AN EXPERT SYSTEM FOR POWER PLANT NDE

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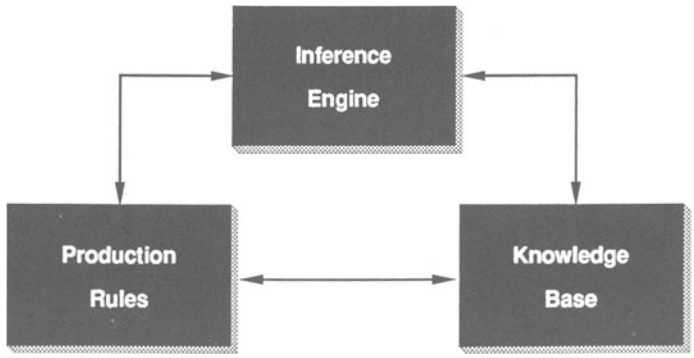
INTRODUCTION

Expert systems are computer software that embody the knowledge of expert(s) in such a form that the system can offer intelligent advice to solve the problem. Knowledge and expertise are principal assets, which, along with capital assets comprised of plant and equipment, make up a modern electric utility. Thus, the capability of expert systems technology to capture the intellectual resources may be beneficial for the industry [1].

Several recent successes of expert systems have been reported in diverse applications such as medicine, oil prospecting, genetics, and national defense. These can be attributed to advances in computer hardware and software technology. Some of the software uses "non-procedural" techniques which allow data and instructions to intermingle. Figure 1 shows elements of an expert system. It consists of a knowledge base that is accumulated from experts familiar with the problem and rules to combine the knowledge. The overall strategy for arriving at a solution is governed by the "inference engine" which systematically matches observed data with known facts in the knowledge base. Expert systems can accumulate vast amounts of information with only a weak connection to the contexts in which the data might be used, similar to human reasoning.

Expert system methods are currently being investigated by EPRI for more than 30 applications ranging from a shutdown analyzer for nuclear reactors to a turbine generator monitoring system.



The Inference Engine Systematically Matches Patterns from the Knowledge Base and with Rules that Combine the Knowledge

Fig. 1. Elements of an Expert System

BWR WELD INSPECTION

Intergranular stress corrosion cracking (IGSCC) of piping in boiling water reactors (BWRs) first received attention in the United States in 1975 when all the BWRs were shut down for inspection of welds in several piping systems. Later in 1982 IGSCC were discovered in larger diameter pipes. Numerous ultrasonic "indications" were observed in the inside surface region near the welded area, and industry took steps to deal with the problems. These steps included augmentation of existing inspection guidelines, more detailed inspection procedures, and control of water chemistry to inhibit initiation of IGSCC.

Ultrasonic inspection of these welds is performed either manually or automatically and is conducted during a plant outage. In manual inspection, the operator "scrubs" the pipe with a contact transducer, usually operating in pulse-echo mode, and observes the response on a calibrated display. In automatic inspection, a transducer manipulator scans the pipe according to programmed instructions as ultrasonic data are acquired and stored during the scan pattern. The data are subsequently imaged and analyzed. Automatic inspection is preferred because modern computing platforms are powerful and economical, and weld data can be well documented and compared between plant outages. In addition, with more emphasis placed on reducing total plant radiation exposure, automatic systems are preferred over manual methods. Manual inspection is performed when weld accessibility is limited and to confirm automatic inspection results.

The cracking occurs on the inside surface, close to the weld in the heat-affected-zone (HAZ). Difficulties in detection of IGSCC by ultrasonic means are primarily due to the close resemblance of IGSCC signals with that of signals from nearby weld joint physical features, such as the weld crown, weld root and counterbores which are ridges machined prior to welding to match unequal pipe wall thicknesses. Figure 2 illustrates the spatial relationship between an IGSCC and other geometrical reflectors in the vicinity. The photograph on top shows a weld metallograph of a field-removed specimen with IGSCC growing very close to the weld root and progressing into the weld. Indication location in the ultrasonic trace (or image) is one of the key

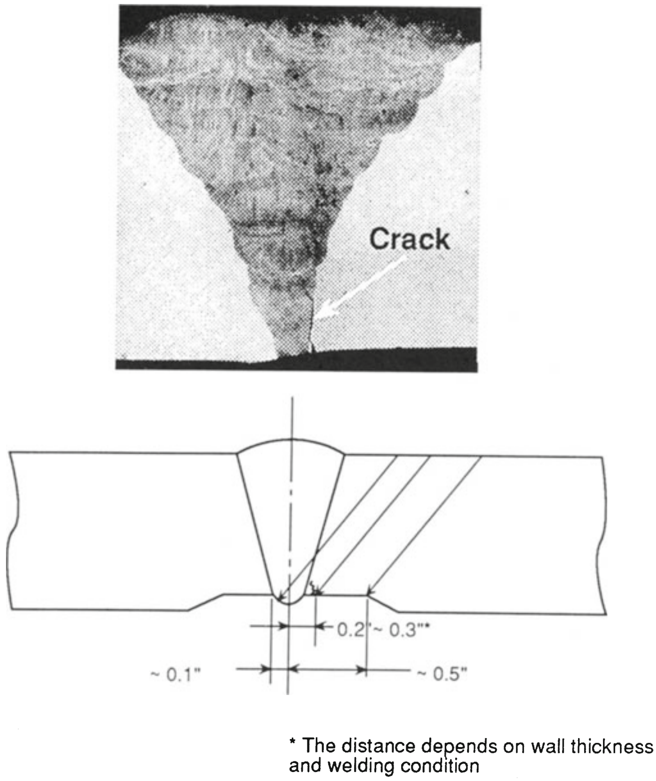


Fig. 2. Sectional view of pipe weld showing typical IGSCC and geometrical reflector locations.

considerations for discriminating IGSCC from geometrical reflectors. As shown in the figure, about 0.1 - 0.5 inch separates typical root, IGSCC, and counterbore indications.

IGSCC DISCRIMINATION

Theoretical studies in the United States and United Kingdom have enabled IGSCC scattering models to predict responses for realistic inspection conditions [3,4]. These have motivated the development of advanced signal processing methods that examine the signal temporal and spatial behavior to provide "features" to discriminate IGSCC from other reflectors [5]. Field trials have been conducted to validate advanced, feature-based approaches for BWR weld examination under realistic plant outage conditions [6].

The EPRI NDE Center undertook the development of an expert system to integrate feature-based approaches with special knowledge used by experienced operators. An expert system shell program operating on a personal computer (PC) was chosen to codify the knowledge. Based on a comprehensive study conducted at the EPRI NDE Center [2] and on consulting sessions with experts in the field, it was determined that accurate discrimination could be performed if ultrasonic image data collected from the specimen could be integrated with radiographic information. To interpret the ultrasonic image, the experts had identified some key parameters that are described as follows.

Signal Amplitude

While signal amplitude is the primary means for detecting indications -- code guidelines require recording and reporting indications whose amplitudes are above established thresholds -- it is a poor discriminator of reflector type. There have been examples where signal amplitudes measured at different inspection angles were used to discriminate reflector types [7]; however, they are not reliable discriminants.

Indication Location

Indication location is one of the key considerations for discriminating IGSCC based on the reflector spatial relationship. Figure 3 is an example B-scan image presentation of a weld specimen similar to that in Figure 2. The B-scan clearly shows the counterbore IGSCC and root image areas. The counterbore image is axially well separated from the crack and root images. In many field welds, however, it is likely that the counterbore could be closer into the weld because of previous weld repair. Indication location may not be a reliable discriminator for such cases.

Metal Path

The distance along the beam axis is another essential parameter used to identify IGSCC and root signals. As shown in the B-scan image in Figure 3, the root signals occur later in time (hence metal path). However, counterbore indications sometimes occur at about the same metal path distance as IGSCC and cannot be separated, especially if the counterbore axial position is close to the weld root.

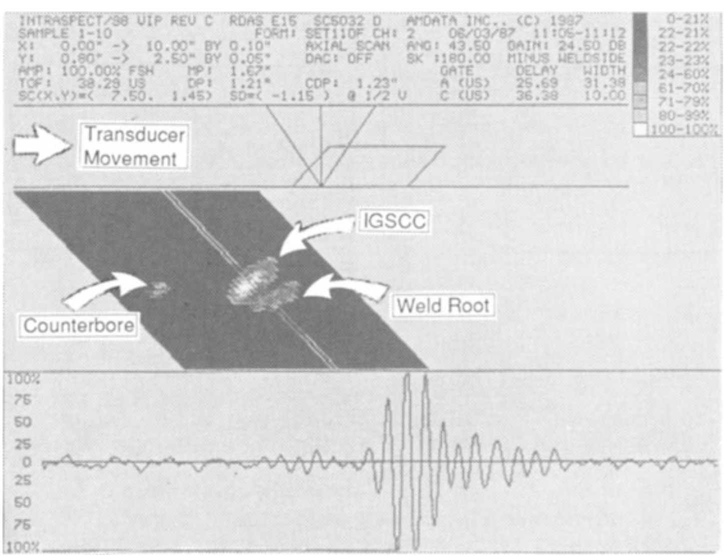


Fig. 3. Example B-scan presentation showing the axial separation between root and crack indications.

Amplitude and Arrival Time Consistency

Since counterbores and roots are machine-made reflectors, they are likely to be consistent in signal amplitude and constant in arrival time as they are scanned circumferentially. IGSCC, on the other hand, have different morphologies, follow grain boundaries, and have facets. Their amplitudes are not expected to be consistent and their arrival times are expected to vary as they are scanned. It was shown that spatial features related to amplitude and time-of-flight consistencies measured as a percentage of a standard were useful in making reliable separation [8].

Signal Echodynamics

The target-motion line, or the echodynamics, can reveal information about reflector type. The target-motion line for IGSCC tends to be straight and strong; for weld roots it is expected to be "twisted" and wide. Small counterbores will have correspondingly short echodynamics; however, longer counterbores could appear similar to IGSCC.

Waveform

The characteristics of individual waveforms have been traditionally used by field operators. These include signal rise-time which tends to be short for IGSCC relative to weld roots. This is most likely due to attenuative effects of the austenitic weld metal through which ultrasound has to travel before it encounters the root. The weld metal preferentially filters out the higher frequencies. Counterbore signals have several variations, depending on the machining quality. Figure 4 illustrates different examples.

Skewing the transducer in a plane parallel to pipe surface produces different responses. Counterbores and weld roots tend to persist for very small skew angles; IGSCC tend to persist for large skew angles because of their facetted structure. However, for automatic systems skewing is difficult because it requires a more complex mechanical scanner.

EXPERT SYSTEM FOR BWR WELD INSPECTION

Overview

The system consists of more than 200 facts and rules in the knowledge base. Accumulation of the knowledge and encoding into the expert system shell was accomplished over a six-month span. The system was implemented on a commercial PC platform capable of controlling an automatic scanner around a subject pipe-to-fitting component weld and digitally acquiring ultrasonic data. The expert logic was encoded in a question-answer format. The operator chooses the most appropriate answer that fits the data to questions posed by the system. The operator could invoke the feature-based imaging options during consultation to display and process B- and C-scans. The different capabilities were integrated so that during a consulting session the operator could switch screens (i.e., operate under a "windows" environment) to observe the data image for assistance. Further, the operator could observe detailed signal behavior by invoking some of the signal processing options programmed into the software package. These include behavior of signal rise-time, fall-time, spectral content, amplitude, and time-of-flight consistency measures, etc.

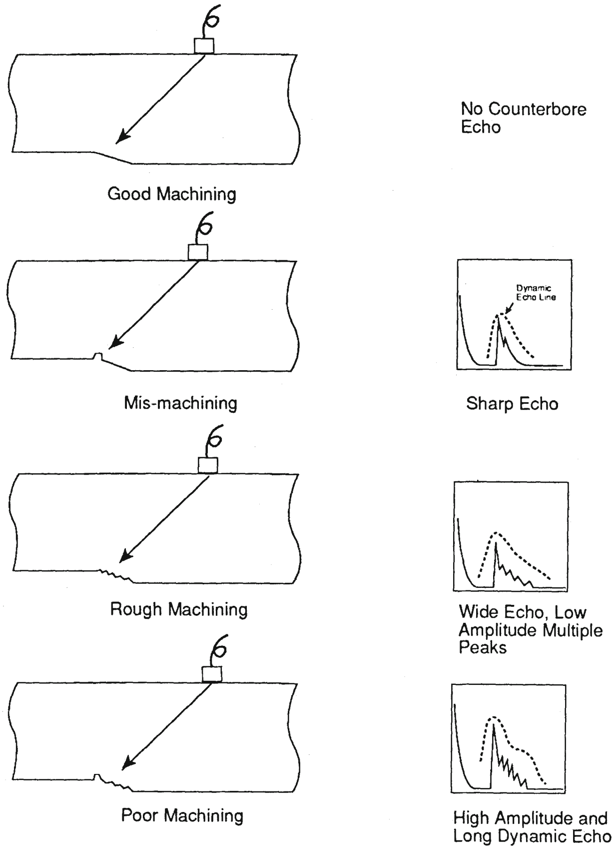


Fig. 4. Examples of various counterbore conditions.

Knowledge Base Development

The different "objects" relevant to IGSCC discrimination were determined to be "location," "signal distribution," "multiple peaks," "echodynamic," "signal rise-time," "echo front," "indication length," and "gate position." The relationship between these objects and reflector type were encoded into facts, and rules to manipulate these facts were derived from expert knowledge. The expert system was structured so that it confidently determined the **possible** reflector type solely from the indication location. It then methodically gathered necessary information to reinforce that decision; if such information were not present in the ultrasonic data it would "gracefully" fail to make a strong decision. Figure 5 illustrates two example rules. Example 1 is a simple rule that makes several interim conclusions on **possible** reflector types based on whether the time-of-flight locations map into the weld region. These conclusions include that the reflector is guessed to be a weld root with certainty 80%, a crack with 40%, etc. Certainty factors pertain to beliefs and vary from +100%, certain belief, to -100%, certain disbelief. Example 1 also concludes that if the time-of-flight location is in the weld, the possibility of the reflector being a counterbore is -75%: counterbores are not machined in the weld. There is not complete disbelief (-100%), however, because the ultrasonic time-of-flight evidence may be faulty due to possible beam

Production Rules

- **A Set of "If *Premise* is True, Then *Conclusion* is . . ."**
  - **— The Premise May Be Hazy and So Can the Conclusion**
- **Example 1**

  If *Time-of-Flight = In-Weld,* Then *Guess-Root cf 80 and Guess-Other cf 60 and Guess-Crack cf 40 and Guess-Counterbore cf -75*

- **Example 2**

  If *Guess-Root and Distribution = Small and Indication = Long and Peak-multiple and Echo-dynamic = Wide,* Then *Signal = Root*

Fig. 5. Example rules used in BWR weld examination expert system

redirection at the weld fusion line. Example 2 considers a more complex rule based on signal distributions and behavior.

The expert decision from ultasonic testing (UT) was combined with available radiographic testing (RT). Rules were developed to emulate experienced field operators in integrating the data. One of the factors considered was the dominance of positive evidence in weld radiographs in influencing the overall decision; for example, the presence of geometrical reflectors in the radiograph could override a reflector decision based on UT. Similarly, if the UT decision was counterbore and the time-of-flight location was in the HAZ and the RT results indicated no reflector, then the combined decision negated the UT counterbore decision. The absence of a reflector in RT but presence of a reflector in UT very much favors an IGSCC decision because IGSCC are seldom manifested in RT. The system is currently being tested on data acquired from field-removed specimens with known reflectors in the EPRI NDE Center inventory.

SUMMARY AND CONCLUSIONS

An expert system for assistance in interpretation of nondestructive evaluation (NDE) data from BWR welds has been developed on a PC system. A PC-based shell program was used to encode rules and assemble facts to discriminate IGSCC in BWR welds from benign, geometrical, weld reflectors. The system has been integrated in a PC platform capable of automatic scanning, digitally acquiring ultrasonic data, and imaging and feature-based processing. The expert system consists of approximately 200 rules and facts acquired from experts in the field. These rules include specific temporal and spatial signal behaviors that are automatically computed by feature-based imaging. The expert system combines ultrasonic and weld radiograph results to arrive at an overall decision on reflector type. The system is undergoing tests at the EPRI NDE Center on field-removed pipe weld samples with service-induced cracking.

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REFERENCES

1. Seminar: Expert Systems Applications in Power Plants, EPRI RP 2923. May 1987.
2. Automated Ultrasonic Pipe Examination and Data Interpretation. Palo Alto, CA: Electric Power Research Institute, NP-5760, April 1988.
3. R.B. Thompson, T.A. Gray, J.D. Achenbach, K.Y. Hu, Ultrasonic Scattering from Intergranular Stress Corrosion Cracks: Derivation and Application of Theory, Palo Alto, CA: Electric Power Research Institute, 1983, EPRI NP-3216.
4. J.M. Coffey, "The Reliability of Ultrasonic Inspection: Developments in Quantitative NDE in the United Kingdom", in Review of Progress in Quantitative Nondestructive Evaluation, Vol. 3, D.O. Thompson and D.E. Chimenti, Eds., New York, Plenum Press, 1984, pp 1-12.
5. R. Shankar, "A PC Imaging System for Reactor NDE", in Nondestructive Evaluation Program: Progress in 1986, Palo Alto, CA: Electric Power Research Institute, 1987, EPRI NP-4902-SR.
6. G.P. Selby, R. Williams, R. Shankar, Feature-Enhanced-Imaging Field Trials: Peach Bottom Unit 3, Palo Alto, CA: Electric Power Research Institute, 1988, EPRI NP-5865.
7. UT Operator Training for the Detection of Intergranular Stress Corrosion Cracking. Charlotte, NC.: EPRI NDE Center, June 1983.
8. R. Shankar, Spatial Features for Flaw Discrimination, Palo Alto, Ca.: Electric Power Research Institute, 1987, EPRI NP-5270-LD.