NDE Approaches for Enhanced Performance and Mitigation of Risks in Demanding Technologies

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Plenary Address - 18 WCNDT-2012, Durban, South Africa, 16th April, 2012
Challenges …..

- Increasing demands on clean and competitive energy, water, agriculture and healthcare. (These demands are to be met with ethics and equity)

- Longetivity – old age problems – newer strains of diseases

- Ageing assets and new high performing assets

- Globalisation of economies – increased competitions – to be met with competence, innovations and ethics

- Increased social and work stresses

- Human resources (engineers) to meet the challenges
Directions of Technology

- Technologies performing at frontiers of limits of performance
- Very large structures plants to nano devices
- Design, analysis, virtual reality, health diagnosis, Asset Management
- Innovations in all stages of life cycle of technology (evolutionary, paradigm changes, cascade, …innovation ecosystem)
- Newer materials processes and performance (modelling and simulation, advanced characterization, testing and analysis for extreme conditions)
- Advanced sensors, wireless networks, embedded systems, on-line measurements and their analysis.
Management......

- Simple and Robust management principles and practices

- Paradigm shifts in management concepts
  (fast, diverse, organic vs inorganic growth,...)

- Interdisciplinary decisions: A wide spectrum in cultures of countries, religions, competences, bureaucracies, priorities.

- Ethics, Equity

- Engineering Challenge – Fractured linkages leading to weakness in decisions
Accidents ……

Challenger disaster, Jan 1986

Bhopal gas tragedy Dec. 1984

Concorde disaster – July 2000

Gulf of Mexico Apr. 2010

Fukushima accidents, Mar. 2011

Prediction, Management of black swan, fat tail, low probability but high risk accident scenarios
Analysis......

- Improper Design and Materials (Challenger),
- Inadequate safety and regulatory practices (Bhopal)
- Improper PSI, ISI, TQM (Gulf of Mexico)
- Inadequate defense in depth and lack of organisational decision making (Fukushima)

Common Thread in all the above ....

- Measurements(relevance, adequacy, sensitivity, robustness)
- Inadequate analysis and correlation to performance in steady state and accident scenarios
DNA of Plant longevity with risk mitigations....

- Steady State Performance
- Extended life with robust performance
- Knowledge of Asset
- Probabilistic + Deterministic Risk Analysis
- Review + Feedback
- Minimum Excursions and Outages
- On-line and Periodic in-situ Monitoring using advanced technologies

Measurements + NDE

Plan
Implement
Demonstrate
Measure
Analysis

Improve with Feedback
Infrastructure and Facilities

Multi NDE and Fusion of images and signals

Nurturing relevant Human Resources

Synergy of Expertise and facilities

Basic Physics Materials Science Modelling and Simulation

Sensors and Instrumentation

Challenges in newer Materials – design, development and manufacturing

Enhanced Capability....

NDE Waves....
A Robust BALANCE SHEET IS OUR ACCOUNTABILITY & LEGACY OF NEXT GENERATIONS OF LIFE ON THIS PLANET.
"The country that learns to build breeder reactor would have solved its energy problems for ever"

"The country which first develops a breeder reactor will have a great competitive advantage in Atomic Energy" - India made an early entry to Nuclear Energy

Breeding ratio: "... it obviously must be greater than one".

"The serious objection to these fast chain piles is the removal of heat".

"The coolant for this type of pile would be a bismuth-lead alloy and would flow downward through the pile between the static and rotating rods. The possibility of using liquid sodium in place of bismuth-lead should also be looked into".

[India pursues a vibrant Fast Reactor Program]
FBR PROGRAMME IN INDIA

Credible confidence in fuel cycle

State-of-art concepts

Innovative concepts

Future FBR
- 1000 MWe
- Pool Type
- Metallic fuel
- Serial construction
- Beyond 2025

CFBR
- 500 MWe
- Pool Type
- $\text{UO}_2$-$\text{PuO}_2$
- Six units (3 twin units)
- To commission in 2023

PFBR
- 1250 MWt (500 MWe)
- Pool Type
- $\text{UO}_2$-$\text{PuO}_2$
- Indigenous design and construction
- To commission in 2012

FBTR
- 40 MWt (13.5 MWe)
- Loop type reactor
  - PuC – UC
- Design: CEA, France
- Since 1985...

Human resources

25 years of successful operation
Technological Challenges in FBR

Compact Reactor Core With High Fissile Content

Use of Liquid Na as Coolant at high temperatures (~ 823 K)

Design and fabrication of Materials that can withstand intense neutron dose, temperature, and loadings including Seismic

Reprocessing of highly active spent fuel

High Level waste management is very important for the success of Nuclear Option

Achieving High Performance with risk mitigation
Our approaches to challenges …

- Analysis based on Modelling and Simulation
- Validation through accurate and sensitive measurements
- Technology Development (1:1 or scaled down models)
- Knowledge Management, feedback Design, Visionary ISI
- Innovations in science, engineering and technology
- Interdisciplinary Approach
- Robust Asset Longer Life
ISI of FBR Components

- **In-Core Components**
  - Fuel subassemblies
  - IHX, Roof slab
  - Discharge pipe etc.

**Issues** - Access constraints, background radiation, temp., opaque sodium thus limited possibility for inspection

**Approach** - Stringent quality assurance (QA) Visual examination & under Sodium Ultrasonic’s viewing employed

- **Out-of-Core Components**
  - Main vessel / Safety vessel
  - Steam generators / Sodium circuit pipes
  - Concrete containment etc.

**Issues**: Access restrictions, temperature, time of inspection

**Approach**: Stringent QA + Advance NDE methods + Robotic devices developed for ISI
Development of Wireless Sensor Network

Advantages:
- Avoid congestion of cables in roof slab
- Avoid trailing cable system
- Reduction in cable and connector boxes cost

R&D Status
- Development of in house designed wireless sensor nodes
- Technology demonstration by deploying them in INSOT and SADHANA
- Tests were successfully conducted in FBTR, RCL for measurement of various parameters like range, throughput etc.
- Software development

Future Plans
- Measurement of reactor parameters using wireless sensor networks
- Development of radiation hardened and high temp. resistant nodes

Tx – Transmitter, Rx - Receiver
In-Service Inspection (ISI) System Developed for Inspection of Main vessel and safety vessel of PFBR
Development of Robotic Devices for ISI of PFBR Steam Generator (SG) Tubes

### Existing ISI Device for SG tubes

- Spider Robot On Mock-up SG Tube Sheet
- ISI Device being deployed in SG for testing

### Improved ISI device for SG tubes

- Flexible Robotic arm
- Linear Actuators
- Pulleys
- Robot’s base

- Improved Device for ISI of SG tubes
  - (SPATIAL HYPER REDUNDANT ROBOT)

- Computer aided simulation
- One set of Disc
Remote Field Eddy Current Technique

RFEC technique Principle
RFEC technique involves detection of back entered low-frequency magnetic fields (energy) in tubes using a receiver coil.

Discretised mesh

Optimal excitation frequency & detector location where RFEC intensity is maximum determined using 3D finite element model and results validated.

Development of Optical Fiber based Raman Distributed Temperature (RTDS) Sensor

RTDS sensor developed for temperature measurement on sodium loops (up to 700°C with spatial resolution of 1 m and temp. resolution of 5°, limited by laser pulse width)

Fiber Bragg gratings designed and developed for strain measurement on a test loop

Thermally influenced molecular vibrations cause Raman back scattered light whose intensity and arrival time are used for temperature and location monitoring

Single fiber grid was used to increase the spatial resolution up to 10 times

✓ Leak detection is possible. For technology demonstration, controlled leaks were simulated using hot water as coolant.
✓ Spatial, statistical and temp. dependent errors analyzed to improve the leak detection capability in coolant loops of reactors.

Test loop for testing
Sodium Loop - Leak Detection

Temperature profile during sodium leak
-- each peak corresponds to one sensor position

Temporal Response of Sodium leak

Leak at surface

Leak at insulation layer 1

Temperature change at insulation layer 2
Sodium Loop - Leak Detection

After removing 1st insulation layer →

- C3-Fiber Sensor
- C4-Fiber Sensor
- Sodium leak track on second insulation layer

After removing aluminum clad

After removing second insulation layer →

- I2-Fiber Sensor
- I3-Fiber Sensor
- Sodium leak track on first insulation layer
- S3&S4 - Fiber sensor
- Sodium leak track on the surface of pipe
Laser scattering for Sensing Surface Damage

Most of the Damage Mechanisms initiate from the surfaces

Evaluation of Intergranular Corrosion in SS

Effect of etching time on IGC in SS
Intergranular corrosion detection in Waste tanks by EC-GMR sensor

Giant magneto-resistive (GMR) effect is large change in resistance of nano layers due to applied magnetic field as a result of spin dependent scattering of electrons. In order to pick-up feeble magnetic fields produced by eddy currents (EC) at sub-surface corroded regions, GMR sensor has been integrated with eddy current coil. GMR sensitivity: 10 nano Tesla

Exciter – Eddy current coil, Receiver: GMR sensor

EC-GMR sensor is capable to detect corrosion 9 mm below the surface

Successful application for detection of internal corrosion in 12 mm thick 304 L waste vault tank by scanning from outer surface – ISI tool with robotics.
Corrosion an Inherent Problem-Solution through Innovative Approach with Advanced NDE

Quantitative Estimation of Corrosion in Structural Elements

Two Novel and Complementary Techniques

Robust Life Prediction for Structural Longevity

Asset History Environmental Details Modelling
Risk Management

Potential techniques for one sided inspection suitable for large structures. Can give quantitative estimation of corrosion and also detect rebar corrosion

Phase Image- Lock in Thermography

Compton Back Scattering
For the Inconel 625 wrought cracker tubes at HWP, Thal and HWP, Tuticorin in various thermal exposure conditions:

- Virgin (Thal)
- RSA (Thal)
- V+747 h (Tuti)
- RSA+23000 h (Thal)
- V+57194 h (Tuti)
- Failed in 1982 (Tuti)
- MC (~20000h) (Tuti)
- 120000 h (1-35, Thal)

Variation in Poisson’s ratio with hardness for cracker tubes in different service exposed conditions at heavy water plants at Thal and Tuticorin. (V-Virgin, MC-Mini Cracker, RSA-Re-solution annealed)

Ultrasonic measurements can be used to monitor the degradation in mechanical properties.

Life span of these tubes for resolution annealing should not be based on merely the service duration, but on some practically measurable parameter, such as Poisson’s ratio and hardness.

Assessment of rejuvenation heat treatment of the tubes using ultrasonic measurements.

\[ \nu = \frac{TOF^2_S}{2 \left( \frac{TOF^2_S}{TOF^2_L} - 1 \right)} \]

Accuracy \( \pm 0.0006 \)
MFL images of defects are obtained by scanning Giant Magneto-Resistive (GMR) sensor in a raster manner over the object. A flexible array of eight GMR sensors developed for automatic fast detection of flaws and loss of metallic area (LMA) in multi-strand steel wire ropes.
Asset and Knowledge Base essential for plants intended to serve for more than 40 years. The knowledge base is designed to serve as an expert system for bigger plants.
Asset and Knowledge Management System (AsKMe)

Archives more than 40,000 documents, records and drawings pertaining to Demonstration Fuel Reprocessing Plant.

Unique features that distinguish it from conventional database

Radiographic archive with user defined (based on experience) software for image analysis and measurements

Provision for Ultrasonic signals and images with analysis

Knowledge capsule – Interviews with senior/retired project colleagues on field problems and their innovative solutions.

Quality Circle problems and solutions

First of its kind attempt in DAE and internationally. Appreciated by Regulators.
Study envisaged the application of six sigma in the fabrication of complex and high density piping. 35,000 weld joints. 12,000 studied.

- Main types of defects that arise could be identified.
- Root causes of the defect could be ascertained to prevent in future pipings.
- R & D initiated – for example oxidation occurs because of lack of purging gas.
- Feasibility studies on using Flux cored / covered TIG welding filler wires to completely eliminate the purging.
- Trial implementation made in complex piping.
- 100% oxidation free joints achieved.
SUCCESSFUL LIFE CYCLE PERFORMANCE REQUIRE...

INNOVATIVE APPROACHES, SEAMLESS INTEGRATION OF DISCIPLINES AND ENABLING TECHNOLOGIES INTEGRATED ASSET AND KNOWLEDGE MANAGEMENT

VALIDATED DESIGN

FOCUSSED INTER-DISCIPLINARY RESEARCH

PROVEN MANUFACTURING TECHNOLOGIES

SYSTEMATIC, PLANNED ISI, LIFE ASSESSMENT

RELIABLE SENSORS, SYSTEMS, SAFE OPERATION PROCEDURES

ROBUST INSPECTION and TQM

INTEGRA TED ASSET AND KNOWLEDGE MANAGEMENT
Approach for Implementing Innovations

- Critically review the internationally evolving designs and failure experiences
- Detail out the prospective options for future SFRs
- Involve Industries to design and manufacture innovative concepts
- Academic institutes for design optimisation by analysis
- Testing in air at Industries and testing in sodium at IGCAR

- Recognising priorities, breakthrough areas by experts, young students and research scholars at the core of innovation
- Innovations eco-system with intertwining of young, senior, academic, research and industry
- Quality and motivated human resources with enabling networks and management ethics is a key to the safety of SFR
Intelligent Welding –
On-line Monitoring & Process Control

On-line monitoring and processing of image data for identifying possible defects by comparing the image with the defective image database.

A robust repair technology for nuclear applications

Challenges: Miniature IR sensors, thermal noise, feature detection and identification – robust fuzzy logic based systems
XRD based Residual Stress Measurements for Life Assessment of Undercarriages of Fighter Aircrafts

The variation in residual stress in the depth direction

Number of Landings = 1050

The variation in surface residual stress in landing gears experienced different number of landings

In collaboration with IAF & HAL, Nasik
X-ray diffraction for life assessment of landing gears of MIG-21

- Stresses, microstructures, micro and macro defects through Radiation based NDE at IGCAR
- Inclusions, Glue variations, Quality Assurance of assemblies – Conventional X-ray
- Remnant core in turbine - through Neutron Radiography- KAMINI
- Micropores, impact damage, fibre breakage in composites through micro focal NDE

MIG-21/23
LCA
Mi-8/17
The simulation paradigm

From: Kuivanen, ‘e-Engineering (Digital Manufacturing)’, VTT (Technical Research Centre of Finland), 2010.

www.monash.edu
Stress Tri-axiality Across Weld Joint of Modified 9Cr-1Mo Steel on Creep Exposure

Concentration of stress tri-axiality in the intercritical region of HAZ, leading to the strain concentration and creep cavitation in the intercritical region of HAZ
Modelling of Nuclear Dissimilar Weld Overlays

PIPE WELD: 15 passes
OVERLAY: 543 passes

INSTRUMENTED MOCK UP
BUTTERING: 94 passes
DISSIMILAR WELD: 46 passes

Full axi-symmetric model of instrumented mock up contains 598 weld passes in four different alloys

Courtesy, CSIRO, Australia
Comparison with deep hole drilling measurements

- Best in class results in international comparison

Courtesy, CSIRO, Australia
Factors Affecting Measurements in NDE

Fixed Factors
- Sensor characteristics
- Material Properties
- Inherent Noise from sensor and electronics

Variable Factors
- Operator qualification and training
- Automation
- Image and Signal Processing

Measurements in NDE

Automation +
Defect Detection based on large defect database +
Heuristic Knowledge of Experienced Operators

Indicates significance

Asset & Knowledge Management

Six Sigma
### PERFORMANCE OF HIGH TECHNOLOGY COMPONENTS AND SYSTEMS - MATURITY MAPPING

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- **Design**
  - Manufacturing Technologies
- **Operation and maintenance**
  - Health Monitoring
- **Excellence in Individual Domains**
- **Fractured Linkages**
- **Barriers of Disciplines and Management**
- **Lack of Integrated and holistic approaches**
Challenging engineering and technological problems need robust measurements and clear convincing analysis, even to concerned non-specialists. Challenges like the Challenger Failure can be addressed with successful and well-appreciated solutions based upon holistic analysis with robust measurements and clear convincing arguments.

Richard Feynman
My Perspective of Missing Links ..... 

- Measurements crucial for successful performance

How well have we understood and translated ...
SIX LEVELS OF TECHNOLOGY MATURITY

1. CONCEPTS
   - Technologies
   - Strategies
   - Financing

2. VALIDATION OF CONCEPT
   - Peer review

3. COMPONENT TESTING AND ANALYSIS
   - Laboratory
     - Modelling
     - Experiment
     - Validation
     - Collaboration

4. Pilot plants and exploration to real life environment:
   - Prototype demonstration of technology
   - Business model

5. Talented human resources
   - R&D competence
   - Management of RD
   - Passion, Ethics, Motivation
   - Patronage and support
   - Peer review of milestones
   - Management structure and confidence to deliver and exceed

6. REAL SYSTEM
   - Successful operation
Small innovative ideas triggering research and application spanning disciplines and organisations

**Acoustic Simulation of PE-16 (µm size precipitates) – Ph D Thesis IzfP Germany**

**Acoustic amplification based tests for dislocation studies (µm-nm)**

**Understanding Movement of Dislocations with Acoustics**

**Ca Oxalate kidney stone acoustic microscopy (10 nm thick layers)**

**Acoustic study of Humpy musical pillars**

**Damage Micro-mechanisms in Near Alpha Titanium Alloy Defence Lab (DMRL)**

**AE energy / load vs. normalized time curve**

**Kaiga Ring beam using acoustic impact echo testing**
Thermal NDE Techniques –
Range and Versatility

- Pinning of edge dislocation (Luders Band) – nanometers to micrometers
- Coating Characterization – Micrometers to Millimeters
- Defect Characterization – Millimeters to centimeters
- Condition monitoring Applications – Centimeters to Meters
- Predictive maintenance of Electrical Installations – Meters to Kilometers
- Conservation and Restoration of Tanjore paintings – cm to m
- Cancer Breast Lesion Detection: few mm to cm
- Moisture entrapment in Building – cm to m

Ab initio design of sensors, equipment, modeling and validation from nm range to tens of m length i.e. $10^{-9}$ to $10^3$ scale of $10^{12}$ (A wide range Applications)
Ethical & Sustainable model

- Politicians
- Bureaucrats
- Economists

- Business
- Public

- Academics
- Ethics
Learn from Buddha on Sustainability

- Detatch
- Experiment
- Clear
- Conviction
- Balance
- Pursue
- Achieve
Incredible India
Science, art, literature and philosophy belong to the whole world, and before them vanish the barriers of nationalities.