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IDAHO NATIONAL ENGINEERING LABORATORY

TEMPERATURE MEASUREMENT ON ZIRCALOY-CLAD
FUEL PINS DURING HIGH
TEMPERATURE EXCURSIONS

PREPARED BY AEROJET NUCLEAR COMPANY FOR
U. S. NUCLEAR REGULATORY COMMISSION
AND
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by

R. H. Meservey

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R. D. Wesley made many valuable contributions to the development of the laser welding equipment and technique and made suggestions for improving the cable swaging procedures.

D. W. Hood, who as a welding engineer, made the laser welded attachment a reality.

J. C. Downey initiated the design of the laser welding tooling.

B. R. Merkley and G. C. Wilson were responsible for the entire scope of development and qualification testing of the thermocouples and of the attachment welds.

ABSTRACT

The development of a sheathed thermocouple suitable for attachment to zircaloy-clad fuel rods and for use during high temperature (2,800°F) excursions under loss-of-coolant accident conditions is described. Development, fabrication, and testing of the thermocouples is covered in detail. In addition, the development of a process for laser welding the thermocouples to fuel rods is discussed. The thermocouples and attachment welds have been tested for resistance to corrosion and nuclear radiation and have been subjected to fast thermal cycle, risetime, and blowdown accident tests.

SUMMARY

Special thermocouples and attachment techniques have been developed for use in measuring surface temperatures of zircaloy-clad fuel pins during high temperature excursions. Although thermocouples have historically been used as the mechanism for measuring temperatures of nuclear reactor fuel pins, their use has not extended to the measurement of surface temperatures of zircaloy-clad pins under loss-of-coolant accident conditions. This is basically a result of the incompatibility of common thermocouple materials with zircaloy at temperatures above about 1,700°F. To overcome these problems, a thermocouple was developed which is metallurgically compatible with zircaloy and with the reactor coolant environment. This latter condition requires that the sheath material not only be compatible with 650°F, 2,500 psi water, but that it survive for short periods at 2,800°F in steam. Thus, the thermocouple must be metallurgically bonded to zircaloy, and both the thermocouple and attachment must operate for extended periods of time under normal pressurized water reactor coolant conditions and for short periods of time at high temperature during the loss-of-coolant accident. During this time, the water is lost and replaced by steam, thus allowing the clad temperature to increase greatly.

Titanium was selected as the sheath material, and a laser welding process using a titanium filler was selected as the method of attachment to the fuel pins. Thermocouples were designed for operation over two separate temperature ranges. The first was to cover temperatures to 2,300°F and these use Chromel/Alumel thermoelements. A second range to 2,800°F is required to cover core hot spot measurements, and these thermocouples utilize platinum/10% rhodium-platinum thermoelements. Magnesium oxide is used as the insulation material for these thermocouples.

The cables are swaged to a final diameter of 0.046 inch and have a thicker wall than is normally used for cables of this diameter. A wall thickness of 0.009 inch was specified to allow for deeper penetration of the laser attachment welds.

A spade or "duck bill" grounded-type measuring junction is used to improve the thermocouple response time. This, too, presents some special problems since the thermoelement materials are not compatible with the titanium sheath. This problem has been solved by placing a small barrier of tantalum between the thermoelements and the sheath during fabrication of the grounded-type junction.

Attachment of the thermocouples to fuel pins is accomplished using an automated laser welding system. Fillet welds are made at regular intervals along each side of the thermocouple cable using a titanium filler wire. The automated tooling was developed to position the thermocouple, fuel pin, and filler wire during welding. A commercial laser welder is used in conjunction with the tooling.

Thermocouples and attachment welds have been extensively tested to qualify them for reactor use. They have been subjected to lifetime corrosion tests in a pressurized water

reactor (PWR) environment produced by an autoclave and to radiation effects tests in a pressurized water loop in the Engineering Test Reactor. In addition, the thermocouple installations have been subjected to fast thermal cycle tests and to blowdown/reflood tests in a pressurized loop.

Through rigorous control of the thermocouple fabrication process and of the fuel pin attachment welding, a highly reliable clad temperature measurement can be achieved on zircaloy-clad fuel pins. As a result of qualification testing of the thermocouple attachments, it is believed that service of at least 6,000 hours can be attained in a PWR environment. The service life of the installation is limited by the corrosion resistance of the titanium-to-zircaloy attachment welds. Work is currently in progress to develop a zircaloy-sheathed thermocouple which will eliminate this corrosion problem and extend the lifetime and upper temperature limit of the thermocouple attachment.

CONTENTS

ACKNOWLEDGMENTS	ii
ABSTRACT	iii
SUMMARY	iv
I. INTRODUCTION	1
II. THERMOCOUPLE DESIGN	2
1. SHEATH MATERIAL SELECTIONS	2
2. FABRICATION PROBLEMS	2
2.1 Tubing Fabrication	2
2.2 Tube Cleaning	3
2.3 Swaging Procedures	4
3. MEASURING JUNCTION	5
4. THERMOELEMENT AND INSULATION MATERIALS	12
4.1 Thermoelements	12
4.2 Insulation Material	12
III. THERMOCOUPLE-TO-FUEL CLAD ATTACHMENT	13
1. LASER WELDING	13
2. AUTOMATED TOOLING	14
3. WELD PARAMETERS	16
4. CLEANING	21
5. WELD INSPECTION AND DEFECTS	21
IV. PERFORMANCE TESTS	22
1. CORROSION LIFE	22
2. NUCLEAR RADIATION	25
3. FAST THERMAL CYCLE	25
4. TIME RESPONSE	26

5.	HEATER ROD BLOWDOWN/REFLOOD TESTS	31
V.	CONCLUSIONS AND RECOMMENDATION	33
VI.	REFERENCES	34

FIGURES

1.	Section of titanium cable swaged without rotation showing hex-shaped ID and cracks	6
2.	Section of titanium cable swaged at a large die entrance angle	6
3.	Section of titanium cable which was allowed to whip as it was fed into the die	7
4.	Section of titanium cable in which the feed was stopped during swaging causing complete cracking of the sheath	7
5.	Section of titanium cable swaged correctly using an automatic feed	8
6.	Section of stainless steel cable swaged without rotation showing hex-shaped ID.	8
7.	Section of zircaloy cable swaged without rotation showing irregular ID	9
8.	Schematic diagram of the tantalum barrier junction	10
9.	Longitudinal section of a tantalum barrier junction	11
10.	Transverse section of a tantalum barrier junction	11
11.	Photograph of laser welded thermocouple attachment showing measuring junction and dummy cable segment	15
12.	Photograph of individual laser welds showing overlapping spots	16
13.	Photograph of the laser welder and associated tooling	17
14.	Closeup of laser welder showing operator, fuel pin in place	18
15.	Section of a low energy (4 joule) laser weld showing incomplete melting of the filler wire	19
16.	Section of a high energy (7.5 joule) laser weld showing the highly mixed nature of the fillet	19

17.	Section of a 6.5 joule weld showing good uniformity and a nearly optimum amount of mixing	20
18.	Weld strength (torque) as a function of exposure time in 650°F, 2,500 psi water for 6.5-joule laser welds	23
19.	Sections of laser welds from autoclave corrosion tests	24
20.	Schematic diagram of the thermal cycle test apparatus	27
21.	Photographs of a 6.5-joule weld at major inspection points of the thermal cycle tests	29
22.	Photographs of a 7.5-joule weld at major inspection points of the thermal cycle tests	30
23.	Schematic diagram of the zircaloy-clad heater rods	32

TABLES

I.	Swage Parameter Effects on Titanium-Sheathed Thermocouples	5
II.	Sample Test Sequence	28

TEMPERATURE MEASUREMENT ON ZIRCALOY-CLAD FUEL PINS DURING HIGH TEMPERATURE EXCURSIONS

I. INTRODUCTION

Increased interest in water reactor safety programs has created demands for reliable temperature measurements on the surface of zircaloy-clad fuel pins. Such measurements have not been attempted in the past possibly through lack of demand and also due to a metallurgical incompatibility between common thermocouple materials and the zircaloy cladding used on the fuel pins. Safety and quality requirements for instrumented fuel pins place severe restrictions on thermocouple attachments. Not only must the thermocouple survive the environment of a reactor accident test (or repeated tests), but the attachment must not alter the properties of the fuel pin cladding. With these requirements, a program was undertaken to develop a fuel pin clad thermocouple installation and to qualify it for use in PWR-type accident tests.

The design goals can be summarized as follows:

Maximum Temperature: 2,800°F with an alternate 2,300°F requirement.

Lifetime Under Reactor Operating Conditions: 3,000 hours required with a 10,000-hour goal.

Environment: Bonded to zircaloy fuel pin clad. Operated in 600°F, 2,250 psi, borated water with "transients" to 2,800°F (2,300°F) in steam during the blowdown accident tests. Must withstand quenching during reflood portion of the reactor tests.

Size: Minimal, consistent with reliable operation, to increase response time and to minimize flow and heat transfer perturbations within the reactor core.

Fuel Pin Attachment: Must be reliable throughout expected lifetime and must not change the metallurgical properties of the zircaloy fuel pin cladding.

With the above requirements as a guide, 0.046-inch-diameter titanium-sheathed thermocouples were developed, and a laser welding technique was selected as a means of attaching them to the fuel pins. The thermocouples and attachment welds have been thoroughly tested and are expected to prove highly reliable throughout a wide range of reactor accident-type applications.

II. THERMOCOUPLE DESIGN

1. SHEATH MATERIAL SELECTIONS

The material selection was based upon two firm requirements: (a) that it be metallurgically compatible with zircaloy, and (b) that it be compatible with the PWR blowdown accident environment. Common sheath materials such as stainless steel and Inconel meet the second criterion but form low melting point eutectics with zircaloy at temperatures of about 1,700°F. Refractory-sheathed thermocouples such as tantalum and tungsten are metallurgically stable in the presence of zircaloy but oxidize rapidly in the high temperature, pressurized water environment^[1]. Materials such as niobium/1% zirconium also corrode rapidly in the PWR environment. Platinum has been used as a sheath material and is extremely stable in the reactor environment; however, it too forms a eutectic with zircaloy^[2].

Zircaloy itself would be a logical choice for the thermocouple sheath material. However, at the time this project was started, the tubing manufacturers were not able to produce zircaloy tubing in the small diameters and long lengths required. The tubing was required to have an 0.062-inch outside diameter (OD) with a 0.008-inch wall and be in continuous lengths of 20 to 23 feet. Thus, with zircaloy not available in the sizes required, titanium was selected as a second choice.

Titanium is metallurgically compatible with zircaloy and, although it does corrode in the PWR environment, the corrosion rate is acceptable for this application. Largely through previous efforts of the aircraft industry, titanium tubing was available in the size required. Thus, titanium tubing with an 0.062-inch OD and 0.008-inch wall was obtained to an Aerojet Nuclear Company specification from two different commercial tubing manufacturers.

2. FABRICATION PROBLEMS

2.1 Tubing Fabrication

Although titanium tubing was available in the required size, it was not available as a "thermocouple clean" item. This requirement exists so that contaminants will not be left on the inside diameter (ID) of the tubing after manufacturing. Such contaminants will permeate the thermocouple insulation material and cause electrical shorting at high temperatures.

Preproduction or prototype runs of tubing revealed that ID cleanliness was indeed a problem. Thermocouples fabricated with this tubing indicated electrical shorts which developed at temperatures around 1,000°F. These shorts remained even after the cable had returned to room temperature. Attempts to clean the tubing using conventional techniques were totally unsuccessful. Thus, an attempt was made to improve the cleanliness during the fabrication process.

The tubing is manufactured by progressive drawing over lubricated mandrils, and it is the carbon content of the lubricant that causes problems. Carbon will migrate into the thermocouple insulation when the cable is exposed to high temperature and thus destroy the insulation resistance of the cable.

Part of the normal fabrication process for the tubing is to clean it with acid between successive draws and annealings. It was determined that acid etching the ID resulted in enlargement of microcracks which were then filled with lubricant during subsequent drawing operations. Once the cracks were filled at the pressures resulting from drawing over the mandril, further acid cleaning would not remove the material from them.

In working this problem with the tubing vendor it was decided to change lubricant types and to cap the ends of the tubing to prevent enlargement of the microcracks by the acid etch. The tubing ID was then thoroughly cleaned with a conventional solvent between annealing operations. This has greatly improved the cleanliness of the tubing; however, additional steps are still required to produce the cleanliness level desired.

2.2 Tube Cleaning

A wide range of techniques was employed to improve ID cleanliness after the titanium tubing was manufactured. These included acid etches, various solvents, abrasive polishes, pressurized abrasive slurries, and combinations of these techniques. Slight improvements were noted in ID cleanliness, but none of the processes eliminated the shunting problem in thermocouples fabricated from the tubing. High temperature ($>3,000^{\circ}\text{F}$) vacuum outgassing was successful in cleaning the tubing, but its metallurgical structure was changed so drastically that it was unsuitable for use in making thermocouples after the treatment. Thus, an example of the operation being successful, but the patient dying.

As a solution, a method of burning the contamination out with high temperature oxygen was developed. In this process, cleaning is accomplished by flowing high purity oxygen through the inside of the tubes while carefully controlling both the time and temperature of the treatment. It is recognized that titanium chips are used in gettering furnaces to scavenge oxygen and, as such, titanium is highly susceptible to oxidation.

Out tests have indicated that proper cleaning of this tubing can be accomplished by flowing oxygen at $1,200^{\circ}\text{F}$ for a period of one hour. During the cleaning period, the tubes are placed in a manifold so that the outsides are purged with argon to prevent nitriding.

Experience has shown that if either the time is shortened or the temperature is lowered by an appreciable amount the cleaning will not be adequate. Conversely, if either parameter is increased significantly, oxidation and embrittlement of the titanium will result. Thus, the process must be carefully controlled.

As a means of determining the effect of the cleaning process on the tubing, oxygen content and microhardness measurements were made as functions of radial distance from

the tubing ID. Measurements made on "as received" and oxygen-cleaned tubing were within the same band of scatter, thus indicating that no appreciable changes had occurred. These tests have been repeated many times on different lots of tubing with the same results, i.e., no apparent change in physical properties due to the oxygen cleaning process.

2.3 Swaging Procedures

Following oxygen cleaning, the tubing ID and OD are cleaned and dried with solvent and cotton swabs. Following this, the insulators and thermoelements are loaded into the tubing in preparation for swaging. As mentioned earlier, a heavier wall is required for these thermocouples to accommodate the laser welding process. Normally, a thermocouple of 0.046-inch diameter would have a 0.005- or 0.006-inch wall. Since a minimum wall thickness of 0.008 inch is required for the titanium-sheathed thermocouples, special swaging techniques are required.

It was determined that a great deal more control must be exercised in swaging the heavy-wall titanium thermocouples than is needed for thin-walled stainless cable. Ordinary sheathed cable is usually swaged by hand-feeding the cables into a swaging machine. Rotation of the swaging heads imparts a rotation to the cable as it is being swaged. Normal procedure requires that the cable be restrained from rotating during the swage operation, and in ordinary cases this produces acceptable cable. In the case of the heavy-walled titanium cable, however, this procedure results in an irregular shaped, badly cracked inside diameter. Tests conducted at the thermocouple manufacturer's facility revealed that the heavy-walled titanium cable is much more responsive to all swage parameters than is thin-walled, stainless-sheathed cable. Table I contains a list of swage parameters and their effect on the titanium cable if they are not carefully controlled or adjusted.

An example of cable swaged by hand-feeding and not rotated is shown in Figure 1. The hexagonal-shaped, cracked ID is readily apparent. An example of cable fed at a large die entrance angle is shown in Figure 2, while the effect of the cable being allowed to whip is shown in Figure 3. Stopping the feed for only five seconds produced the extensive cracks shown in Figure 4. These cable sections should then be compared to that shown in Figure 5, which resulted when the above parameters were controlled by the use of an automatic cable feed mechanism ahead of the swaging machine. This cable was fed at a uniform rate straight into the dies and was rotated as it was fed.

Although these results are for the titanium-sheathed thermocouples, similar results were obtained when heavy-walled stainless steel and zircaloy cables were swaged. In general, the effects were not quite so dramatic with the heavy-walled stainless as they were with titanium. Zircaloy, however, produced results which indicated an even greater sensitivity to swage parameters than did titanium. Examples of stainless steel and zircaloy which were swaged manually without rotation are shown in Figures 6 and 7, respectively. Both samples were swaged from 0.062-inch-OD by 0.008-inch-wall tubing. A more complete description of the cable swaging tests is presented in Reference 3.

TABLE I
SWAGE PARAMETER EFFECTS ON TITANIUM-SHEATHED THERMOCOUPLES

Parameter	Effect on Cable
Swage dies	Worn or poorly made dies will cause cracks, misshapen (oval) wires, and low insulation resistance in the cables.
Entrance angle of cable into dies	Must be controlled and fed straight into dies. Should the entrance angle change, oval and/or cracked cable will result.
Cable feed rate	Can have a wide range of values as long as the rate is not changed during swaging.
Cable rotation	Cable must be allowed or caused to rotate in the direction of rotation of the dies. Preventing rotation will result in ID cracking and a hexagonal shape on the ID.
Cable whipping	The cable tends to whip or vibrate as it is being swaged and if not prevented will result in cracked or damaged cable. In effect, this changes the feed angle and allows the dies to overwork the cable walls.
Stopping the feed	This is probably the most serious problem of all in that it results in severe sheath cracking with cracks extending entirely through the wall.

Thus, it can be seen that the swaging of heavy-walled cable such as this requires the use of an automatic feed mechanism as part of the swaging operation. Care must be exercised to ensure that the cable is fed at a continuous steady rate along the axis of the dies. The cable must also be uniformly rotated in the direction of rotation of the dies to ensure a uniform, high quality product.

3. MEASURING JUNCTION

A grounded spade or "duckbill" type measuring junction is required on fuel clad thermocouples to increase the measurement response time as much as possible. Since both the Chromel/Alumel and platinum/10% rhodium-platinum thermoelements form eutectics with the titanium sheath, the use of a grounded junction presented another fabrication problem. Since both of these eutectics form below the intended ranges of the

Fig. 1 Section of titanium cable swaged without rotation showing hex-shaped ID and cracks.

Fig. 2 Section of titanium cable swaged at a large die entrance angle.

Fig. 3 Section of titanium cable which was allowed to whip as it was fed into the die.

Fig. 4 Section of titanium cable in which the feed was stopped during swaging causing complete cracking of the sheath.

Fig. 5 Section of titanium cable swaged correctly using an automatic feed.

Fig. 6 Section of stainless steel cable swaged without rotation showing hex-shaped ID.

Fig. 7 Section of zircaloy cable swaged without rotation showing irregular ID.

thermocouples, it was necessary to provide a metallurgical barrier between the thermoelements and the sheath. This does not seem to be a problem when one considers the exploded views often shown in drawings of thermocouple junctions. It does, however, when one tries to fit a barrier around a welded bead which is down inside a 0.028-inch-diameter tube (sheath).

A technique was developed, however, which allows one to remove a small amount of insulation material from the end of a cable and then weld a junction or bead on the thermoelements. A small tantalum tube having 0.003-inch walls is then placed over the bead, thus forming the barrier between it and the titanium sheath. The tip of the cable is then flattened in a forming die and a seal or closure weld made across the end. The grounded junction thus is formed through a mechanical, rather than metallurgical, bond between the thermoelements and sheath. A schematic diagram of the tantalum barrier junctions is shown in Figure 8. This includes dimensions of critical areas of the junction.

Photomicrographs made of longitudinal and transverse sections of actual junctions are shown in Figures 9 and 10, respectively.

A radiographic inspection technique has been developed for nondestructive examination of the completed junctions. This allows them to be thoroughly inspected to verify that

THERMOCOUPLE BARRIER JUNCTION

Fig. 8 Schematic diagram of the tantalum barrier junction.

Fig. 9 Longitudinal section of a tantalum barrier junction.

Fig. 10 Transverse section of a tantalum barrier junction.

the thermoelement material is not in contact with the sheath prior to acceptance and installation on a fuel pin. The radiographic inspection procedure is part of an Aerojet Nuclear Company specification for the thermocouples.

4. THERMOELEMENT AND INSULATION MATERIALS

4.1 Thermoelements

As mentioned previously, thermoelement materials were selected for operation over two separate temperature ranges. Chromel/Alumel thermoelements were selected for thermocouples intended for use in the range to 2,300°F. Platinum/10% rhodium-platinum was selected for use in the range to 2,800°F. Both materials were procured to standard commercial thermocouple wire specifications^[4] with no special precautions or requirements involved in their procurement. The diameter of both types of wire was 0.0045 to 0.005 inch for the individual thermoelements.

4.2 Insulation Material

Because of its widespread use in the industry and in cables built to RDT Standards which are intended for reactor use, magnesium oxide (MgO) was used as insulation in the titanium-sheathed thermocouples. Results of a literature search indicated that titanium should be chemically stable in the presence of MgO, and laboratory tests confirmed this. Thus, commercial thermocouple grade^[5], crushable MgO insulators were used in the fabrication of these cables.

The thermocouple specification required that the insulation compaction density in the finished cable be in the range of 85 to 95% of the theoretical maximum. Tests to the RDT Standard for determining cable insulation compaction density^[6] confirm that all of the cables manufactured to date (about 500) meet these requirements.

III. THERMOCOUPLE-TO-FUEL CLAD ATTACHMENT

1. LASER WELDING

Laser welding was selected as the means of attaching thermocouples to fuel pins because the process results in a minimum perturbation to the fuel pin cladding. Attachment welds can be made without increasing the metallurgical grain size of the fuel pin cladding. Although laser welding is certainly not new, several significant problems had to be solved before the process was suitable for production type work.

The production facility is built around a commercial laser welder/driller. Although the unit was supposed to be designed for repetitive pulsed operation, it was quickly determined that it was not suitable for continuous day-after-day use. Thus, several minor design changes were necessary to adapt the laser to continuous production type work.

A considerable amount of work was also done in developing a suitable attachment weld. Several parameters are available to the welding engineer, and quite a lot of testing was involved in obtaining an optimum combination of these parameters. The weld parameters available include spot diameter, aperture setting, filter setting, beam energy, spot overlap, number of spots per weld, and filler wire type and size.

Design goals for the laser welded attachments included maximum weld strength with minimum perturbation to the fuel pin clad. The attachment welds were expected to last at least 3,000 hours, with 10,000 as a desirable goal, under full operating conditions in a PWR environment. During this lifetime, they will experience several high temperature excursions during blowdown accident tests with quenching during the reflood portions.

Early development work indicated that positioning of the laser beam, thermocouple, filler wire, and fuel pin was critical if repeatable welds were to be obtained. Extremely small amounts of misalignment resulted in over- or underpenetration of the weld in the thermocouple sheath. Underpenetration resulted in weak welds while overpenetration (100%) caused leaks in the thermocouple sheath. This occurs through outgassing of the MgO insulation when in contact with the molten sheath. The result is a small pin hole or "blow hole" in the weld. The thermocouple side of the weld is critical since it only has a 0.009-inch wall while the fuel pin has a wall of about 0.025 inch. Thus, it was determined that a human system with a heartbeat and wobbly joints could not produce the degree of repeatability required for the fuel pin attachments. A conceptual design for automated tooling was then prepared and submitted to a commercial supplier for finalization and production.

2. AUTOMATED TOOLING

Tooling was designed which will provide precise, repeatable positioning of the laser beam, thermocouple, filler wire, and fuel pin. The tooling not only provides precise adjustment of the above parameters but also provides adjustments for spot overlap, number of spots per weld, and filler wire size. An air-driven, pneumatic logic system is used to provide completely automatic operation once initial adjustments have been made.

Actual welding is achieved by manual adjustment and manual operation to verify positioning during the first few weld spots. Once satisfactory positioning has been established, the tooling is placed in the automatic mode, and positioning will be maintained while welds are made down one side of an entire length of thermocouple cable. Spot overlap and number of spots per weld can be previously selected, and the tooling will provide the correct number of spots, advance a predetermined amount, and repeat the weld. When welding along one side of the cable is complete, the fuel pin is rotated in the tooling and the welds along its other side are made.

After one thermocouple is attached, the fuel pin is removed and rotated, and others are then attached in a like manner. The tooling provides for the attachment of as many as four thermocouples, at 90-degree radial locations, per fuel pin. Measuring junctions can be located at any axial location desired.

Because of the attachment geometry and the difference in coefficients of thermal expansion for titanium and zircaloy, the instrumented fuel pin can act as a bimetallic strip. This results in unwanted stresses with possible bowing of the fuel pin. For this reason, segments of "dummy" titanium-sheathed cable are welded to the pins to serve as extensions of the active thermocouples. This is done in such a manner that the effective lengths of all thermocouples on a fuel pin are equal. In addition, symmetry is maintained by using dummies or active thermocouples to ensure that each pin has either two cables 180 degrees apart or four cables 90 degrees apart. The dummy cables are made from scrap lengths of the regular titanium-sheathed thermocouples and are identical except that both ends are seal welded closed and they do not have measuring junctions.

A photograph of a typical laser welded thermocouple installation is shown in Figure 11. The attachment welds, measuring junction, and dummy extension can be clearly seen in the photograph. Figure 12 is a closeup view of an attachment weld in which eight individual overlapping spots can be seen.

Because both zircaloy and titanium oxidize rapidly at the temperatures required for welding, the tooling is equipped with an argon purge system. Through this device the weld area is flooded with argon, and clean, bright welds result.

An overall view of the laser welder and tooling is shown in Figure 13. A closeup of the weld area showing a fuel pin and thermocouple in position is presented in Figure 14.

Fig. 11 Photograph of laser welded thermocouple attachment showing measuring junction and dummy cable segment.

3. WELD PARAMETERS

As mentioned previously, several parameters exist which effect the quality of the laser welds. One of the most important of these is the laser beam energy. This is controlled by the voltage applied to the capacitor which supplies energy to the flash tube. The flash tube, in turn, pumps or excites the laser rod and thus ultimately determines the energy in the individual pulses from the laser.

Energy in the individual laser pulses, to a great extent, determines the degree of penetration obtained in the weld. The higher the beam energy the greater the weld penetration. Conversely, low beam energies produce low penetration welds and in some cases result in incomplete melting of the filler wire. For this laser welding application, a high degree of control and repeatability was required for the beam energy.

Welding of titanium to zircaloy turned out to be a less than ideal situation for this application. The material formed from a mixture of these two metals corrodes in the PWR environment at a greater rate than does either of the individual metals. A high energy, deep penetration weld is desirable because of its greater strength. However, these conditions also produce a high degree of mixing between the two metals, and this highly mixed material experiences an accelerated corrosion rate in the PWR environment. Thus, such welds quickly lose their strength, and complete weld failure often results.

Conversely, low energy welds produce little mixing and have good corrosion resistance, but they also have a very low initial strength. Thus, the matter of selecting the proper laser weld energy becomes a problem of selecting an acceptable compromise between high initial strength and an acceptable corrosion rate. Examples of low and high energy welds are shown in Figure 15 and 16, respectively. These are photomicrographs of sections of laser welds made at 4.0- and 7.5-joule energies. Notice that even the high energy weld does not increase the grain size of the zircaloy. The depth of the heat pulse from the weld can be seen as a change in reflectivity of the metal.

When weld bond failures occur as a result of corrosion, they always occur at the titanium filler-zircaloy interface where mixing is greatest. By changing to a zircaloy filler

Fig. 13 Photograph of the laser welder and associated tooling.

Fig. 14 Closeup of laser welder showing operator, fuel pin in place.

Fig. 15 Section of a low energy (4 joule) laser weld showing incomplete melting of the filler wire.

Fig. 16 Section of a high energy (7.5 joule) laser weld showing the highly mixed nature of the fillet.

wire, the corrosion susceptible interface is changed to the one between the filler wire and the thermocouple sheath. However, because of the relatively thin wall on the thermocouple sheath, considerable mixing always occurs at this interface. Thus, with zircaloy filler wire, accelerated corrosion occurs even at low weld energies. This behavior has been verified experimentally and will be discussed further under the section on corrosion testing.

Extensive performance testing has shown that a 6.5-joule weld represents the best compromise between strength and corrosion resistance for the present application. An example of 6.5-joule welds is shown in Figure 17.

Fig. 17 Section of a 6.5-joule weld showing good uniformity and a nearly optimum amount of mixing.

Misalignment or misdirection of the laser beam can also produce the same effect as increasing or decreasing the beam energy. This results from directing most of the beam energy either on the thermocouple or on the fuel pin side of the filler wire. However, these problems have largely been eliminated through the careful use of the automated tooling.

Other weld parameters which should be mentioned are the selection of the weld length and spacing. Based upon criteria that the attachment welds should be at least as strong as the thermocouple cable itself, a weld length of about 0.10 inch was selected. By using a 0.030-inch spot diameter, and a 50% spot overlap, eight individual weld spots are required to make a 0.10-inch-long weld. One of these welds is placed on each side of the thermocouple cable, thus increasing the effective weld length to 0.20 inch. These welds are then spaced one inch apart along the entire length of the attachment to the fuel pin. End welds, i.e., junctions and the last weld at the top of the pin, are each made 0.2 inch long as added insurance against damage at these points.

4. CLEANING

To meet reactor in-core instrumentation cleanliness requirements and to ensure the best possible welds, all materials are thoroughly cleaned prior to welding. Thermocouples, filler wire, and the fuel pins are each etched in an acid bath to remove up to 0.0005 inch of material. They are then placed in a stop solution, followed by a thorough rinse in demineralized water. After final drying, the components are placed in the tooling and welded.

5. WELD INSPECTION AND DEFECTS

Because of the high degree of reliability required for in-core instrumentation, a detailed weld inspection system has been worked out. Control and inspection of the laser welding begins by making calorimeter measurements of the laser beam energy. If the energy measurements fall within a specified range, then welding can proceed. However, destructive test (control) samples are made before and after each fuel pin is welded. Torque and metallography tests are performed on these control samples.

Torque tests are used to measure the breaking torque strength of the welds. Individual welds are expected to break at torques above 45 in.-lb. Torque strength is directly related to the weld energy and this serves as a check on the calorimeter energy measurements. Metallurgical cross sections through the welds serve as a third verification of the proper weld energy and gives a direct measurement of the weld penetration.

In addition to examination and testing of the control samples, a permanent record is made of the energy of each laser pulse. This is accomplished by measuring the light which leaks through the reflector at the top end of the laser rod. A circuit was designed to detect, code, and record the energy level of each laser pulse. The circuit also provides audio and visual alarms should the energy fall outside of a preselected range. Energy values which fall outside of this range are also printed in red ink for easy identification. The printout is coded such that the energy of any individual weld spot can be identified later. The printout of weld energies for any fuel pin then becomes a part of a permanent quality assurance package for that fuel pin. A more complete description of the energy monitoring circuit is presented in Reference 7.

After all of the thermocouples are welded to a given fuel pin, a 100% visual inspection is performed on the welds. Examples of repairable weld defects include omitted welds and spot mislocations toward the fuel pin side of the filler wire. Nonrepairable welds include leaks and most other defects which raise a question of weld or thermocouple integrity. The visual inspection reports also become a part of the data package for the instrumented fuel pin.

IV. PERFORMANCE TESTS

1. CORROSION LIFE

Corrosion of the attachment welds was of great concern since earlier testing had indicated that the material formed in the titanium-to-zircaloy weld evidenced a higher corrosion rate than the pure materials. Preliminary tests also indicated that the corrosion rate was a strong function of the amount of mixing of the two metals and hence was a function of the weld energy.

For these reasons, a continuing series of corrosion tests was performed on samples of laser attachment welds. An autoclave was used as the test chamber to maintain a pressurized water environment at 650°F and 2,500 psi. Chemistry of the water in the autoclave was controlled to simulate certain parts of the actual reactor coolant. Deionized water was used as a base, and boron was added to create a concentration of 2,000 ppm. Lithium at a concentration of 2 ppm was also added. The oxygen content was maintained at 5 to 10 ppm so that these results would be conservative with respect to oxidation in a reactor. Actual reactor coolant water has an oxygen content of about 0.1 ppm.

The tests were conducted by carefully weighing, measuring, and photographing laser welded samples prior to placing them in the autoclave. After insertion, the samples were operated at the specified pressure and temperature for a period of 500 hours. At the end of a 500-hour period the samples were removed, weighed, measured, and rephotographed. These 500-hour cycles were continued until a total of 10,000 hours was accumulated. Samples containing 4.0-, 6.5-, and 7.0-joule welds were tested. The 4.0- and 7.0-joule welds failed by bond line corrosion after 5,500 to 6,500 hours. The 6.5-joule welds failed in the same manner after 6,000 to 7,000 hours of exposure.

In addition to the standard measurements, some destructive tests were performed on the 6.5-joule welds. Torque tests and metallographic examinations were made on 6.5-joule welds at 1,000-hour increments.

A means has been devised to apply a tangential force to individual attachment welds. The breaking force (torque) is recorded on welds removed at 1,000-hour increments. The torque required to break 6.5-joule welds exposed up to 6,000 hours is shown in Figure 18. As can be seen, the weld strength is a strong function of the exposure time in the autoclave environment. Metallographic cross sections of welds exposed for 1,000 and 5,000 hours are shown in Figure 19. Although a slight amount of corrosion can be seen at the edge of the 5,000-hour sample, gross corrosion of the weldment has not started. Failure is defined as the time at which the weldment actually separates from the zircaloy cladding. Four- and 7.5-joule welds have shown total failure at 5,500 to 6,500 hours. The 6.5-joule welds failed after exposures of 6,000 to 7,000 hours. All failures were of the bond line type in which the weldment separated from the zircaloy. Zircaloy-sheathed thermocouples which were welded with zircaloy filler wire show virtually no corrosion after 10,000 hours of exposure.

Fig. 18 Weld strength (torque) as a function of exposure time in 650°F, 2,500 psi water for 6.5-joule laser welds.

Fig. 19 Sections of laser welds from autoclave corrosion tests.

Although the oxygen concentration in the autoclave water was nearly 50 times greater than that of reactor water, the corrosion rate was not 50 times greater. Examination at 7,000 hours of the oxide layer on the zircaloy tubes revealed a degree of oxidation which would be expected after about 12,000 hours in a reactor environment^[8]. Thus, while these tests were conservative, they were not overly so.

2. NUCLEAR RADIATION

Laser welded thermocouple attachments have been tested in a nuclear radiation environment to determine the effect of a radiation exposure on weld strength. These tests were conducted in a pressurized water loop in the Engineering Test Reactor (ETR) at the Idaho National Engineering Laboratory. A total of 16 titanium-sheathed thermocouples were laser welded to sections of zircaloy fuel pin cladding and installed in a capsule in the ETR loop. Thermocouple outputs were monitored periodically throughout the test, and visual and metallurgical examination of the welds was made at the conclusion of the test.

The irradiation test was conducted for a total time of approximately 3,000 hours. During this time, the loop was operated at 450 to 500°F and 2,000 psi. At the capsule location in the ETR, the 3,000-hour operating time amounted to a total accumulated thermal neutron flux of 4.5×10^{20} nvt and a total fast neutron flux of 2.7×10^{19} nvt. The gamma field was 1.7×10^{12} R at the capsule location.

As was expected from prior thermocouple irradiation effects testing^[9,10], no failures or degrading of the Chromel/Alumel thermocouples was observed. Visual and metallurgical examination of the welds at the conclusion of the test revealed no abnormal appearance of the welds. Only the normal light corrosion expected from 3,000 hours of operation in the pressurized water environment was observed. No failures of thermocouples or welds occurred during the tests.

Torque tests were conducted on the welds after the samples were removed from the reactor. The results indicated that the weld strength was the same as would be expected from welds which had been exposed for the same time in hot pressurized water and with no radiation present. Thus it was concluded that nuclear radiation of this level did not change the weld strength by a noticeable amount. It is known that both zirconium and titanium are hardened by nuclear radiation but that these effects are also annealed out in the temperature range of interest.

3. FAST THERMAL CYCLE

Thermocouple attachment welds were subjected to a series of high temperature thermal cycles to test their performance during the blowdown/reflood portion of the reactor safety tests. Samples containing the laser welds were inserted into a quartz vessel in a preheated tube furnace and then quenched by bottom flooding the quartz vessel. Prior to insertion of the sample, the quartz tube contained steam flowing at a rate of five to eight grams per minute, and the temperature was stabilized at some preselected value. In this manner, sample heat-up to the desired temperature was attained in one to two minutes. A thermocouple attached to the sample revealed when the desired test temperature had been reached. At this time the steam flow was stopped and bottom flooding of the quartz vessel was initiated. A flooding rate of two inches per second was used. Solenoid valves were used

to initiate and control steam flow and flood water, and to drain the vessel after each test. A schematic diagram of the test apparatus is shown in Figure 20.

Tests were conducted by running a single test at 1,100°F and then five tests each at temperatures of 1,400, 1,500, 1,600, and 1,700°F for a total of 21 thermal cycles. Inspections of the welds were performed periodically throughout the test series. The test and inspection sequence is presented in Table II. During each inspection the welds were examined and photographed under a microscope.

Photographs of a sample 6.5-joule weld taken at each inspection point are shown in Figure 21. This particular weld survived all 21 thermal cycles. As a means of comparison, this same series of photographs is shown for a 7.5-joule weld in Figure 22. This particular weld contained a high degree of mixing between the zircaloy and titanium. It exhibited a nugget type of corrosion in which the weld failed prior to completion of the 21 cycles. Examples of metallographic sections through these two types of welds were shown in Figures 16 and 17. Thus the thermal cycle tests provide a means of obtaining accelerated corrosion information about the welds and of determining the types of corrosion which can be expected under high temperature conditions.

4. TIME RESPONSE

Two types of time response tests were performed on the thermocouple junctions as a means of determining their relative behavior and to check the basic operation of the measuring junctions. These tests were in no way intended to duplicate reactor time response requirements or to predict the thermocouple performance in a reactor environment.

The first type performed was a standard test in which the thermocouple was plunged into a beaker of boiling water. The time response was then determined from photographs made of oscilloscope displays of the thermocouple output as a function of time. Tests conducted with many thermocouples over a period of time indicate an average time constant (0 to 63%) of 52 milliseconds. Identical tests conducted on the thermocouples made from the same bulk cable material, but with a standard flattened, grounded junction, also gave 52-millisecond average time constants. This indicates that, for this type of test, the presence of the tantalum barrier in the junction does not affect the response of the thermocouple.

A second type of response test was performed by focusing a laser beam on the thermocouple junction and then pulsing the laser at various energies. This produced a step energy input to the junction, and its output could then be displayed and recorded on an oscilloscope as was done in the hot water tests. A continuity circuit was employed in the hot water tests to indicate the instant that the tip of the thermocouple touched the water. For the laser tests, a photodiode was used to indicate the time at which the laser light reached the thermocouple.

Fig. 20 Schematic diagram of the thermal cycle test apparatus.

TABLE II
SAMPLE TEST SEQUENCE

<u>Inspection Number</u>	<u>Test Temperature (^oF)</u>
1	1,100 Inspect 1,400 1,400 1,400
2	Inspect 1,400 1,400
3	Inspect 1,500 1,500 1,500
4	Inspect 1,500 1,500
5	Inspect 1,600 1,600 1,600
6	Inspect 1,600 1,600
7	Inspect 1,700 1,700 1,700
8	Inspect 1,700 1,700
9	Inspect

By selecting the proper laser beam energy, a step temperature increase of many hundreds of degrees can be obtained. A disadvantage of using the laser technique is that the temperature pulse is of short and unknown duration, and hence only relative response times can be determined. It does prove useful, however, in that it is convenient and does produce an extremely fast, high temperature input to the thermocouple junction. The technique has also been modified to test the response of thermocouples in welded or installed conditions by simply focusing the laser beam on the measuring junction.

Fig. 21 Photographs of a 6.5-joule weld at major inspection points of the thermal cycle test.

Fig. 22 Photographs of a 7.5-joule weld at major inspection points of the thermal cycle tests. The nugget type corrosion can clearly be seen.

Average time constants measured for the barrier junctions using the laser technique were about 26 milliseconds. Bare 0.005-inch Chromel/Alumel wires indicated time constants of about 3 milliseconds in these tests.

5. HEATER ROD BLOWDOWN/REFLOOD TESTS

The thermocouples were laser welded to zircaloy-clad heater rods for a series of "proof" tests in a blowdown/reflood facility. The heater rods were made from reactor grade zircaloy fuel pin cladding. They were thus of the same size as the Loss-of-Fluid Test (LOFT) fuel pins, and they were constructed in such a manner that the internal heating coil produced a chopped cosine type temperature distribution in the rod. A schematic diagram of the heater rods is shown in Figure 23. Thermocouples were attached to the heater rods in the same locations and in the same manner as they would be for the actual fuel pins.

The blowdown/reflood tests were conducted in a single-pin facility which allowed a single instrumented heater rod to be subjected to a typical pressurized water reactor flow environment and then undergo blowdown and reflood cycles. Flow rates, temperatures, blowdown times, reflood rates, and flood water temperatures were adjusted to be typical of those desired for water reactor safety tests.

During the blowdown portion of the tests, the heater rod power was allowed to remain at some preselected value to provide a high temperature excursion. Power levels were selected to provide temperature transients ranging from 1,000 to 1,700°F. As with the fast thermal cycle tests, the attachment welds were inspected after each blowdown/reflood test. Photographs were made of the welds during each inspection.

Because of the involved and difficult nature of the tests, these were quite expensive to run. For this reason the series was limited to nine tests. Peak cladding temperatures ranged between 1,000 to 1,700°F for these tests and, although the laser welds were weakened somewhat, actual weld failure did not occur. Thermocouple signals were monitored throughout the tests, and all of the thermocouples performed well during the entire test series.

Metallography was performed on the attachment welds at the conclusion of the tests, and it revealed no detectable difference from that obtained from fast thermal cycle specimens which had experienced a similar thermal history. Thus it was concluded that the thermocouples and attachment welds were capable of surviving a series of reactor safety tests such as those predicted for LOFT.

Fig. 23 Schematic diagram of the zircaloy-clad heater rods.

V. CONCLUSIONS AND RECOMMENDATION

As a result of development and testing of titanium-sheathed thermocouples as described in this report, it was concluded that successful temperature measurements can be made on zircaloy-clad fuel pins during high temperature excursions. The thermocouples have an upper temperature limit in this application of about 2,800°F for short periods of time during temperature excursions. The laser welds which are used to attach the titanium-sheathed thermocouples to the zircaloy-clad fuel rods have a corrosion lifetime in the pressurized water reactor environment of about 6,000 hours. The thermocouples and attachment welds are capable of surviving a series of repeated blowdown/reflood tests with high temperature excursions during each cycle. In general, a highly qualified thermocouple installation is available for in-reactor use on zircaloy-clad fuel pins.

While the titanium-sheathed thermocouples meet the temperature requirements, they do have a limited lifetime in the high temperature water. Preliminary tests have shown that these thermocouples can now be made with zircaloy sheaths. This then allows the use of all zircaloy attachment welds, which have excellent corrosion resistance. Samples of these zircaloy-sheathed thermocouples have been tested in the 650°F water environment for 10,000 hours with no indication of a weld corrosion problem. It is thus recommended that future work in this area be directed toward the development and use of similar zircaloy-sheathed thermocouples.

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