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EMBEDDED CLADDING SURFACE THERMOCOUPLES ON ZIRCALOY-SHEATHED HEATER RODS

S. CURTIS WILKINS

June 1977

MASTER

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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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Approved:

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by

S. Curtis Wilkins

EG&G IDAHO, INC.

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ABSTRACT

Titanium-sheathed Type K thermocouples embedded in the cladding wall of zircaloy-sheathed heater rods are described within the text. These thermocouples constitute part of a program intended to characterize the uncertainty of measurements made by surface-mounted cladding thermocouples on nuclear fuel rods. Fabrication and installation details, and laboratory testing of sample thermocouple installations are included.

SUMMARY

The perturbing influence of surface-mounted thermocouples used for cladding surface temperature measurements on nuclear fuel rods results in a measurement uncertainty. The protrusion of the thermocouple into the coolant flow around the fuel rod measurably lowers the cladding surface temperature. As part of a program intended to characterize the uncertainty in the measurements as made with surface-mounted thermocouples, titanium-sheathed Type K thermocouples were embedded in the cladding wall of zircaloy-sheathed electrically powered heater rods which simulate nuclear fuel rods. The heater rods will be tested in a high temperature, high pressure flow loop under blowdown-reflood conditions. Comparison of the temperatures measured by the embedded thermocouples and the surface-mounted type used on nuclear fuel rods is expected to yield a characterization of the temperature measurement uncertainty.

The installation technique for the embedded thermocouples used the same titanium-sheathed thermocouple cable used for surface-mounted units on zircaloy-clad fuel rods in the Loss-of-Fluid Test reactor. A short section of the cable was reduced in diameter, flattened, and laid in a rectangular groove machined in the surface of the heater rod. A zircaloy ribbon was laser-welded over the flattened thermocouple to hold it in place and at the same time avoid corrodible Ti/Zr welds.

The weakened cladding wall of the heater rod successfully survived high pressure autoclave testing, and the embedded thermocouple installation was not damaged by blowdown testing. Samples operated in steam at high temperature, followed by quenching with ambient temperature water, survived nine such cycles although the foil cover oxidized badly and partially chipped off.

Impulse risetimes (10 to 90%) of the embedded units were measured at 16 to 18.5 msec in static water. A calibration check with a freeze point standard on samples installed on zircaloy cladding tubes showed the thermoelectric output to agree with the standard ANSI calibration to within 0.9%.

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EMBEDDED CLADDING SURFACE THERMOCOUPLES ON ZIRCALOY-SHEATHED HEATER RODS

I. INTRODUCTION

The cladding surface temperature of nuclear fuel rods is one of the important measurements to be made in water reactor safety tests. A simple method of making this measurement is by attaching a metal-sheathed thermocouple to the cladding surface. Unfortunately, the thermocouple protrudes into the coolant flow around the fuel rod and acts as a heat sink on the rod, resulting in a depressed surface temperature compared to the unperturbed case.

Modifications of the fuel rod cladding, such as machining grooves for the thermocouple installation, are not permitted in some cases. A characterization of the surface-mounted thermocouple measurement is thus required to derive the unperturbed surface temperature.

A technique has been proposed for deriving the true surface temperature from a knowledge of the coolant temperature and the cladding temperature at a known distance below the surface^[1,2].

Zircaloy-sheathed electrically powered heater rods were instrumented with surface-mounted thermocouples, simulating the core fuel rods in the Loss-of-Fluid Test (LOFT) reactor. The temperature indicated by these thermocouples will be compared to the true surface temperature as derived from temperatures measured with embedded cladding thermocouples on the same heater rods. The results can then be applied to measurements in the LOFT core with surface-mounted thermocouples.

II. EVOLUTION OF THERMOCOUPLE DESIGN

1. EMBEDDED BARE WIRES

The initial attempt to produce an embedded cladding thermocouple used a novel concept in which two bare thermocouple wires were laid in parallel grooves on the heater rod surface and covered with a foil strip laser-welded in place. The insulation for this installation was provided by an oxide layer produced on the zircaloy cladding and foil cover by exposure to an oxygen atmosphere at about 540°C (1000°F).

About 50 mm (2 in.) of the Type K wires were exposed by stripping off the titanium sheath of the LOFT cladding cable. The transition region between the cable end and the embedded wires was sealed by laser-welding, using titanium filler wire. This was a difficult and tedious operation and resulted in an assembly which was difficult to check for leaks. The thermocouple junction was made by welding the tips of the two wires together and locating it in a cutout area joining the two parallel grooves. A cross section of the embedded wires is shown in Figure 1.

Fig. 1 Cross section of bare-wire embedded thermocouple.

This installation was not successful, since the high solubility of oxygen in zircaloy caused the thin zirconium oxide layer to be absorbed at elevated temperatures. The region around the wires has an oxygen-poor atmosphere and the oxide layer cannot be sustained. Loss of the insulating layer resulted in shorting of the two thermocouple wires.

An apparent solution to this problem is to coat the exposed thermocouple wires with a ceramic layer prior to laying them in the two parallel grooves. However, producing a ceramic layer which is thin and rugged but still provides adequate insulating properties did not appear to be an immediate possibility. Thus, further work on this type of installation was discontinued.

2. SWAGED TITANIUM-SHEATHED CABLE

Swaging the available titanium-sheathed Type K thermocouple cable to a size which could be embedded in a 0.64-mm (0.025-in.) thick zircaloy wall was considered to be a feasible process. The cable could be swaged in several steps from its original 1.17-mm (0.046-in.) diameter to 0.36 mm (0.014 in.) while maintaining sheath integrity and wire continuity. This type of thermocouple was installed in a groove in the cladding surface, and laser-welded in place using titanium filler wire.

Two problems developed with this type of installation, both showing up when samples were operated in a steam-reflood cycle (see Section IV-3 for a description of the apparatus used) at about 980°C (1800°F).

2.1 Ti/Zr Weld Corrosion

Figure 2 shows a cross section of a 0.36-mm (0.014-in.) diameter titanium-sheathed thermocouple installed on a section of zircaloy cladding. This sample was operated in several

Fig. 2 Cross section of embedded 0.36-mm (0.014-in.) diameter titanium-sheathed thermocouple.

steam-reflood cycles and showed severe corrosion of the titanium/zircaloy laser welds. When weld penetration is deep in the thermocouple sheath, the corroded region can result in leaks, as well as destruction of the mechanical attachment to the cladding. The heavy-walled 1.17-mm (0.046-in.) diameter cable had shallow attachment weld penetration, with titanium filler wire added; thus the corrosion problem on these welds was minimal.

This phenomenon has been observed by other investigators^[3,4] and is thought to vary in severity in proportion to the extent of Ti/Zr mixing in the weld. The same problem occurs whether titanium or zircaloy filler wire is used, being more severe when zircaloy is added. Thus, a zirconium-rich weld is assumed to be more susceptible to this preferential corrosion.

A proposed solution to this problem would stake the thermocouple in the groove by using zircaloy filler wire which is incompletely melted adjacent to the thermocouple sheath. Alloying of titanium and zirconium would thus be avoided and corrosion would not occur. However, the second problem found during steam-reflood cycling changed the philosophy about attachment.

2.2 Development of Parasitic Junctions

Although the thermoelectric output of this type of thermocouple installation appeared to be satisfactory, as compared with a reference thermocouple, later examination revealed that these thermocouples had several junctions at which an electromotive force could be generated. These could be located quite well by sliding the tip of a hot soldering iron along the thermocouple sheath while watching the thermocouple output on a digital meter. The regular spacing of these points seemed to be more than coincidental.

From X-rays of cable made during development of these thermocouple installations, 90-degree twists were known to occur at regular intervals in the wires within the cable, a frequent occurrence in swaged cables (see Figure 3). Many of the cables used for this work

Fig. 3 X-ray of swaged titanium-sheathed thermocouple cable showing twist in thermoelements.

were found to have such twists, typically at 25-mm (1-in.) intervals. The number of twists in a given cable may or may not increase as a result of further swaging. A correlation for this effect was not established.

With the aid of X-rays, the locations of 90-degree twists in cables were marked and found to correspond with the locations of new junctions after steam-reflood cycling. Evidently this effect is due to a decrease in the separation of the two thermocouple wires at the location of twists, with insufficient insulation at those points to maintain electrical isolation during a high temperature excursion.

Cables were swaged to successively smaller diameters and tested in steam-reflood cycles to determine the smallest diameter at which these parasitic junctions could reliably be expected not to form. Two or three steam-reflood cycles to about 980°C (1800°F) resulted in failure for 0.71-mm (0.028-in.) diameter cables. Those swaged to 0.76-mm (0.030-in.) diameter all survived 15 such cycles, considered to be adequate for the intended application.

The ability of these thermocouples to survive steam-reflood cycling was not noticeably affected by flattening the cable as long as the cable was flattened in the plane of the thermocouple wires and none of the 90-degree wire twists existed along the flattened section. Both of these situations resulted in poor insulation resistance or in shorted wires.

3. FINAL THERMOCOUPLE DESIGN

3.1 Flattened Cable Thickness

Since the titanium-sheathed cable could be swaged to only 0.76-mm (0.030-in.) diameter, flattening the cable at the measuring junction was necessary in order to embed the thermocouple in the 0.64-mm (0.025-in.) thick wall of the zircaloy sheath of the heater rod. To reduce the diameter of the cable without affecting its ability to resist the formation of parasitic junctions during thermal cycling, the wall thickness of the cable sheath was reduced by acid etching. A 1:3:10 solution of HF/HNO₃/H₂O is suitable for this purpose; stronger solutions etch more rapidly, but less evenly. The result may be a rough surface which tends to crack during the flattening step.

The tendency toward sheath cracking during flattening was strongly dependent on the final sheath thickness. Only partial success in avoiding sheath cracking resulted with cable etched to a 0.64-mm (0.025-in.) diameter. A success rate of about 80% was noted in avoiding cracking of cable etched from 0.76- to 0.66-mm (0.030- to 0.026-in.) diameter.

The thickness to which the cable was flattened did not seem to have a direct relation to the occurrence or severity of cracking. Thus, the minimum acceptable thickness after flattening was based on insulation resistance measurements on the flattened cable. Comparison of insulation resistance was made before and after flattening the cable and

before and after steam-reflood cycling. A thickness of 0.38 mm (0.015 in.) was found to be the minimum for which the insulation resistance remained at least 50 k Ω after thermal cycling, while still having adequate insulation web thickness. Although the insulation resistance decreased slightly immediately after flattening, the order of magnitude was unchanged (typically 100 M Ω). The change can be attributed to the change in geometry of the insulation web from circular to nearly rectangular.

3.2 Junction Design

Since temperatures as high as 1090°C (2000°F) were anticipated during operation of these thermocouples in a pressurized flow loop, a means of precluding the eutectic formation between titanium and Chromel-Alumel wires was required. Contact of these materials was avoided by using tantalum as an intermediate material at the measuring junction.

The tantalum was incorporated in the form of a short length of small-diameter tubing inserted over the ends of the two thermoelements and slipped into the end of the titanium sheath. Sheath closure was made by laser-welding a titanium foil disc over the cable end. The measuring junction is thus mechanically grounded to the cable sheath. Details of junction fabrication are included in a later section.

3.3 Installation on Heater Rod

Since preferential corrosion of titanium/zircaloy welds had previously been identified as a problem, attachment of the titanium-sheathed thermocouple to the zircaloy-sheathed heater rod was accomplished without making this type of weld.

Figure 4 shows a diagram of the cross section of the thermocouple installation. A rectangular groove was machined in the zircaloy sheath, in which the flattened thermocouple was laid. The depth of the groove is sufficient to accommodate the thermocouple and a strip of zircaloy foil, the upper side of the foil being flush with the

Fig. 4 Diagram of cross section of titanium-sheathed thermocouple embedded on zircaloy-clad heater rod.

heater rod surface. The foil strip was welded to the heater rod with a bead of overlapping pulsed laser spots around the foil's edge. Figure 5 shows a diagram of the installation and Figure 6 shows photos of the completed installation on a heater rod. Welding was facilitated and the strength of the cover improved by machining a land such that the foil strip which fits the groove is wider than the thermocouple it covers. The all zircaloy welds are not subject to preferential corrosion and the titanium-sheathed thermocouple is still firmly attached to the rod. Although heat transfer through the thermocouple may not be as good as when the heater rod and thermocouple sheath are welded directly, the thermocouple is indeed embedded, with only a slight distortion of the original heater rod surface (see Figure 7).

Fig. 5 Diagram of embedded thermocouple installation on zircaloy-clad heater rod.

Fig. 5a Completed embedded thermocouple installation on zircaloy-clad heater rod.

Fig. 6b Side view of completed embedded thermocouple installations on zircaloy-clad heater rod.

Fig. 7 Cross section of embedded titanium-sheathed thermocouple on cladding of zircaloy heater rod.

III. FABRICATION TECHNIQUE

The thermocouple cables used for surface-mounted thermocouples on zircaloy-clad fuel rods in the LOFT reactor were modified over a length of only about 25 mm (1 in.) at the measuring junction end. Major steps in the procedure are illustrated in Figures 8 through 14.

Fig. 8 Cross section of 1.17-mm (0.046-in.) diameter titanium-sheathed thermocouple cable.

Fig. 9 Tantalum tube over laser-welded junction of 0.91-mm (0.036-in.) diameter titanium-sheathed thermocouple.

A section of cable (as in Figure 8) with parallel thermoelements was selected by X-raying the cable. This cable section was swaged to a 0.91-mm (0.036-in.) diameter and a junction was welded on the thermoelements. A short length of tantalum tubing was inserted

Fig. 10 Tip of titanium-sheathed thermocouple swaged to 0.76-mm (0.030-in.) diameter.

Fig. 11 Junction end of 0.76-mm (0.030-in.) diameter titanium-sheathed thermocouple sealed by laser-welding a titanium disc over the tip.

Fig. 12 Flattened thermocouple junction inserted in groove on heater rod surface.

Fig. 13 Zircaloy foil cover in place over flattened titanium-sheathed thermocouple on heater rod surface.

Fig. 14 Zircaloy foil cover laser-welded in place on heater rod surface.

into the end of the titanium sheath and over the welded measuring junction (Figure 9). This prevented contact of the Chromel/Alumel thermoelements with the titanium sheath and subsequent eutectic reaction at high temperature. The cable section was then swaged to 0.76-mm (0.030-in.) diameter (Figure 10) and the tip capped with a titanium disc laser-welded circumferentially in place (Figure 11). The diameter of the swaged section was etched to 0.66 mm (0.026 in.) and flattened to 0.38-mm (0.015-in.) thickness over a length of about 25 mm (1 in.).

The heater rod was prepared by machining surface grooves at the desired thermocouple locations. The installation is described in Subsection II-3-3.3 and in Figure 4. Figures 12 through 14 show a thermocouple in such a groove, the zircaloy foil strip laid over the thermocouple, and the strip welded in place. The thermocouple cables were attached to the heater rod surface at uniform intervals along the length of the heater rod by a laser welding process.

IV. TESTING

Since the embedded thermocouples were intended for use in a hot, pressurized flow loop, with subsequent blowdown tests, it was desirable to know something about their ability to survive these conditions. The test cycle consists basically of three parts: (a) a pressurized state in hot water, (b) a blowdown to atmospheric pressure and operation in a steam atmosphere, followed by (c) reflood with ambient water. An attempt was made to simulate each of these three conditions separately. The collective effect can be determined only by operation in a hot, pressurized flow loop.

1. AUTOCLAVE TESTING

Since the embedded thermocouples were installed in rather deep grooves in the heater rod wall (up to 75% of the wall thickness), there was concern as to whether the installation would be strong enough to avoid collapsing the heater rod in a pressurized water environment. Confidence in the strength of the installation was improved by autoclave testing a sample thermocouple installed in a groove in a section of zircaloy-sheathed heater rod, exactly as done on the actual heater rods. The test section of heater rod was cut from one end of the rod, such that the original end cap was left intact. Sufficient insulation and the heater element were removed from the other end to insert a zircaloy end cap and weld it in place. Only a short length of thermocouple cable was attached to the heater rod sample, with 25 mm (1 in.) embedded at the measuring junction end. The output of the thermocouple thus was not monitored during the test. The sample was tested at 15.5×10^6 pascals (2250 psi) and 316°C (600°F) for 4 hours. The end caps were removed from the sample after completion of the test and the insulation and heater element were also removed. No evidence of moisture was seen in the insulation upon its removal. The remaining tube, with the thermocouple installation, was helium leak tested and no leaks were found. The test sample was then sectioned to examine the area around the groove in the heater rod wall for cracking. A photograph of a cross section of the groove after testing, with the thermocouple removed, is shown in Figure 15. No evidence of cracking can be seen.

Fig. 15 Cross section of grooved heater rod wall after autoclave test.

2. BLOWDOWN TESTING

A second concern about the integrity of the thermocouple installation involved its ability to withstand a blowdown in the hot flow loop. Since one end of the zircaloy cover was not sealed, water under pressure would be forced under the cover and around the flattened thermocouple itself. An autoclave blowdown test was conducted to see if the cover would remain intact under the sudden release of pressure. A sample thermocouple, which was not monitored during the test, was installed on a section of pressurized water reactor type zircaloy cladding, with the same dimensions as the heater rod sheath. Two blowdown cycles from 15.5×10^6 pascals (2250 psi) and 316°C (600°F) were conducted in distilled water. Figures 16 and 17 show photos of a section of the welded cover before and after the two blowdown cycles, respectively. No damage to the cover is evident as a result of blowdown. Pressure release through the open end of the cover is evidently rapid enough to preclude rupturing the cover.

Fig. 16 Zircaloy foil cover over embedded thermocouple prior to blowdown test.

Fig. 17 Zircaloy foil cover over embedded thermocouple after two blowdown cycles.

3. STEAM-REFLOOD TESTING

The lifetime of the embedded thermocouples, when cycled through high temperature steam to reflood with ambient temperature water, was tested. It was hoped that a minimum of five or six cycles could be expected from the embedded installation.

A schematic of the apparatus used for steam-reflood testing is shown in Figure 18. A vertical tube furnace has a quartz tube through the hot zone; the quartz tube is fixtured at the lower end to allow steam or water to be forced into it, and also has a drain provided. A simple steam generator consisted of a large flask filled with water on a hot plate, attached to the lower end of the quartz tube by a length of flexible tubing. A check valve in this line prevented water from flowing back into the steam generator. Steam was forced through the quartz tube and allowed to purge the air from it. A stainless-steel-sheathed thermocouple was inserted through the quartz tube into the hot zone of the furnace for temperature

Fig. 18 Diagram of steam-reflood apparatus.

INEL-A-2466

reference. When the furnace was stabilized at 980 to 1090°C (1800 to 2000°F) and had been purged with steam for typically 1 to 2 minutes, the test thermocouple was inserted into the hot zone of the furnace through the quartz tube. The test and reference thermocouples were monitored to check their agreement and to identify failure of the test unit, should it occur. After stabilization, agreement of the two thermocouples was typically within 1%, frequently within 1/2%.

After stabilization in the steam environment, the steam flow was shut off and water forced into the quartz tube from its lower end to simulate reflood of the test sample. After the two thermocouples indicated the nominal water temperature, the test sample was removed from the furnace. Oxidation in air at high temperature was thus avoided. The water was then drained from the quartz tube and the steam flow again started in preparation for another cycle.

Figures 19a and 19b show both ends of the embedded section after five steam-reflood cycles. Operation of the thermocouple was successful, within the accuracy stated above, but the zircaloy foil cover is badly oxidized. In fact, a hole can be seen near the end of the cover. Severe oxidation of the titanium thermocouple also occurred, and spalling of the oxide has begun.

The same regions of the zircaloy cover after nine steam-reflood cycles are shown in Figures 20a and 20b. Large sections of the cover have come off as a result of extreme embrittlement due to oxidation. The thermocouple continued to operate satisfactorily, and although further oxide spalling from the titanium sheath can be seen, no degradation in operation resulted.

Two points should be made concerning this test. First, although the zircaloy cover over the embedded thermocouple section did not survive completely intact, the thermocouple was still held firmly in the groove at the edges, where the welds remained largely uncorroded. Considerable effort was necessary to chip the welds away when the thermocouples were removed for inspection. In fact, in most cases the embrittled thermocouples were broken in the attempt to remove them. Thus, the thermocouple was still held securely in place and still operated satisfactorily. Second, the oxidation condition of the zircaloy cladding should be noted in Figures 19 and 20. The fractured oxide surface indicates rapid oxidation, more so than normally seen in a steam environment. The white areas may be the result of nitriding of the zircaloy surface, implying that air was a component of the atmosphere. This could result from an incomplete purge of the quartz tube in the furnace or from air aspirated into the system with the steam. The severity of corrosion of the zircaloy surface indicates that the test samples probably experienced the equivalent of many more than nine steam-reflood cycles in a hot flow loop where air has been excluded. In short, the test thermocouples survived nine cycles at more severe conditions than expected in actual operation, and could have been tested further.

(a)

(b)

Fig. 19 Ends of zircaloy foil cover over embedded titanium-sheathed thermocouple after nine stream-reflood cycles to about 980°C (1800°F).

(a)

(b)

Fig. 20 Ends of zircaloy foil cover over embedded titanium-sheathed thermocouple after nine steam-reflood cycles to about 980°C (1800°F).

4. IMPULSE RISETIME TESTING

The impulse risetime (10 to 90%) of the embedded titanium-sheathed thermocouple was tested using a laser beam pulse as the heat source. The apparatus used for this test is diagrammed in Figure 21. An embedded thermocouple was installed on a short length of new zircaloy cladding and the cladding cut away on the side opposite the thermocouple installation. The ends of the remaining section of the zircaloy tube were inserted through rubber stoppers with holes of a size which provided a tight fit. The stoppers were inserted into the ends of a stainless steel tube, also with one side cut away, such that the inside surface of the zircaloy cladding adjacent to the embedded thermocouple was visible.

Fig. 21 Diagram of cross section of thermocouple impulse risetime test apparatus.

The pulsed laser beam was directed at the inside surface of the cladding opposite the thermocouple junction, so that the heat source was inside the cladding as in actual operation. The split tube arrangement can be filled with water, in a further attempt to simulate operating conditions. The laser beam spot size was adjusted to approximately the width of the embedded thermocouple to minimize the sensitivity to slight changes in the laser pulse location. The laser beam energy was adjusted to heat the junction as high as possible without damaging the inside surface of the cladding, which is only about 0.18 mm (0.007 in.) thick underneath the thermocouple. The laser pulse is very nearly a square pulse of about 7.5-msec duration. The thermoelectric output of the thermocouple was recorded

on an oscillograph, and the impulse risetime measured directly from the chart trace. Tests were conducted with and without water surrounding the thermocouple on two separate units. The impulse risetimes in air are included in Table I.

TABLE I
EMBEDDED THERMOCOUPLE IMPULSE RISE TIME

<u>Unit</u>	<u>Medium</u>	<u>Impulse Risetime 10 to 90% (msec)</u>	<u>Standard Deviation (msec)</u>	<u>Average Response (°C/msec)</u>	<u>Average Peak (°C)</u>
1	Water	18.4	1.1	5.7 (10.2°F/msec)	112 (234°F)
	Air	23.2	0.6	4.9 (8.8°F/msec)	125 (257°F)
2	Water	16.1	1.9	5.8 (10.4°F/msec)	88 (190°F)
	Air	19.3	0.2	4.6 (8.2°F/msec)	87 (188°F)

By way of comparison, the standard LOFT surface-mounted thermocouples tested previously in this manner had an average impulse risetime of 50 msec in water. The impulse risetime of an intrinsic thermocouple attached to the zircaloy cladding surface was 11.9 msec.

5. FREEZE-POINT CALIBRATION CHECK

A sample embedded installation was checked for thermoelectric wire calibration at the freezing points of four metals: tin, zinc, aluminum, and copper. Tin and zinc are taken as primary points on the International Practical Temperature Scale of 1968 and aluminum and copper as secondary points.

The sample was inserted into the center of the crucible containing the pure metal, and the freeze plateau for each sample maintained for a minimum of 20 minutes. The interior chamber in which the crucible was heated was purged with argon gas during the course of each freeze-point check. Table II lists the pertinent data for the calibration check.

TABLE II
FREEZE-POINT STANDARD CALIBRATION CHECK ON EMBEDDED
TI-SHEATHED THERMOCOUPLES ON ZIRCALOY CLADDING

<u>Metal</u>	<u>TC Output [a] (mV)</u>	<u>TC Temperature (°C)</u>	<u>Freeze Point IPTS 1968 (°C)</u>	<u>Difference (%)</u>
Sn	9.486	233.60 (452.48°F)	231.97 (449.54°F)	+0.65
Zn	17.288	421.11 (790.00°F)	419.58 (787.24°F)	+0.35
Al	27.544	662.34 (1224.22°F)	660.37 (1220.66°F)	+0.29
Cu	44.159	1075.00 (1967.00°F)	1084.50 (1984.10°F)	-0.86

[a] Reference junction at 0°C (32°F).

V. CONCLUSIONS

Testing of the embedded thermocouple design reported herein revealed the following:

- (1) Thermocouples embedded to a depth of 75% of the wall thickness of zircaloy-clad heater rods can survive autoclave and blowdown cycles at typical pressurized water reactor (PWR) conditions without damage to the cladding.
- (2) Embedded thermocouples with a zircaloy foil cover have a limited cladding attachment lifetime under steam operation-reflood conditions; due to oxidation and disintegration of the foil cover, although thermocouple operation is not affected.
- (3) Embedded cladding surface thermocouples with grounded measuring junctions of the design in this report have impulse risetimes (10 to 90%) of less than 20 msec.
- (4) The accuracy of metal sheathed thermocouples swaged beyond normal limits is generally not within the original specification of the manufacturer. However, for the units tested in this report, the accuracy was consistently within 0.9% up to the melting point of copper.
- (5) Embedded thermocouples having zircaloy, rather than titanium, sheaths would permit installation to be shallower while still avoiding Ti/Zr welds which corrode preferentially in a pressurized hot water environment.

VI. REFERENCES

1. G. A. Wikhammer, E. O. Moeck, I. P. L. McDonald, *Measurement Techniques in Two-Phase Flow*, APPE-24 (October 1964).
2. E. O. Moeck, *Surface Mounted and Imbedded Thermocouples at Post Dryout Conditions*, CRNL-454 (March 1970).
3. J. B. Cotton, "Oxidation Behavior of Titanium-Zirconium Alloys and Titanium-Zirconium Welds," *Chemistry and Industry* (February 24, 1962).
4. R. H. Meservey, *Temperature Measurement on Zircaloy-Clad Fuel Pins During High Temperature Excursions*, ANCR-NUREG-1303 (April 1976).

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