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EVALUATION RESULTS OF TMI-2 SOLENOIDS AH-V6 AND AH-V74

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ABSTRACT

Two Class 1E solenoid operators were removed from the Three Mile Island Unit 2 Reactor Building and examined to determine whether they had degraded as a result of accident and post-accident conditions. Both units were functional during post-accident operation. This report discusses the examination, findings, causes of the anomalies, and recommendations for system improvement.

SUMMARY

AH-V6 and AH-V74 are two Class 1E solenoid valve operators that were removed from the Three Mile Island Unit 2 Reactor Building. These two solenoids are part of the Reactor Building Air Cooling and Purge System and were manufactured by Valcor Engineering Corporation. Both solenoids were operational the entire time they were inside the Reactor Building. In situ tests performed on the devices corroborate this earlier observation except that one of the AH-V6 limit switches failed to respond to the valve position.

The two solenoids were removed from the Reactor Building and examined at the Idaho National Engineering Laboratory. In the examination, both solenoids were found to be electrically normal. Their electrical and operational characteristics were found to be typical of those of new units. The AH-V6 solenoid coil shell, however, was considerably rusted from Reactor Building spray fluid that had entered the solenoid housing. Also discovered during the test, the lead wire insulation of both solenoid coils embrittled, although this condition did not affect either device's ability to function. Tests on AH-V6 also revealed that the insulation of the rectifier broke down, and one of the limit switches failed. It is believed that the limit switch failed because of corrosion that resulted from moisture intrusion.

While both solenoid assemblies survived the accident, several weak points were observed in their design and installation geometry. Regarding the design aspect, the use of lead wires insulated with Tefzel and silicon rubber on the solenoid coil and limit switches renders the units vulnerable to radiation damage because of the insulation's relatively low damage threshold. Also, the insulation used on the AH-V6 rectifier broke down when tested at 500 Vdc. Although the failure mode was not determined, it nevertheless may have been design related. Regarding the installation aspect, a flaw in the installation configuration of AH-V6's associated conduit permitted the intrusion of water into its housing.

Obviously, the insulation problem can be corrected by using insulating materials that are more radiation tolerant and high temperature resistant. The water intrusion problem associated with the installation geometry could be eliminated by sealing the flexible conduit.

ACKNOWLEDGMENTS

The examination of the devices was performed at the Auxiliary Reactor Area 3 facility of the Idaho National Engineering Laboratory. Rolf Strahm was instrumental in coordinating the test, Bob Rowe directed the test and was instrumental in developing the test procedures, and Bill Colson and Jim Wasylow conducted the test. Thanks also to Richard Heilman and Gary Kristoff of Valcor Engineering Corporation and Fred Blatt of Unitrode for providing valuable input during test plan preparation.

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DESCRIPTION OF SOLENOID VALVES

Solenoid valves AH-V6 and AH-V74 are two of seven valves of the same generic type installed in the Three Mile Island Unit 2 (TMI-2) Reactor Building. Both valves were classified as Class 1E components; however, they were not qualified for a loss-of-coolant accident (LOCA) at the time of their installation.

The valves are part of the TMI-2 Reactor Building Air Cooling and Purge System. AH-V6 (Figure 1) is a 1-in., two-way shutoff valve used as an isolation valve of the Reactor Building pressure instrument sensing line. AH-V74 (Figure 2) is a 2-in., 3-way valve used as a pilot valve for the LOCA dampers. The LOCA dampers are openew following an accident to divert the air from its normal flow path to the Reactor Building dome, thereby effecting condensation of the steam released during the accident. The valves are located in the northeast quadrant of the Reactor Building between the Reactor Building wall and the biological shield at approximately the 335-ft elevation.

The two valves have similar circuit schemes (Figures 3 and 4), except that AH-V74 does not have a position indication feature. They both have a local control station and control room controller with either capable of operating its respective valve. They also have an automatic contrcl feature that closes them at the onset of an accident. They are of different safety channels; AH-V6 is in the Division 1 or green channel, and AH-V74 is in the Division 2 or red channel.

The solenoid operator assemblies of the two valves are basically of identical design (Figure 5). Each has a 125 Vdc coil with an integral rectifier to permit operation on an alternating current source. Also, each has two reed limit switches, two four-point terminal blocks, a rectifier, and a transient suppressor, all mounted on a yoke fastened atop the solenoid coil. The only distinct difference between the two solenoids is in the shape of each one's base, which was machined to match the profile

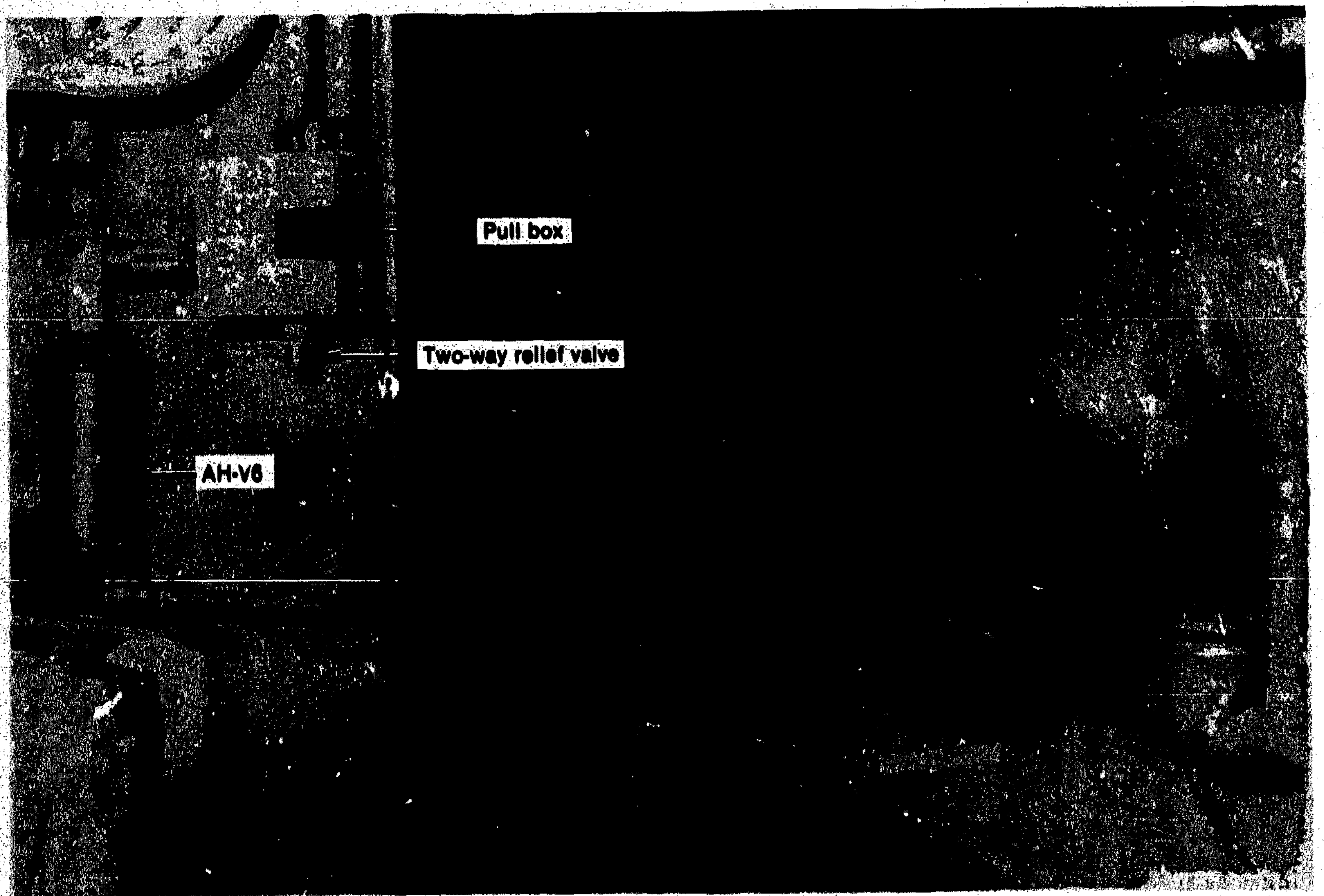

Figure 1. Installation configuration of solenoid valve AH-V6.

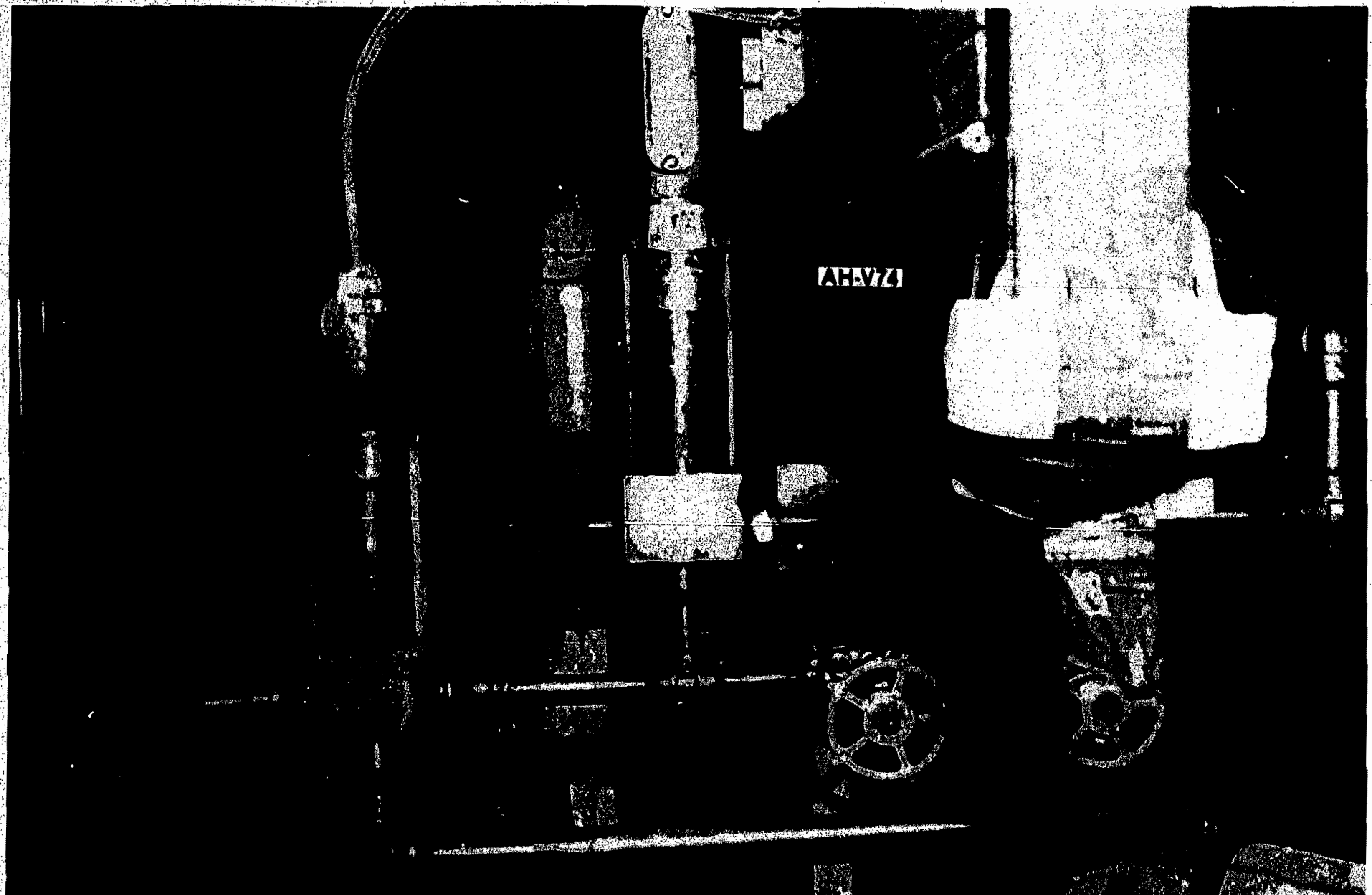

Figure 2. Installation configuration of solenoid valve AH-V74.

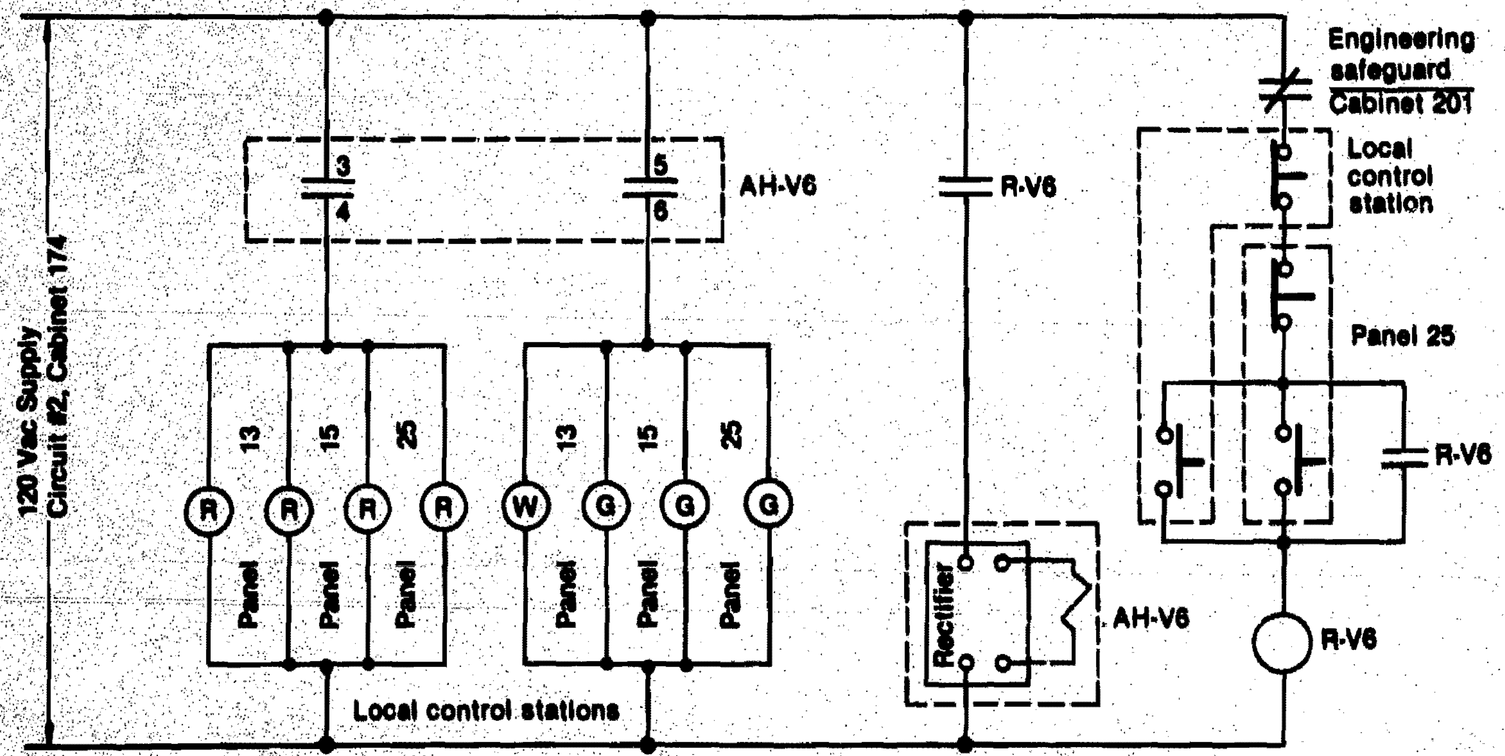

Figure 3. Control wiring diagram of solenoid valve AH-V6.

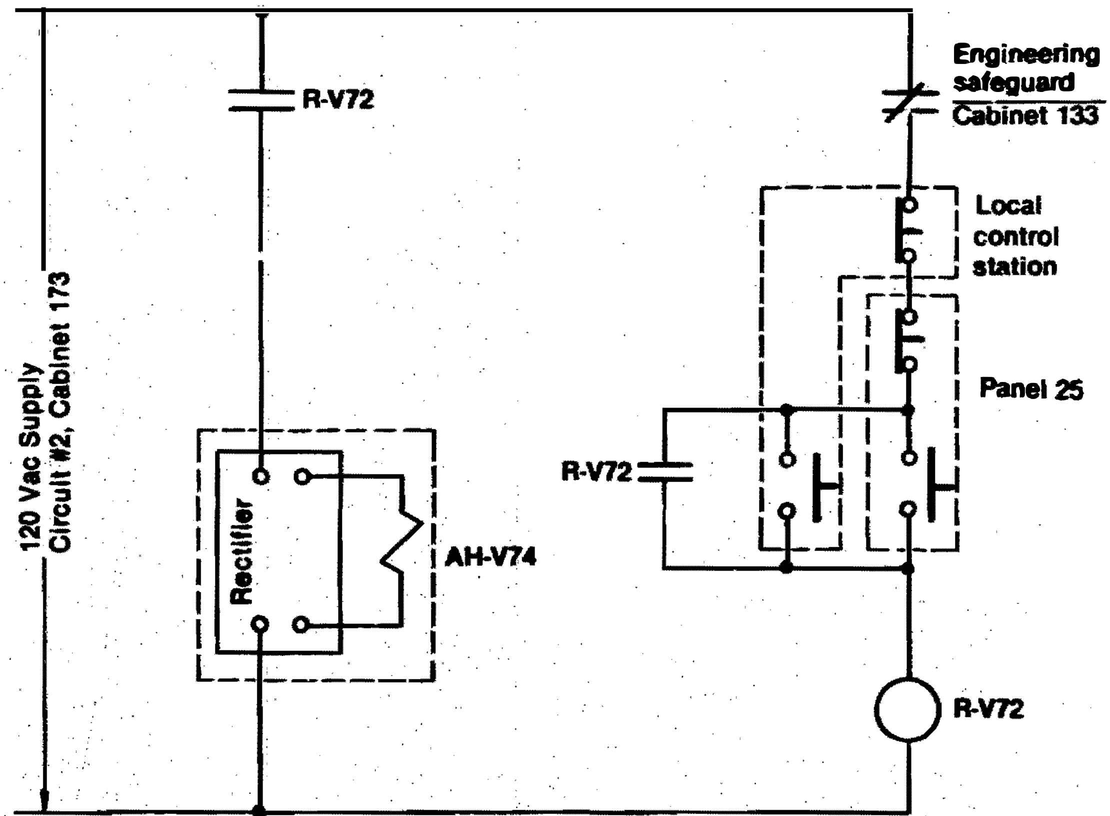

Figure 4. Control wiring diagram of solenoid valve AH-V74.

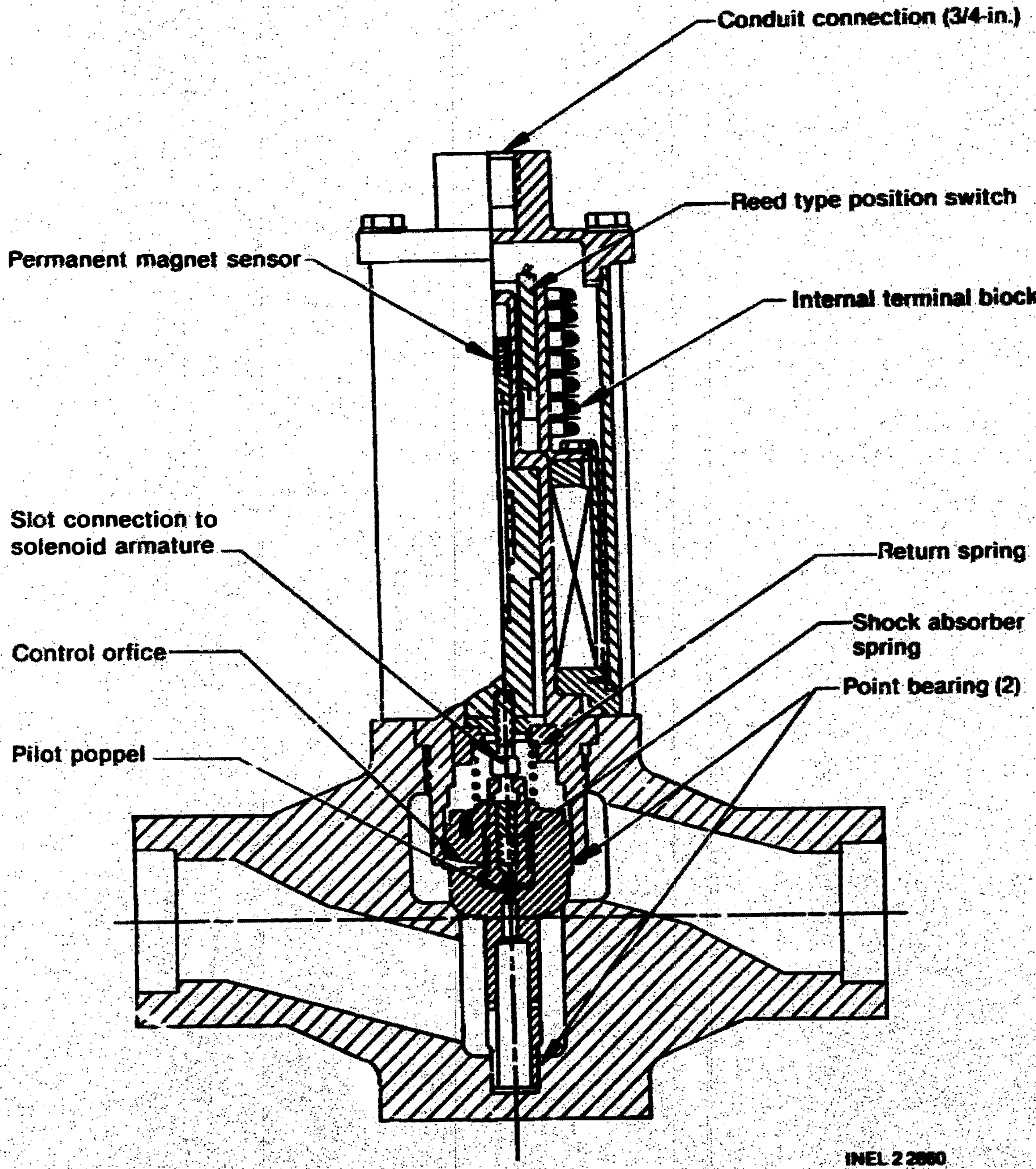

Figure 5. Cross section of a typical Valcor solenoid valve.

of the bonnet of the valve the solenoid operates. The coils are encased in a shell of nickel-plated carbon steel and potted. They have Class H insulation and NEMA 4 enclosures. The solenoid housing is also made of nickel-plated carbon steel. To meet NEMA 4 standards, three O-rings made of ethylene propylene rubber (EPR) seal the enclosure, one on the solenoid base, one on the top rim of the housing, and one on the bottom rim of the housing. The coils have a dc resistance of about 120 to 130 ohms. The two limit switches, actuated by a magnet mounted on the valve plunger, are individually set--one to actuate closed when the valve is closed (CLOSE) and the other to actuate closed when the valve is open (OPEN). Figure 6 is a photograph of a reed switch in its normal position for a typical solenoid valve limit switch. The electrical properties of the two solenoid assemblies are summarized in Table 1.

TABLE 1. ELECTRICAL PROPERTIES OF SOLENOIDS AH-V6 AND AH-V74

Voltage	90 to 130 Vac
Inrush current	1.5 amps max at 110 Vac and 70°F
Holding current	1.5 amps max at 110 Vac and 70°F
Duty	Continuous at 110 Vac max
Enclosure rating	NEMA 4
Reed switch properties	
Switching voltage	125 Vdc
Switching current	0.5 amp max
Switching capability	65 watts max

Both solenoid assemblies were removed from the Reactor Building without their associated valves. As seen in Figures 1 and 2, the valves are welded in place; consequently, their removal under the existing post-accident conditions was impractical.

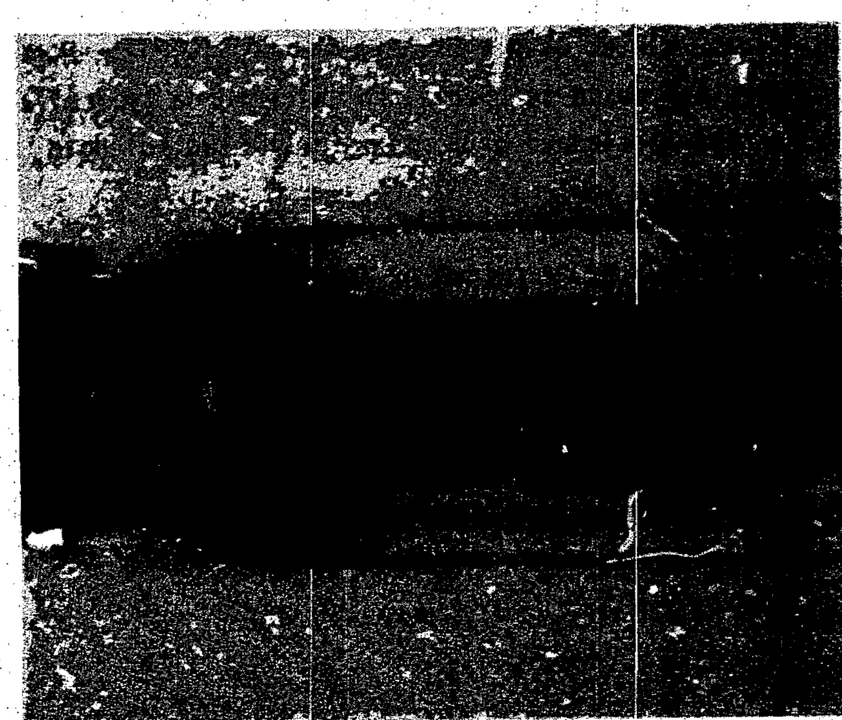

Figure 6. A typical reed switch in the normal position.

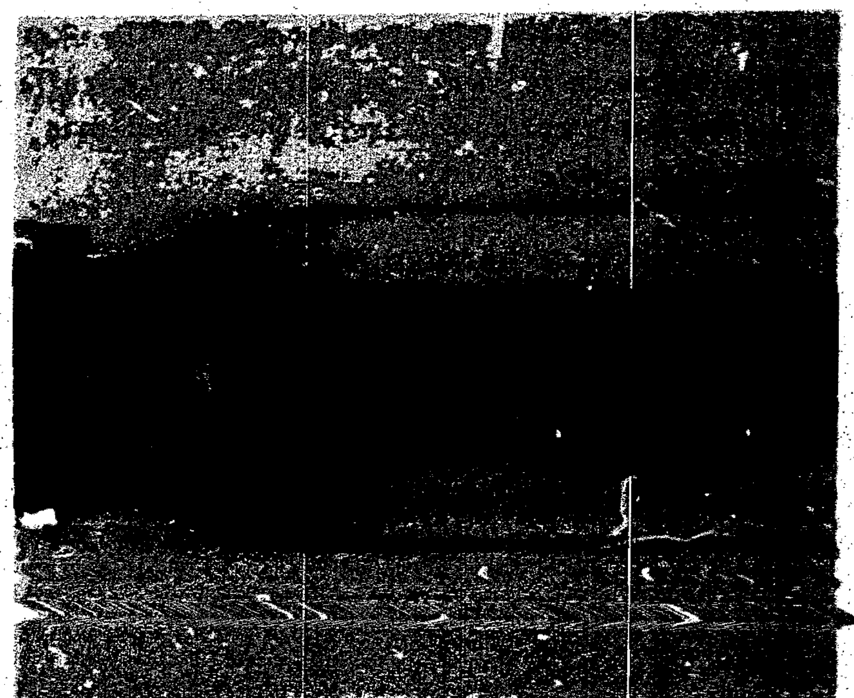

Figure 6. A typical reed switch in the normal position.

TESTING AND EXAMINATION

In Situ Tests

Solenoid AH-V74, which was removed from the Reactor Building in November 1981, was in situ tested to establish baseline information on the device. In this test, the solenoid holding current was measured at 0.7 amp, which is less than the designed maximum value of 1.5 amps, an indication that the solenoid operated normally.

Solenoid AH-V6 was tested two times, before and after the Reactor Building gross decontamination experiment in March 1982. In these two tests, the valve was stroked to measure the holding current and to determine the circuit dc resistance, inductance, and insulation resistance. A time domain reflectometry test was also performed on the coil and the limit switch circuits. In both test runs, the solenoid drew less than the designed maximum of 1.5 amps. Also, the position indication changed when the valve was stroked although the OPEN switch, which is closed when the valve is open, did not respond. It remained closed whether the solenoid was energized or deenergized. The switch contact should have opened when the solenoid was deenergized and closed when energized.

Testing at the INEL

Examination of Electrical and Operational Properties

Off-site examination of the two solenoid assemblies was carried out at the Idaho National Engineering Laboratory (INEL). Electrical and operational characterization tests were conducted to measure inductance and resistance, response time, pickup and dropout voltage, temperature rise, insulation resistance, and dielectric voltage withstand.

The solenoids were characterized electrically and dynamically using a test valve also manufactured by Valcor Engineering Corporation. The test valve has a bonnet assembly identical to those of AH-V6 and AH-V74. The body of the test valve, however, is different; it is made of carbon steel instead of stainless steel and was made specially to accommodate the AH-V6 and AH-V74 solenoids. Four solenoids were tested--the two TMI-2 units (AH-V6 and AH-V74) and two test units supposedly identical to AH-V6 and AH-V74. The test units were to provide baseline information to be compared to data for the TMI-2 units.

The TMI-2 solenoids exhibited no abnormal operational behavior nor abnormal electrical characteristics during the examination. However, the OPEN limit switch of AH-V6 would not respond to the change in valve plunger position, an anomaly observed during the in situ test. During the in situ test, the OPEN limit switch remained closed irrespective of the valve position; however, during the test at the INEL, the same switch remained open, regardless of the valve position. The CLOSE limit switch meanwhile responded properly.

The measured electrical properties and operational characteristics of both TMI-2 units, as summarized in Table 2, compared well with one another and to a close degree with those of the test units. The test units, which were not manufactured in the same years of the TMI-2 units, have slightly different electrical properties. The AH-V6 test unit was made before the accident but after the startup in 1977, while the AH-V74 test unit was made in 1982. As indicated in Table 2, the test units have an appreciably larger inductance and lower pickup and dropout voltage. The deviation is deduced to be due to more conductor turns in the test units. This deduction is explained below.

The inductance of a magnetic circuit is

$$L = \frac{0.4 \pi N^2}{R \times 10^8} \text{ henrys} \qquad (1)$$

where

L = inductance

N = number of turns of conductors

R = reluctance of the magnetic circuit.

TABLE 2. EXAMINATION RESULTS FOR SOLENOIDS AH-V6 AND AH-V74

Parameters	AH-V6		AH-V74	
	Test Solenoid	TMI-2 Solenoid	Test Solenoid	TMI-2 Solenoid
Solenoid Coil With Air Core				
Inductance (mH)	1106	881	1257	850
Dissipation Factor	0.203	0.25	0.193	0.251
ESR[a] (ohms)	170	164	183	160
Ohmic Resistance (ohms)	120.94	136.81	128.24	133.73
Solenoid Coil Mounted on Test Valve				
Inductance (H)	3.10	2.59	3.32	2.55
Dissipation Factor	0.459	0.458	0.444	0.466
ESR (ohms)	1070	890	1100	900
Pickup Voltage (volts)				
Trial 1	31.75	38.7	34.06	37.01
Trial 2	32.15	39.0	34.02	36.95
Trial 3	31.92	38.9	33.95	36.90
Dropout Voltage (volts)				
Trial 1	8.10	9.9	8.69	9.58
Trial 2	8.06	9.9	8.67	9.51
Trial 3	8.10	9.9	8.67	9.56
Response Time (milliseconds)				
Pickup				
Trial 1	275	270	260	260
Trial 2	275	270	260	260
Trial 3	275	270	260	260
Dropout				
Trial 1	370	380	370	370
Trial 2	370	380	360	370
Trial 3	370	380	360	370
Temperature Rise--final temp (°C)				
Trial 1	78	68	66.7	80.7
Trial 2	81	69	66.3	79
Trial 3	81	69	66.7	81
Insulation Resistance (ohms)				
Solenoid	--	3×10^{10}		--
2.5×10^{10}				
Transient Suppressor	--	8×10^{9}	--	7×10^{9}
Rectifier	--	7×10^{9}[b]		--
9×10^{9}				
Limit Switch	--	Removed	--	7×10^{9}

TABLE 2. (continued)

Parameters	AH-V6 Test Solenoid	AH-V6 TMI-2 Solenoid	AH-V74 Test Solenoid	AH-V74 TMI-2 Solenoid
Dielectric Withstand				
Solenoid				
V_d (Vac)[c]	--	1002.1	--	1002.2
I_L (ma)[d]	--	1.019	--	1.0029
Transient Suppressor				
V_d (Vac)	--	1006.5	--	1000.5
I_L (ma)	--	1.015	--	1.0096
Rectifier				
V_d (Vac)	--	3.6	--	1000.6
I_L (ma)	--	2.084	--	1.0088
Limit Switches				
V_d (Vac)	--	Not Tested	--	1000.6
I_L (ma)	--	--	--	1.0095
Transient Suppressor Suppression Voltage (volts)	300	300	300	300

a. ESR = Equivalent series resistance.

b. Insulation resistance dropped to 90,350 ohms after 7 min.

c. V_d = Dielectric withstano test voltage.

d. I_L = Leakage current.

The reluctance of a magnetic circuit is the property of the circuit geometry and permeability of the materials. Since the TMI-2 and test solenoids are, for all practical purposes, identical in both geometry and material makeup and all were tested using one valve, their individual reluctance is thus the same. As noted from the above relation, the inductance of the solenoids is a function of the square of their number of turns. Hence, the higher inductance of the test solenoids is attributed to their greater number of turns. This greater number of turns of the test solenoids is further corroborated by their lower pickup and dropout voltage, also explained below.

A minimum amount of force is needed to actuate the test valve plunger. This force is a function of the square of ampere turns. Hence, in achieving the specific ampere-turns required to operate the valve, an increase in the number of turns is accompanied by a decrease in amperes.

The Ohm's Law equation states

$$E = IR \tag{2}$$

where

E = voltage

I = current

R = resistance.

Since the resistance is practically the same for all the solenoids, a decrease in I is accompanied by a decrease in E, which explains the lower pickup and dropout voltage of the test solenoids.

The response time test showed that all four solenoids operated the test valve with exactly the same response of about 260 milliseconds pickup time and 370 milliseconds dropout time (Figures 7 through 14). This consistent response time signifies that the velocity, and hence the

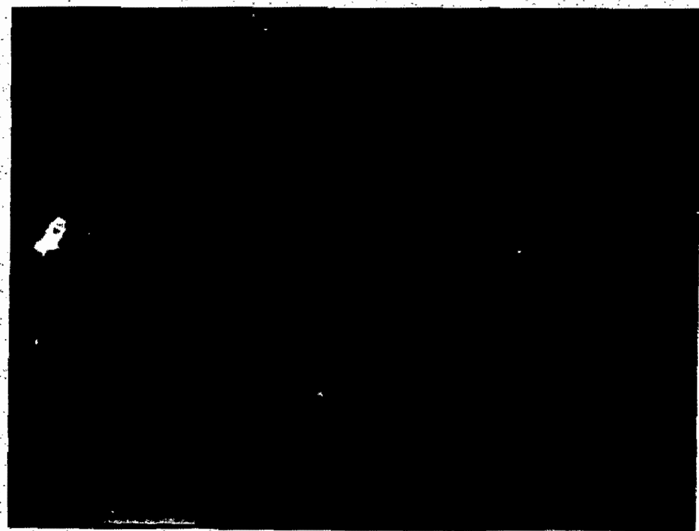

Figure 7. Scope trace of the opening response time test of the AH-V74 test solenoid. Scope setting: 50 milliseconds per division.

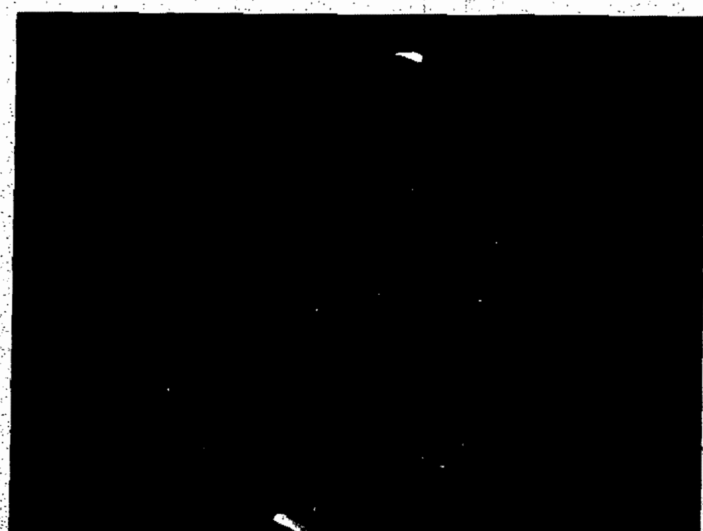

Figure 8. Scope trace of the closing response time test of the AH-V74 test solenoid. Scope setting: 100 milliseconds per division.

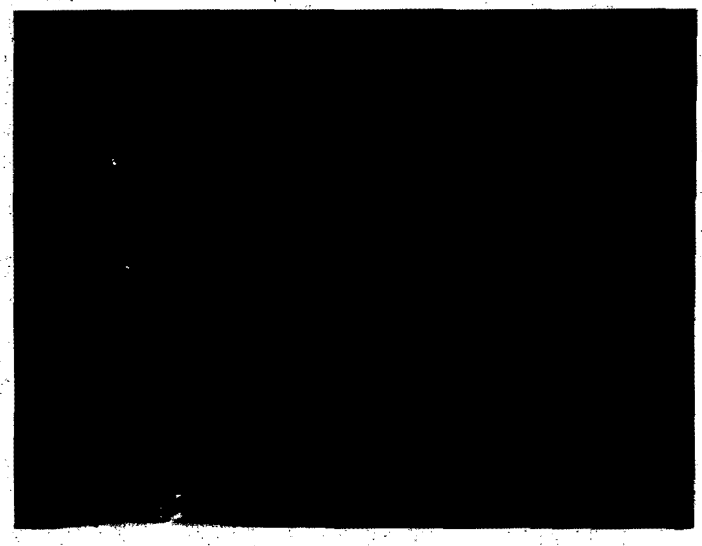

Figure 9. Scope trace of the opening response time test of the AH-V6 test solenoid. Scope setting: 50 milliseconds per division.

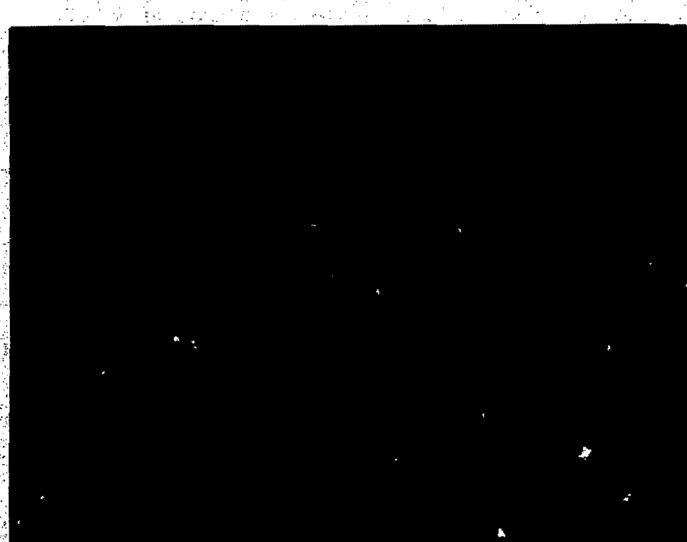

Figure 10. Scope trace of the closing response time test of the AH-V6 test solenoid. Scope setting: 100 milliseconds per division.

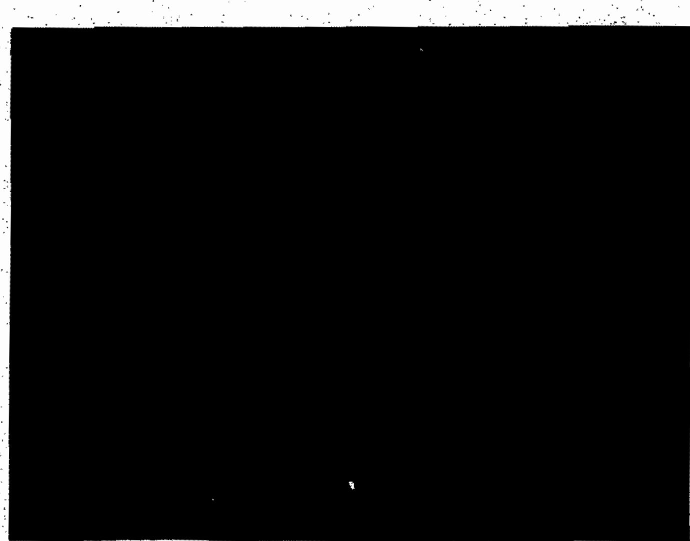

Figure 11. Scope trace of the opening response time test of the AH-V74 solenoid. Scope setting: 50 milliseconds per division.

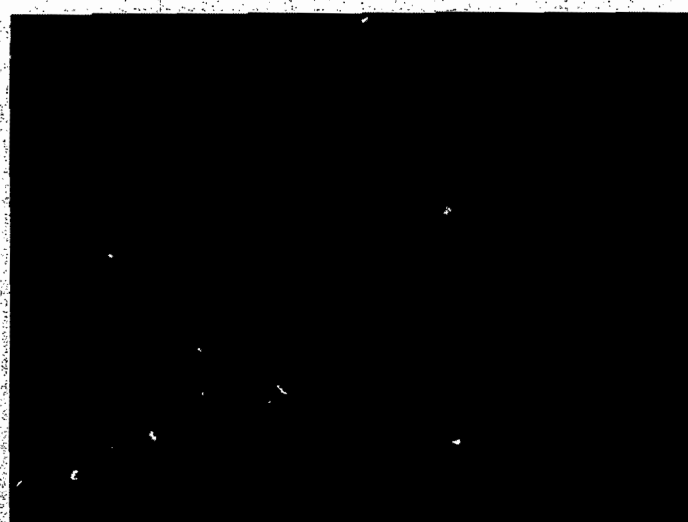

Figure 12. Scope trace of the closing response time test of the AH-V74 solenoid. Scope setting: 100 milliseconds per division.

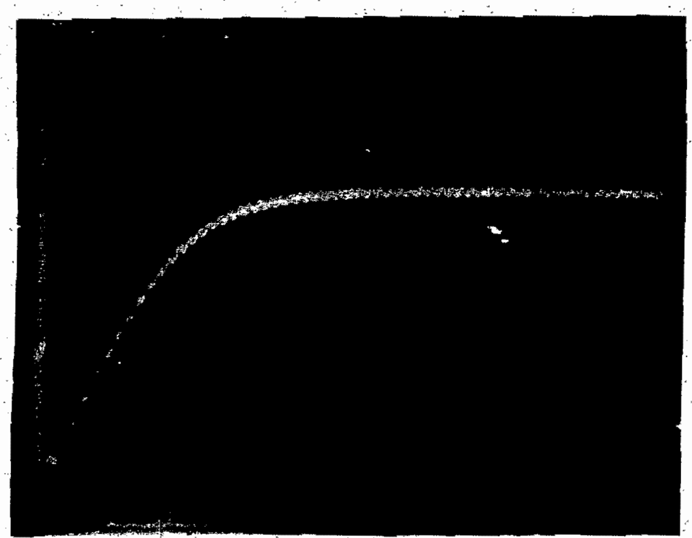

Figure 13. Scope trace of the opening response time test of the AH-V6 solenoid. Scope setting: 100 milliseconds per division.

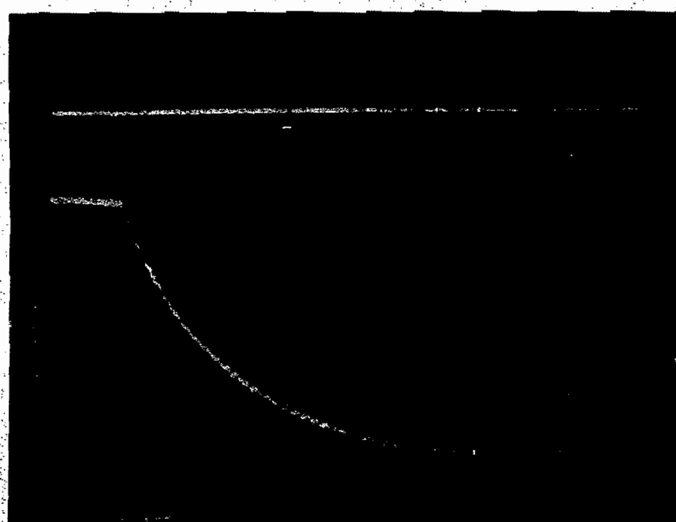

Figure 14. Scope trace of the closing response time test of the AH-V6 solenoid. Scope setting: 100 milliseconds per division.

acceleration developed by the plunger, is the same for AH-V6, AH-V74, and the two test units. Since force is the product of mass times acceleration, the force developed by each solenoid is about the same. This observation reinforces other observations that indicated the TMI-2 solenoids are intact and electrically normal.

The temperature rises of the TMI-2 solenoids agreed well with the test units and were significantly less than the 180°C for which the insulation was designed. The insulation resistance of $>10^8$ ohms exceeds the minimum value expected of a new unit. Furthermore, there was no insulation breakdown when the insulation was subjected to a 1000 Vac dielectric voltage withstand test. These three tests supported the presumption that the TMI-2 solenoids did not suffer any degradation electrically or operationally.

The transient suppressors of AH-V6 and AH-V74 evidently were not affected by the accident. They behaved much like the test unit did. The suppression voltage was found to be about 300 volts.

The insulation of AH-V74's limit switches, transient suppressors, and rectifier was found to be sound following an insulation resistance measurement test at 500 Vdc for ten minutes and dielectric voltage withstand test at 1000 Vac for one minute. The insulation of the AH-V6 rectifier broke down during the insulation resistance measurement test.

Examination of Physical Characteristics

Although the accident did not affect the solenoids electrically, it did cause physical degradation. Figures 15 through 19 are photographs of the solenoid coil shell assemblies of AH-V6 and AH-V74. As Figures 15 through 17 reveal, AH-V6 was extensively rusted. AH-V74 was only superficially rusted on its shell base (Figure 19).

The rusting on AH-V6 was concentrated around the lower end of the unit and on the top surface of the shell. Spectrochemical analysis of the deposition in those areas indicated the presence of an appreciable amount

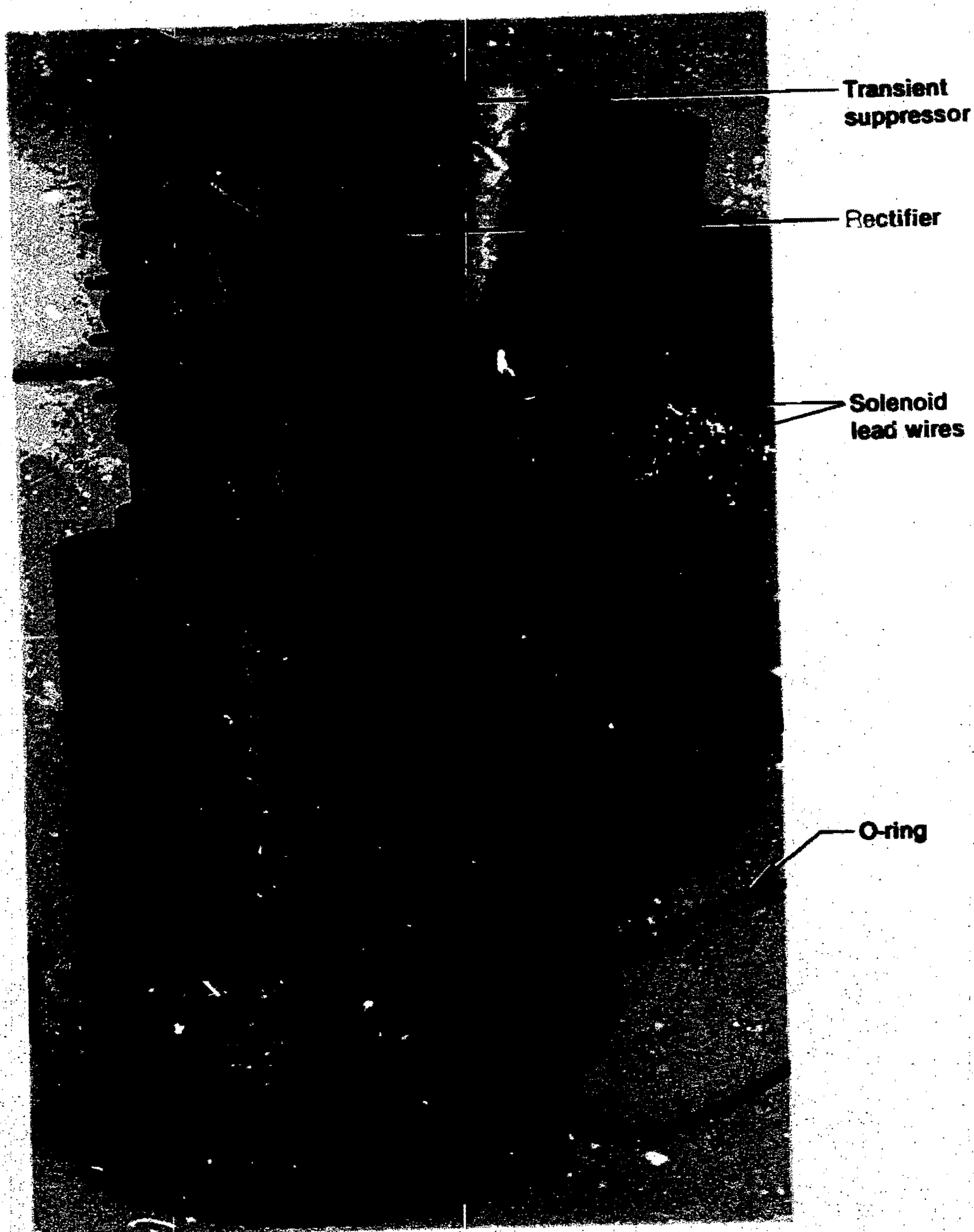

Figure 15. Front view of disassembled solenoid AH-V6 showing rust around base.

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Figure 16. Rear view of disassembled solenoid AH-V6 showing rust around base.

Figure 17. Base of solenoid AH-V6. Because of the effective seal of the O-ring, the base remained clean of rust.

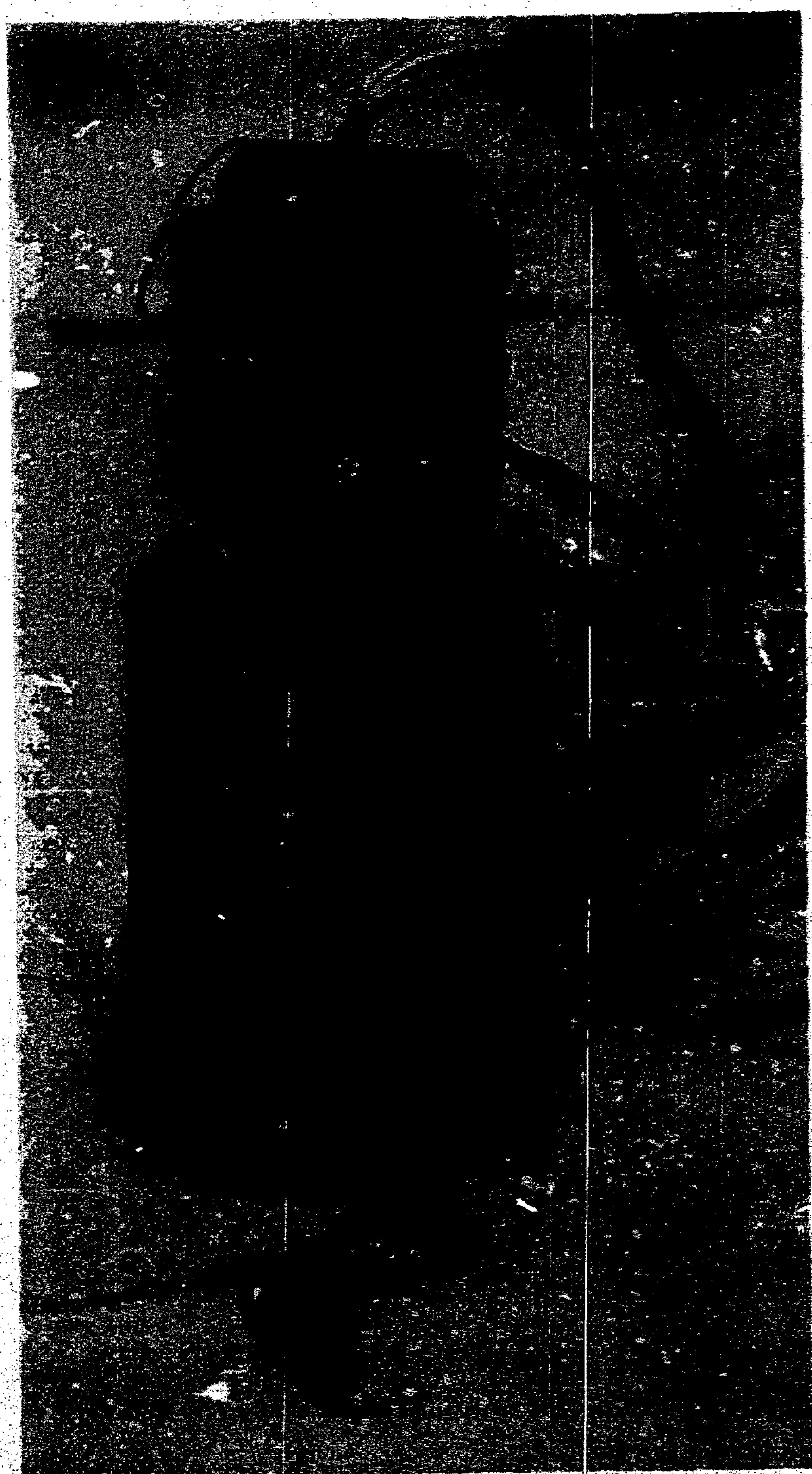

Figure 18. Disassembled solenoid AH-V74, which shows superficial rust at the bottom; otherwise the shell is clean.

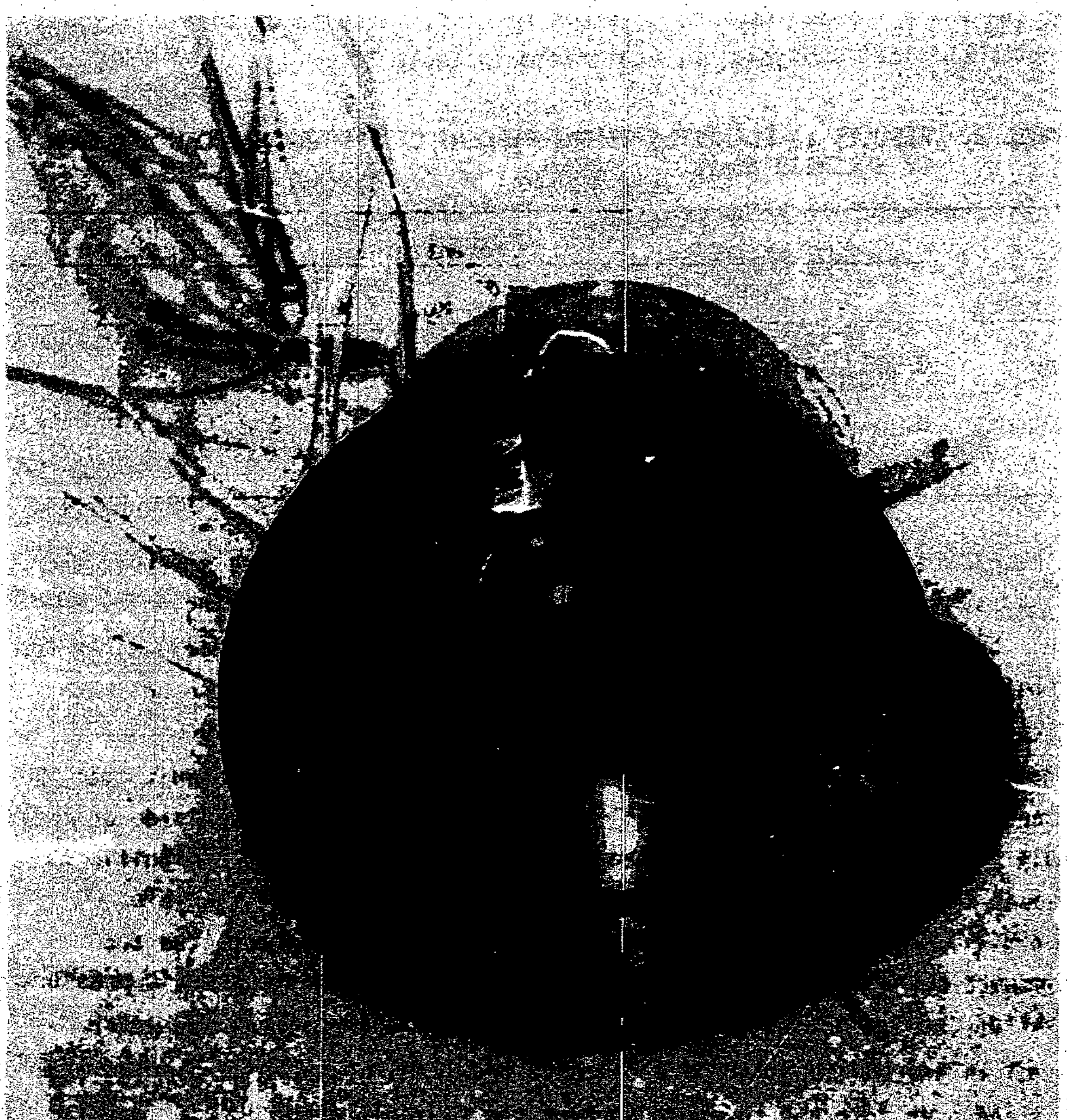

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Figure 19. Base of solenoid AH-V74, which became rusted due to water seeping in from outside the unit, not through its center.

of sodium and boron whose source evidently was the Reactor Building Spray System. It is speculated that while the building was being sprayed, some of the fluid seeped into the solenoid housing. Results of the spectrochemical analysis are summarized in Table 3.

TABLE 3. RESULTS IN ESTIMATED WEIGHT PERCENT OF SPECTROCHEMICAL ANALYSIS OF SOLENOID AH-V6

	Element										
Surface	Al	B	Cr	Cu	Fe	Mg	Mn	Na	Ni	Si	Zn
Top	0.005	0.06	0.02	0.2	25	0.01	0.1	0.2	2	1	--
Bottom	0.1	0.24	0.02	0.2	25	0.02	0.1	0.2	2	1	0.03

Figure 1 is the installation arrangement of AH-V6. The solenoid and limit switch lead wires are brought out of the solenoid housing into the pull box through the flexible conduit. In the pull box, the lead wires and cables M835C and M836C are spliced. As seen in the figure, the pull box sits higher than the solenoid cover. It has a special two-way relief valve that acts as a pressure equalizer and drain. The flexible conduit that connects the solenoid to the pull box is attached on the lower side of the pull box. Analyzing the arrangement, the only possible way a significant amount of water could get into the solenoid is through the flexible conduit. The water may have gotten into the pull box through the two conduits connected on top. Because of the higher-than-atmospheric pressure setting and low drainage capacity of the pressure equalizer, the water level in the pull box may have risen to the level of the side opening and spilled over into the solenoid through the flexible conduit. The water settled on the top and bottom sections of the annulus between the solenoid shell and the enclosure. Due to the O-rings on the bottom of the solenoid, the fluid got trapped in the annulus for an extended period of time.

Visual and physical examinations also revealed a yellowish discoloration of the braid on the insulation of the solenoid coil lead wires of both AH-V6 and AH-V74. The insulation was also found to be more brittle. A subtle discoloration of the Tefzel insulation of the limit switch lead wires was likewise noted. There was, however, no observable change in the pliability of the Tefzel insulation. The degradations noted can most likely be attributed to radiation.

Only the limit switches of AH-V6 were examined; those of AH-V74 were not used. As mentioned earlier, the OPEN limit switch would not close even when influenced by an external magnet. Subsequent x-ray examination of the device disclosed that the tip of the movable contact, as illustrated in Figure 20, broke off from the armature. The tungsten contact of the stationary contact was also separated.

The switch was first observed by the TMI-2 Operations Department to be giving false information before any in situ test was performed. This false information was probably the result of loose parts getting wedged between the stationary contact and the armature, thereby giving a continuous closed contact indication. The loose parts finally got dislodged when the solenoid's orientation was altered during its removal from the valve. To determine the failure mode, the switch metal encapsulation was sliced open. The removal of the metal insulation revealed several facts. The switch glass envelope was discolored and broke apart as soon as the encapsulation was removed. Visual examination of the exposed components (Figure 21) revealed what appeared to be a burned end of the armature arm, presumably caused by a fabrication flaw that may have made the joint structurally weak, thereby resulting in the premature failure of the device. The tungsten contacts of the stationary and movable arms were also rusted, an unexpected condition since the reed switch was supposed to be hermetically sealed. Although rusting cannot be declared with certainty to have caused the reed switch to fail, the actual intrusion of moisture into the device is in itself considered a fault. The moisture intrusion is surmised to be either through the switch terminal seal or through a crack in the glass envelope.

Both solenoid assemblies were found to be contaminated with fission products. The gamma spectrum analysis performed on the AH-V6 enclosure indicated the presence of ^{134}Cs and ^{137}Cs (Appendix A).

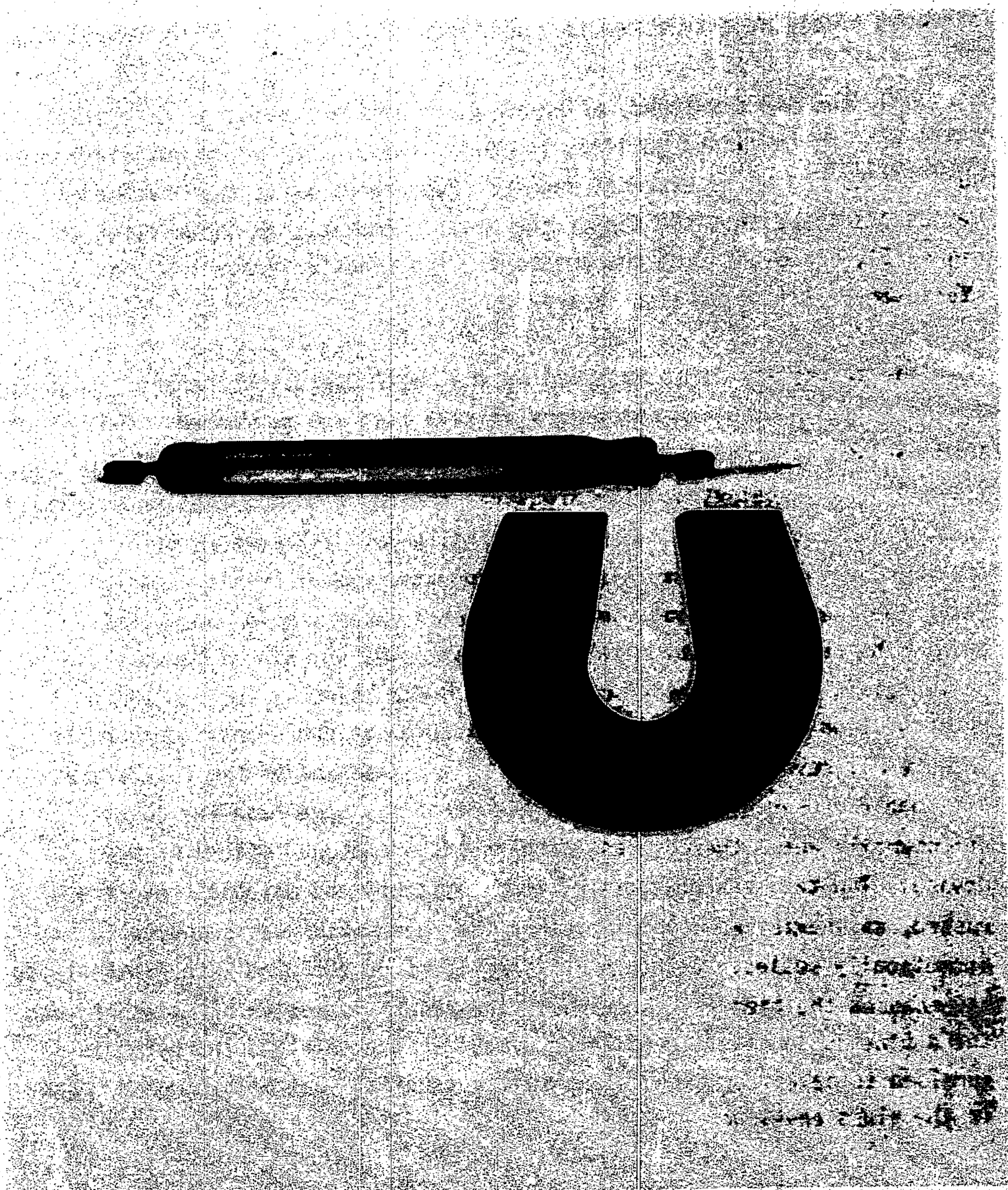

Figure 20. Negative of an x-ray of the defective limit switch of AH-V6, with magnet used in an attempt to move the loose parts back to their proper positions.

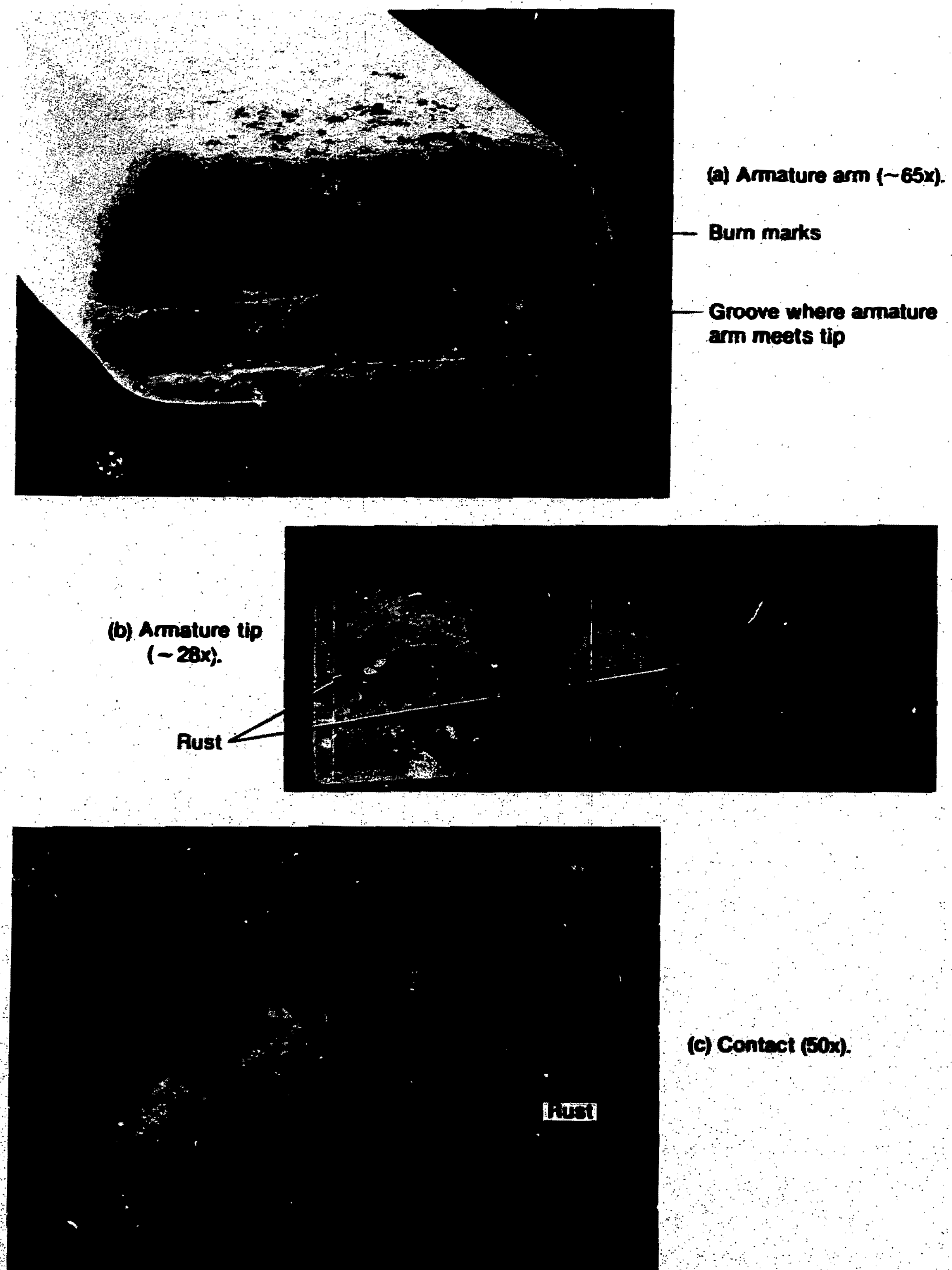

Figure 21. Damaged components of solenoid valve AH-V6.

CONCLUSIONS AND RECOMMENDATIONS

The examination of solenoids AH-V6 and AH-V74 revealed several aspects about this generic type of device that may compromise its operation during or following a LOCA. For example, the examination revealed degradation to the silicon rubber insulation of the solenoid coil lead wires of both units and insulation failure of the AH-V6 rectifier. The use of Tefzel as insulation for the limit switch lead wires also presents a problem. While Tefzel and silicon rubber have a high temperature tolerance, a necessary property of Reactor Building components, they also have a relatively low radiation damage threshold. Since insulation breakdown could result in shorting or grounding--either circumstance disabling to the solenoid--the use of silicon rubber, Tefzel, and the insulation material used for the rectifier would make the solenoid vulnerable to failure during a design LOCA. Obviously, the problem can be corrected by using insulating materials that are radiation tolerant as well as high temperature resistant.

Flooding is another potential problem that could render this type of solenoid inoperable during accident or post-accident operations. With O-rings on the base and flange of the solenoid shell, water can collect in the solenoid housing and seep all the way up to the terminal block, short-circuiting the unit. In the case of AH-V6, the problem can be eliminated by attaching the flexible conduit to the top side of the pull box. Since the problem is more one of installation geometry than design, flooding can be prevented through such measures as increasing the drainage capability of the interfacing pull box and sealing the cable entry point of the solenoid.

Water intrusion inside the reed switch should be evaluated. The hermetic seal of the device could be improved by encasing the reed switch supporting terminal with qualified shrink-tubing from the neck of the reed switch glass encapsulation to and including a few inches of the connected lead wire. Furthermore, the present mounting design of the limit switch permits cracking of the glass encapsulation by overtightening the fastening set screw, a circumstance that may have occurred in AH-V6. To circumvent this problem, a new feature of mounting the limit switches without pinching the body should be incorporated.

Although the presence of diodes within the assembly does not constitute a weak point in the design, their presence in a high radiation area somewhat decreases the solenoid's reliability for the simple reason that there are more components to fail. Diodes generally fail because of high leakage or by shorting, and a failure by any one of the diodes in this mode would render the solenoid inoperable. Since reliability is the main consideration in using a dc coil in lieu of an ac coil, an improvement to the present design would be to (a) locate the rectifier and transient suppressor outside the Reactor Building or (b) totally eliminate the rectifier and use a dc power feed to the solenoid. Also, since the transient suppressor is primarily used for the protection of switching and indicating components, a judicious design of the solenoid control circuit would do away with the need of the suppressor. This recommendation, suggested mainly to enhance system reliability, should be considered and implemented as a long-term improvement.

APPENDIX A

RESULTS OF GAMMA SPECTRUM ANALYSIS ON AH-V6 ENCLOSURE

EG&G Idaho

INTEROFFICE CORRESPONDENCE

Date: March 1, 1983

To: R. C. Stralm

From: C. P. Willis

Subject: SUBJECT: ISOTOPIC GAMMA ANALYSIS OF THE SOLENOID ACTIVATOR COVER AHV-6 -- CPW-5-83

The activator cover was repackaged in polyethylene bags and submitted to the RML for spectral gamma analysis. The sample was analyzed at a distance of 150 cm from the detector face and counted for a period of 10 hours as a point source. Cesium 134 and 137 were the only radioactive isotopes detected above the natural background.

The results obtained are:

Cs 134	1.6 ± 0.3	μ ci
Cs 137	21 ± 2	μ ci
Ba 137m	18 ± 2	μ ci

mt

cc: J. W. Rogers
O. D. Simpson
Central Files
C. P. Willis Files