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METALS AND CERAMICS DIVISION

REMOTE INSPECTION OF WELDED JOINTS

R. W. McClung

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Oak Ridge, Tennessee 37830
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R. W. McClung

ABSTRACT

Maintenance and repair of reactor components by remote welding will require development of adequate nondestructive examination techniques to assure the integrity of the weld. High temperature and radiation levels will require remote inspections and add to the complexity of the performance. Recommended developments include improved closed-circuit television for visual examination, evaluation of new high-temperature penetrants, study of neutron radiography, improved transducers for ultrasonics, and application of acoustic emission and eddy currents. Sophisticated mechanical positioning, manipulation, and scanning equipment will be required for most of the techniques.

INTRODUCTION

The long-range economic utilization of nuclear reactors for production of electrical power requires that practical economic maintenance and repair be possible. The latter functions become more complicated than those encountered in other industry because of the high temperature and radiation background associated with some of the components. However, despite the difficulties, necessary maintenance operations in nuclear reactors have been conducted successfully. In regions of very high radiation background, ingenious mechanical devices have been developed to allow simple repairs. For example, the Homogeneous Reactor Test (HRT) was a proving ground for a number of remote maintenance methods.[1–4] The Molten Salt Reactor Experiment (MSRE)

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[1] J. S. Culver, Viewing Equipment for Use in the HRT Core and Blanket Vessels, ORNL-2886 (Mar. 1, 1960).

[2] B. D. Draper and E. C. Hise, Remote Maintenance Procedure Report, CF-59-11-128 (Nov. 26, 1959).

[3] P. P. Holz, Some Miscellaneous Maintenance Tools Used to Manipulate Loose Objects in the HRT Core, CF-59-11-123 (Nov. 17, 1959).

[4] P. P. Holz, Additional Miscellaneous Maintenance Tools Used in the HRT Core, CF-60-9-103 (Sept. 26, 1960).

also demonstrated the feasibility of remote maintenance and repair of radioactive components.[5] In both of these examples much of the work was mechanical (e.g., flanges, bolts, etc.). Relatively little of the past work has included study of remote welding techniques for repair or replacement of components. Even less has been done on remote inspection techniques for welds made remotely. However, despite the paucity of effort on inspection of remotely made welds, work has been accomplished toward the remote application of inspection techniques, in both nuclear reactors[6–9] and hot cells.[10] This report discusses the present technology that may be applicable to the remote examination of welds made during maintenance operations for Molten Salt Reactors (MSR). Most of the discussion would be equally applicable to other reactor systems.

ENVIRONMENT AND OTHER PARAMETERS[11]

The materials and environmental conditions assumed are those associated with an MSR and encountered in evaluation of a remotely made weld

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[5] P. N. Haubenreich and J. R. Engel, "Experience with the Molten-Salt Reactor Experiment," Nucl. Appl. Technol. 8(2), 118–136 (1970).

[6] R. W. McClung, "State of the Art of Nondestructive Testing for Service and Postoperation Examination of Reactor Pressure Vessels," pp. 165–167 in Incipient Failure Diagnosis for Assuring Safety and Availability of Nuclear Power Plants (Conference Proceedings, Gatlinburg, Tennessee, October 30–November 1, 1967), CONF-671011 (January 1968).

[7] R. D. Wylie, "Design for In-Service Inspection," pp. 220–227 in Incipient Failure Diagnosis for Assuring Safety and Availability of Nuclear Power Plants (Conference Proceedings, Gatlinburg, Tennessee, October 30–November 1, 1967), CONF-671011 (January 1968).

[8] C. E. Lautzenheiser, "Requirements for Pre-Service and In-Service Inspection of Nuclear Coolant Pressure Boundaries," pp. 2–10 in Proceedings of Sixth International Conference on Nondestructive Testing, June 1–5, 1970, Hannover, Germany, Vol. N, Dortmund, Germany, March 1970.

[9] R. W. McClung and K. V. Cook, Development of Ultrasonic Techniques for the Remote Measurement of the HRT Core Vessel Wall Thickness, ORNL-TM-103 (Mar. 15, 1962).

[10] R. W. McClung and D. A. Douglas, "Nondestructive Testing of Irradiated Materials in the United States," pp. 179–202 in High Activity Hot Laboratories Working Methods, Vol. 1, Proceedings of an International Symposium Organized by ENEA and EURATOM, McGraw-Hill, New York, 1965.

[11] Based on R. B. Briggs, Oak Ridge National Laboratory, personal communication, October 1970.

(e.g., after removal and replacement of a major component, such as a heat exchanger). The primary metal for consideration is Hastelloy N, and a type 300 series stainless steel is considered a potential alternate. The welds are predominantly cylindrical in pipes having diameters from 1 to 20 in. and wall thicknesses up to 1 in. Larger cylinders include the heat exchanger and the core vessel, with diameters of approximately 5 and 30 ft, respectively.

Anticipated temperatures in the reactor cell range from 1000 to 1200°F. However, localized cooling for both welding and inspection can probably bring temperatures down to the range 200 to 600°F and possibly even to 200 to 400°F.

The anticipated level of radiation[12] in the reactor cell ten days after the system is shut down and drained is expected to be approximately 10^5 R/hr. The dominant radiation will be gamma rays from relatively noble fission products deposited on the metal surfaces of the heat exchanger tubes and on the graphite in the core vessel. The area of highest dose rate (calculated to be 1.4×10^5 R/hr) is at the midplane immediately adjacent to a heat exchanger. Values in other portions of the cell may be 25 to 30% of the maximum. Most of the radiation will have photon energies of 0.8 MeV and below.

Care must be exercised during the examination to avoid the introduction of materials that could be detrimental to the continued serviceability of the components. For example, no sulfur-bearing oils and no aluminum or low-melting alloys should be introduced for contact with Hastelloy N because they may react to cause loss of desired properties. Similarly, for stainless steels, chlorine-free materials must be used.

Because of the high radiation and temperature levels in the reactor cell, personnel access is obviously forbidden. Therefore, mechanical systems would have to be designed and built to allow remote performance of the examination. Some attendant restrictions on the mechanical equipment include the fact that examination equipment must be inserted

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[12] J. R. Tallackson, private communication to R. W. McClung, Jan. 29, 1971.

into the reactor cell from above through access ports (perhaps 1 ft in diameter) and be manipulated over distances up to 30 or 40 ft (not necessarily immediately below an access port). In addition, because of limited space within the cell, the examination equipment should not extend outward more than 1 ft from the component being examined.

CUSTOMARY METHODS FOR NONDESTRUCTIVE EXAMINATION OF WELDS

Under normal circumstances several methods of nondestructive examination would be applicable to the examination of welds in Hastelloy N or stainless steel. These include visual examination, use of liquid penetrants, radiography, and ultrasonic methods. No detailed discussion of the basic methods is intended in this report. Descriptions will be limited to those aspects pertinent to remote operation within the restrictions that were previously mentioned. Those wishing more information about the methods are referred to the Nondestructive Testing Handbook[13] and Welding Inspection.[14]

Visual Examination

Many features about the quality of a weld can be noted by visual examination. Among the conditions that may be observed are surface cracks, undercut, overlap, weld irregularity, and dimensional inaccuracies. However, the surface appearance alone is inadequate to prove careful workmanship or good internal quality. The visual examination should be made before, during, and after the welding and be further supplemented with other methods of nondestructive examination.

In the stringent environment being discussed, such visual examination must be done with optical aids, such as closed-circuit television

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[13] American Society for Nondestructive Testing, Nondestructive Testing Handbook 2, ed. by Robert C. McMaster, Ronald Press, New York, 1959.

[14] AWS Committee on Methods of Inspection, Welding Inspection, American Welding Society, New York, 1968.

(CCTV). The CCTV has been successfully applied in radioactive environs for surveying reactor internals and monitoring operations in hot cells.[15,16] Care must be taken to minimize the effects of high temperature and radiation on the components of the camera to avoid excessive image degradation and failure.

Liquid Penetrant Examination

Liquid penetrants containing visible or fluorescent dyes are commonly used to detect the presence of surface-connected flaws in welds. However, the commonly used materials are not applicable at the high temperature expected in the reactor cell during the examination. A recent experimental product[17] shows promise of being applicable for penetrant examination at temperatures as high as 600 to 900°F. At room temperature the penetrant, remover, and developer are in crayon form. The high-temperature penetrant was developed for use on multipass welds. No information is available on the sensitivity to cracks or other discontinuities. Use of penetrant techniques in the remote environment would require the development of procedures for performance and examination of results. The CCTV previously discussed could probably be used to advantage.

Radiographic Examination

Radiography is a primary requirement for the examination and acceptance of welds. However, the excessive radiation levels and high temperatures to be encountered in the reactor cell raise genuine doubts

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[15] J. P. Pele, G. Hoyaux, and J. M. Baugnet, "Underwater Nondestructive Testing at the BR2 Reactor," pp. 203–219 in High Activity Hot Laboratories Working Methods, Vol. 1, Proceedings of an International Symposium Organized by ENEA and EURATOM, McGraw-Hill, New York, 1965.

[16] W.K.A. Walrave, "Equipment for Nondestructive Examination," pp. 221–228 in High Activity Hot Laboratories Working Methods, Vol. 1, Proceedings of an International Symposium Organized by ENEA and EURATOM, McGraw-Hill, New York, 1965.

[17] H. G. Bogart, Magnaflux Corporation, personal communication, January 1971.

about the possibility of valid radiography for the examination of the remotely made welds. Radiography has been demonstrated and used on highly radioactive objects in special facilities (e.g., hot cells) and with special techniques, but in every case significant effort was taken to minimize the exposure of the film to the background radiation.[18–20] The film is usually placed for a very short time in a fixed position and massive shielding prevents most of the background radiation from giving an overexposure of fog. Similar steps for radiography on any of several closely associated radioactive components in a reactor becomes so difficult as to be impractical.

The above discussion and extreme pessimism applies to x- or gamma-radiography since the customary x-ray film is sensitive to the background radiation. A potential alternative method of radiography uses neutrons as the penetrating radiation.[21] Some of the primary detection methods for neutron radiography (e.g., foils of indium or gadolinium, track-etch plates such as mica or cellulose nitrate, and neutron-sensitive image intensifiers) are not sensitive to x- and gamma-rays and thus allow radiography of highly radioactive specimens (e.g., irradiation capsules or used fuel elements from nuclear reactors) or radiography of nonradioactive specimens in the presence of high background radiation. For example, useful neutron radiography is commonly performed using a neutron beam accompanied by high intensity gamma radiation from a nuclear reactor. At the present stage of development of both techniques and equipment, the sensitivity and resolution of neutron radiography for metals (i.e., welds) is less than is expected of x-radiography. Another problem is the limited choice and capability of portable sources for neutrons.

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[18] R. W. McClung and K. V. Cook, Feasibility Studies for the Nondestructive Testing of the EGCR Through-Tube Weldment, ORNL-TM-46 (Nov. 14, 1961).

[19] R. W. McClung, "Radiography in the Presence of Background Radiation," Mater. Evaluation **23**(1), 41–45 (January 1965).

[20] High Activity Hot Laboratories Working Methods, Proceedings of an International Symposium Organized by ENEA and EURATOM, Grenoble, France, June 1965, note particularly papers on pp. 25–89 and 139–197 of Vol. 1.

[21] H. Berger, Neutron Radiography, Elsevier Publishing Company, Amsterdam, 1965.

Despite the problems, limited work has been done on welds, and with advances in both the technology of neutron radiography and availability of improved sources (e.g., ^{252}Cf), better performance capabilities for the neutron radiography of welds should be expected. Extensive development would be required for equipment to place both source and detector in proper position near the weld to be examined in the reactor cell.

Ultrasonic Examination

Ultrasonic methods of nondestructive examination of welds have, in recent years, been used increasingly. There are probably several reasons, including (1) significant advances in capability of both equipment and personnel; (2) increased awareness of the ability of ultrasound to detect discontinuities such as cracks and lack of fusion, which are difficult to detect radiographically; and (3) desire for the ultimate in confidence in critical components (as a result many complementary examination methods are used). Many of the mechanical scanning systems used for ultrasonic examination of materials lend confidence to the ability to manipulate probes remotely. The mechanical capability coupled with the minimal effect of radiation on ultrasonic transducers has led to its utilization on many occasions for the examination of radioactive components in both reactors[22–24] and hot cells.[25]

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[22] R. D. Wylie, "Design for In-Service Inspection," pp. 220–227 in Incipient Failure Diagnosis for Assuring Safety and Availability of Nuclear Power Plants (Conference Proceedings, Gatlinburg, Tennessee, October 30–November 1, 1967), CONF-671011 (January 1968).

[23] C. E. Lautzenheiser, "Requirements for Pre-Service and In-Service Inspection of Nuclear Coolant Pressure Boundaries," pp. 2–10 in Proceedings of Sixth International Conference on Nondestructive Testing, June 1–5, 1970, Hannover, Germany, Vol. N, Dortmund, Germany, March 1970.

[24] R. W. McClung and K. V. Cook, Development of Ultrasonic Techniques for the Remote Measurement of the HRT Core Vessel Wall Thickness, ORNL-TM-103 (Mar. 15, 1962).

[25] R. W. McClung and D. A. Douglas, "Nondestructive Testing of Irradiated Materials in the United States," pp. 179–202 in High Activity Hot Laboratories Working Methods, Vol. 1, Proceedings of an International Symposium Organized by ENEA and EURATOM, McGraw-Hill, New York, 1965.

However, several problems must be resolved to allow use of ultrasonics for examination of MSR welds. Welds have been successfully inspected on many materials, including carbon steels and aluminum. However, difficulty has been encountered in the application of ultrasound to welds in stainless steel and nickel-base alloys. A large variable attenuation of the sound and the presence of reflections from grain boundaries interferes with calibration and ultrasonic examination on such materials. Laboratory studies should be undertaken to determine the cause of inspection difficulty and to devise techniques and/or equipment modifications necessary to overcome the problems, allowing high-confidence inspection.

Materials to couple ultrasound from the transducer into the weldment will have to be selected on the basis of susceptibility to reactor contamination or activation, remote applicability, and adequate ultrasound transmission at the expected temperatures. A potential alternate solution to the problem of coupling the sound is the use of electromagnetic induction transducers not requiring a liquid coupling.[26,27] Recent work has shown that useful ultrasonic vibrations can be generated in specimens by electromagnetic techniques, but the sensitivity is significantly below that possible with conventional piezoelectric devices. Further work is needed to improve the operation of these new transducers before this method could be considered applicable for the cited inspection of welds.

Mechanical scanning devices will be required to move the transducer in a preprogrammed plan over the weldment. Accurate positioning of the transducer may be assured by CCTV. It may be possible to design and build accessories that can be attached to the mechanical system to be used for the performance of the remote welding.

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[26] H. Wuestenberg, "Berührungslose elektrodynamische Ultraschallwandler und ihre Verwendung in der Ultraschallprüfung," pp. 37–48 in Proceedings of the Sixth International Conference on Nondestructive Testing, June 1–5, 1970, Hannover, Germany, Vol. B, Dortmund, Germany, March 1970.

[27] E. R. Dobbs and J. D. Llewellyn, "Generation of Ultrasonic Waves Without Using a Transducer," Nondestructive Testing (British) 4(1), 49–56 (1971).

ADVANCED METHODS FOR NONDESTRUCTIVE EXAMINATION OF WELDS

Because of the difficulties anticipated in applying the common methods for nondestructive inspection of welds, it may be desirable, or even necessary, to develop or improve certain advanced methods of nondestructive examination to provide assurance of weld integrity. Among the methods that offer promise are eddy currents and acoustic emission.

Eddy Current Examination

Methods using electromagnetic induction of eddy currents have been used for detecting flaws and measuring electrical conductivity, permeability, thickness, and the space between adjacent components. Application to welds has been sparse, in part because the effective depth of penetration of the eddy currents is usually small (typically less than 0.1 in.), and also because unwanted signals due to variations in coil-to-specimen spacing (lift-off) are difficult to eliminate. The latter would be significantly affected by roughness of the weld bead. Recent advances in eddy-current theory and modeling have led to optimum design of coils and systems that now allow performance significantly superior to any previously attainable.[28–30] Advanced instrumentation has reduced the variations in signal due to lift-off to a negligible quantity.[31–32] Therefore, the eddy-current method deserves new consideration for the examination of several aspects of remotely made welds.

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[28] C. V. Dodd and W. E. Deeds, "Analytical Solutions to Eddy-Current Probe Coil Problems," J. Appl. Phys. 39(6), 2829–2838 (1968).

[29] C. V. Dodd, W. E. Deeds, J. W. Luquire, and W. G. Spoeri, Some Eddy-Current Problems and Their Integral Solutions, ORNL-4384 (April 1969).

[30] C. V. Dodd, W. E. Deeds, J. W. Luquire, and W. G. Spoeri, "Analysis of Eddy-Current Problems with a Time-Sharing Computer," Mater. Evaluation 27(7), 165–168 (1969).

[31] C. V. Dodd, Design and Construction of Eddy-Current Coolant-Channel Spacing Probes, ORNL-3580 (April 1964).

[32] C. V. Dodd, "A Portable Phase-Sensitive Eddy Current Instrument," Mater. Evaluation 26(3), 33–36 (1968).

1. Eddy-current techniques that were developed for the measurement of space between components[33,34] (e.g., coolant channel spacing between nuclear fuel plates) could be useful for measuring the separation of surfaces to be joined by welding.

2. Although improvements have been made to the eddy-current method, it is still limited in its depth of penetration (even though greater depths can now be inspected than before). However, because of the questions concerning the applicability and benefit of liquid penetrant and visual techniques, eddy currents could be considered as a replacement for the detection of surface or near-surface defects.[35]

3. Welds in austenitic stainless steels may crack unless the deposit contains 4 to 9% ferrite. An eddy-current method can measure the amount and distribution of ferrite in the weld (as well as other conditions leading to variations in electrical or magnetic properties) and determine the tendency for crack formation.

The eddy-current technique has been used in areas of high background radiation[36,37] and at the expected temperatures. With proper design of the test system, these environmental conditions do not adversely affect the performance. As discussed under Ultrasonic Examination, the same mechanism used for welding could probably be used as the basic scanner for eddy currents.

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[33] C. V. Dodd and R. W. McClung, "Fuel Element Coolant and Other Spacing Measurements," Trans. Am. Nucl. Soc. **4**(1), 136 (1961).

[34] C. V. Dodd, "Design and Construction of Eddy-Current Coolant-Channel Spacing Probes," Microtecnic (Lausanne) **18**(5), 286–289 and **18**(6), 369–371 (1964).

[35] C. V. Dodd, W. E. Deeds, and W. G. Spoeri, "Optimizing Defect Detection in Eddy-Current Testing," pp. 35–46 in Proceedings of the Sixth International Conference on Nondestructive Testing, June 1–5, 1970, Hannover, Germany, Vol. C, Dortmund, Germany, March 1970.

[36] R. W. McClung and D. A. Douglas, "Nondestructive Testing of Irradiated Materials in the United States," pp. 179–202 in High Activity Hot Laboratories Working Methods, Vol. 1, Proceedings of an International Symposium Organized by ENEA and EURATOM, McGraw-Hill, New York, 1965.

[37] C. V. Dodd, unpublished work, 1971.

Acoustic Emission Techniques

All of the previously discussed techniques are applied to determine the as-fabricated condition of the weld only after the welding operation is completed. Each is an active technique in that energy or matter is applied to the area to be examined (e.g., sonic vibrations, x rays, penetrants), and changes in the energy or matter are interpreted in terms of the specimen. The acoustic emission method is a passive technique in which detectors are used to listen for energy produced within the specimen as it undergoes a change (e.g., stress waves released at crack pop-in or propagation). Extensive development on acoustic emission has been performed recently at several sites.[38–40] Included has been the real-time monitoring of simple weldments both during and after the actual welding process.[41] Preliminary results on purposely cracked welds have shown correlation between acoustic emission and cracking in the welds. Further study is needed to determine its degree of applicability to the materials and configurations being considered. No mechanical scanning would be required for acoustic emission since fixed transducers are sufficient to detect the emitted energy.

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[38] D. L. Parry, "Nondestructive Flaw Evaluation in Nuclear Power Installations," pp. 107–126 in Incipient Failure Diagnosis for Assuring Safety and Availability of Nuclear Power Plants (Conference Proceedings, Gatlinburg, Tennessee, October 30–November 1, 1967), CONF-671011 (January 1968).

[39] A. T. Green and C. E. Hartbower, "Stress-Wave Analysis Techniques for Detection of Incipient Failure," pp. 127–162 in Incipient Failure Diagnosis for Assuring Safety and Availability of Nuclear Power Plants (Conference Proceedings, Gatlinburg, Tennessee, October 30–November 1, 1967), CONF-671011 (January 1968).

[40] H. N. Pedersen and J. C. Spanner, "Detection, Location and Characterization of Flaw Growth in Metals Using Acoustic Emission Methods," pp. 163–164 in Incipient Failure Diagnosis for Assuring Safety and Availability of Nuclear Power Plants (Conference Proceedings, Gatlinburg, Tennessee, October 30–November 1, 1967), CONF-671011 (January 1968).

[41] W. D. Jolly, "The Application of Acoustic Emission to In-Process Inspection of Welds," Mater. Evaluation **28**(6), 135–139, 144 (June 1970).

The transducer materials (not necessarily the design) would probably be similar to those used for active ultrasonic techniques and could tolerate the short-term exposure to the environmental temperature and radiation. The coupling of the transducers to the weldment would be simpler than for the active ultrasonic technique since movement of the transducer during the examination would not be required. If signals of acoustic emission are detected, supplementary examinations would be necessary to pinpoint the location of the flaw.

Other Methods of Examination

In addition to the methods mentioned above on which some experience exists for examination of welds, other new methods of nondestructive examination should be considered, although near-term applicability may not be obvious. Among these are thermal techniques and holography. Development programs should be continuously surveyed, and, if promising possibilities occur, feasibility for application to welds should be studied.

SUMMARY AND RECOMMENDATIONS

Nondestructively inspecting a remotely made weld at high temperatures and in a high radiation background is a difficult problem but one for which worthwhile solutions can be obtained. The anticipated environment includes temperatures (after cooling) in the range 200 to 600°F and radiation levels (ten days after draining) in excess of 10^5 R/hr. Sophisticated mechanical devices will be required to move the inspection probes and devices remotely into position at the weld to be examined, and mechanical scanning capability of the weld area must be provided for several of the methods. Comments on the following methods briefly summarize recommendations to achieve a working system of nondestructive inspection.

1. Closed-circuit television is recommended for visual examination of the weld, before, during, and after fabrication and to provide visual monitoring of the performance of other examination methods. Specially

designed equipment will be required to assure proper performance in the environment.

2. Conventional penetrant techniques are inapplicable. Advanced high-temperature penetrant techniques should be studied and procedures developed if feasibility is demonstrated.

3. X- or gamma-ray radiography is probably impractical because of the extremely high intensities of ambient radiation anticipated. Advanced neutron radiographic techniques should be investigated.

4. Ultrasonic techniques can be performed remotely in the environment. Work is needed to improve the capability of ultrasonics to perform calibrated, meaningful inspections on welds in stainless steel and nickel-base alloys. Techniques must be developed for remotely coupling the sound from the transducer into the specimen. Advanced studies for electromagnetic induction of ultrasound (which would not require coupling) should be made to improve sensitivity.

5. Eddy-current techniques should be developed for measurement of joint fit-up, detection of near-surface flaws, and measurement of variations in the microstructure of the welds as indicated by variations in the electrical and magnetic properties.

6. Acoustic emission techniques should be pursued for real-time monitoring of the weld integrity through detection of the stress waves emitted by the formation or propagation of cracks.

7. Other more sophisticated examination methods should be considered for application to this difficult problem.

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