247-05

CONF - 800719--4

External attachment of titanium sheathed thermocouples to zirconium nuclear fuel rods for the LOFT reactor

Richard K. Welty

Exxon Nuclear Company, Inc., 2101 Horn Rapids Road, Richland, Washington 99352

Abstract

The Exxon Nuclear Company, Inc. acting as a Subcontractor to EG&G Idaho Inc., Idaho National Engineering Laboratory, Idaho Falls, Idaho, has developed a welding process to attach titanium sheathed thermocouples to the outside of the zircaloy clad fuel rods.

The fuel rods and thermocouples are used to test simulated loss-of-coolant-accident (LOCA) conditions in a pressurized water reactor (LOFT Reactor, Idaho National Laboratory).

The design goals were to (1) reliably attach thermocouples to the zircaloy fuel rods, (2) achieve or exceed a life expectancy of 6,000 hours of reactor operation in a borated water environment of 316°C at 2240 psi, (3) provide and sustain repeatable physical and metallurgical properties in the instrumented rods subjected to transient temperatures up to 1538°C with blowdown, shock, loading, and fast quench.

A laser beam was selected as the optimum welding process because of the extremely high energy input per unit volume that can be achieved allowing local fusion of a small area irrespective of the difference in material thickness to be joined.

A commercial pulsed laser and energy control system was installed along with specialized welding fixtures. Laser room facility requirements and tolerances were established. Performance qualifications, and detailed welding procedures were also developed. Product performance tests were conducted to assure that engineering design requirements could be met on a production bases.

Irradiation tests showed no degradation of thermocouples or weld structure. Fast thermal cycle and heater rod blowdown reflood tests were made to subject the weldments to high temperatures, high pressure steam, and fast water quench cycles. From the behavior of these tests, it was concluded that the attachment welds would survive a series of reactor safety tests.

Introduction

The LOFT reactor (Loss-of-fluid-test) located at the Idaho National Engineering Laboratory, Idaho Falls, Idaho is an experimental reactor whose purpose is to:

(1) Evaluate the capability of analytical methods that predict the loss-of-coolant-accident (LOCA) responses for large pressurized-water power reactors, the performance of engineered safety systems, and the margins of safety in the safety systems performance.

(2) Identify any unexpected events or thresholds not presently accounted for in the analysis of reactor response or in the design of engineered safety systems.[1]

To accomplish these objectives, test instrumentation is required in the reactor core. One of the most important instrumentation items is thermocouples attached to the outside of the zircaloy clad fuel rods, an example of which is shown in Figure 1.

These fuel rods and thermocouples are used to measure the surface temperature of the cladding during testing in the LOFT reactor. Attachment of these fragile thermocouples, having a sheath thickness of only 0.009 inch, to the fuel rods is a difficult task. To compound the problem, only a limited number of materials are suitable for use as small diameter thermocouples that can be welded to zircaloy clad fuel rods.

Titanium was selected for the thermocouple-sheath material due to its availability and superior performance in terms of corrosion resistance when the intermixing of the titanium and zircaloy is limited.

This resulting limitation in alloy mixing between the titanium and zircaloy and small heat affected zone permissible in the thermocouple sheath, coupled with the close tolerance positioning required of the thermocouple on the fuel rod presented a unique welding challenge. A laser was selected to fulfill this role.

Figure 1. LOFT instrumented fuel rod.

Discussion

Laser system

The laser used for this project was a KORAD, model KWD welder/driller system employing a Neodymium doped YAG (Yttrium-Aluminum-Garnet) laser rod. Figure 2 is a photograph of the overall system. Principal items in the photograph are: (a) the laser head, (b) optical viewing, (c) tooling, to hold the fuel rod and thermocouple, (d) T.V. camera, (e) energy monitor, (f) T.V. screen, and (g) high-low energy alarm.

Figure 3 is a photograph of the laser head showing (a) photodetector, (b) back reflector, (c) laser cavity (Xenon gas filled helical flashlamps are used), (d) front reflector, (e) negative lens, and (f) focusing lens.

Figure 4 is a closeup of the (a) energy monitor, (b) T.V. screen and (c) high-low energy alarm.

The energy monitor is connected to a printer which prints out a record of the weld position and energy delivered for each pulse of the laser.

Figure 5 is a photograph of a typical thermocouple weld with print out. The number three weld position is shown with the energy in joules for the eight spots which comprise that particular weld.

The average energy shown in this photograph is 7.13 ± 0.03 joules which is a typical range for this type of weld.

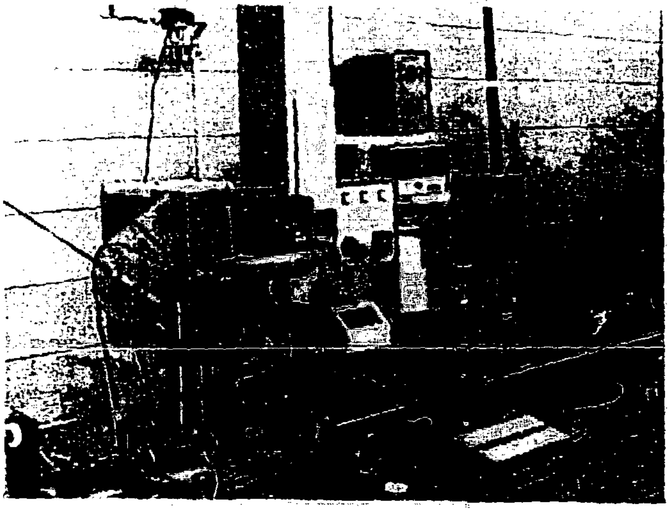

Figure 2. LOFT laser welding system.

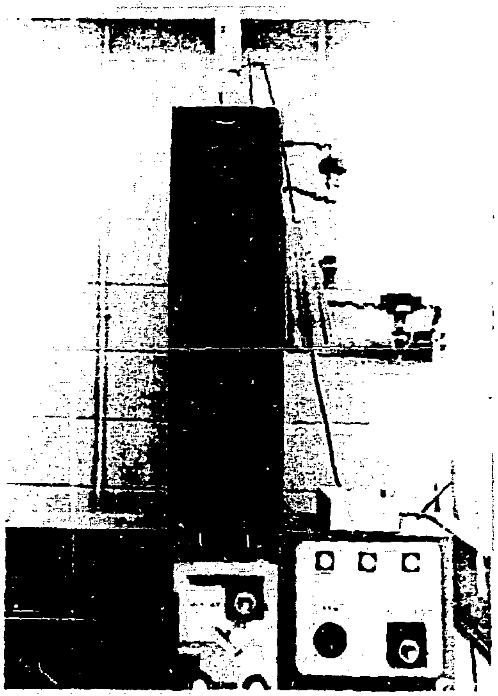

Figure 3. Laser welder head.

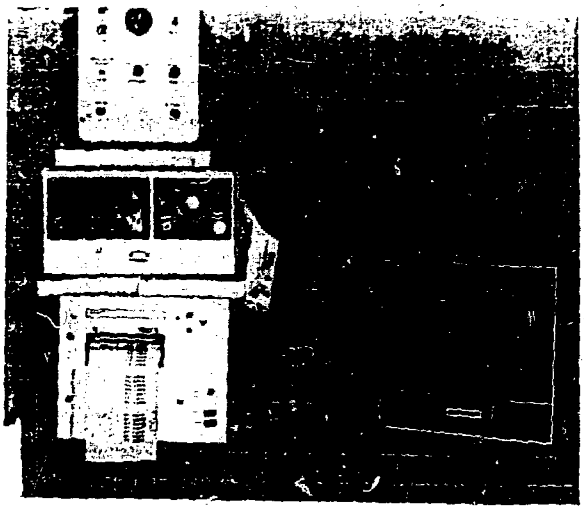

Figure 4. Laser support systems.

Figure 5. Typical thermocouple weld and energy print out.

Process development. Several process tests were conducted to verify the basic laser energy variability. This was accomplished by using a beam splitter which was located in the laser optical system just below the laser cavity as shown in Figure 6. This produced a beam which was reflected to a photodiode and recorded through an oscilloscope on poloroid film.

The beam splitter was calibrated against a calorimeter and provided consistent agreement with the calorimeter to within 0.5% for several levels of laser energy.

The laser was tested by cycling automatically at a pulse rate of 20 pulses per minute. These pulse heights were recorded in detail on the poloroid film and compared to calorimeter readings taking during the same time period.

The laser provided consistent energy output to within 5% of a given voltage setting. The power monitor, which records the energy for each pulse, was also checked in a similar manner. The power monitor was also within 5% agreement with laser energy.

These observations led to establishing the weld energy variance allowable (± 10%) when making the weld. An important observation that was made when studying the photographs from the laser variability tests was the lower energy output observed in the first or second pulses at the start of the 20 pulse minute series.

These pulses were as much as 20% lower in energy than succeeding shots. (See Figure 7)

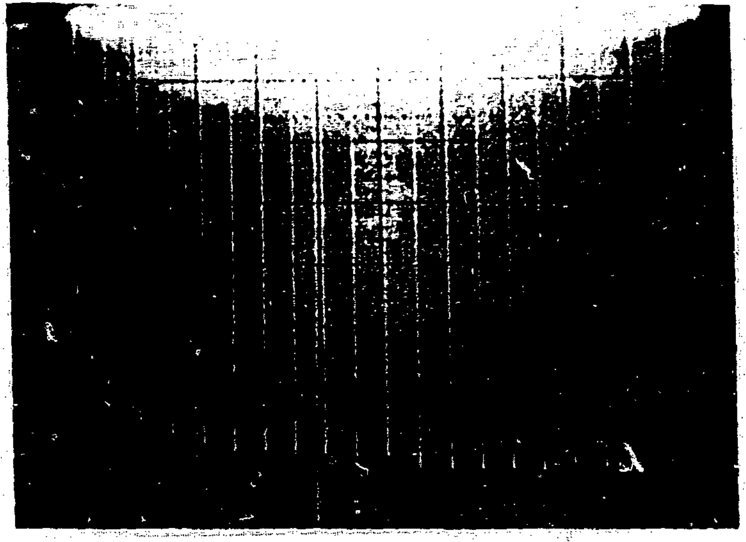

Figure 7. Laser beam pulse heights.

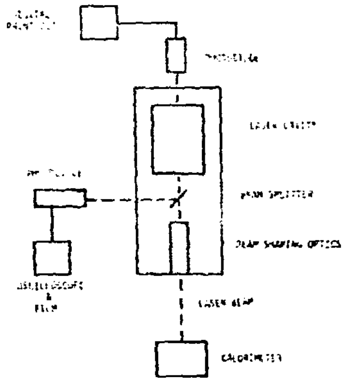

Figure 6. Laser beam splitter.

These low energy pulses were accounted for in production welding by placing a beam blocker between the laser and work piece. The beam blocker prevents the laser radiation from striking the work piece until the third pulse, at which time the beam blocker opens and welding commences. By the third pulse, the laser is stabilized in output energy. Another problem that caused considerable difficulty in controlling the apparent laser output energy was back reflection of the laser beam from the work piece. Apparent laser energy increases of up to 10-15% were observed on the power monitor, when it was known that the variability of the laser and power monitor were stable in output energy to ± 5%. What was happening was the laser beam was reflecting back from the work piece, through the front reflector, through the laser rod, and out the back mirror into the photodiode, resulting in an erroneous high energy readings.

The solution to this was to increase the reflectivity of the front mirror from 65% to 72%. There is a detrimental aspect to this increase in reflectivity in that the laser cavity temperature goes up, and the laser rod, and reflectors are more susceptible to thermal damage.

Weld development. Considerable laser testing was conducted to optimize process parameters for the T.C. attachment weld. The principle variables investigated were:

- laser energy
- laser beam spot size
- filler wire diameter
- weld penetration into sheath and fuel rod

Table 1 shows the range of values tested.

Table 1

Laser Beam Welding Test Parameters

Parameter	Size and Percent				
Laser energy (joules)	4.0	6.5	7.0	7.5	
Laser beam spot dia. (in)	0.020	0.030	0.040	0.050	
Filler wire dia. - titanium (in)	0.015	0.012		0.014	
Percent penetration - sheath	10	25	50	75	100
Fuel rod	10	25	50	75	

Thermal cycling tests were performed at Idaho Falls[2] to determine the effect between laser energy and mixing of the zircaloy and titanium metals. Two distinct weld failure modes occurred as a result of these tests. Bond line failures occurred with welds made at low energy. These welds are characterized by very shallow penetration and very little or no mixing of the base metals. High energy welds result in greater mixing of the base metals. These welds are initially very strong but corrode and fail rapidly during the thermal cycling tests.

Figure 8 is a photograph of a typical Loft thermocouple attachment, sectioned across the weld.

The average wall thickness of the thermocouple is 0.009 inches. The maximum penetration into the thermocouple-sheath is 24%. The average thickness of the zircaloy wall is 0.024 inches. The maximum penetration into the clad is 9%. The laser spot size is 0.030 inches. 0.014 in. diameter titanium filler wire was used to make this weld. (The filler wire results in the joint between the thermocouple and the rod.) This weld was made at 5.2 joules. These are typical values for a Loft thermocouple fuel rod weld.

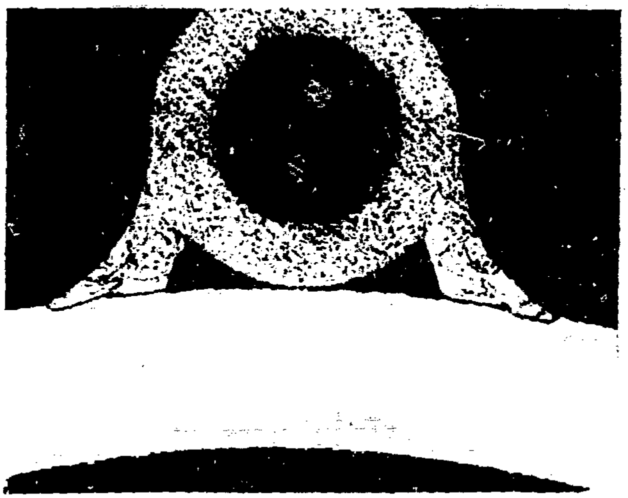

Figure 8. Typical thermocouple weld attachment.

Process qualification and production welding. The laser welder system was qualified by establishing the following performance criteria:

- Equipment qualification

  Calorimeter tests
  Operating tolerances
  Preproduction sample welding
  Maintenance procedures

- Performance qualification

  Laser theory and safety
  Operation functions
  Calorimeter checks
  Preproduction welding

Laser output energy versus pumping voltage is established through a series of tests using the calorimeter. A curve is developed of energy versus voltage over the normal range of welding for the thermocouples. This relationship is used as a reference during production welding. The operating tolerances for alignment of the laser beam on the filler wire were arrived at through a series of process tests. Since the targets are extremely small, and any misalignment will cause weld upsets, the operating variance is limited to ± 0.002 inches for centering the laser beam over the filler wire. This is controlled during welding by scribing two parallel lines, 0.004 apart on the reticle in the binocular viewing system. These lines are used to track the filler wire by the machine operator during welding for every pulse of the laser.

Preproduction welding comprises welding samples with representative materials and subjecting the welds to acceptance criteria evaluations. All welds must meet:

Dimensional requirements
Weld penetration limits
Metallographic examination
Discoloration (oxidation)
Physical standards (weld defects)
Helium leak check
Torque testing

Routine maintenance procedures were also established. The most important of which are daily checks of the laser rod and optics for dust, burned spots, moisture, etc.

Performance qualification was arrived at through classroom and on the job training. Before any personnel are allowed to use the laser they are trained in a short course on laser theory and safety. This is especially important since we are using a YAG laser rod, which emits radiation at 1.06 microns and is invisible to the human eye. Proper operation of the machine and calorimeter checks are a prelude to preproduction welding where typical thermocouple welds are made and examined as described above.

Preproduciton welding is accomplished by welding a typical full length fuel rod to which four thermocouples, including measuring junctions and dummy thermocouples have been attached. This fuel rod is examined carefully and must meet all the standards set forth in the acceptance criteria.

Finally, production welding is controlled by welding process control samples before and after every fuel rod. These process control samples are short sections of tubing with at least 8 laser welds on both sides of a thermocouple.

Two of these welds are torque tested and are required to fail within specified ranges depending on the manufactured source of the thermocouples.

Another weld, selected randomly, is cross sectioned and the weld penetration measured.

Figure 8 is a photograph of an example of an acceptable thermocouple weld. It demonstrates minimal mixing between the titanium and zircaloy, extend of penetration of the toe of the weld into the fuel rod, penetration into the root of the weld and degree of filler wire melting. This type of weld is used as the standard for process control metallographic character.

In contrast, reject welds are shown in Figures 9 and 10. Figure 9 is a photograph of a weld with excessive penetration. It shows a high degree of alloy mixing, deep penetration into the fuel rod, and some porosity in the weldments.

Figure 10 is a photograph of a weld with minimal penetration. It shows a lack of filler wire melting on the back side and an incomplete bond line between the filler wire and fuel rod.

Figure 11 is an exceptional 200X photograph of a weldment made in the spade area of the T.C. It shows typical features of a laser weld, with acceptable penetration into the fuel rod and thermocouple and low degree of mixing of the base metals.

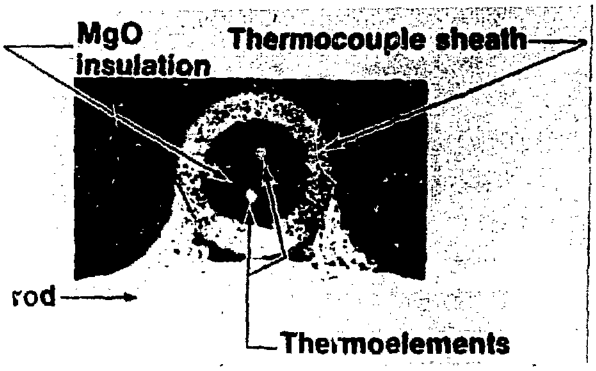

Figure 9. LOFT thermocouple weld with excessive penetration.

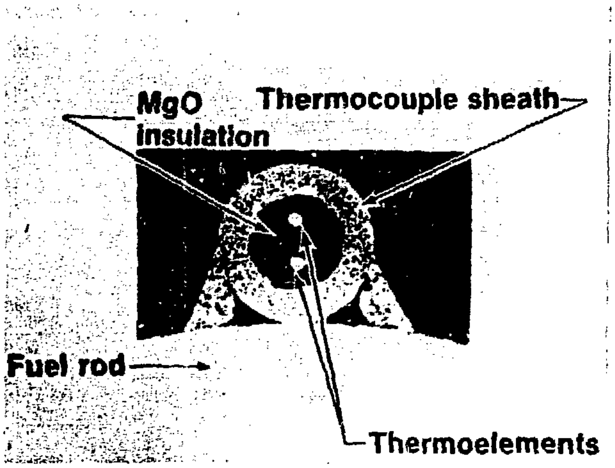

Figure 10. LOFT thermocouple weld with minimal penetration.

Conclusion

This program has been very successful in meeting the needs of the LOFT program. To date approximately 237 fuel rods with thermocouples have been welded. Some of these rods require over 4000 spots per rod. Well over a million shots have been made with the KORAD laser system, making this program probably one of the greatest data bases that exists for this type of welding.

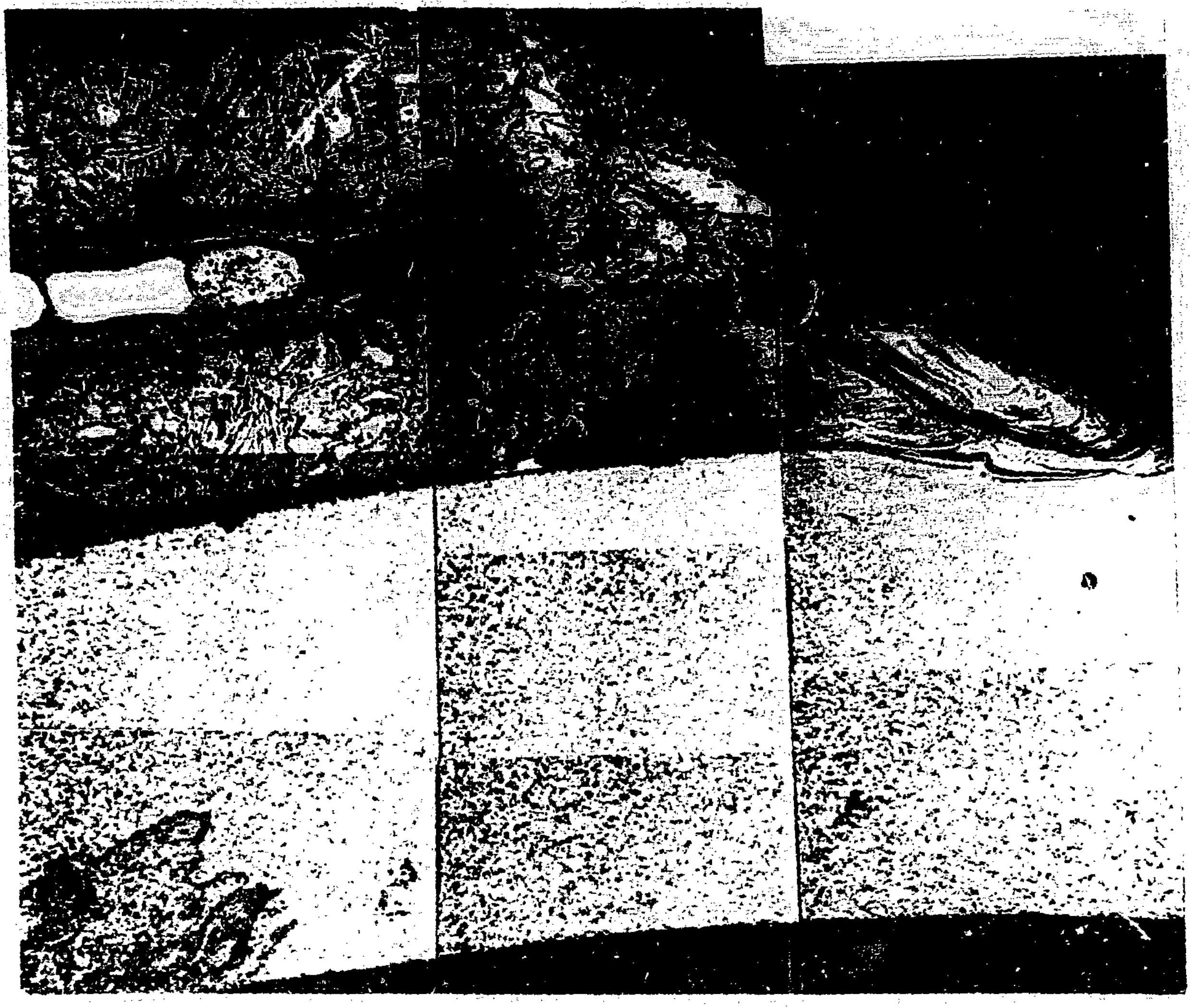

Figure 11. LOFT thermocouple weld in the Spade area.

Acknowledgments

The author wishes to recognize D. W. Hood of EG&G Idaho National Engineering Laboratory, for his leadership in developing this laser process. He was capably assisted by H. D. Stuckl and F. W. Turner, also of EG&G Idaho, Inc. To M. C. Russell and T. E. Howell (EG&G) for providing program management and to R. D. Reid and E. G. Coye, Exxon Nuclear Company, Inc., for their assistance in making this program a success.

References

1. Russell M. L., "Loft Fuel Modules Design Characterization and Fabrication Program". ANCR-1223, September 1975.

2. Meservey, R. H., "Thermal Cycle Testing of Laser Welded Thermocouple Attachments". MAS-7-73, February 1973.