorder chart traveling at 16 in./min, the arc durations can only be reported as less than 0.3 s.

4. The maximum currents can be reported only as approximate values due to the transient nature of the currents and the recorder limitations discussed in Note 3 above.

5. The conduit was equipped with a thermocouple on the bottom and another on the top. Maximum conduit temperature rise was determined by the difference in pre-test and post-test conduit temperatures recorded on Item No. 18-287.

TABLE IV-1

Summary of sustained ARC Tests

III-3.0 EFFECT OF CONDUIT SPACING ON ELECTROMAGNETIC COUPLING FROM POWER CABLE FAULTS

INTRODUCTION

In some power generating station applications, where electrical conduits carrying instrumentation cables are in close proximity to other conduits carrying relatively high power electrical distribution cables, electromagnetic energy from high current faults that may develop in the distribution cables may be coupled to the instrumentation cables.

A series of tests were performed by the Applied Physics Laboratory of FIRL to determine the magnitude of the coupling and its dependence on conduit type and conduit separation. The tests and results are described below.

III-3.1 CABLE LAYOUT, FAULT-CURRENT GENERATION AND MEASUREMENT INSTRUMENTATION

To produce a measurable value of EMI for comparative purposes, with separation of the conduits as the variable, it was necessary to rearrange the electrical circuit configuration from that installed at Davis-Besse. To increase fault current and increase EMI, the impedance of the circuit was reduced by eliminating the conduit and/or ground conductor as a fault path return. This would also eliminate the cancellation effect (typically 80%; Ref. IEEE-68-TP90-PWR) on the strength of the magnetic field due to the return current traveling parallel to the faulted conductor. See Figure III-1 for the cable/conduit layout.

From this arrangement several different configurations were tested. Included were both power cable (source) and instrument cable (target) with no conduit; and both cables in adjacent steel conduits. In all of the "conduit" configurations the general geometry of the cable layout was the same: the source cable (3 paralleled, twisted #8 copper wires) was arranged in a rectangle 30 ft by 20 ft, and the target cable (130 ft of shielded twisted pair instrumentation cable supplied from plant site) was placed in a straight line close to a 20-ft side of the source cable rectangle. Measurements of induced voltage in the target cable were made with source and target conduits "touching," and with 1 inch and 3 inch separations measured between conduit outer walls. For the tests without conduits, the source and target cables were taped together; for tests with the cables in touching conduits, the conduits were in contact in as many spots as possible.

The source cable was powered (from the side of the rectangle 30 ft from the target cable) through a three-phase contactor by two phases of a 480-V/3Ø/60-Hz line. A 100 Amp delay fuse was inserted in series with the source cable. Closing the contactor produced fault currents of about 18,000 Amps for one to two power-line cycles.

Both source and target waveforms were monitored by wide bandwidth (greater than 150 MHz) oscilloscopes.

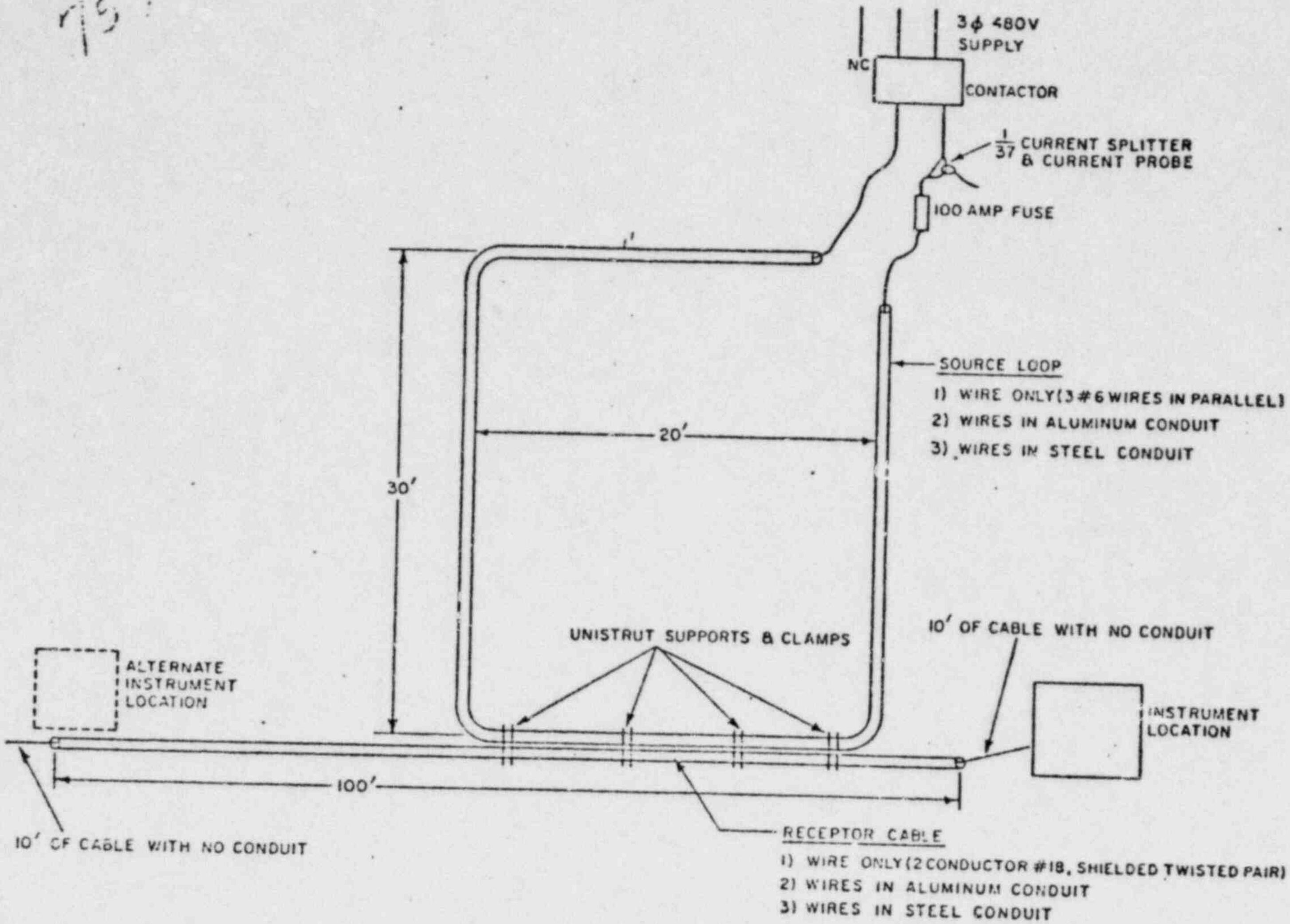


FIGURE III-1

Current source and receptor configuration

The voltage induced in the target cable was measured three ways: wire to wire; wire to shield; and wire to wire-shorted-to-shield; the last of which is not a normal condition. This essentially is a voltage between the conductor and the shield. All measurements were performed with the far ends of the source and target cables both open and shorted.

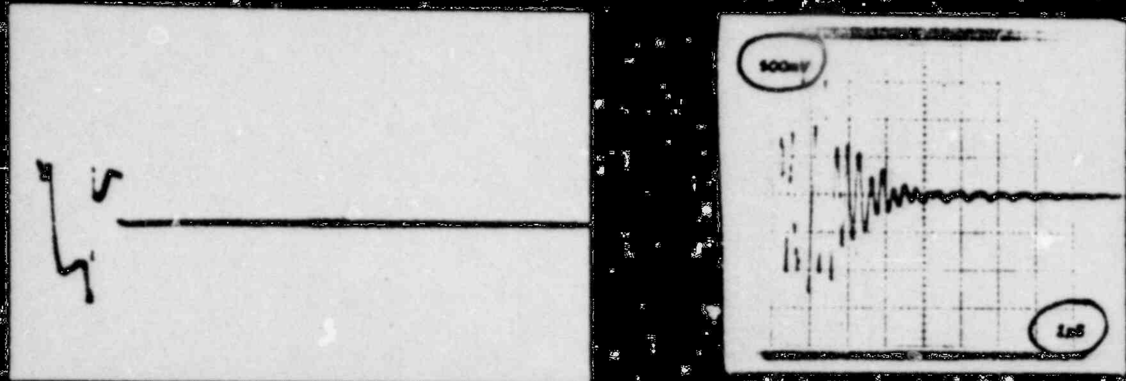
Maximum voltages were recorded with the far end of the target cable shorted and measurements made between wire and wire-shorted-to-shield. All further measurements were made using this configuration to obtain the highest noise levels possible.

III-3.2 EXPERIMENTAL RESULTS

The oscilloscope triggering was arranged so that the fault-current monitoring scope was triggered by the first positive-going voltage appearing at the scope input. The induced-voltage monitoring oscilloscope was triggered by the sweep of the fault-current monitoring scope; thus both sweeps started at the same time.

Although there was some variation of waveform due to fault incidence, the induced voltage was a rapidly dampened, high-frequency (about 3MHz) transient waveform with maximum amplitude of about 3 volts, peak to peak, over a time span of 3 to 5 micro seconds and decreasing exponentially on the order of 20 micro seconds. See figures III-8, 9, 17, 18, 19, and 20.

0.5 volts/div., 10 ms/div.



(a) (b)

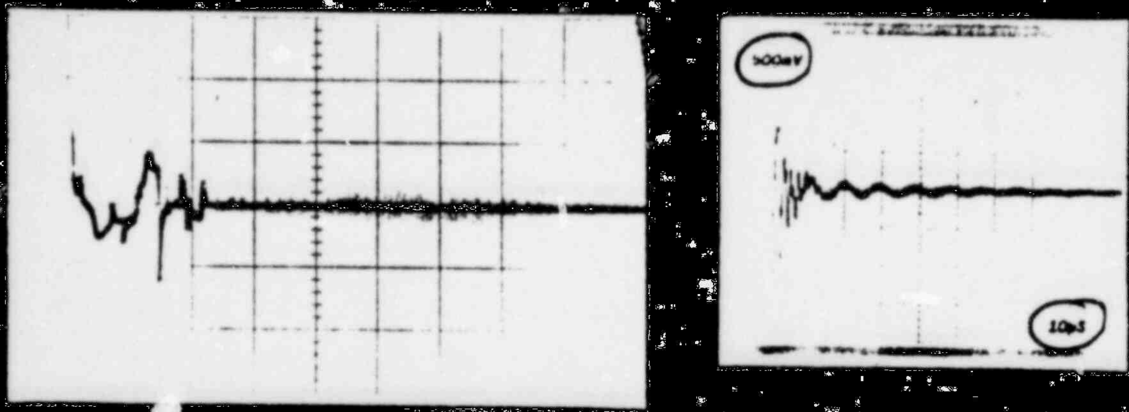
Figure A-8. Oscilloscope Traces, No Conduit - No Separation

0.5 volts/div., 10 ms/div.

(a) (b)

Figure A-9. Oscilloscope Traces, No Conduit - No Separation

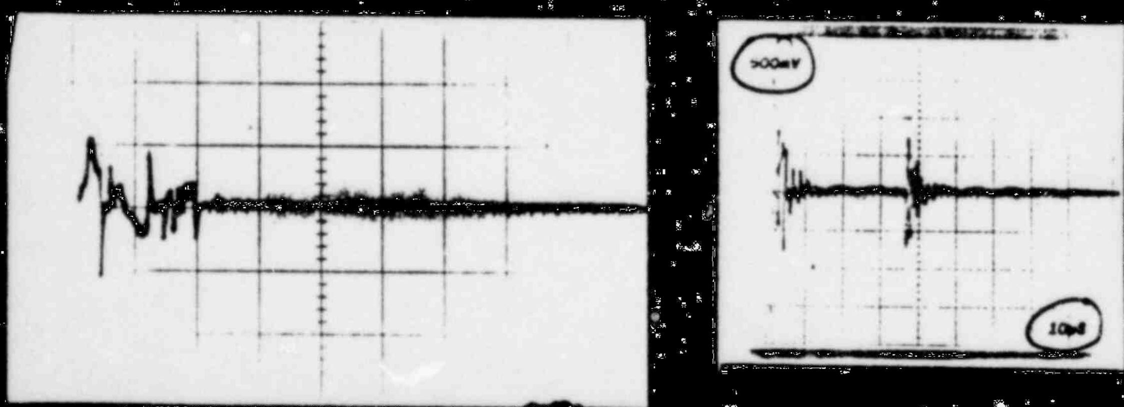
0.5 volts/div., 10 ms/div.



(a) (b)

Figure A-17. Oscilloscope Traces, Steel Conduit - Both Circuits - 3 Inch Separation

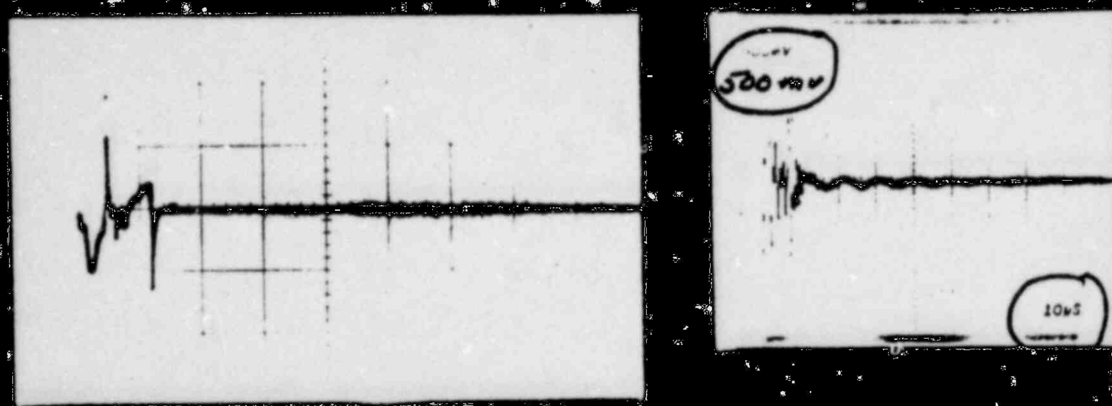
0.5 volts/div., 10 ms/div.



(a) (b)

Figure A-18. Oscilloscope Traces, Steel Conduit - Both Circuits - 1 Inch Separation.

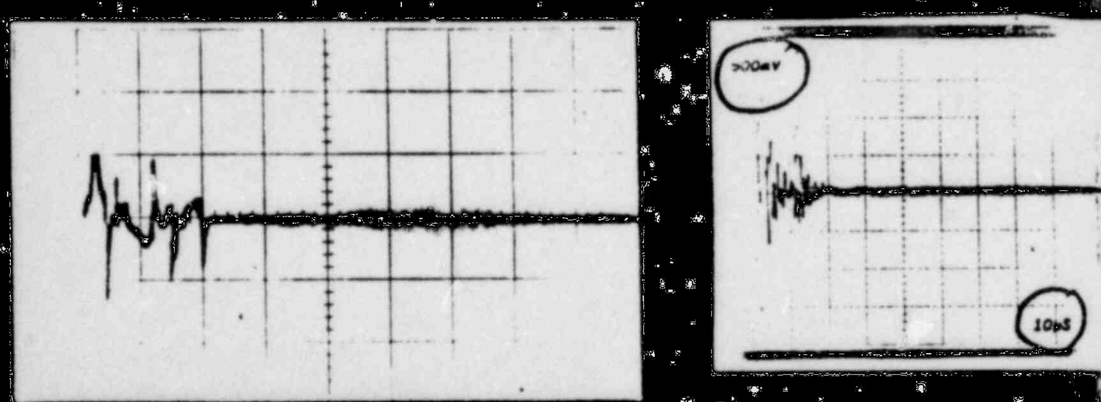
0.5 volts/div., 10 ms/div.



(a) (b)

Figure A-19. Oscilloscope Traces, Steel Conduit - Both Circuits - Conduits Touching

0.5 volts/div., 10 ms/div.



(a) (b)

Figure A-20. Oscilloscope Traces, Source Cable in Steel Conduit - Target Bare - Separation Zero

III-3.3 DISCUSSION OF EMI TEST RESULTS

At first glance the results of the tests may seem surprising since so little voltage was induced in the nearby target cable by an extremely high current change in the source cable. We must also take into consideration the fact that the layout of the test was designed to maximize the pickup by the parallel runs of target and source cables, and most importantly the fact that the tests simulated a phase-to-phase or phase-to-ground fault that had a current return outside the source cable or conduit (pickup would be reduced otherwise, in that there would be magnetic field cancellation by the return current).

The factors that must be taken into account to understand the results are: (1) the fact that for any power distribution network of large dimension the conductors themselves present an inductance that prevents extremely rapid current change - and it is primarily the rate of current change that provides coupling to nearby cables; (2) the instrumentation cable tested incorporates in its makeup the specific remedy for unwanted electromagnetic coupling - it is a tightly twisted pair within a fairly good conductive shield.

It must be noted the characteristic response of the instrumentation cable was a damped sine wave having a frequency of about 3 MHz; this frequency is a direct result of the cable length of 120 ft. If a short electromagnetic disturbance is coupled to the line, the disturbance will "rattle around in" or bounce from end to end of the line (assuming a line mismatched at each end, as our cable was) until it dissipates. The time between recurrences of the disturbance at one end of the line will be the time it takes the disturbance to travel to the other end of the line and back. In our case, this is about 2/3 (ft/nanosecond) x 240 ft, or approximately 0.36 μs. This would result in a repetitive waveform with a frequency of 2.8 MHz. This approximate calculation agrees well with the observed frequency of approximately 3 MHz.

Based on this analysis, the actual frequency observed in a current-fault occurrence would be expected to be primarily determined by the receptor cable length, and the amplitude to depend on the fault magnitude and the source-to-target cable spacing and geometry.

III-3.4 SUMMARY AND CONCLUSIONS OF ELECTROMAGNETIC COUPLING

From 131 fault-current coupling measurements, using fault currents between 13,000 and 18,500 Amps, and tests specifically configured to induce EMI, no induced voltages were obtained greater than 3 V peak-to-peak for longer than 20 micro seconds in a nearby instrumentation cable. The separation between the fault-current conductor, or its conduit, and the instrumentation cable, or its conduit, was varied from 0 to 3 inches. Table III-2 lists the maximum voltage observed under each set of conditions.

Although there are uncertainties in the data, primarily due to our inability to switch the source voltage at a controllable, repeatable instant, we believe the data demonstrate that the voltages coupled to instrumentation cables near fault currents of 18,500 Amps are in the order of 0.5 to 3V peak-to-peak; this was true for spacings of 0 to 3 inches. These specific conclusions hold only for parallel runs of about the length investigated - about 20 ft. However, we can conclude that the spacing of from 0 to 3 inches should have little influence on the magnitude of the coupling, no matter what the length of the parallel cables.

TABLE III-2. MAXIMUM OBSERVED TARGET CABLE VOLTAGE (PEAK-TO-PEAK)

Configuration	Free Air Space (in.)		
	Zero	1	3
No conduit on source or target cable	2.75 [26]	-	-
Both cables in 1-in steel conduit	3.0 [13]	3.0 [8]	3.0 [8]
Source in steel conduit - target bare	2.75 [17]	-	-

The circled numbers give the number of measurements obtained for each set of conditions.

We feel compelled to state again that we were only able to get measurable induced voltages through a contrived conduit arrangement not typical of what exists at Davis-Besse. Therefore, the test evidence linking "target" cable length to frequency of the induced voltage is strictly academic. Again it must be noted that the tests were artificially contrived by not taking credit for the cancellation effect of the return current in the conduit for the sole purpose of achieving measurable signals on the target cable. Where lower values of fault current are used and the conduit or cable ground conductor returns the fault current, no measurable signals on the target cable could be recorded.

IV-1.0 CONCLUSIONS

A. From the results of the point fault tests it is concluded that point faults in the Davis-Besse conduit system

1. Do not propogate beyond their own conduit.

2. Do not elevate the temperatures significantly of the faulted conduit.

3. Are not a factor in separation criteria.

B. From the results of the EMI tests and the noise rejection capability of the RPS and SFAS systems it is concluded that:

1. On the Davis-Besse conduit system, no EMI is introduced into the target cables that exceeds a 3 volt peak-to-peak signal for a longer duration than 20 micro seconds. The only safety systems that use low level analog signals that could be affected by this EMI are the RPS and SFAS systems. Since the RPS and SFAS bistables do not electronically seal-in for a signal less than 52 milliseconds and 15 milliseconds in duration respectively, the induced signal will not cause the RPS or SFAS systems to trip. Therefore the EMI produced will not adversely affect the safety functions of these systems.

2. EMI in the Davis-Besse conduit system is not increased for separation less than one inch.

3. Conduits closer than one inch do not degrade other systems because of EMI since separation is not a factor due to the shielding used on Davis-Besse instrumentation circuits

C. From the results of the heat transfer tests it was found: The maximum temperature of the faulted conduit carrying No. 12 AWG power cable was 230°C (test A1-1C) with 85 Amperes. Lower currents caused lower temperatures and higher currents, due to melting of conductor, and therefore shorter times, also caused lower temperatures of the faulted conduit. Combining this with the results of the B series of tests on #12 AWG which showed the vertical configuration with conduits touching to be the worst case, results in the first design criterion based on thermal considerations. (Reference is made to Figure II-16.) Quotations from Appendix A.

"1. Conduits carrying control, instrumentation, or power cable (where the power cable is limited to 480 volt or lower and No. 12 AWG or smaller) are allowed to touch each other."

As it was not practical to seek another laboratory to do high power testing, in the time frame involved, and relatively few conduits were involved (a dozen or so) the design criteria for conduit separation for power cables 13.8, 4.16 KV and 480V load centers was based on Regulatory Guide 1.75 i.e., one inch separation. These two design criteria are:

"2. Conduit carrying essential class IE 4.16 KV power cables or 480 volt center power cables will have a 1-inch minimum separation from conduits carrying class IE circuits of a redundant channel."

"3. Conduit carrying non-essential 13.8 KV, 4.16 KV, or 480 volt load center power cables that bridge conduits carrying essential class IE circuits or redundant channels will be separated from conduit carrying circuits of the redundant channel to give a minimum separation of 1 inch."

The 1 inch vertical configuration was shown to be the worst case from the heat transfer tests (Test A1-5B) and the maximum source conduit temperature was 480°C for conductors larger than #12.

Using the worst temperature case of the faulted source conduits (Test A1-5B) and the vertical configuration, which is the most susceptible to heat transfer (i.e., the worst case) gives the curve and axis point to determine the worst target temperatures. From Figure II-16 this temperature is 167°C for the vertical configuration with 1 inch separation. Using the same figure for the horizontal-touching gives a maximum temperature of 127°C, and for crossing with 1/8 inch separation, a temperature of 120°C.

Considering: 1. the cables used have been tested for 160°C for 13 hours LOCA conditions and, 2. the maximum temperature of 167°C could only be reached by manually adjusting the fault current to hold it constant to counteract the inherent increase in resistance due to temperature rise;

The following design criteria are conservative and justified:

"4. Conduit carrying essential class IE power cable of 480 volt or lower voltage with conductor size larger than number 12 AWG, and not covered by 2. above, will meet the following criteria:

a. Will have a minimum of 1/8-inch separation from the surface of any conduit crossing above which contains an essential class IE circuit of the redundant channel.

b. Are allowed to touch conduits containing an essential class IE circuit of the redundant channel when installed in a horizontal, side-by-side configuration.

c. Will have a minimum separation of 1 inch from conduits containing an essential class IE circuit of the redundant channel mounted directly above and running parallel."

To control bridging of conduits it is necessary to impose a fifth design criterion relating back to the previously stated items therefore:

"5. Conduit carrying non-essential power cable 480 volt or lower voltage with conductor size larger than number 12 AWG, and not covered by 3. above, that bridge conduits carrying essential class IE circuits of redundant channels will be treated as in 4. a., b. and c. for proper separation from the redundant channel."

It is therefore concluded that conduits placed closer than 1 inch, but limited by the five criteria established above, creates no adverse impact to adjacent redundant channels of Class IE circuits.