Advances in Ultrasonic Instrumentation for Core-mapping of Fast Breeder Reactors

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Abstract - Indian Fast Breeder Reactors (FBRs) are sodium-cooled pool type reactors. 500MWe Prototype Fast Breeder Reactor (PFBR) is being commissioned at Kalpakkam, Tamil Nadu. The FBR core has large number of fuel subassemblies (FSAs) which are submerged in hot opaque liquid sodium. Due to high operational temperature more than 500°C, radiation and flow of coolant, FSAs tend to grow, bow or protrude above the core-plenum level. ED, BARC and IGCAR have jointly designed and developed 8-Channel automated ultrasonic instrumentation and transducers for detection of protrusion of in-core FSAs and the system is designated as Under Sodium UltraSonic Scanner (USUSS). Before every Fuel Handling (FH) campaign, USUSS is employed for clearance. These inspections indicate the absence of excessive protrusion of FSAs and full lowering of safety shut-down rods. ED, BARC and IGCAR havealso designed and developed Sweep-Arm scanner for detection of growth & bowing of FSAs in DM water using 4 channel ultrasonic imaging system. Future FBRs of India will have improvised versions of Ultrasonic Instrumentation which will perform core-mapping to locate, detect and quantify growth, bowing and protrusion of FSAs. Grippers are used during FH operation to load/unload a specific FSA through the slots on it. This methodology can be employed to accurately position the gripping mechanism near to slots of FSA. Countries like USA, Japan, France, Lithuania, Belgium and Korea have designed and developed ultrasonic visualization systems for core inspection of FSAs of Liquid Metal FBRs (LMFBRs). The paper elaborates the advances in ultrasonic instrumentation suitable for core-mapping of FBRs carried out by India and other countries.

Keywords- FBR, under sodium,core-mapping, FSAs, high temperature transducer, Sweep-Arm Scanner

1. Introduction

Fast Breeder nuclear Reactor (FBR) is capable of breeding more fissionable fuel than it consumes like most common breeding reaction is the production of Plutonium-239 from non-fissionable Uranium-238. There are two types of fast breeder reactors: Loop type and Pool type. In Loop type reactor, the primary coolant is circulated through primary heat exchangers outside the reactor core. In Pool type reactor, the primary heat exchangers and pumps are immersed in sodium adjacent to the reactor core.

LMFBRs use liquid metal as a coolant which is used as heat transfer fluid from the reactor core to the steam generator. A variety of liquid metal coolants namely mercury, sodium, lead bismuth eutectic have been used worldwide and majority of countries have used liquid sodium as a coolant in FBRs as it has a high thermal conductivity and it causes negligible corrosion of mechanical components. This type of reactor is also called as Sodium cooled Fast Breeder Reactor (SFR). In FBRs, the in-service inspection like core –mapping is necessary to examine the integrity of the in-core FSAs. Since liquid sodium is optically opaque and electrically conductive, ultrasonic imaging technique is only method which is widely used worldwide for imaging the submerged reactor core, core supports, and refueling hardware [1, 6, 7, 15, 18, 24, 31, 35]. When the nuclear reactor is in shutdown condition, the neutron flux is negligible, so only the gamma radiation is effective.

Some of major applications of the ultrasonic instrumentations in FBR are: Identifying in-vessel core FSAs, Determining the orientation of hexagonal core components and other remotely placed equipment, Ascertaining the structural integrity of material and structure during operation, Determining the elevation and lateral profiles of FSAs (Growth and Bowing measurement), Searching of missing components in reactor core [35].

2. Core-Mapping of FBR

In fast breeder reactor, the heat is generated by nuclear fission in the core which consists of large number of FSAs. Each FSAis a hexagonal wrapper tube which contains fuel pins containing fuel pellets. In PFBR, there are 181 FSAs and each FSA consists of 217 fuel pins. During normal operation of the reactor, the temperature of liquid sodium is more than 550°C. Deformation of the FSAs can occur due to void swelling, thermal creep and irradiation creep. Differential swelling can occur because of gradients in flux and temperature at different locations in the core due to the inter-assembly heat transfer. At the periphery, subassemblies can tend to bow outwards as a consequence of neutron flux gradient. Higher the flux gradient, higher will be the bowing. Due to high temperature and flow of liquid sodium, there is also possibility of growth of FSAs. Since positive reactivity is added when the core assemblies displace radially inward, the phenomena of bowing has importance for safety and control point of view. So does the Core-mapping, which is required to locate, identify and measure the growth and bowing of FSAs. For inspection and viewing, system based on ultrasonics is generally deployed during the shutdown campaign at 180°C.The system software must have a provision to compare current data with the reference/base-line data of the FBR core.

3. Transducer

There are two types of ultrasonic transducers (Fig. 1(a))which are employed for in-situ inspection of components of FBRs:(1) Immersible and (2) Waveguide based. Immersion type transducers are immersed in liquid sodium for FBRs and placed nearer to the object under inspection and provides high resolution image. Waveguide based transducer keeps the ultrasonic transducer at room temperature i.e. outside the reactor vessel with the help of a waveguide.

The selection of piezoelement material is mainly based on three important parameters: Higher Curie temperature (T_c) (Suitable for shutdown operation of FBRs), Higher Acoustic coupling factor (d_{33}) and low damping coefficient. Generally, Lead- Zirconate-Titanate (PZT) [7, 22], Bismuth Titanate [19, 28], Lead Metaniobate [13, 19, 29] and Lithium Niobate [2, 7, 10, 13, 22, 35] are suitable materials for such harsh environment. PZT has been tested in liquid sodium environment at 180 °C [33], 220 °C [18] and 280 °C temperature [10]. Its lower Curie temperature restricts its use for higher than 300 °C. Bismuth titanate is most suitable material at elevated temperature as it has high Curie temperature and it has only 4% decrease in the transfer coefficient at 22.7 MGy radiation dose [28]. At atmospheric oxygen partial, pressures with 1000 °C, there is no any significant effect on the efficiency of ultrasonic transduction of $YCa_4O(BO_3)_3$, $LiNbO_3$, and AlN. YCOB is more stable than $LiNbO_3$ and YCOB is capable of efficient ultrasonic transduction up to1000°C [25].

The surface finish of front face plate or diaphragm plays a major role for effective sodium wetting.Wetting time depends on amount of oxygen dissolved in sodium and front faceplate layer [6, 24]. The acoustic coupling material deteriorates due to the formation of the oxide layer on the front face of the transducer casing [8]. Diamond like carbon (DLC) coating and optical polishing have provided reliable wetting performance [2, 28]. It has been observed that gold coating immediately dissolves in sodium [6] and nickel alloy [22, 29, 33], Alloy 52 [5], Alloy 200 [5] provide good sodium wetting. Recently nickel coating layer was micro-polished to obtain average surface finish less than 0.02 µm on plate waveguide for improvement of sodium wetting [14]. For initial wetting in Pb/Bi eutectic alloy, the lens of the transducer was soldered by the $SN_{60}PB_{40}$ solder (Fig. 1(l)). However, the long term wetting with liquid metal could not be achieved by this solder [8].

The bonding material used between crystal and diaphragm should have sufficient ductility to minimize stresses at the crystal to diaphragm interface [7].Now a days, diffusion bonding technique is adopted for better joints of materials which have a different thermal coefficient of expansion and also suitable for thermal shock environment. The gold to gold bonding is suitable pair for diffusion bonding for bismuth titanate element at 400 °C [20]. Low temperature silver solder is a chemically stable, radiation-resistant bonding material to achieve mechanical coupling between the piezo element and faceplate [5].

The housing materials used in harsh environment are: stainless steel (used in liquid sodium at 300 °C [35] and 260 °C [13]), nickel (used in liquid sodium at 200°C [32] and 250°C [29]), stainless steel AISI 316 (used in liquid Pb/Bi alloy at 160°C-460°C) [20], AISI 304L used in TUHST transducer andAISI 316L [2].

Mostly, triaxial "Mineral Insulated cables" (MI cables) have been used for under-sodium viewing in a harsh environment in nuclear reactor [7, 35]. The detailed construction of cable has been given by [23].

4. Designs Methods of Different Ultrasonic Imagers/Viewing systems

For FBRs, the main requirement for the design of imaging system issufficient space availability in reactor core vessel for maneuvering ultrasonic viewing assembly which provides adequate resolution ofultrasonic image. The design of ultrasonic imager depends on the deployment of the transducer assembly similar to PFR, UK which had a cylinder of 10m long and 250 mm diameter for insertion of the inspection assembly [22] and FBTR, India which has an "experimental canal" of diameter 104 mm in the reactor vessel [33].

4.1 Sweep-Arm Scanner with Single and Multi-Element Transducers

Due to deployment complexity and limited space available in reactor core, the sweep-arm based system is used to move the transducer assembly in both circular and lateral direction in order to scan required inspection area of the core. It improves the coverage of inspection area in the core and reduces scanning time compared to the conventional method. PNNL, USA had designed and developed the ultrasonic azimuthal-scanner with linear array of 8 focused ultrasonic transducers (Fig. 1(g)) for Fast Flux Test Facility (FFTF), a prototype liquid metal cooled fast reactor [5, 24].

India has developed and deployed the ultrasonic viewer to scan the space below the core cover plate mechanism (CCPM) of the reactor to image the CCPM and demonstrated its horizontal (side) viewing capability in liquid sodium of the FBTR core. The viewer consists of a 10 m long and 33 mm diameter SS tube (Spinner tube) inside 90 mm diameter guide tube. Ultrasonic transducer has been placed at bottom of the tube with active face looking side wards. The motion of transducer assembly and spinner tube is controlled by the motor drive panel. The linear or rotational increment distance of this sweep-arm viewer was 1-mm with clockwise or counter clock-wise angular rotationstep size of 0.9° over an angle of 72° [33].

BARC and IGCAR have jointly designed, developedand deployed an automated sweep-arm scanner suitable for core-mapping of top heads of FSAs of PFBR. It was used for detection of simulated growth and bowing of FSAs in DM water. A laboratory grade prototype mechanism has been designed; fabricated and deployed for automated two axes X-θ Sweep Arm Scanner for under water C-scan imaging of FSAs for a core diameter of 1170 mm. The sweep-arm has length of 300mm with four PZT downward lookingultrasonic transducers, mounted linearly with 90mm pitch such that arm can scan the radial distance of 585mm as depicted in Fig. 1(j). This scanner provides circular resolution of 1° and spatial linear resolution of 1mm in lateral direction [27]. Previously the same group has developed automated USUSS (Fig. 1(h)) to detect the growth and protrusion of FSAs in PFBR, immersed in liquid sodium at 180°C when reactor is shut down. Before every FH operation, it is necessary to check the acoustic health of the immersible ultrasonic transducers. For that, BARC has designed and developed a Non-Contact Ultrasonic Inspection System (NCUIS) (Fig. 1(k)) using four air-coupled ultrasonic transducers in T-R mode [26]. The Ultrasonic imaging of the immersible reactor components namely Control and Safety Rod Drive Mechanism (CSRDM)/ Diverse Safety Rod Drive Mechanism (DSRDM)/ Control and Safety Rods (CSR) was carried out successfully in water by scanning the above core plenum by deploying the USUSS.

UK Atomic Energy Authority (UKAEA) and National Nuclear Corporation (NCC), UK have worked jointly for in-service operation in reactor core. They used 8 downward facing and 4 side mounted transducer in ultrasonic viewer assembly with frequency of 5MHz as shown in Fig. 1(e). The viewer can rotate around its own axis such that transducer can be swept over an annular region of the reactor core. The height precision of viewer is 0.25 mm [4, 22].

4.2 Conventional Linear Array and Orthogonal Linear Array

PNNL, USA has designed and developed the linear phased array system for under sodium imaging in sodium cooled fast reactor at 260 °C. The prototype transducer array assembly was designed with 12/24 transducers (Fig. 1(m)) of 2MHz rectangular Lead meta-niobate piezoelectric (K-81) elements spaced at λ/2 distance (wavelength in sodium). Scan angle of the focused ultrasonic beam was ±30 degrees and spatial resolution was ≤ 1mm. They have also developed a brush-type linear ultrasonic waveguide transducer (UWT) array [5, 11].

France has developed an ultrasonic orthogonal array system "IMARSOD" for in-service inspection and repair technique (ISI&R) for French LMFR. Earlier they have developed the "VISUS"-non-imaging ultrasonic system to detect and locate possible obstacles during operation in Phenix reactor as depicted in Fig. 1(c). The IMARSOD system has two orthogonal 128 elements linear arrays, one transmitting and the other receiving as shown in Fig. 1(b). They have validated this system in water and its liquid sodium test data is not available [3].

4.3 Circular Array based Parabolic Transducers

This imaging system has been developed in Germany [13, 39]. They have used 8 receiving transducers with focal lenses called "multihead" fitted circularly around the central focused transmitter-receiver sensor as shown in Fig. 1(f). These were arranged such that longitudinal axis of all transducers fall in the same spatial point. The viewer used arm based handling devices for imaging. The lateral and axial resolution capability of viewer is 0.5 mm and 1.0 mm respectively. Time required for one square meter imaging area was 3 to 6 hours with frequency 4 MHz in liquid sodium at 250°C temperature.

4.4 Matrix based 2-D Array Transducer Elements

The 2-D matrix array based imaging system has been developed and tested by the Toshiba Corporation and Japan Atomic Power Corporation for their FBR. The array imager has 36×36 (1296) piezo elements (Fig. 1(d)) of PZT material (5 MHz) with 5 mm pitch. Each square piezo element has size 2.5 mm×2.5 mm. For data processing they used cross correlation method and SAFT (Synthetic Aperture Focusing Technique) to synthesize 3D ultrasonic images. They tested imagers in liquid sodium environment at 200 °C. The captured image results stated that imagers have circumferential resolution 2.0 mm and axial resolution 0.5 mm in liquid sodium [18].

4.5 Waveguide based imaging

The main purpose of waveguide is to isolate the sensing transducer from the high temperature and radiation environment. It enhances the transducer performance and increases detection of sensitivity by using the piezo element such as PZT ceramics. Since A-scan results of the waveguide show the multiple reflections of acoustic waves inside the waveguide, the measurement of the results become more complex. These multiple reflections are called "spurious echoes" in pulse echo mode imaging and they are produced due to dispersion, mode conversion, wave reverberation, diffraction within waveguide of finite diameter and scattering echoes from random grains or voids in the rod materials. They cause poor SNR and reduce detection sensitivity.

Nuclear Engineering Division, ANL, USA has compared the four designs of same length waveguides such as smooth rod waveguide, threaded rod waveguide, bundle rod waveguide and spiral-sheet rod waveguide. They stated that smooth rod can transfer more energy into liquid sodium and has less attenuation compared to all but it has a largest time of span for mode conversion which would decrease the signal quality and resolution. Spiral sheet waveguide has smallest time of span and high SNR [30, 37]. Based on tested results they have designed and developed 12” “Prototype Waveguide” which was combination of both bundled-rod (35% thin rods) and spiraled-sheet (65% shim stock)design with gold plated focus lens (focal length 1” in air) as shown in Fig. 1(p). They tested it in liquid sodium at 343 °C and the estimated attenuation was 1.6 dB/m. C-scan images show that prototype waveguide can detect defects with 1 mm width and 0.5 mm depth in molten sodium [37]. Joo*et al.* [9] has developed a wave guide which was made from a SS foil with a thickness of 0.1 mm and that was wrapped axially around a capillary tube with 4 MHz ultrasonic frequency. It was used for measurements of velocity of medium with temperature 600-800 °C by the Ultrasound Doppler Velocimetry (UDV) method.

Atomic Energy Research Establishment (AERE), UK has proposed a new waveguide technique for generating and receiving the narrow ultrasonic A0 lamb wave for the fast reactor. They tested 10 m “plate” type waveguide (Fig. 1(q)) in water and obtained good SNR at low frequency (2 MHz) [3]. They also tested 2 m long strip waveguide in water at ambient temperature and in liquid sodium at 400 °C [12].

The Fast Reactor Development, Korea Atomic Energy Research Institute has designed and developed a 10 m plate-type ultrasonic waveguide sensor module (Fig. 1(i)). In the plate type waveguide sensor A0 leaky Lamb wave which is produced by liquid wedge is used for single mode generation in low frequency range. The C-scan imaging in under water experiment was carried out and resulted in resolution of 2 mm [16]. The prototype waveguide was also tested in liquid sodium at 200 °C using XYZ scanner (Fig. 1(n)) to obtain C-scan image. In order to obtain effective radiation of the leaky longitudinal wave into liquid sodium, thin beryllium layer was coated on the inner surface of waveguide [17]. The C-Scan under sodium experiment was concluded that the prototype waveguide has obtained SNR of over 10 dB and resolution of approximately 1 mm into sodium [14]. Kim *et al*. [21] have proposed a “diffusion” bonding technique to coat thin beryllium and nickel layers and the obtained SNR was almost 16 dB with 0.5 mm resolution in 200 °C liquid sodium.

Ultrasound Institute of Kaunas University of Technology, Lithuania and SCK-CEN, Belgium has developed a buffer rod waveguide sensor for R&D experiments in Pb/Bi eutectic at 160-460 °C. For measurements, they have used 50-mm steel buffer rod and the titanium reflector. However, the buffer rod sensor is not suitable for imaging purposes as the pulse response does not consist of a single short pulse [20].

4.6 In-Situ “Bowing” Measurement of FSAs and Fuel Identification System

Currently, ultrasonic scanner system for PFBR uses 4 side-view and4 downward viewing transducers for detection of lateral and vertical displacement of FSAs respectively. Swaminathan K. *et al*. [32] have proposed two methods: (1) Circle-Fitting method and (2) Data-based method for in-situ bowing measurements of FSAs in PFBR. Authors have tested and simulated these two methods in water using immersible transducers. Later they proposed a new method based on “Hough transform” using sparsely scanned ultrasonic image for determining the center of the circular top surface of a mock FSA head in under water testing [34].

MYRRHA, a Belgium fast research rector which is cooled by lead bismuth eutectic (LBE) use ultrasonic fuel identification system to encode an identifier on the flow nozzle of a fuel assembly (Fig. 1(o)) by means of series of notches of varying depths[8, 36].

5. Conclusion

Core-mapping of FBRs/SFRs has remained a vital shutdown activity and also a technological challenge to the system designers. To carry out such important in-service inspection, advancements in the field of semiconductor technology, computer, software, automation and controls have majorly contributed in providing accurate and repeatable results. Worldwide, scientists/engineers have tried to inspect core of FBRs/SFRs for measurements of growth/bowing of FSAs due to harsh environment in reactor core.

For perfect wetting of the transducer assembly with liquid sodium, materials like polished nickel, nickel alloy, thin gold coating and diamond like carbon (DLC) coating have been tried. However, the solution of wetting is still not solved perfectly. For high temperature applications PZT, Lithium Niobate, BismuthTitanate, AIN, YCOB and Lead metaniobate have been used. It is claimed that YCOB crystal is capable up to 1000 °C. Currently the diffusion bonding with gold-to-gold and silver-to-silver bonding are widely used for harsh environments. For housing of transducer, SS and Ni are widely used as they can maintain good leak tightness and wetting in high temperature. Mineral insulated (MI) cables have been obvious solution for transmission of signal to/from the transducers. The different ultrasonic imaging methods have been reviewed and it is concluded that there is an ample scope to expand under sodium high speed (or real time) imaging technique which can work for high temperature imaging of in-core FSA of FBRs/SFRs. The matrix 2-D array based ultrasonic imaging system which is only used by Karasawa *et al.*[18] and achieved good image resolutions. A prototype (combination of bundle rod and spiraled-sheet design) and plate type waveguides can provide good resolution and SNR in liquid sodium environment. Extendable Sweep-arm technique which can view the in-core FSAs for detection and location of growth and bowing have been attempted by UK, USA and BARC-IGCAR ofIndia.

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7. References

[1] A.N. Sinclair, A.M. Chertov, "Radiation endurance of piezoelectric ultrasonic transducers – A review," *Ultrasonics*, vol. 57, no., pp. 1-10, March 2015.

[2] Baba, Atsushi, Clifford T. Searfass, and Bernhard R. Tittmann, "High temperature ultrasonic transducer up to 1000 C using lithium niobate single crystal," *Applied Physics Letters*, vol. 97, no. 23, pp. 232901, 2010.

[3] Baqué, François, et al.,"Development of Tools, Instrumentation and Codes for Improving Periodic Examination and Repair of SFRs," *Science and Technology of Nuclear Installations 2012*, 2012.

[4] Barrett, L.M.; Mcknight, J.A.; Fothergill, J.R.; "Ultrasonic viewing in fast reactors," *Phys. Technol.*, vol. 15, no. 6, pp. 308–314, 1984.

[5] Bond, Leonard J., et al., "Materials issues in high temperature ultrasonic transducers for under-sodium viewing," *Review of Progress in Quantitative Nondestructive Evaluation Volume 31, AIP Publishing*, vol. 1430, no. 1. 2012.

[6] Day, C.K.; Smith, R.W., "Under-Sodium Viewing," *1973 Ultrasonics Symposium*, vol., no., pp.191-194, 1973.

[7] Denslow, Kayte M., Shuh-Haw Sheen, and Paul Raptis, "Under-Sodium viewing: a review of ultrasonic imaging technology for liquid metal fast reactors," *Pacific Northwest National Laboratory*, 2009.

[8] Dierckx, M.; Van Dyck, D.; Vermeeren, L.; Bogaerts, W., "Research Towards Ultrasonic Systems to Assist In-Vessel Manipulations in Liquid Metal Cooled Reactors," *Nuclear Science, IEEE Transactions on* , vol. 61, no. 4, pp. 2024-2033, Aug. 2014.

[9] Eckert, S., G. Gerbeth, and V. I. Melnikov, "Velocity measurements at high temperatures by ultrasound Doppler velocimetry using an acoustic wave guide," *Experiments in fluids*, vol. 35, no. 5, pp. 381-388, 2003.

[10] Fothergill, J. R., P. Willis, and S. Waywell, "Development of high-temperature ultrasonic transducers for under-sodium viewing applications," *British Journal of Non-Destructive Testing*, vol. 31, no. 5, pp. 259-264, 1989.

[11] Griffin, J.W.; Posakony, G.J.; Harris, R.V.; Baldwin, D.L.; Jones, A.M.; Bond, L.J., "High temperature ultrasonic transducers for in-service inspection of liquid metal fast reactors," *Ultrasonics Symposium (IUS), 2011 IEEE International* , vol., no., pp. 1924-1927, 18-21 Oct. 2011.

[12] Halverson, S. L., et al., "Radiation exposure of a lithium niobate crystal at high temperatures," *Nuclear Science, IEEE Transactions on*, vol. 17, no. 6, pp. 335-340, 1970.

[13] Hans, R., E. Kranz, and H. Weiss, "Under sodium viewing-a method to identify objects in an opaque medium," *Liquid metal engineering and technology. Proceedings of the 3rd international conference, Oxford*, vol. 3, 9-13 April 1984.

[14] Hoe-Woong Kim, Young-Sang Joo, Chang-Gyu Park, Jong-Bum Kim, Jin-Ho Bae, "Ultrasonic Imaging in Hot Liquid Sodium Using a Plate-Type Ultrasonic Waveguide Sensor," *Journal of Nondestructive Evaluation*, vol. 33, no. 4, pp. 676-683, December 2014.

[15] Jasiūnienė, Elena, "Ultrasonic imaging techniques for non-destructive testing of nuclear reactors, cooled by liquid metals: review," *Ultragarsas (Ultrasound)*, vol. 62, pp. 39-43, 2007.

[16] Joo, Young-Sang, et al., "Development of ultrasonic waveguide sensor for under-sodium inspection in a sodium-cooled fast reactor," *NDT & E International*, vol. 44, no. 2, pp. 239-246, 2011.

[17] Joo, Young-Sang, et al., "Effects of beryllium coating layer on performance of the ultrasonic waveguide sensor," *Ultrasonics*, vol. 53, no. 2, 387-395, 2013.

[18] Karasawa, Hirokazu, et al., "Development of under-sodium three-dimensional visual inspection technique using matrix-arrayed ultrasonic transducer," *Journal of nuclear science and technology*, vol. 37, no. 9, pp. 769-779, 2000.

[19] Kažys, R., AlgirdasVoleišis, BirutėVoleišienė., "High temperature ultrasonic transducers: review," *Ultragarsas (Ultrasound)*, vol. 63, no. 2, pp. 7-17, 2008.

[20] Kazys, R.; Voleisis, A.; Sliteris, R.; Voleisiene, B.; Mazeika, L.; Kupschus, P.H.; Abderrahim, H.A., "Development of Ultrasonic Sensors for Operation in a Heavy Liquid Metal," *Sensors Journal, IEEE* , vol. 6, no. 5, pp. 1134-1143, Oct. 2006.

[21] Kim, Sang-Hwal, Chang-Gyu Park, and Young-Sang Joo, "Performance Test of a Diffusion Bonded Waveguide Sensor for Under-Sodium Visualization," *Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea*, 29-30 May 2014.

[22] McKnight, J. A., E. J. Burton, and P. Fenemore, "Recent advances in the technology of under-sodium inspection in LMFBRs." *Liquid metal engineering and technology. Proceedings of the 3rd international conference, Oxford*, vol. 3, 9-13 April 1984.

[23] Mineral Insulated Cable. [Online].Available: http://www.micable.com/

[24] Ord, R. N., and R. W. Smith, "*Development of an under-sodium ultrasonic scanner for in-reactor surveillance*," Hanford Engineering Development Lab., Richland, Wash, USA, 1972.

[25] Parks, D.A.; Shujun Zhang; Tittmann, B.R., "High-temperature (>500 °C) ultrasonic transducers: an experimental comparison among three candidate piezoelectric materials," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on* , vol. 60, no. 5, pp. 1010-1015, May 2013.

[26] Patankar, V. H., et al., "Design and Development of Automated Ultrasonic Instrumentation for Detection of Growth and Bowing of Under-Sodium Fuel Subassemblies of FBR," *Proceedings of NDE 2009 Seminar, Trichy, TN*, 10-12 Dec. 2009.

[27] Patankar, V. H., et al., "Sweep-arm Scanning Technique for Core-mapping of Fuel Sub-assemblies of Fast Breeder Reactor," *Asia Pacific Conference on Non-Destructive Testing (14th APCNDT)*, Mumbai, 18-22 November, 2013.

[28] R. Kazys, A. Voleisis, R. Sliteris, L. Mazeika, R. Van Nieuwenhove, P. Kupschus, and H. AïtAbderrahim, "High temperature ultrasonic transducers for imaging and measurements in a liquid Pb/Bi eurectic alloy," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 52, no. 4. pp. 525–537, Apr. 2005.

[29] Rajendran, A., et al., "Development of an ultrasonic under-sodium scanner for the fast breeder test reactor," *Trends in NDE science and technology: proceedings of the fourteenth world conference on NDT*, vol. 2, 1996.

[30] Sheen, S. H. et al., "Linear-array ultrasonic waveguide transducer for under sodium viewing," *No. ANL-GENIV-178. Argonne National Laboratory (ANL)*, 2010.

[31] Svet, V. and Dement'ev, D., "Ultrasound Imaging in Nuclear Reactors Cooled by Liquid Metals," *Open Journal of Acoustics*, vol. 5, no. 1, pp. 11, 2015.

[32] Swaminathan, K.; Asokane, C.; Sylvia, J.I.; Kalyanasundaram, P.; Swaminathan, P., "An Ultrasonic Scanning Technique for In-Situ `Bowing' Measurement of Prototype Fast Breeder Reactor Fuel Sub-Assembly," *Nuclear Science, IEEE Transactions on* , vol. 59, no. 1, pp. 174-181, Feb. 2012.

[33] Swaminathan, K.; Rajendran, A.; Elumalai, G., "The development and deployment of an ultrasonic under-sodium viewing system in the fast breeder test reactor," *Nuclear Science, IEEE Transactions on*, vol. 37, no. 5, pp. 1571-1577, Oct 1990.

[34] Swaminathan, K.; Swaminathan, P., "Hough Transform Method for Determining the Fuel Sub-Assembly's In-Situ 'Bow' in Breeder Reactor Using Its Sparsely Scanned Ultrasonic Image," *Nuclear Science, IEEE Transactions on* , vol. 60, no. 4, pp. 3033-3039, Aug. 2013.

[35] Taguchi, Junzo; Uesugi, Nobuo; Miyazawa, Tatsuo; Sato, Keiji; Horikoshi, Shigeru, "An Ultrasonic Viewing System in Liquid Sodium," *Nuclear Science, IEEE Transactions on* , vol. 27, no. 1, pp. 821-825, Feb. 1980.

[36] Van Dyck, D.; Dierckx, M., "An Ultrasonic Fuel Identification System for Liquid Metal Cooled Reactors Resilient Against Multiple Transducer Failures," *Nuclear Science, IEEE Transactions on* , vol. 61, no. 4, pp. 2291-2299, Aug. 2014.

[37] Wang, K., et al. "Development of a Novel Ultrasonic Waveguide Transducer for Under-Sodium Viewing." *Review of Progress in Quantitative Nondestructive Evaluation: Volume 30A; Volume 30B*, AIP Publishing, vol. 1335, no. 1, 2011.

[38] Watkins, R. D., et al., "A proposed method for generating and receiving narrow beams of ultrasound in the fast reactor liquid sodium environment," *Ultrasonics*, vol. 20, no. 1, pp. 7-12, 1982.

[39] Wessels, J., "In service inspection of the reactor block of sodium-cooled fast breeder reactors," *Nuclear engineering and design*, vol. 130, no. 1, pp. 33-42, 1991.

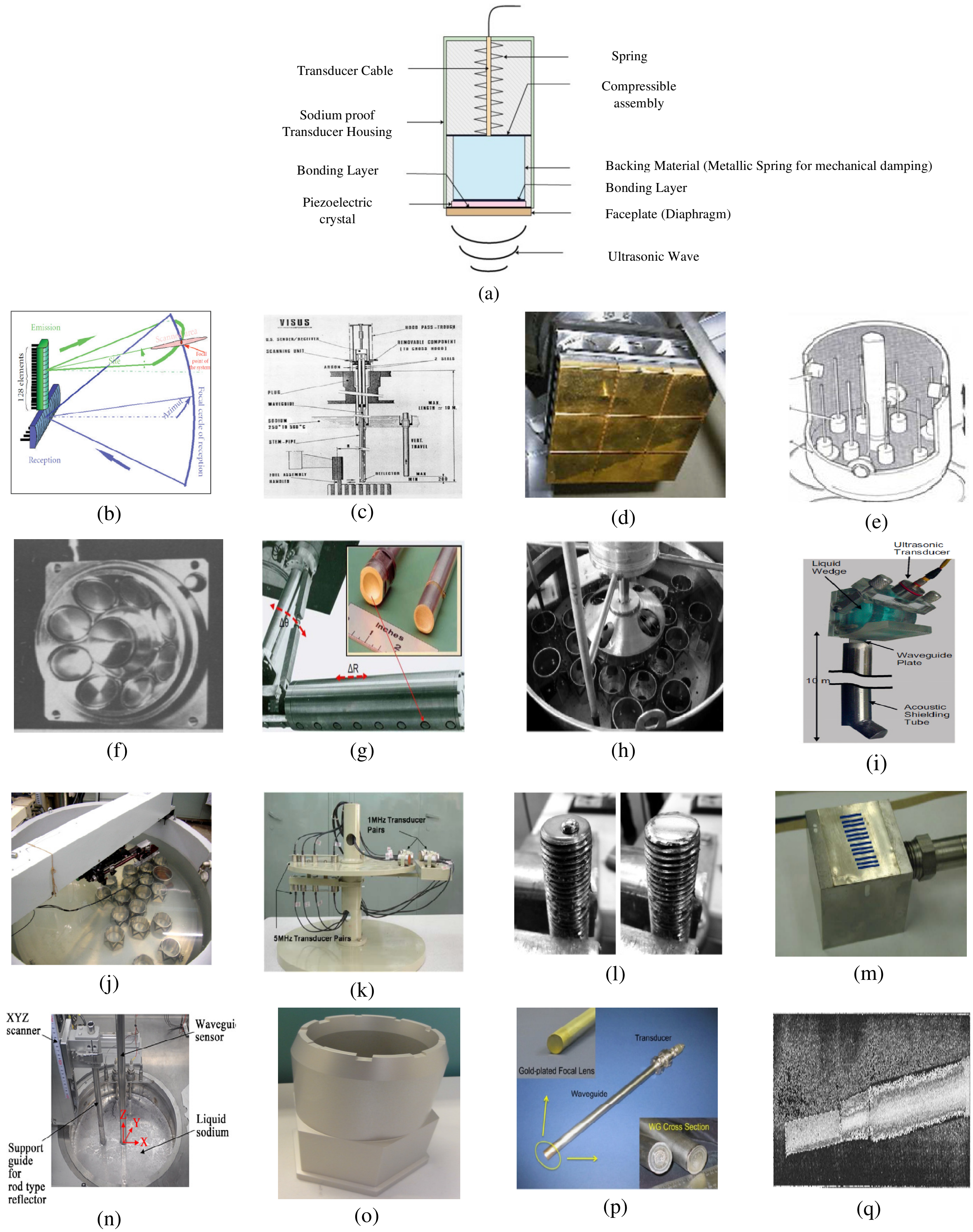

Fig. 1(a) Schematic of Transducer Assembly, (b) “IMARSOD” [3], (c) “VISUS” [3], (d) 2-D matrix of 36×36 transducers [18], (e) Linear array imaging system [22], (f) “multihead” [13], (g) Sweep arm scanner head and its individual piezoelectric transducer elements [5], (h) Transducer holder assembly of USUSS [26], (i) 10 m plate waveguide with liquid wedge, (j) 2-Axes automated sweep arm scanner [27], (k) NCUIS [27], (l) Stainless steel 316L waveguide with molten eutectic $Sn_{60}pb_{40}$ solder, (m) 12-element ultrasonic linear array [11], (n) Waveguide based beam profile measurement experiment setup [14], (o) A fuel assembly bottom mock-up with a different up-down notched identification code [8], (p) Prototype Waveguide, (q) Plate type waveguide [38].