Chockie Group International, Inc.

Future Directions

for the Inspection of CASS

Summary Report from the Workshop on Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping

CASS Material — An Inspection Challenge

Cast austenitic stainless steel (CASS) is widely used in the primary coolant piping system in pressurized water reactors (PWR) in the United States, Japan, Sweden, France, and other countries. The inspection of cast austenitic stainless steel piping in nuclear plants has been, and continues to be, difficult and challenging. The attributes that make CASS a good candidate for the primary piping system significantly hamper the ability to reliably detect and to accurately locate and size flaws.

The inspection of cast austenitic... continues to be difficult and challenging.

Although there have been no known failures of CASS piping and the service loads on PWR primary coolant piping are relatively low so that even severely aged CASS are considered capable of tolerating major flaws, there is increasing pressure to continue to improve the inspection systems and to ensure the integrity of aging CASS piping systems. Early attempts to inspect cast austenitic piping using conventional technology were not adequate to reliably detect, accurately locate, and size defects. Although, in certain cases there were successful inspections (as noted in the article by Mark Davis on page 10), the inhomogeneous nature of the macrostructure and the unknown characteristics of piping material has been a major impediment to inspections.

In recent years programs in the U.S., Europe, and Japan have made major contributions to improve the ability to inspect CASS piping material. Reasons for investing in these improvement programs include:

- the critical nature of the primary piping system
- concerns with possible thermal aging embrittlement
- concerns about possible, yet unknown failure mechanisms
- unexpected failures that have occurred in other plant material (e.g., the situation at Davis Besse)

Recently, the Chockie Group International took the initiative to bring together interested parties to begin to work in an integrated manner on the future improvements to CASS inspection. On the following pages are summaries of the workshop discussions and proposed future initiatives.

Contents

The Workshop

A one-day workshop was held at the Paradise Point Resort in San Diego, California, on May 13, 2006. The workshop was organized to bring together a select group of interested and involved parties to review the current state-of-the-art in the inspection of CASS piping, and determine what can be done, what are the gaps, and how to fill the gaps. In other words, what are the "*next steps*"?

... to review the current state-of-the-art in the inspection of CASS piping, and determine ... what are the "next steps"?

An International Perspective

Twenty-five individuals from six countries were in attendance. A list of the participants can be found on page 11. Unfortunately due to plant outage commitments and other issues a number of individuals that wished to participate were not able to make it to the workshop.

Two Sessions – Current Status & "Next Steps"

The workshop was organized into two sessions. During the morning session the current status of CASS inspection capabilities, experiences, and general concerns were discussed.

In the afternoon session the participants were divided into two groups to identify possible next steps. One group examined the inspection technologies and where further improvements are required. The second group reviewed the issue of critical flaw size in CASS material.

At the conclusion of the workshop the group prepared a list of recommended "*next step*" activities. This list is reviewed on page 4. On page 5 is a detailed description of the number one priority issue, establishing an allowable flaw size CASS material

Current Issues of Concern

During the morning session the workshop participants discussed issues that they have related to the current state of CASS inspection. In general, their comments can be grouped into the following subject areas:

- material characterization
- accessibility and surface condition
- performance demonstration
- critical flaw size
- detection, sizing, and false calls

Material Characterization

One of the key issues that most participants mentioned was the need to know the macrostructure of the material being inspected. Although inspections in fine-grained CASS have been promising, it is clear that for large coarse-grained material, it is often not possible to discriminate between the metallurgical reflectors such as large continuous grain boundaries or weldment boundaries and cracks.

Several stated that it is very difficult to justify or qualify any inspection technique without knowing the material characteristics. There is a need to determine the macrostructure for both static and centrifugally cast material. The inspection technique or procedures may be different depending on the material.

If information on the macrostructure was available, it would be useful in assessing and ranking the relative inspectibility of the weld

and in determining how effective UT inspections might be at the location.

A number of years ago there was a material characterization research effort sponsored by the United States Nuclear Regulatory Commission. However, the focus of the research work was eventually redirected away from characterization to finding flaws in any CASS material.

The question was raised on how one would go about establishing the characteristics of the material used in the plant piping system. How does one nondestructively determine the macrostructure of the material in the field?

Accessibility & Surface Condition

How does one nondestructively determine the macrostructure of the material in the field?

The surface condition and weld access create problems for inspection. There are certain welds that can be relatively easily assessed from the inside. For example, the nozzle to safe end welds are very close to the vessel and could be accessed from the inside during the 10-year ISI vessel examinations. Several pointed out the accessibility of the RPV and steam generator inlet and outlet nozzles welds. Recent work by PNNL and the Ringhals CASS inspection program have confirmed the benefits from such inspections from the inside using a combination of eddy current and UT techniques. Surface breaking flaws could easily be detected, located, and length sized using eddy current.

However, surface conditions, both on the OD and the ID, can be problematic for an effective inspection – especially with the larger lower frequency transducers.

Performance Demonstration

Another concern is the potential cost and complexity of developing a CASS inspection qualification program along the lines of the performance demonstration initiative. How to simulate cracks in the CASS samples was mentioned as a serious problem. It was also pointed out that depending on the range of CASS material characteristics found at the plants the qualification program could become a very costly venture. Also mentioned was the issue of simulating cracks in the CASS qualification samples.

It was noted that the ASME Codes and Standards require a qualified process. A possible inspection protocol could consist of an automated eddy current examination for surface breaking flaw detection and automated UT with a frequency 1 MHz or lower for detection and sizing in the lower third of the pipe-wall. This CASS inspection strategy could be incorporated in the proposed ASME Code Case ISO 90-03 with the addition of volumetric examination of the accessible nozzle-to safe end weld from the inside of the pipe during the normal 10-year ISI.

Critical Flaw Size

There were a number of comments related to the need to focus on critical flaws. Previous studies have concluded that since the service loads on PWR primary coolant piping are relatively low, even severely aged CASS can tolerate anywhere from about 38% to 50% through-wall circumferential flaws. However, as many pointed out, there is a need to clearly specify what are the allowable flaw sizes for the piping systems components (flaws that can be tolerated within the required safety margins).

Detection, Sizing, and False Calls

Several stated that recent work in Japan, Sweden, and the US has shown that although detection is possible with adequate access, macrostructure properties, and technique, the depth sizing has often not been possible. It was suggested that if one could detect and length size the allowable flaws in CASS material then one could possibly make a calculation of the depth size.

It was proposed that multiple checks and angles are needed to avoid false calls. The PISC "critical" false call requirements may be appropriate for CASS inspection procedures.

Future Directions

The Next Steps

During the morning session the participants had a rather open discussion about the nature and issues of current CASS inspection processes. After lunch the discussions were more focussed on how they would recommend moving forward to improve the CASS inspection capabilities.

At the end of the day the group had identified six "*next step*" activities.

...the need to define the allowable flaw size in CASS material... the number one priority initiative.

The group considered the need to define the allowable flaw size in CASS material to be the number one priority initiative.

Recommended Next Step Activities

- define the allowable flaws
- characterize the plant components
- apply advance (newer) techniques
- develop open procedure qualifications
- evaluate probes and equipment for optimum performance
- develop smaller and more flexible probes

Nathaniel Cofie gave a presentation of a possible flaw tolerance evaluation program to establish an acceptable initial flaw size for inspection. He proposed determining the allowable flaw size (one that can be tolerated in the component and still meet the ASME Section XI safety margins in IWB-3600) for the components by:

- considering all degradation mechanisms
- performing a flaw growth analysis

...interest in a possible international flaw tolerance evaluation program.

There was quite a bit of interests in such a program. Greg Selby from the EPRI NDE Center and Wally Norris from the Nuclear Regulatory Commission expressed interest in a possible international flaw tolerance evaluation program. Kazunobu Sakamoto from the Japanese Nuclear Energy Safety Organization and Olivier Dupond from EDF R&D also indicated that this could be a good international cooperative effort. An overview of his proposed program is presented on page 5.

Nathaniel Cofie and Alan Chockie will work with the various interested organizations to determine the possible level of support and timing/logistics of an international flaw tolerance evaluation program.

The other five "*next step*" activities (that were listed in no particular or prioritized order) are considered necessary to eventually establish qualified CASS inspection processes.

The characterization of the plant piping system components would involve identification of such factors as the physical layout/structure, pedigree of the material, contours, and accessibility.

The application of advance (newer) techniques will need to be driven by the ASME or regulatory body (e.g., NRC). The group indicated that the driving factor for the development of advanced techniques will be safety, not cost saving. Also, it was felt that open procedure qualifications would require blind personnel qualifications.

The probes currently being proposed are too large for effective field implementation. Smaller and more flexible probes need to be developed that provide the performance capabilities of the current generation of large low frequency units.

Although there are various CASS inspection development activities underway in Japan, the US, and Europe, there appears to be a need for more coordinated international CASS development efforts. Hopefully this workshop has laid a foundation for such coordinated programs. CGI will attempt to keep all interested parties informed as to the future programs and directions for the inspection of cast austenitic stainless steel piping. Please contact Alan Chockie (see page 13) concerning future CASS inspection activities and possible follow-on workshop sessions.

Flaw Tolerance Approach for the Inspection of CASS Components

by Nathaniel G. Cofie

Structural Integrity Associates, Inc.

Introduction

The inspection of cast austenitic stainless steel (CASS) components, especially piping welds has been a major challenge for the nuclear power industry. One way to manage the inspectibility of CASS components is through the use of flaw tolerance evaluation to establish an acceptable initial flaw size for inspection. The flowchart in Figure 1 provides a summary of the flaw tolerance evaluation to establish the acceptable inspection flaw size for CASS components. The methodology consists of determining the allowable flaw size for the component considering all possible degradation mechanisms (such as thermal aging), performing a flaw growth analysis to determine possible flaw growth during the inspection interval (or plant life) and using this information to establish a reasonable flaw size that the inspection technology should be capable of detecting.

One way to manage the inspectability of CASS components is through the use of flaw tolerance evaluation to establish an acceptable initial flaw size for inspection.

Allowable Flaw Size

The allowable flaw size is the flaw size that can be tolerated in the component and still meet the ASME Section XI safety margins in IWB-3600. It is generally a combination of flaw length and flaw depth that defines the allowable flaw size. In other words, a long 360^{o} flaw will result in a smaller depth compared with a flaw length which is 10% of circumference. The important

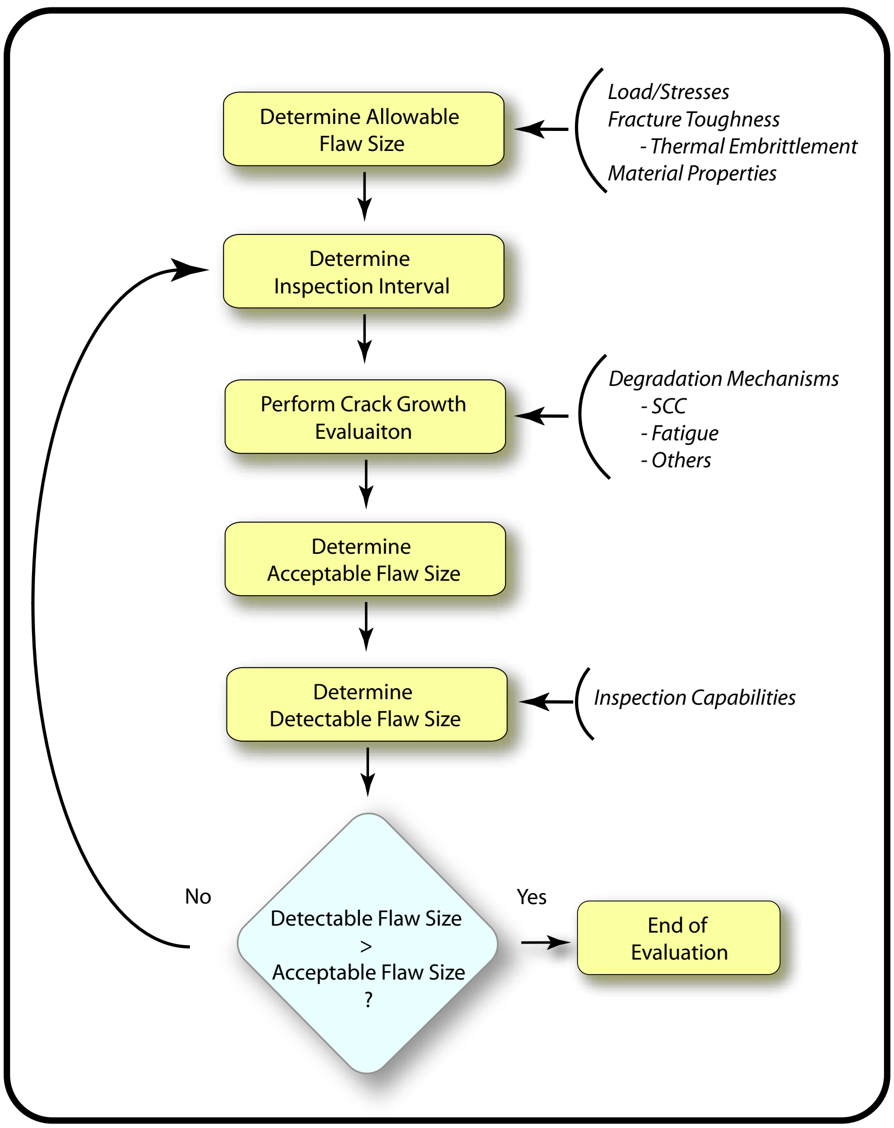


Figure 1. Flaw Tolerance Evaluation of CASS Components

inputs into calculating the allowable flaw size are the operating stresses, the applicable fracture mechanics regime, the material properties, and especially the fracture toughness of the CASS component.

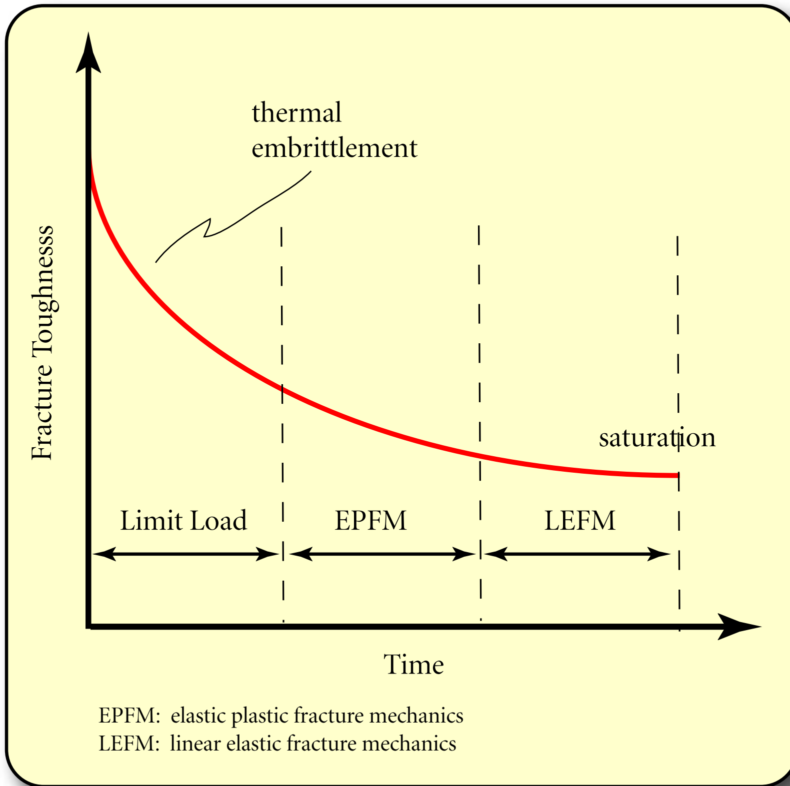


Figure 2. Changes in Fracture Mechanics Regime for CASS Components Resulting from Thermal Aging

Loads/Stresses

The stresses required to calculate the allowable flaw size are typically available in the Stress Report for the component. Loads/stresses are required for all operating conditions defined in ASME Code, Section III (Levels A, B, C and D). The stresses may be due to a combination of primary loads as well as secondary loads. For piping components, the primary bending stress in ASME Code, Section XI correspond to the unconcentrated primary stresses defined in Equation (9) of ASME Code, Section III, Section NB-3650. The secondary (expansion) stress is the unconcentrated stress intensity value for loads defined in Equation (10) of ASME Code, NB-3650.

Fracture Mechanics Regime

The fracture toughness of CASS components have been of concern in fracture mechanics evaluation since it degrades with time as a result of thermal embrittlement (thermal aging). Unaged CASS components typically have adequate toughness comparable to wrought austenitic stainless steel and as such, limit load (net section plastic collapse analysis can be used as the failure criterion for determining the allowable flaw size during the early life of the component.

However, at reactor operating temperatures, the toughness of CASS components degrades such that elastic plastic fracture mechanics (EPFM) principle has to be used for determination of the allowable flaw size since the material has become semi-ductile at some time. With further operating time, the toughness will degrade to a point where the material has become brittle and as such, linear elastic fracture mechanics (LEFM) principles have to be used to determine the allowable flaw size.

Figure 2 illustrates how the fracture mechanics regime changes with time as a result of thermal aging. As illustrated in this figure, after significant exposure to thermal aging, the fracture toughness reaches a saturation value. This saturation value can be used as conservative fracture toughness in the flaw

The acceptable flaw size can be compared with the flaw size that the inspection technology is capable of detecting.

tolerance evaluation. The change in toughness with time has been the subject of research by various organizations, notably Argonne National Labs. The latest state of the art in determining the toughness of CASS components subject to thermal aging is documented in NUREG-4513, Rev. 1 [1].

Material Properties

In addition to the fracture toughness, other material properties required for the determination of the allowable flaw size include the elastic modulus, yield and ultimate strength. These properties also change with thermal aging and should be considered in determining the allowable flaw size.

Safety (Structural) Factors

Safety (structural) factors that need to be considered in determining the allowable flaw size are provided in ASME Code, Section XI. The technical basis for these safety margins are documented in References 2 and 3.

Crack Growth

Having determined the allowable flaw size, the acceptable flaw size during the inspection can only be determined if the flaw growth during the inspection interval is determined. Two flaw growth mechanisms typically considered in Section XI are stress corrosion cracking (SCC) and fatigue. CASS components because of the high delta ferrite in their composition are generally fairly resistant to SCC. Hence, fatigue is the primary mechanism considered for flaw growth analysis. The inputs required to perform the fatigue evaluation consists of stresses from the Stress Report, transients from the Design Specification and a crack growth law which is provided in ASME Section XI for air environment. For water environment, the crack growth law in Reference 3 is typically used.

Acceptable and Detectable Flaw Sizes

Having established the allowable flaw size and the flaw growth during the inspection interval (or for the plant life), the acceptable flaw size during inspection can be established. The acceptable flaw size can then be compared with the flaw size that the inspection technology is capable of detecting (detectable flaw size). If the detectable flaw size is greater than the acceptable flaw size, then the flaw tolerance methodology has been demonstrated which ends the evaluation. On other hand, if the detectable flaw size is less than the acceptable flaw size, then the inspection interval can tightened and then the flaw growth evaluation is repeated and an updated acceptable flaw size is determined.

References

1. O. K. Chopra, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," NUREG/CR-4513, ANL-93/22, Rev. 1

2. Scarth, D.A., Wilkowski, G.M., Cipolla, R.C., Daftuar, S.K. and Kashima, K.K., "Flaw Evaluation Procedures and Acceptance Criteria for Nuclear Piping in ASME Code Section XI," Proceedings of the 2003 ASME Pressure Vessels and Piping Conference, Cleveland, Ohio, July 21-24, PVP-Vol. 463, pages 45-61

3. Section XI Task group for Piping Flaw Evaluation, ASME Code, "Evaluation of Flaws in Austenitic Steel Piping," Journal of Pressure vessel technology, Vol. 108, August 1986, pages 352-366

CASS Inspection Development in Japan

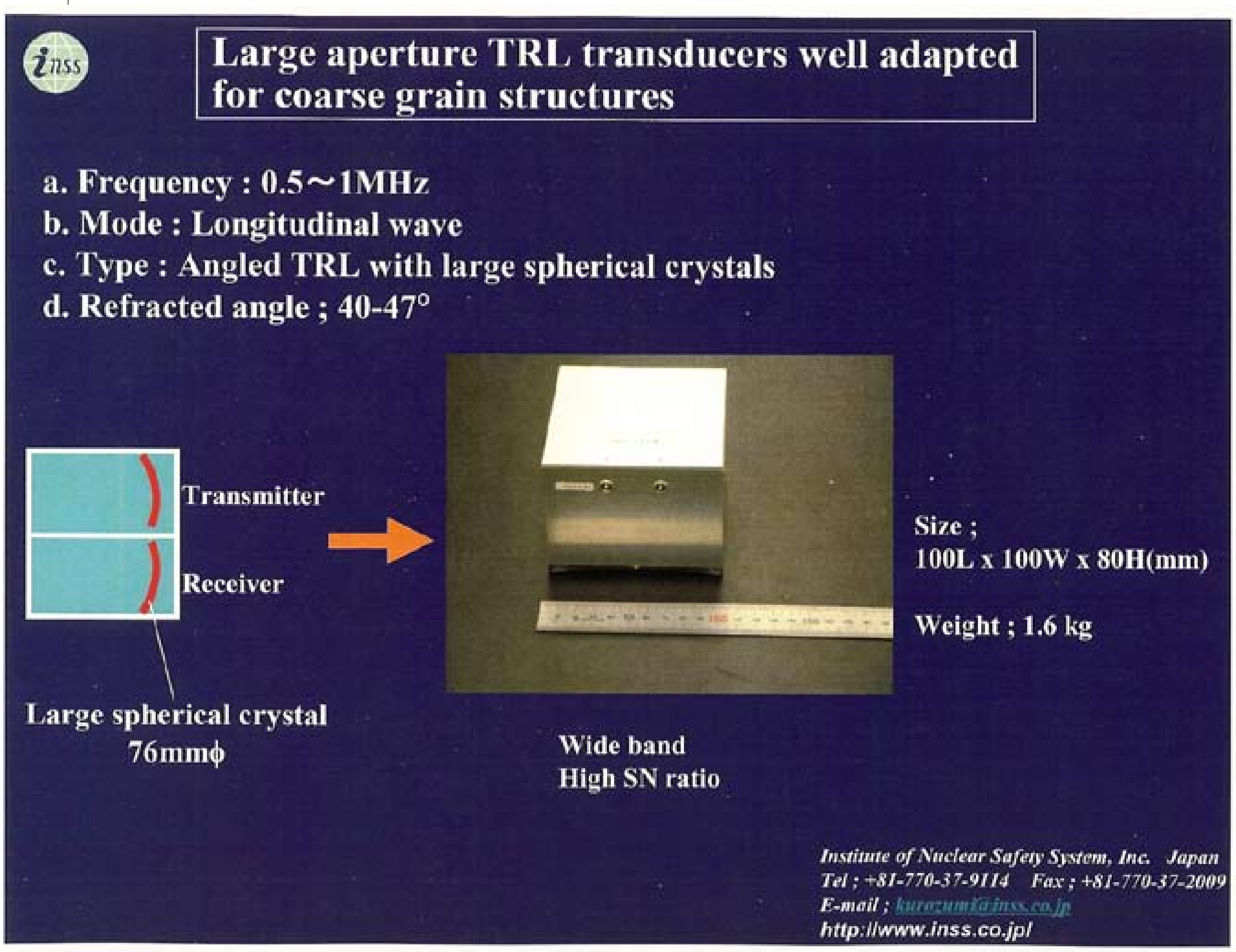
By Dr. Yasuo Kurozumi

Institute of Nuclear System Safety, Inc.

Dr. Kurozumi has been involved for more than ten years in the development of improved UT inspection techniques for CASS material. His work at the Institute of Nuclear Safety Systems, Inc. (INSS) in Japan has led to the development of an automated CASS inspection system using a large-aperture low frequency twin-crystal (TRL) transducer. He prepared the following two slides to provide a brief overview of the latest CASS development activities at INSS.

In the first slide he noted that large aperture TRL transducers have been found to be well adapted for the coarse grain structure of the CASS material in the Japanese PWRs. The current INSS transducer has a slightly shallower focal depth and larger refracted angles than those used in the past. The transducer consists of a large (76 mm diameter) piezoelectric element that is split into two parts. The two parts consist of a separate transmitter and receiver side of the transducer, thereby combining the advantages of a focusing unit and a twin-crystal unit.

The INSS team found that this latest version of the large aperture TRL transducer has improved detection performance for larger crack tips (20 to 50% through wall) in their 70 mm

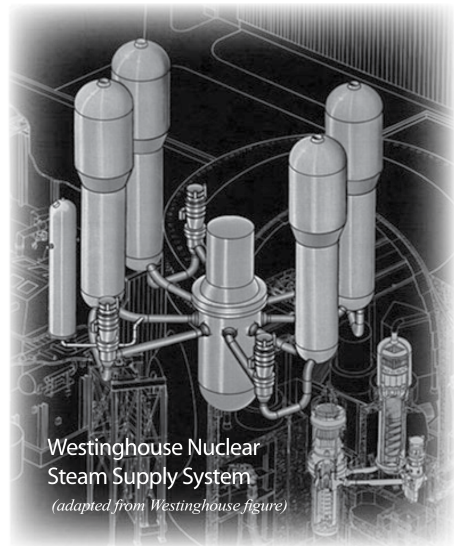


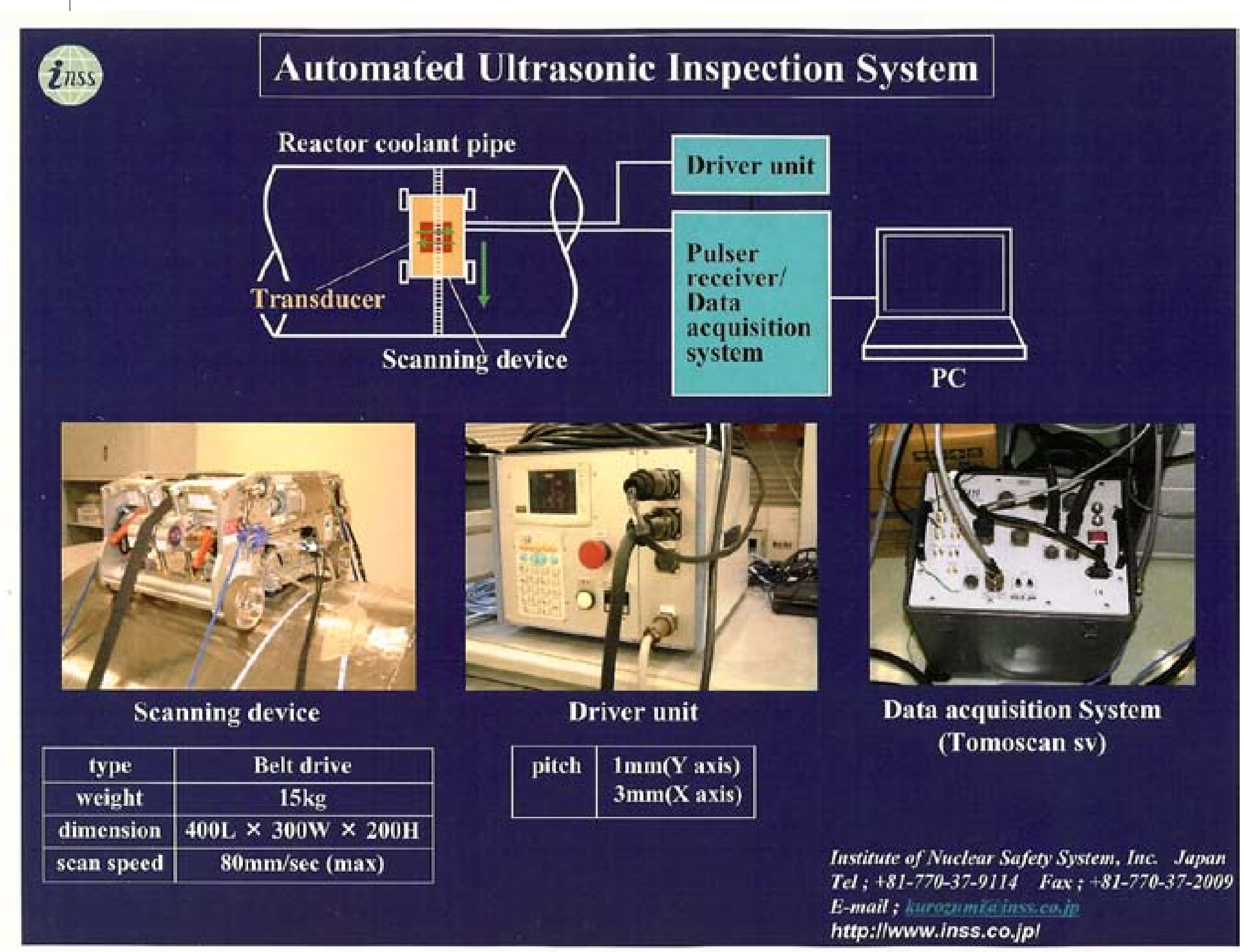
thick CASS test piece. However, they found it was not possible to detect the tip diffraction echo of the 10% through wall fatigue crack. Consequently, they could not depth size this smaller crack. Also, they tended to undersize the 30% through wall fatigue crack.

In the second slide Dr.. Kurozumi addressed the issue of conducting an automated inspection of the CASS pipe. The system shown in the slide represents the INSS fifth generation system.

Many of the practical lessons they have learned over the years in testing on the primary piping at the plants have been incorporated into this latest system. Weight, complexity, and set-up and take-down time are some of the factors that INSS has been addressing.

Many of the practical lessons they have learned over the years in testing on the primary piping at the plants have been incorporated into this latest system.


Westinghouse Nuclear Steam Supply System
(adapted from Westinghouse figure)



> Mark Davis was unfortunately unable to attend the workshop. However he prepared the following write-up to provide a historical perspective on the inspection of CASS material.

Cast Stainless Steel Piping Examination for Plant Vogtle

By Mark Davis

Davis NDE, Inc.

In 1984, the NRC outlined 10 key items that Georgia Power needed to address for the licensing of Plant Vogtle. One item involved Ultrasonic Testing of the cast stainless steel (CASS) material for the Reactor Loop Piping. The NRC stated that a UT technique shall be developed and demonstrated for the CASS material. Prior to this time period, the Westinghouse Refracted 41 degree Refracted L Wave method was primary UT method for conducting Ultrasonic Testing of CASS materials.

... phased array techniques using refracted longitudinal waves offers a much better approach to the CASS materials.

However, the Westinghouse technique could not produce a specific refracted angle due to the water column wedge. Also, the water column technique had very limited capability to detect the ¼ t SDH, or even to detect the end of the calibration block

I designed a calibration block from Vogtle CASS Piping Materials with ¼, ½ and ¾ SDH's and a 10% ID notch:

- The block was sent to Krautkramer in Lewistown, PA
- Two 1 inch diameter, 1 MHZ, highly damped transducers were determined to provide the best results for the CASS 10% ID Notch.
- Curved plexiglas wedges to produce a 45 degree refracted L-waves were designed for each pipe diameter (3 diameters)
- The RL probes were focused for the bottom 1/3 thickness of the material
- A Sonic Mark 1 with a 600 volt pulser was used with the CASS Probe

On the Vogtle Calibration Block, the ¼, ½, ¾ SDHs and the 10% ID Notch were all detectable.

I took the probe, UT instrument and Calibration Block to the NRC's offices in Atlanta. The NRC had 2 CASS samples with known cracks and known depths.

I scanned both of the NRC samples and detected both ID connected cracks with good signal to noise ratio (2/1 SN).

Not only were the cracks detectable, but I sized the cracks to within 10 % of their known depth.

The NRC issued a letter of demonstration for Detection and for Sizing. This method has been used for the last 15 to 20 years. I believe phased array techniques using refracted longitudinal waves offers a much better approach to the CASS materials. Using the power of multiple elements (16 to 128), may offer much more power for penetration, and improved detectibility, resolution and sensitivity.

Mr. Davis was the Corporate NDE Level III for Southern Company at Plant Vogtle in Augusta, Georgia from 1982 to 1985.

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