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ABSTRACT

Small diameter zircaloy sheathed thermocouples have been developed by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory. Surface mounted thermocouples were developed to measure the temperature of zircaloy clad fuel rods used in the Thermal Fuels Behavior Program (TFBP), and embedded thermocouples were developed for use by the Loss-of-Fluid Test (LOFT) Program for support tests using zircaloy clad electrically heated nuclear fuel rod simulators. The first objective of this developmental effort was to produce zircaloy sheathed thermocouples to replace titanium sheathed thermocouples and thereby eliminate the long-term corrosion of the titanium-to-zircaloy attachment weld. The second objective was to reduce the sheath diameter to obtain faster thermal response and minimize cladding temperature disturbance due to thermocouple attachment.

Thermocouples, currently in production for the TFBP, utilize tungsten rhenium thermoelements and beryllium oxide insulation internal to the zircaloy sheath. These thermocouples, limited by the melting point of zircaloy (1820^{o}C), were fabricated to a diameter of 0.71 mm by means of rotary swaging and intermediate annealing at 650^{o}C, followed by rapid cooling in an inert gas atmosphere. The tip of the thermocouple was then flattened to 0.48 mm, which produced a 1-mm-wide and 1.5-mm-long tab for laser welding to the surface of

zircaloy fuel rods. The thermocouple was attached to the stainless steel extension cable through the use of an explosion bonded zircaloy-stainless splice sleeve.

Zircaloy sheathed thermocouples, using Chromel-Alumel thermoelements and magnesium oxide insulation, with a diameter of 0.61 mm, have been successfully utilized with zircaloy clad nuclear fuel rod simulators in LOFT support tests. The thermocouple tips, which were flattened to 0.43 mm, were totally embedded and laser welded to the zircaloy cladding. Use of drawing instead of rotary swaging techniques were shown to avoid thermoelement twists and excessive insulation compaction. Quenching in inert gas at the end of each annealing cycle produced finer grain structure and increased ductility.

Tests to 10 000 hours in an autoclave at pressurized water reactor (PWR) conditions indicated no serious corrosion of the zircaloy sheath to zircaloy cladding bonds. Thermal response time in static water was determined to be 24 ms for the TFBP devices and less than 10 ms for the LOFT embedded version. Both types were shown to be within 0.75% of standard calibration curves at the melting point of aluminum (660^{o}C), and were able to withstand blowdown reflood conditions by surviving more than four 980^{o}C to ambient temperature water quenches before the onset of excessive oxidization, embrittlement, or loss of insulation resistance. These thermocouple types represent the smallest known zircaloy sheathed thermocouples to have been fabricated and tested.

INTRODUCTION

Small diameter zircaloy sheathed thermocouples have been developed and tested by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory for use in reactor safety research. Two distinctly different types were produced for different temperature and mounting conditions. These thermocouple types represent the smallest known zircaloy sheathed thermocouples to have been fabricated and tested. Swaging and drawing reduction techniques were used with intermediate annealing steps, but both types were shown to be compatible with zircaloy cladding and to have standard calibration curves. Development of the surface thermocouple was in behalf of the TFBP for use in in-pile nuclear tests at the Power Burst Facility (PBF). Development of the embedded thermocouple was in behalf of the LOFT Program for use on electrically heated fuel rod simulators. The performance of these thermocouples was compared, in steam-water blowdown tests, with that of standard LOFT 1.17-mm titanium sheathed thermocouples at the LOFT Test Support Facility (LTSF).

Historically, the LOFT Program provided the impetus to find a method of making long-term fuel rod cladding temperature measurements. These temperature measurements are necessary to assess the predicted cladding temperatures during a simulated loss-of-coolant accident (LOCA).

Since the fuel rod cladding material was zircaloy, a compatible sheath material was needed for direct attachment to the outside of the fuel rods. The logical choice would have been a miniature zircaloy sheathed thermocouple so as not to perturb the measurement environment, to avoid the corrosion resulting from the use of different metals, and to ensure identical thermal expansion.

In the early 1970s, a vendor willing to produce such a zircaloy sheathed thermocouple could not be located, nor could suitable sheath tubing be procured. Stainless steel, which is much easier to use in the production of small thermocouples, forms a eutectic with zircaloy, which results in melting at 940°C, far below the desired cladding temperature measurement of 1540°C. A search revealed that titanium could be reduced to small sizes and was compatible with zircaloy. Titanium could withstand the desired temperature and, after considerable development, was used to produce a satisfactory thermocouple as currently used[1]. However, the thermocouple had limited life due to preferential corrosion of the titanium-zircaloy laser weld attachments which is further reduced if heavy mixing occurs during welding.

To extend the life expectancy, vendors have been encouraged to provide small diameter zircaloy tubing from which zircaloy sheathed thermocouples can be produced for laser welding to the zircaloy fuel rods. A first step was the development of swaging parameters, annealing processes, and handling techniques for the production of the 1.17-mm zircaloy sheathed thermocouples currently being applied. Efforts to further reduce the diameter resulted in the zircaloy sheathed thermocouples discussed in this paper.

SURFACE THERMOCOUPLE

The goal of the project was to produce the smallest practical fuel rod cladding surface thermocouple with the highest temperature range compatible with the size. This effort led to the fabrication of the swaged, 0.71-mm, zircaloy sheathed, tungsten-5% rhenium/tungsten-26% rhenium (W5%Re/W26%Re) thermoelement, high purity beryllium oxide (BeO) insulated, and tantalum barrier grounded junction thermocouple (referred to subsequently as the surface thermocouple for simplicity) for the TFBP fuel rod temperature measurements.

For the purpose of further reducing the thermocouple temperature profile when attached to a fuel rod cladding surface, a flattened or spaded junction was utilized[2,3]. A zircaloy-stainless explosion bonded splice sleeve was used for attachment to the stainless extension cable.

MATERIAL SELECTION

Since some in-pile nuclear fuel tests may be expected to cause the fuel rod cladding to fail, a general purpose surface thermocouple capable of measuring temperatures to the melting point of zircaloy (1820°C) was envisioned. This temperature limited the thermocouple wire combinations to a very few, from which the W5%Re/W26%Re wire combination was selected as best suited for the full range. Although some investigators feel that the W3%Re/W25%Re combination is superior, this combination has extension wires which are compensating to

250°C, whereas those for the W5%Re/W26%Re combinations are compensating to 870°C. The temperature range of platinum-rhodium (Pt-Rh) thermoelements is marginal for this application and, since these materials transmute in nuclear environments they were dropped from consideration.

The selection of W-Re alloy wires also avoided possible eutectic formations that are prevalent when Type K or Pt-Rh wires are used with a zircaloy sheath. Use of the W-Re alloy provided greater freedom in designing the measuring junction, a concern which becomes increasingly important as the diameter of the thermocouple is decreased.

High purity (99.99%) BeO was selected as the insulating material because of its superior resistivity at elevated temperatures, compared with magnesium oxide (MgO) and aluminum oxide. Since BeO and zirconium oxide are compatible up to about 1980°C, the possibility of a reaction between zircaloy and beryllium oxide[4] in the upper part of the temperature range was avoided by oxidizing the inside surface of the zircaloy sheath prior to assembly. Thus, the thin oxide layer on the inside surface of the sheath extends the compatibility of materials above the melting point of zircaloy. This layer also inhibits migration of contaminants, which results in higher insulation resistance.

COMPONENT AVAILABILITY

The surface thermocouple configuration was also limited by the available materials. Ultimate minimum size was controlled by the smallest double-bore crushable BeO insulators which could be obtained; they were 0.81 mm in diameter. Thus, zircaloy tubing of 0.89-mm inside diameter was procured for the sheath material and 0.13-mm-diameter wires were shown to be suitable for use in the 0.18-mm-diameter BeO insulator holes.

EMBEDDED THERMOCOUPLE

An embedded thermocouple was developed for use on electrically heated fuel rod simulators that were used in tests supporting the LOFT Program. The goal of this effort was to produce an embedded thermocouple with a diameter approximately equal to the zircaloy fuel rod cladding wall thickness; typically 0.61 mm. This effort led to the 0.61-mm, zircaloy sheathed, Chromel-Alumel[a] (Type K), MgO insulated, and ungrounded junction thermocouple (referred to subsequently as the embedded thermocouple for simplicity).

TECHNIQUE SELECTION

A standard two-wire thermocouple utilizing a zircaloy sheath was selected, which allows operation to 1250°C without eutectic inter-actions. An ungrounded junction was chosen to minimize ground loop and ac-induced noise in a sufficiently small size to ensure rapid thermal response.

Two other types of concentric thermocouple configurations were considered. The first, using a central molybdenum wire and coaxial zircaloy sheath (coaxial thermocouple), each acting as one thermo-element of the couple, could readily be fabricated to sufficiently small sizes. Although apparently feasible, this configuration was not chosen due to lack of previous test data. The second was a variation of the type used by Thomson and Fenton[5], in which the conductor makes a transition from Chromel to Alumel wire within a zircaloy sheath. This configuration was not chosen because twice as many penetrations in the test apparatus would have been required. A distinct advantage of both types is that a very heavy sheath wall can be maintained while achieving very small thermocouple diameters.

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a. Chromel-Alumel is a trademark of the Hoskins Manufacturing Company and is basically composed of nickel-chromium and nickel-aluminum, respectively.

COMPONENT AVAILABILITY

Zircaloy tubing with an outside diameter of 1.22 mm and MgO insulators with outside diameters of 0.81 mm were used for fabrication of embedded thermocouples due to immediate availability of materials. The MgO had an advantage in that it was more compressible than BeO and yielded smaller thermocouples; therefore, it was chosen for the lower maximum temperature, electrically heated fuel rod simulator application. Type K thermoelements with outside diameters of 0.13 mm were compatible with the 0.18-mm insulation holes.

FABRICATION

Unlike stainless steel or Inconel, which are commonly used in the fabrication of small thermcouples, zircaloy is not easily swaged or drawn. Final reduction steps for zircaloy, by drawing or swaging, become unusually small (to 0.05 mm per reduction cycle) and require alternate reduction and annealing to prevent embrittlement. Although not used in this work, alternate drawing-annealing and swaging-annealing operations are known to make possible the construction of even smaller diameter cables.

SURFACE THERMOCOUPLE

The use of a standard rotary swager for reduction of metal sheathed thermocouple cables results in certain characteristics which are superior to those of cables reduced by drawing techniques. The sheath wall thickens during swaging, which results in easier laser welding of the thermocouple to the fuel rod cladding and produces greater insulation compaction, resulting in higher insulation resistance. Thus, swaging was the reduction technique used in the production of the surface thermocouples.

Rotary swaging tends to produce periodic twists in the pair of thermocouple wires at the joints between adjacent insulators. The twists present two problems: (a) they cannot be present in a section of cable to be flattened, and (b) parasitic junctions form at the locations of twists when the cable is reduced below a certain diameter as a result of the rotary hammering action of the swager. The twists can be minimized by judicious selection of linear and rotary feed rates (of the cable into the swager) and by use of adequate die lubrication.

Another problem encountered in using swaged cable is cracking of the zircaloy sheath due to the high insulation compaction when the cable end is flattened by rolling or compression. The use of Turks-head forming or stationary spindle swagers may allow further flattening of small, highly compacted cables.

EMBEDDED THERMOCOUPLE

Metal sheathed thermocouple cable reduced in diameter by drawing has the advantage of maintaining parallelity of the thermoelements. The problem of parasitic junctions forming in very small diameter cables at the locations of twists caused by the swaging process is thus avoided. For the embedded thermocouple, drawing proved to be superior and was used in the fabrication process. Differences in final sheath wall thickness and percentage elongation required attention but did not prove to be a disadvantage of the drawing technique.

The difference in insulation compaction of drawn cable compared with that of swaged cable proved to be an advantage. Whereas the compaction tends to increase slightly with each reduction pass during swaging, the compaction during drawing reaches a maximum value (typically 70 to 75% as determined by density tests) after a few reductions, and tends to remain relatively constant thereafter. Thus, the sheath cracking problem which occurs when swaged cables with very high insulation compaction are flattened was also avoided.

ANNEALING

Construction of small diameter thermocouples, either by drawing or swaging, requires careful annealing of both sheath and thermoelement materials due to the extreme reductions required between available materials and the desired final thermocouple size. Care in annealing becomes especially important when brittle material such as zircaloy is used. Thermoelement annealing can force even further constraints, as in the case of Type K, or not be possible at all, as in the case of W-Re alloys.

Sheath Annealing

Satisfactory reduction of zircaloy sheathed thermocouple cable is highly dependent on proper annealing of the sheath between reduction steps. Tests of a number of annealing cycles showed that satisfactory results were obtained in restoring ductility to the zircaloy sheaths by annealing for a minimum of five minutes at 650°C in a vacuum (6.7×10^{-3} Pa or better) or an inert atmosphere. Commercial grade argon and helium contain sufficient oxygen and hydrogen to produce deleterious effects on the zircaloy sheaths. Accordingly, ultra-high-purity argon or helium was used as a purge gas during annealing, or commercial grade gas was passed through a titanium-chip gettering furnace before use in the purge.

The cooling rate at the end of the annealing cycle was also found to be an extremely important factor. Just as quenching certain titanium alloys is a significant part of the annealing process[6], rapid cooling of zircaloy from the annealing temperature to ambient temperature produces a smaller grain size, improving the ductility of the thermocouple sheath as a result. Care must be taken to avoid oxidation during the quench. For this reason, cool, flowing, pure argon gas was selected for quenching. Figures 1 through 3 show the grain structure of various sheath samples. A sample of as-received tubing is shown in Figure 1, and has an ASTM grain size[7] of 9.5. Figure 2 shows the structure which results from cold working, and

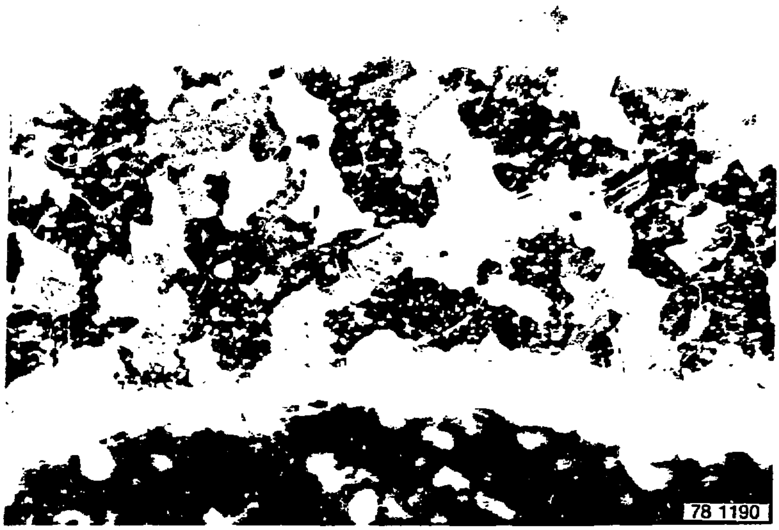

Fig. 1 Cross section of as-received zircaloy tubing; ASTM 9.5.

Fig. 2 Cross section of cold worked zircaloy sheath.

Figure 3 shows the same sample annealed as described and cooled rapidly in argon, with a resulting ASTM grain size of 10.5. Faster cooling rates were shown to yield even smaller grain sizes and better ductility.

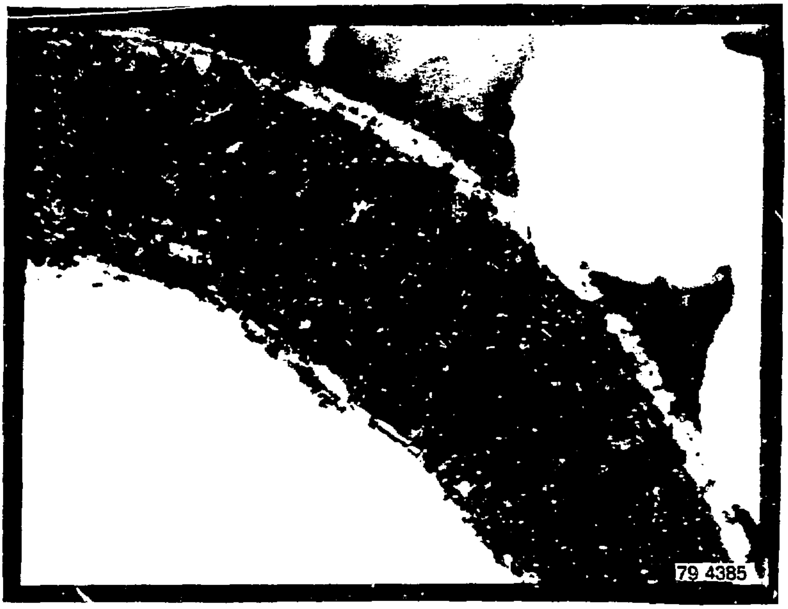

Fig. 3 Cross section after annealing; ASTM 10.5.

The importance of the smaller grain size and the increased ductility is especially apparent when the zircaloy sheath is flattened or when small diameter cables with correspondingly thinner sheath walls are required. A useful rule of thumb suggests that the sheath wall should be ten grain diameters across; an ASTM grain size of 10.5, achieved with rapid cooling in argon gas, was adequate for the thermocouple wall thicknesses under consideration.

Thermoelement Annealing

Large reductions in cable diameter causes work-hardening of the thermoelements, which results in two effects on the wires: (a) the thermoelectric properties of the wire combination can be altered, and (b) the lack of ductility can lead to broken wires. Thermoelement annealing, if the temperatures are compatible with the annealing temperatures of zircaloy, is effective in restoring the thermoelements to their original properties.

The usual annealing temperature of Chromel-Alumel wires is from 870 to 1040^{o}C, with annealing being nearly instantaneous. Proper annealing can be preformed at lower temperatures but requires proportionately longer times. Satisfactory conditions can be restored by annealing at 650^{o}C for a minimum of 30 minutes, a cycle which was chosen to be compatible with the annealing temperatures for the zircaloy sheath. Sufficient wire ductility was maintained with this cycle to permit as much as 25% elongation during drawing, beyond which the Chromel wire would be severed.

Surface thermocouples, using W-Re alloys, are constructed without regard to annealing of the thermoelements due to the extreme temperatures required. Thus, thermocouple size is limited due to W-Re alloy embrittlement as a result of high insulation compaction or excessive elongation.

JUNCTION FORMATION AND ATTACHMENT

Insulated measuring junctions for the embedded thermocouples were made by removing the insulation to a depth of 0.5 mm and fusing the ends of the thermoelements together with a pulsed laser beam. The cable end was then filled with powdered MgO and closed by laser welding a zircaloy disk circumferentially onto the sheath. The thermocouple was then flattened in the plane of the two wires to a thickness of 0.43 mm over a length of 25 mm. The desired flattened thickness of 0.31 mm (one-half the zircaloy fuel rod cladding wall thickness) was not attained.

A rectangular groove 0.43 mm deep, 25 mm long, and 0.68 mm wide was machined in the surface of the fuel rod simulator cladding with one end of the groove tapered upward to the surface such that the transition was gradual. The thermocouple cable was attached axially to the cladding using zircaloy filler wire and laser welding. A cross section of the cable is shown in Figure 4 and a cross section of the embedded section as installed on the 0.77-mm fuel rod simulator cladding is shown in Figure 5.

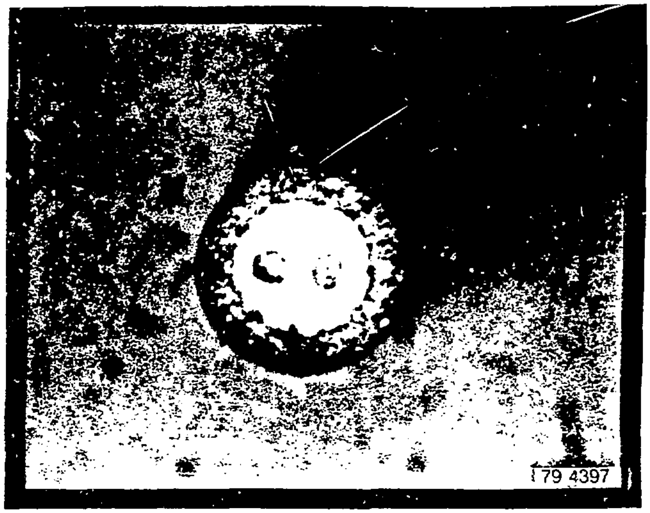

Fig. 4 Cross section of embedded thermocouple cable.

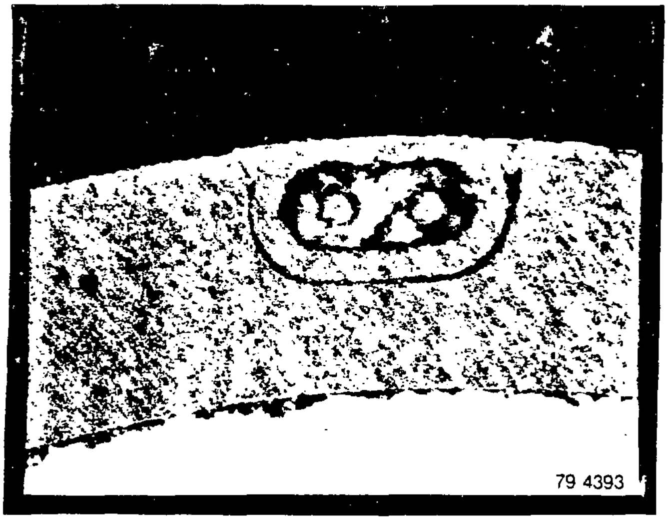

Fig. 5 Cross section of installed embedded thermocouple.

To minimize fluid temperature dependence and to decrease thermal response time, a flattened grounded junction was chosen for the surface thermocouple. Physical construction is as shown in Figure 6.

Since welding W-Re alloy wires makes inherently brittle materials even more brittle, a junction was made without welding by inserting a short length of tantalum tubing (0.46-mm outside diameter, by 0.25-mm inside diameter, and 1.52 mm long) over the tips of the two W-Re alloy

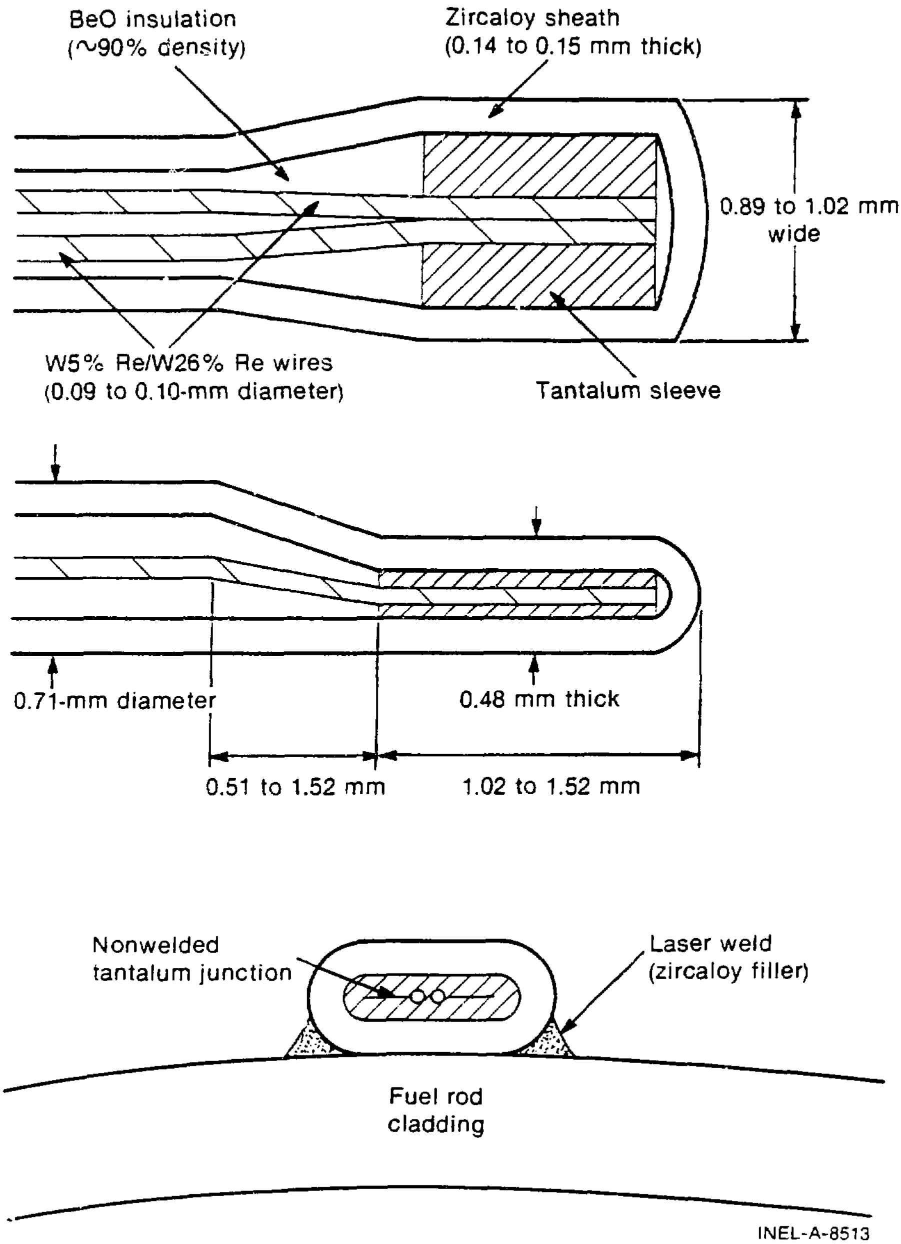

Fig. 6 Diagram of surface thermocouple cladding attachment.

wires inside the zircaloy sheath as shown in Figure 7. The cable was swaged, flattened to a thickness of 0.48 mm (as shown in Figure 8) through the use of an arbor press, and welded closed for laser attachment to the zircaloy fuel rod cladding using zircaloy filler wire. Figure 9 shows the cross section of a defective weld away from the measuring junction. Two problems are illustrated: (a) the laser weld

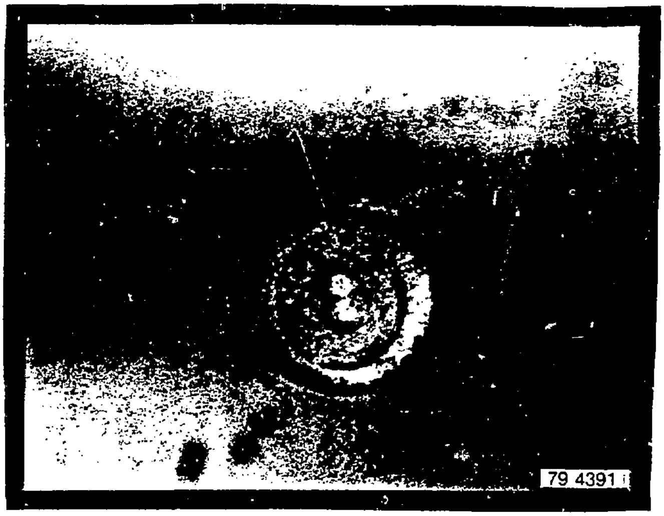

Fig. 7 Junction of surface thermocouple prior to swaging.

Fig. 8 Junction of surface thermocouple after flattening.

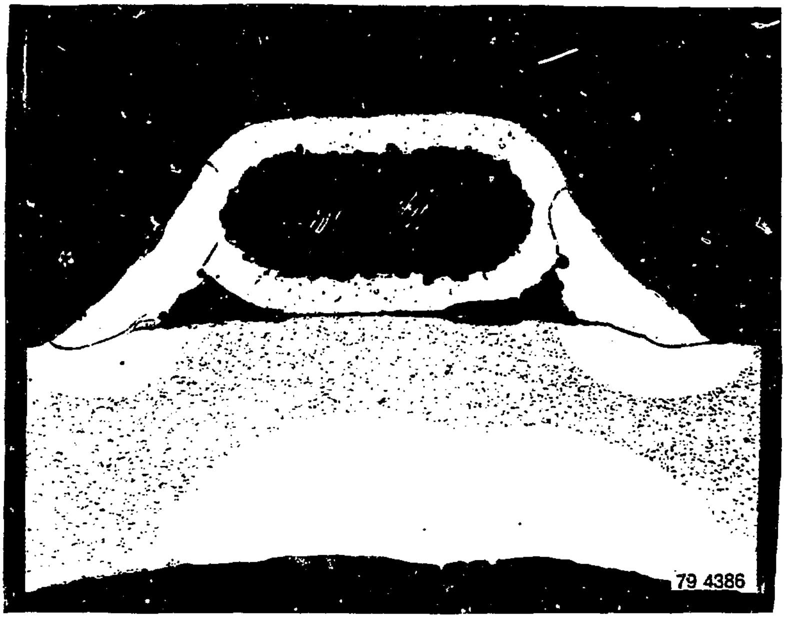

Fig. 9 Cross section of surface thermocouple removed from junction; defective.

has penetrated the thermocouple sheath and (b) the laser heated section inside the fuel rod cladding specimen, in attempted thermal response tests, was neither large enough nor centered properly.

TESTING

Testing has been performed to determine corrosion, embrittlement, accuracy, integrity, thermal response time, and, indirectly, radiation resistance. Steam reflood, thermal response, freeze point calibration, and inferred irradiation testing results are reported. Further testing, consisting of up to 50 cycles at rates in excess of $220^{\circ}C/s$ (between 260 and $1370^{\circ}C$), was performed on the surface thermocouple to ensure mechanical and electrical integrity of the tantalum grounded junction.

STEAM REFLOOD

Severe laboratory simulation of the conditions experienced during a blowdown test and subsequent reflood was produced with the apparatus diagrammed in Figure 10. Steam was passed through the tube furnace and heated to the desired temperature. After a stable steam flow was established, the test sample, consisting of a section of fuel rod cladding and embedded or surface thermocouple samples, was inserted into the furnace. When equilibrium was again established, as indicated by the test thermocouple, the steam flow was shut off and water at ambient temperature was supplied at a controlled rate until the sample was quenched.

Embedded thermocouples were steam-reflood cycled between 930°C steam and ambient temperature water until the test was concluded after the fourth cycle because fine cracks began to appear in the sheath and the thermocouple attachment welds as shown in Figure 11. The condition of the thermocouple cable above the embedded section was excellent, indicating that several more such cycles would have been possible before failure of the thermocouple. Insulation resistance at the end of the fourth cycle was 4.5 megohms for the 2.5-m lengths tested.

In order to demonstrate the utility of zircaloy sheaths, comparison tests were performed on titanium (Ti) sheathed thermocouples. Figure 12 shows a laser-welded attachment of the embedded thermocouple sheath just above the embedded section after four cycles. Figure 13 shows a similar weld, after four cycles, for a titanium sheathed surface thermocouple attached to the same section of fuel rod cladding on which the embedded thermocouple was installed. The latter attachment was a high-energy laser weld, with severe mixing of titanium and zircaloy, which was shown to be more susceptible to corrosion than normal lower energy welds. The severe corrosion of the titanium-zircaloy weld illustrates the severity of the test and the preferential corrosion of this combination of materials[8,9].

Subsequently, more severe tests were performed on surface and titanium sheathed thermocouples in which samples were cycled between steam at 980°C and ambient temperature water. Figure 14 shows a laser weld attachment of a zircaloy sheathed surface thermocouple

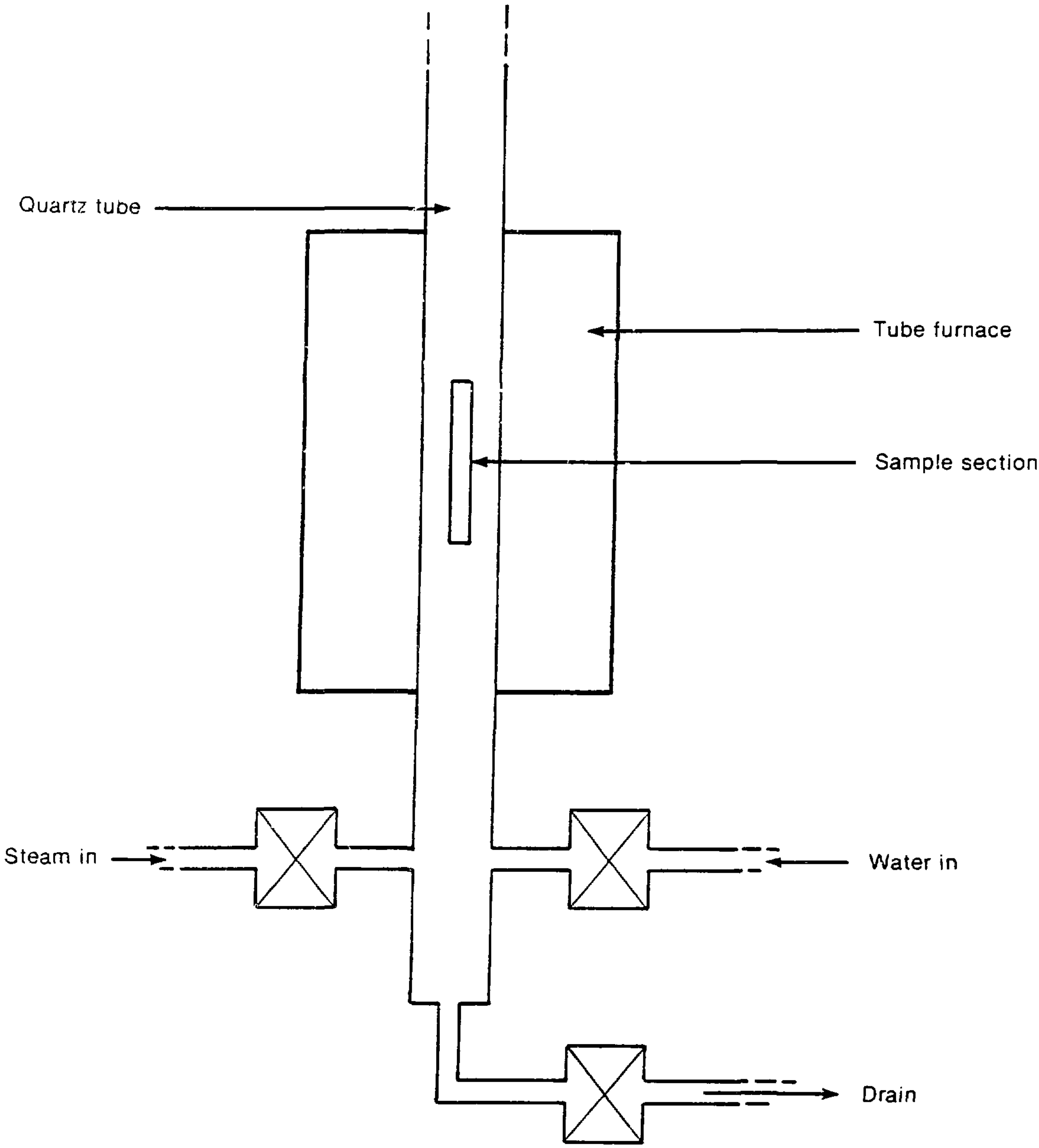

Fig. 10 Steam-reflood cycle apparatus.

Fig. 11 Embedded thermocouples; 930^{o}C cycles.

Fig. 12 Embedded thermocouple laser weld; 930^{o}C cycles.

after four cycles; the samples failed open circuit after the fifth or sixth cycle. Titanium sheathed surface thermocouples tested in the same manner became detached from the cladding after a few cycles due to preferential corrosion of the zircaloy-titanium welds. The same result did not occur in autoclave tests at typical PWR conditions until after 5000 to 6000 hours for titanium and 10 000 hours for zircaloy[10].

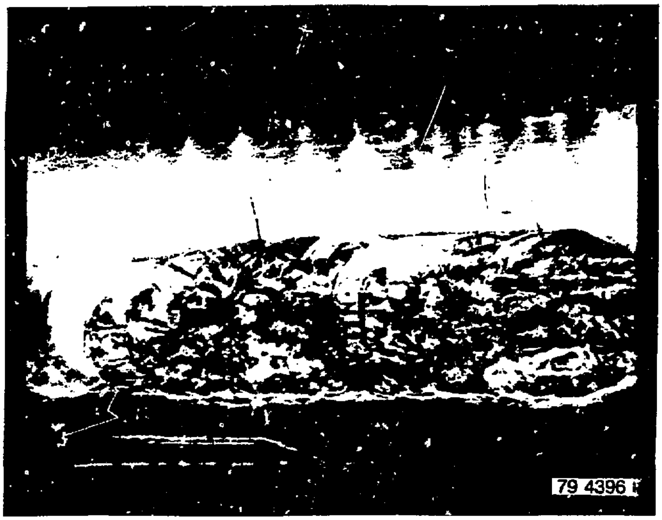

Fig. 13 Titanium sheathed thermocouple laser weld; 930°C cycles.

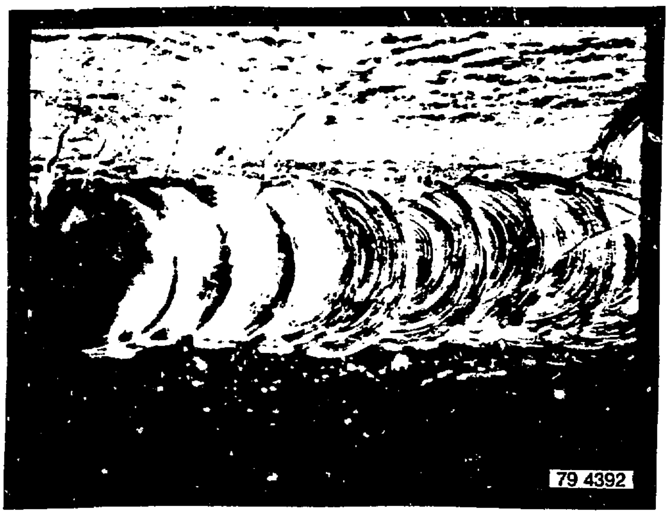

Fig. 14 Zircaloy sheathed surface thermocouple laser weld; 980°C cycles.

THERMAL RESPONSE

Since the thermocouples were intended for use in measuring transient temperatures, determination of their thermal response time was important. To simulate the in-use conditions of the thermo-couples, a method was devised for producing a heat pulse at the inside surface of the section of fuel rod cladding underneath the thermocouple installation. A section of the cladding wall, opposite the thermocouple, was cut away, exposing the inside cladding surface. A pulsed laser was fired at the point on the inside cladding surface nearest the thermocouple junction and the thermocouple thermal response was recorded. Since the laser pulse was 5 ms in duration, in lieu of a step function, the recorded response (between 10 to 90%) is not the same as "rise time," but serves as a measure of thermal response.

The laser beam spot size was adjusted to a diameter slightly greater than the width of the thermocouple to minimize the sensitivity of the system to laser spot location. Spot size, laser power, and pulse width were kept constant throughout the testing. An inert gas purge was necessary at the point where the laser beam impinged upon the inside fuel rod cladding surface to prevent oxidation and surface degradation.

A final step in attempting to simulate in-use conditions for the thermocouple was to submerge the fuel rod cladding section with the thermocouple installed into a vessel filled with water, as shown in Figures 15 and 16. For comparison, data were collected with both static water and air as the media surrounding the thermocouple.

Results shown in Table I clearly illustrate the faster thermal response of smaller diameter surface and embedded thermocouples.

FREEZE POINT CALIBRATION

Cold working due to swaging or drawing is known to affect the calibration of thermocouple wires. Thus, as discussed previously, annealing is necessary to restore the thermoelectric and mechanical properties of the wires. The effectiveness of the wire annealing in the final thermocouple configuration was checked at the standard freeze point temperatures of tin, zinc, aluminum, and copper in accordance with the International Practical Temperature Scale (IPTS) of 1968.

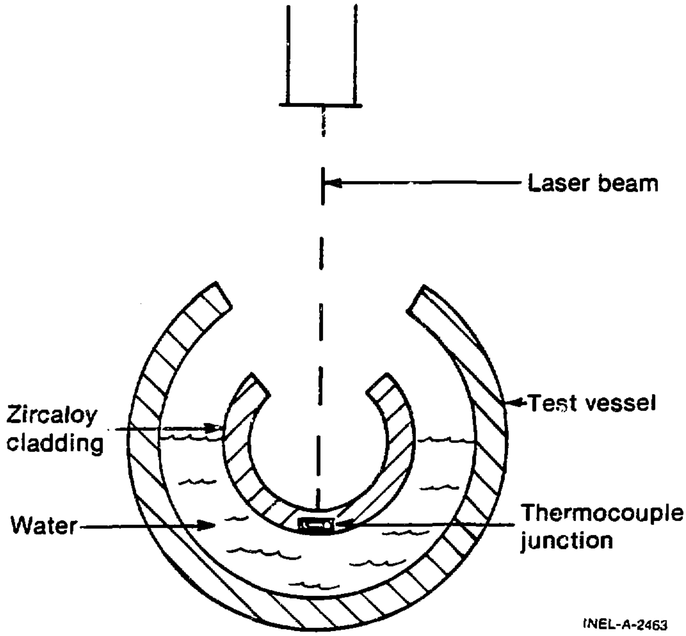

Fig. 15 Cross section of embedded thermocouple test apparatus.

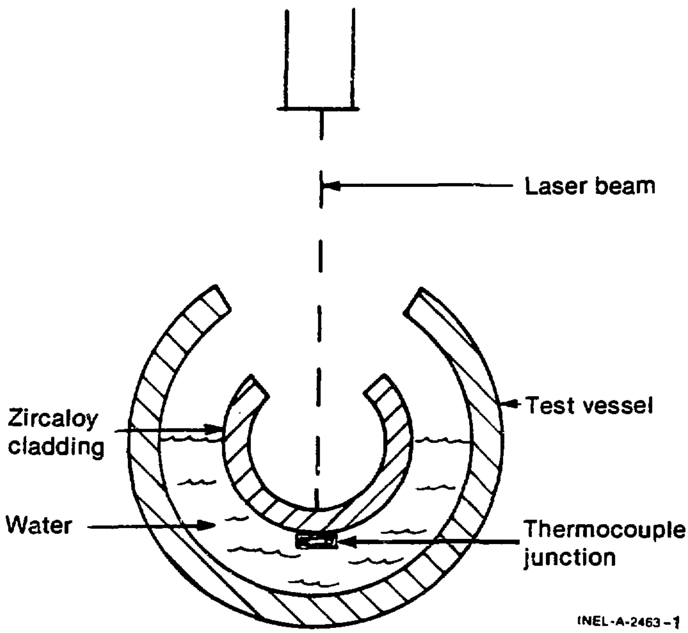

Fig. 16 Cross section of surface thermocouple test apparatus.

TABLE I

THERMAL RESPONSE TEST RESULTS

Thermocouple	Static Water Response Time (ms)	Static Air Response Time (ms)
1.17-mm, titanium, surface	49.4	72.3
0.71-mm, zircaloy, surface	23.7	26.4
0.61-mm, zircaloy, embedded	9.7	22.9

Samples were inserted into a well extending into the center of the sealed crucible containing the pure metal, and the freeze plateau of each metal was maintained for a minimum of 20 minutes. The thermocouple samples and the chamber in which the crucibles were heated were purged with argon gas during the tests. A Type K special grade wire thermocouple (± 0.375%) was included, which added credibility to the test. Table II is a compilation of the freeze point calibration test results.

Negative differences were believed to be predominantly attributed to incomplete annealing. The embedded thermocouple, annealed for 30 minutes as the final fabrication step, initially indicated even lower temperatures than shown in Table II, with deviations of -1.0% for zinc, -0.09% for aluminum, and -3.4% for copper. An additional annealing cycle of one hour at 650°C yielded the improved values given in Table II. Minimization of reduction by starting with smaller materials is expected to result in thermocouples which will provide more accurate temperature measurements. Insulation resistance was greater than 100 megohms before and after the tests, and was in excess of one megohm at the freeze point of copper.

IRRADIATION

Presently, neither of the thermocouples under consideration have undergone radiation testing. The embedded thermocouple has been used

TABLE II

FREEZE POINT CALIBRATION TEST RESULTS

IPTS-68 Standard Temperature (°C)	Surface Thermocouple: Measured Temperature (°C)	Surface Thermocouple: Temperature Difference (%)	Embedded Thermocouple: Measured Temperature (°C)	Embedded Thermocouple: Temperature Difference (%)	Special Type K Thermocouple: Measured Temperature (°C)	Special Type K Thermocouple: Temperature Difference (%)
(Sn) 231.97	232.71	0.32	232.54	0.25	232.63	0.28
(Zn) 419.58	416.81	-0.66	420.21	0.15	419.30	-0.07
(Al) 660.37	655.42	-0.75	657.40	-0.45	660.72	0.05
(Cu) 1084.50	1067.92	-1.53	1071.29	-1.22	1085.91	0.13

in transient steam-water depressurization and reflood conditions on electrically heated zircaloy fuel rod simulators and the surface thermocouples are being readied for in-pile fuel rod tests at the PBF. However, the materials zircaloy, MgO, BeO, tantalum, Chromel, Alumel, and W5%Re/W26%Re have been widely used in nuclear instrumentation with good success[11,12,13].

CONCLUSIONS

The feasibility of construction of both (a) swaged, zircaloy clad, 0.71-mm, W5%Re/W26%Re, BeO, tantalum grounded flattened junction thermocouples for fuel rod cladding surface mounting, and (b) drawn, zircaloy clad, 0.61-mm, Type K, MgO, ungrounded flattened junction embedded thermocouples for electrically heated fuel rod simulators has been demonstrated. These devices represent the smallest known zircaloy sheathed thermocouples for attachment to zircaloy fuel rods or fuel rod simulators.

Conclusions are:

(1) Extremely small reductions with intermediate annealing is required.

(2) The annealing and cooling process is critical.

(3) Approximately ten grain diameters in the sheath wall, resulting from annealing, are required for adequate ductility.

(4) Laser welding is suitable for securing the flattened junction and cable sheath to the fuel rod cladding.

(5) Small embedded and surface thermocouples have faster thermal responses than larger thermocouples; embedded versions have faster thermal responses than surface thermocouples.

(6) Steam-reflood tests, which provide a severe test of the longevity, corrosion, and embrittlement properties of materials and laser welding techniques, are successful in demonstrating the utility of zircaloy sheathed thermocouples.

(7) Zircaloy thermocouple sheath to zircaloy cladding welds have better longevity than heavily mixed titanium-zircaloy welds.

(8) Small diameter thermocouples have nearly standard calibration curves (within 0.175% at the freeze point of aluminum).

(9) Irradiation characteristics of small zircaloy sheathed thermocouples are expected to be satisfactory due to the materials utilized in fabrication.

The surface thermocouple is limited to the melting point of zircaloy and testing has proven the mechanical and electrical integrity of the tantalum grounded junction. The embedded thermocouple performed satisfactorily under limited temperature conditions. Use of Turks-head forming or stationary spindle head swagers for smaller flattened junctions, use of alternate swage and drawing reduction passes, and use of smaller materials was postulated for the successful fabrication of even smaller thermocouples.

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