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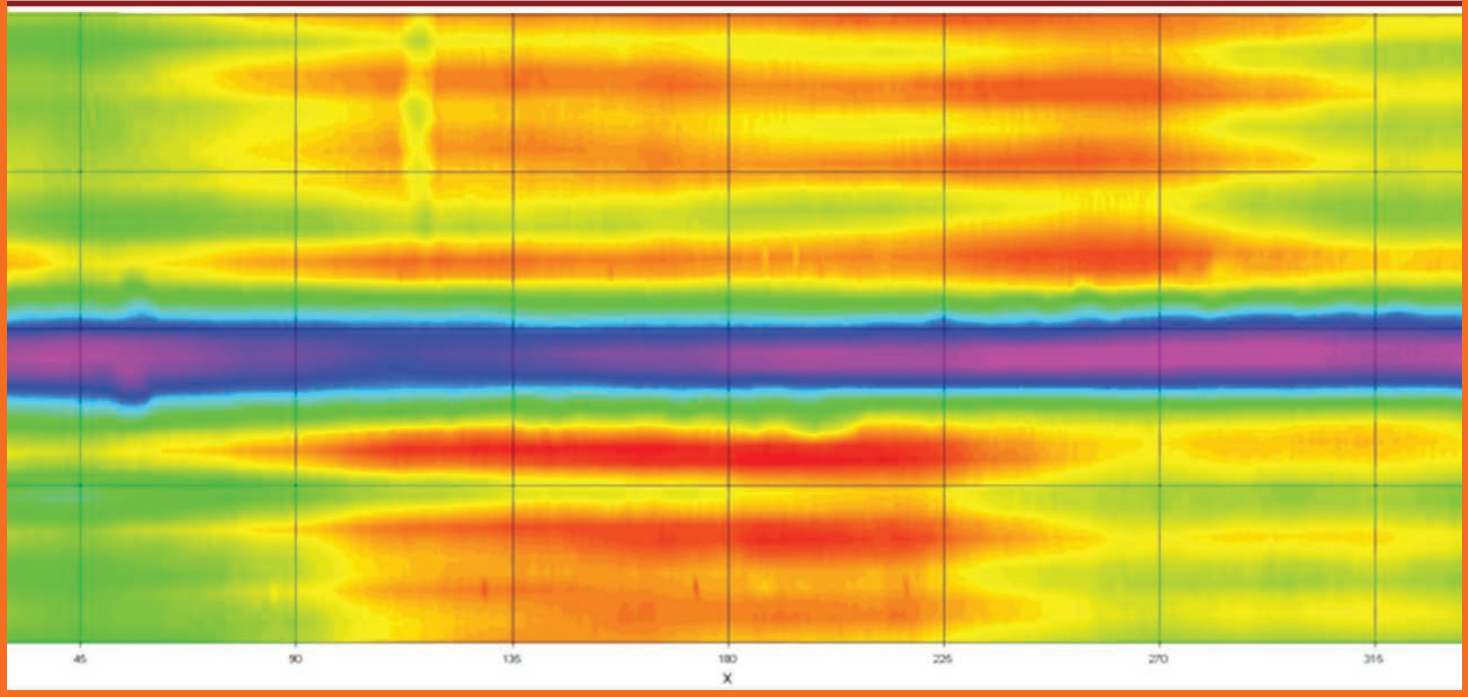
Emerging Technologies in NDE



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JUNE 2023
Volume 20 - Issue 2

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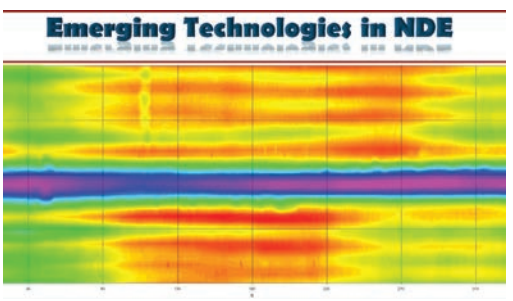

Cover page depicts Microwave Imaging of HDPE (High-Density Polyethylene) pipe.
Source : Evisive NDT File

OBJECTIVE - This Journal of Non Destructive Tesing & Evaluation (JNDE) is published quarterly by the Indian Society for Non Destructive Testing (ISNT) for promoting NDT Science & Technology. The objective of this Journal is to provide a forum for dissemination of knowledge in NDE & related fields. Papers will be accepted on the basis of their contribution to the growth of NDE Science & Technology.

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LETTERS

PRESIDENT TALK



DIWAKAR JOSHI

Dear Friends

Greetings!

March 2023 issue of JNDE was on "Infrared Thermography". It was well received by the readers,thanks to Dr.Ravibabu, our guest editor.The current issue is on Radiological NDE.Papers in this issue covers the topics on Microwave NDE, Emmissivity correction in IR Thermography and also AI on Thermal images, Applications of Terhertz pulses, Ultrasonic Flow meter application and also on Petent Landscaping on NDE in Gas turbine.

Our PFMB has made available 2 programs viz. 2D/3D Radiological Imaging and Applications and Advances in Electromagnetic NDE for all chapters.

You will be happy to note that ICN scheme is revised to ISO 9712: 2021 with all sectors and undergone successful audit by NABCB. This is a proud moment for ISNT and I appreciate the tremendous hard work put by NCB team for this achievement. IS13805 examinations are showing an upward trend. The first online General and Specific examination was conducted by NCB on ISNT day. Thanks to Dr. Bikash and Dr. Manoharan for making this happen.TMB is working on the final authorization of chapters and institutes by conducting physical audits. TMB is presently working for developing training material, question banks, practical books, course outline and other things to support the ATCs.

There is a visible increase in Chapter activities including webinars, training programs and workshops, which is a good sign.

Preliminary work of NDE 2023 has already been started. The theme this time is "Transformative NDE : Unleashing the Power of Advanced Technologies". The focus will be on NDE 4.0 and topics such as artificial intelligence, robotics, and advanced sensors, which have the potential to revolutionize NDE practices and enable more efficient and effective inspection processes. I appeal all of you to promote and spread the word to ensure maximum participation in the conference to make it a grand success. An ISNT industry meet was conducted in Pune and got a very good response from Pune and outskirts industries.

I thank all authors, the editorial board, advertisers, and the whole team for releasing this issue in time, and request readers to share their feedbacks and suggestions.

Diwakar D. Joshi
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MANAGING EDITOR TALK



BIKASH GHOSE

Greetings from Indian Society for Non-destructive Testing.

This JNDE June 2023 issue in your hand has brought interesting papers from emerging technology areas. I am sure the papers will be of much interest to you. This special issue on "Emerging Technologies in NDE" is edited by Dr Debashish Mishra from GE Research, Bengaluru. My sincere thanks to Dr Debashish for exposing the readers to different areas and for helping us to bring out the issue on time.

A paper on patent landscaping as an example case of NDE in Gas Turbine showcases how patent analytics can be used towards shaping innovation strategy. The paper on Microwave NDE brings out the history of the technique along with the challenges and current state of affairs. Varied application areas of Terhertz is summarised in one article and an innovative application of ultrasonic flow meter is brought out in another article. Emissivity related correction approach in IR thermography was discussed in one paper and another discusses about the AI application in thermography images and its application in NDE 4.0. By and large the issue brings out an interesting technological landscape for our enthusiastic readers.

The chapter activities section summarizes the activities conducted by various chapters in the last three months (March 2023 – May 2023). All must be waiting for the next grand event of ISNT, NDE 2023, to be organised at The Hotel Orchid in Pune during 7-9 Dec 2023.

My heartfelt thanks to all the advertisers and contributors of this issue who helped release the issue before on time. One can now submit the original research articles to JNDE through the online portal of JNDE http://jnde.isnt.in.

Bikash Ghose
Managing Editor, JNDE
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GUEST EDITOR'S TALK



DR. DEBASISH MISHRA

This issue of the Journal of Non-destructive evaluation has a collection of articles from various emerging technologies in Non-destructive evaluation area. This issue has covered - Non-metallic components inspection using microwave techniques, application of terahertz radiation for various NDT applications, emissivity correction approaches for infrared thermography, AI application in infrared imaging and intellectual property landscaping for NDT applications. I am thankful to all the contributing authors for this edition. Happy reading!

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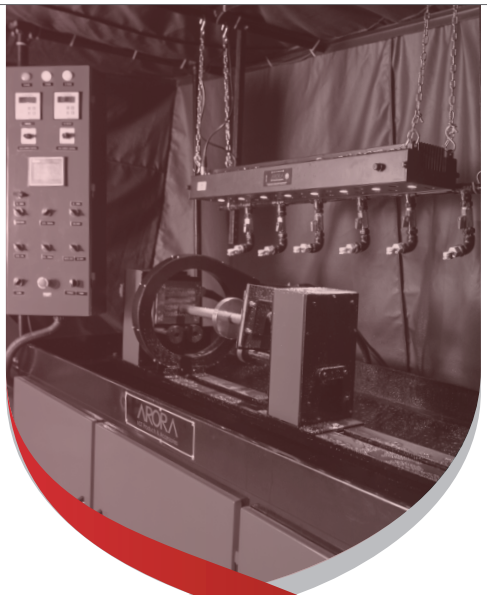





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CHAPTER ACTIVITIES

CHAPTER ACTIVITIES For the period from Dec 2022 to Feb 2023

AHMEDABAD

Technical Talk :

Technical talk on: Future of NDTs and challenges from 17:30 hrs to 18:30hrs- By Mr. Vineet Sharma - Head Inspection Refinery - RIL Jamnagar dated 08/04/2023.

Technical Talk and Exhibition by sponsors: M/s SIGMA NDT dated 08/04/2023.

Technical Talk on Phased Array Ultrasonic Testing (PAUT) by Mr. Yatin Raval ASNT NDT Level III (Ultratech) date 29/04/2023.

Other Activities :

Annual General Meeting of Ahmedabad Chapter on 25/02/2023.

EC Meeting on 08/04/2023 at Jamnagar.

Launch of First Newsletter of ISNT Ahmedabad chapter date 29/04/2023.





Technical Talk on PAUT





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Flaw Guide
NDT Products

Fluorescent Penetrants

Water & Solvent Removable
Post Emulsified
Hydrophylic & Lipophylic





0.5 x 10 u Ni-Cr Panel

Approved By
NPCIL / RDSO

ISO 9000-2015 Certified

Flaw Guide
NDT Products

Magnetic Powders

Dry & Wet Application

Colours
Black-Red-Gray



Packings
1, 5 & 25 Kg.

Flaw Guide
NDT Products

Red (Visible) Penetrants

Solvent Clean Type
Water Washable
Dual Mode
High Temp.Application



Aerosol & Bulk Packings

High Quality Products

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Flaw Guide
NDT Products

Fluorescent Powders For MPI

Water & Oil Suspended Carrier Oil



Packings
1 / 5 / 20 Kgs

Flaw Guide
NDT Products

White Contrast Black Ink
Fluorescent Ink

For MPI



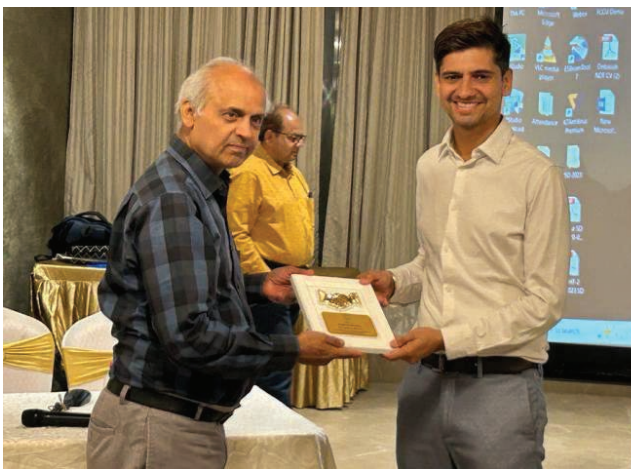
Ready to Use
Aerosol Sprays
&
Powders in Bulk

CHAPTER ACTIVITIES











Event at Jamnagar

HYDERABAD

COURSE & EXAM :

Re-Exam/Re-certification exam on PT on 4th April,2023

Re-Exam/Re-certification exam on RT/ RTFI on 20th May, 2023

TECHNICAL TALK :

One day National Workshop on " Non destructive Testing and Evaluation," on 4th March, 2023 at Government City College, Hyderabad.



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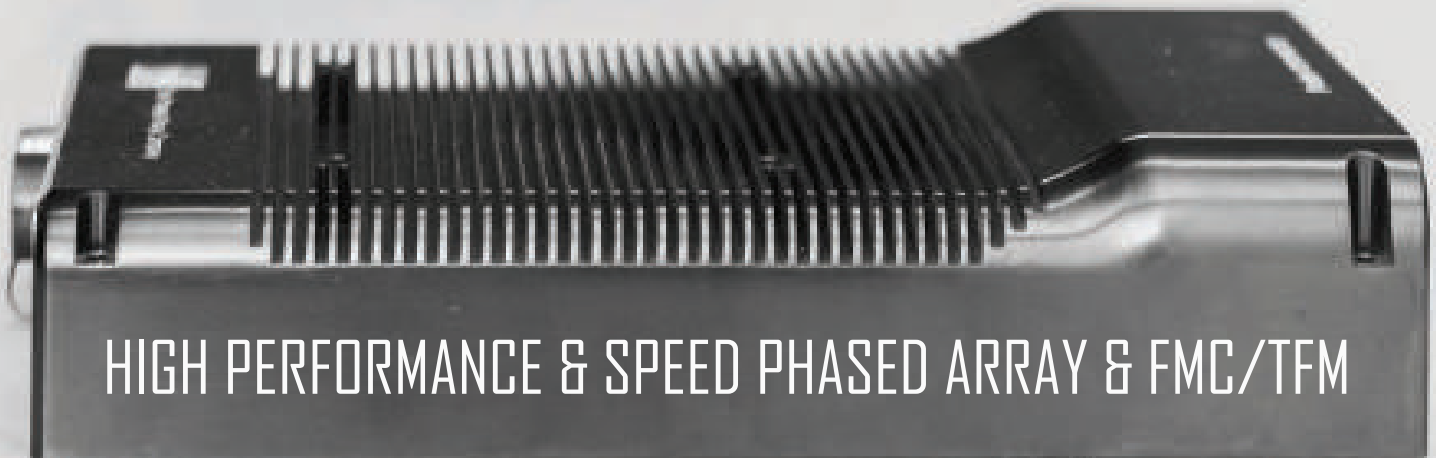


HIGH PERFORMANCE & SPEED PHASED ARRAY & FMC/TFM

CHAPTER ACTIVITIES

Sri V.A. Chandramouli Memorial Lecture on 3rd April, 2023 by Sri K. Viswanathan.

Other Activities:

EC Meeting on 10th March, 2023.

EC meeting on 17th April 2023.

AGM on 20th May, 2023.



KOTA

COURSE & EXAM :

NDT Level- L-III examination (03 participant) in Feb.- March-2023.

TECHNICAL TALK :

Lecture on In situ property measurement system (IProMS) of 220 MW Nuclear Reactor Pressure tube by BARC engineer .

Line management training on Eddy current testing of Calandria tube after removal pressure tube during EMMCR to QA engineers and Supervisors. (10.04.2023 to 11.04.2023)





SRIHARIKOTA

TECHNICAL TALK :

Development of microwave devices for LINACs and RADARs -

Technical Talk by : Dr. Amol Bhagavat, Program Director, M/s SAMEER, Guwahati on 04-05-2023.

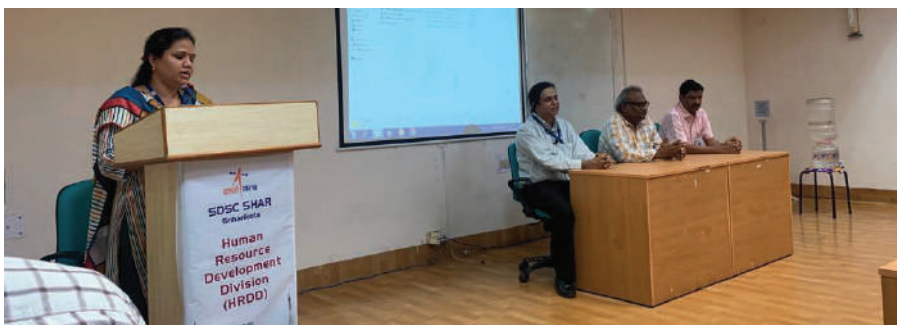












TIRUCHIRAPPALLI

COURSE AND EXAMINATION :

- 17.04.2023 – 24.04.2023 Liquid Penetrant Testing Level - II
- 25.04.2023 – 29.04.2023 Magnetic Particle Testing Level - II
- 02.05.2023 – 20.05.2023 Radiographic Testing Level - II
- 22.05.2023 – 03.06.2023 Ultrasonic Testing Level - II

CHAPTER ACTIVITIES

TECHNICAL TALK :

1. 14-03-2023-Internet Addiction: Recognizing and Managing Compulsive Online Behaviour.
2. 21.03.2023 - World Water Day 2023 -Accelerating Change-Global Campaign.
3. 28.03.2023 - Ongoing Climate Change, Global Warming and Sea level Rise-An Analysis.
4. 04.04.2023 - National Maritime Day-Corrosion of Copper based alloys in marine environment.
5. 11.04.2023 - Cyber Security challenges for common man through Wind Turbine Generators.
6. 18.04.2023 - Performance of Industry Sector.
7. 25.04.2023 - Career Opportunities for Young India - Part – I.
8. 02.05.2023 - Career Opportunities for Young India – Part II, (Choice of Engineering Courses for +2 Students)
9. 05.2023 - Stay Safe Online: Understanding Cyber Laws & Best Practices.

MUMBAI

COURSE AND EXAMINATION :

MPT Level II was conducted at NPCIL from 28th Nov – 02nd Dec ,22 for 16 nos. candidates.

LPT Level II was conducted at NPCIL from 05th Dec – 10th Dec, 22 for 20 nos. of candidates.

NDT Level III Training Program was conducted virtually 13th Feb to 31th March 2023.

(MPT, LPT, VT, UT, RT, Basic)

UT Level II was conducted at NPCIL from 17thApril – 27th April, 23 for 24 nos. candidates.

ECT Level II was conducted at NPCIL from 02nd May – 11th May, 23 for 23 nos. candidates.

RTFI Level II was conducted at NPCIL from 15th May – 19th May, 23 for 21 nos. candidates.

LT Level II was conducted at NPCIL from 22th May – 27th May, 23 for 26 nos. candidates.

VT Level II was conducted at NPCIL from 31st May – 03rd June, 23 for 19 nos. candidates.

TECHNICAL TALK :

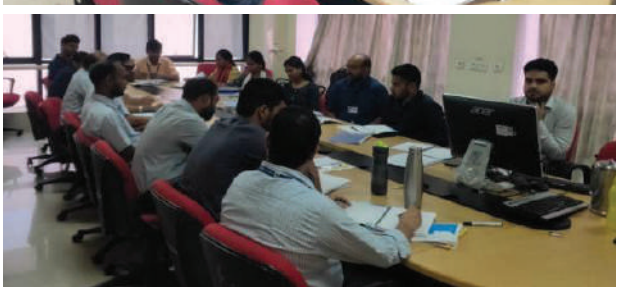
21th Jan 2023 : Topic – Flaw Detection and Characterization in tubes using Eddy Current Testing by Shri. Arbind Kumar

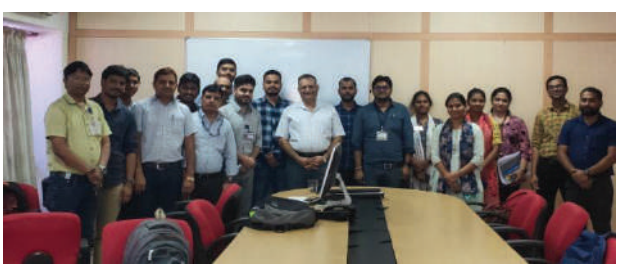
18th Feb 2023 : Topic – NDT: Risk & Cognetive Biases by Mr. Santosh Gupte











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KALPAKKAM

Indira Gandhi Centre for Atomic Research (IGCAR),Kalpakkam and Indian Society for Non-destructive Testing (ISNT) Kalpakkam Chapter have jointly organized the "Dr. Baldev Raj Memorial Bridge Course on Non-destructive Evaluation and Quality Assurance (BRM-BCNQ-2023)"during May 22-26, 2023 at IGCAR for the benefit of students entering the final year of their B. E./B.Tech/ M.E./M.Tech. The objective of this bridge course is to introduce advanced NDE technologies and more importantly, providing practical hands-on experience in the state-of-the–art NDE equipments available at IGCAR. This bridge course is a step towards capacity building so that the participating students will be able to plan towards a successful career in professions involving NDE & QA. Around 25 Students from premier institutes such as IIT, NIT and 19 participants from various groups of IGCAR attended the programme.







NAGPUR

ISNT Nagpur Chapter had conducted seminar on NDT for Casting & Welding at M/s. Jayswals Neco Industries Limited on 14th May, 2023. More than 20 members from ISNT & various Industries representatives attended the program.







PUNE

- EC meeting No. 9 :- Conducted on dated 15.03.2023 with amended Date.
- Woman's Day celebration at Sai Shradhha ITI Institute on dated 10th of March 2023. Total 50 candidates were attended the program.
- ISNT DAY Celebration with an Industry meet (INDCONN) conducted for NDE 2023 at Hotel Kalasagar, Pune, on 21st April 2023
- EC Meeting No. 10 will be conducted on dated 03.06.2023.















CHENNAI

Courses & Exam. conducted:

Surface NDT MT & PT Level-II course and examination was held on 26th April 2023 to 06th May 2023 Number of participants attended the courseAnd examination was 7. Mr.E.Sathya Srinivasan was the course director.

In-house ISNT VT Level-II certification course at GHAVP site from 24th to 30th April 2023 Number of participants attended the course and examination was 25. Mr.S S Ananthan was the course director.

Technical Talk:

Penetrant Testing And Its System Performance By Mr.Rahul Jadav General Manager – Technical & Mr.D.Silambarasan – Sales Manager , MR (3AK) Chemie (P) Ltd on Saturday 18th March 2023 at 18.00 Hrs at ISNT Head Office Conference Hall , Chennai

Other ActivitiesL

EC Meeting was held on 16th April 2023 EC Meeting was held on 25th May 2023

ISNT Chennai chapter organized ISNT Day on 21st April' 2023, at Radha Regent, Chennai. The Welcome address was given by Shri RG.Ganesan, Chapter Chairman.

The Chief Guest Dr C Senthil Kumar, Scientific Officer(H), Officer In-Charge, from Southern Regional Regulatory Centre, Atomic Energy Regulatory Board, Chennai, addressed the gathering and talked about the Nuclear power generation in India and especially MAPS and KKNPP.

Chapter Awarded for the following Candidates:

Best member Award (Thambithurai Award) to Mr.Chockalingam, SO/F, Atomic Energy Regulatory Board, Chennai.

Best Participant in Certification Courses (Pari Award) to Mr.Kumar Saurabh, Manager (NDT), Hindustan Aeronautics Limited, Kanpur.

Best Technical Talk award (Rajamani Award) to Prof.Dr.Krishnan Balasubramaniam, IITM, Chennai.









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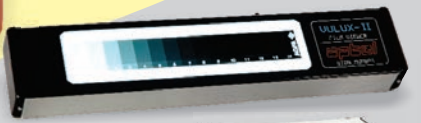

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TRAINING MANAGEMENT BOARD

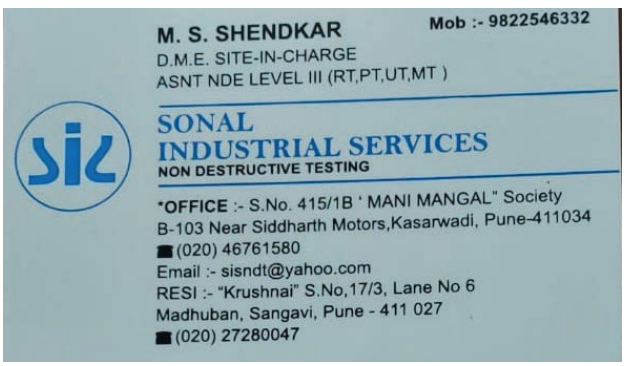
Training Management Board (TMB) – ISNT

The Training Management Board (TMB) was officially formed by ISNT in February 2022 to act as a nodal agency to address all NDT training related activities (which lead to formal certification as Level 1, 2 or 3 personnel under IS 13805 and ICN schemes of ISNT). Over the period of nearly 15 months since its formation, TMB has made good progress on several fronts by creating multiple Task Forces focussing on different tasks including creation of harmonized timetables, Training material for course instructors, Course notes for trainees, Question Bank / Mockup exams, Train-the-Trainers programme. The other major activity which was the focus of TMB was to establish a robust process with appropriate guidelines, mechanisms and teams to establish Authorized Training Centres (ATC) of ISNT across the country (and later abroad) who can conduct effective and harmonized training courses for both the schemes in all the NDT methods at all Levels of certification. This was achieved by the dedicated Task Force set up for the purpose under the leadership of "Controller of Authorization". This enabled empanelling a several ATCs under the "Interim Authorization" scheme with validity until June 31, 2023(Current ATC list can be viewed at https://isnt.in/list-of-atcs-is13805/). The "Call for Applications" from interested entities for Full Authorization as an ATC valid for 5 years through an audit and assessment process is out now and we welcome all to take advantage of the same. Through its focused efforts, TMB envisages a standardized and harmonized training system to be in place in the near future which ensures a world class NDT training ecosystem in all aspects.

We also welcome volunteers to join and contribute to TMB activities in whatever way they can to help accelerate the fulfilment of our objectives.

To learn more about TMB and its activities please visit https://isnt.in/

For any queries related to TMB, please send an email to tmb@isnt.in





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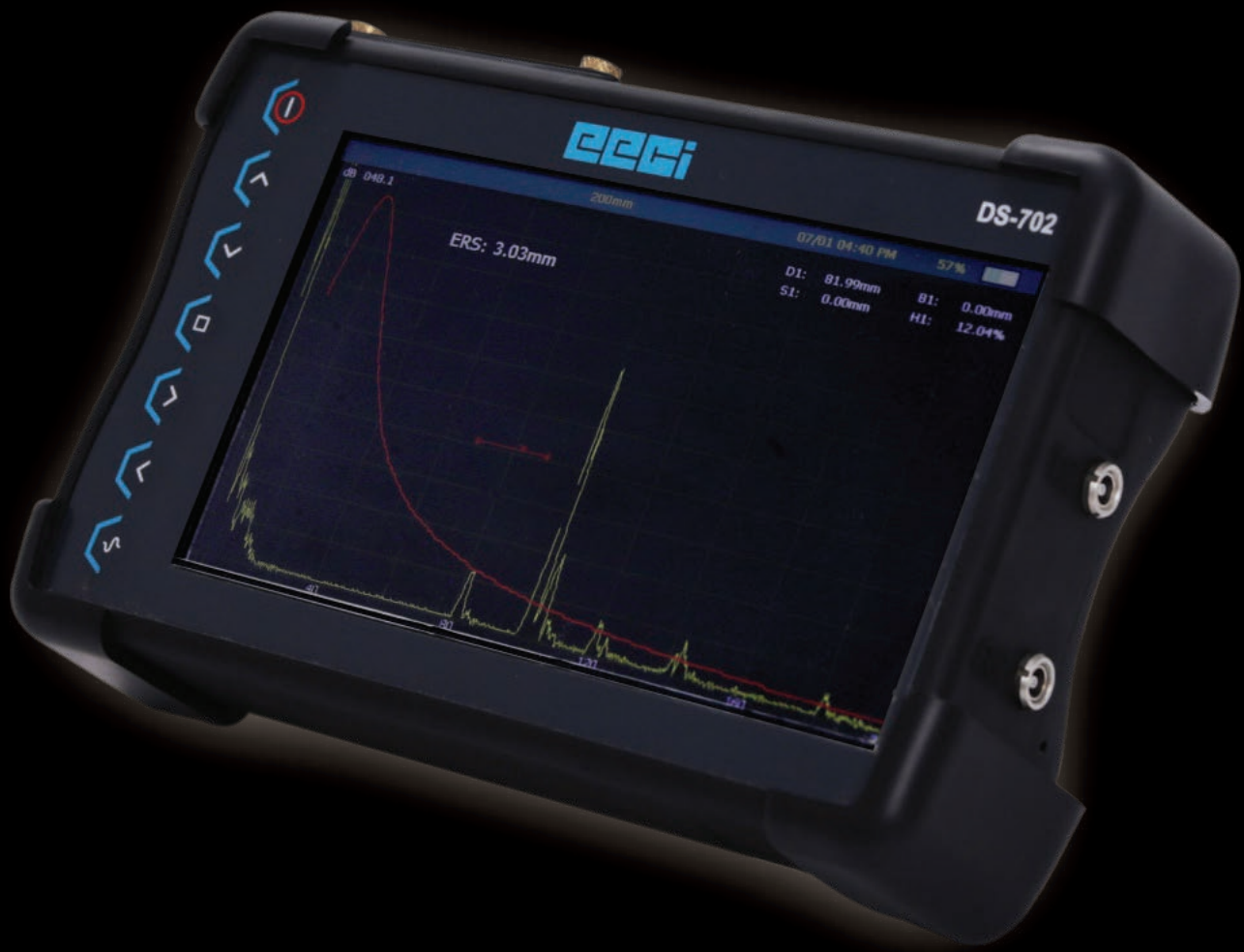

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PROGRAM FORMULATION AND MANAGEMENT BOARD (PFMB)

I wish to inform you that the Program Formulation and Management Board of ISNT (PFMB) has been constituted with Shri V. Manoharan as the Chairman, Dr. Deepesh Vimalan as Hon. Secretary and 14 technology/industry experts as members of the board.

PFMB has formed 4 technology groups –Radiological Imaging, Electromagnetic NDE, Thermal Imaging, and Acoustic NDE and Chairman for each working group were identified.

Office Bearers

Shri V. Manoharan, Chairman

Shri Deepesh Vimalan, Hon. Secretary

Members :

Dr. S. Thirunavukkarasu
Mr. A.K. Das
Dr. Phani Suryakiran
Mr. Bhausaheb Pangare
Dr. Arumugam. M
Prof. Prabhu Rajagopal
Dr. Menaka
Prof. Kavitha Arunachalam
Mr. P. Vijayaraghavan
Prof. Ravibabu
Mr. Komma Reddy Vamshi
Dr. Debasish Mishra
Mr. Umankanthan Anand
Dr. Ramadas Chennamsetti

Ex-Officio Members

Mr. Diwakar D. Joshi, President -ISNT
Mr. Bikash Ghose, Hon. Gen. Secretary -ISNT
Mr. Kalesh Nerurkar, Hon. Treasurer ISNT

Invitees

Dr. Paritosh Nanekar, Chairman-NCB
Dr. M.T. Shyamsunder, Chairman -TMB

Objectives

The main Objectives of PFMB are as follows:

- To conceptualize, formulate and organise various non-certification programs such as Webinars, Workshops, Conferences, Seminars etc. to create platform for constant interaction with ISNT members, meet the requirement of industry, academia and research community.
- To interact with other international NDT societies, National technical societies to formulate and organise joint programs.

Scope

- To plan and organise two annual conferences of maximum 2 days' duration (other than NDE) and execute through an organizing committee nominated by PFMB
- To conceptualize, formulate and execute programs such as Webinars, Workshops, Conferences, Seminars etc. of relevance to the NDT community to be organised by ISNT throughout the year across the country.
- To publicize the proposed program
- Develop and implement mechanism for executing the programs along with ISNT Chapters or independently (only if no chapter is interested).
- Create various topical working groups within PFMB and formulate programs as stated above for meeting specific requirement.
- To connect with various industries / institutes and formulate program to meet the specific needs
- Interact with international NDT societies (ISNT partner societies with MOUs) for conducting joint programs, pre-dominantly Webinars
- Interact with national technical societies for conducting joint programs
- Establishing a model for sustained revenue generation for continued operations and growth of PFMB

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- EN ISO 9712 Level 2 & 3 Preparatory (RT,PT,UT,MT,VT)
- Welding inspectors / Welders, QC managers' certification
- Fabrication Inspector
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- Management Systems - Internal Auditor, and Awareness
- ASME codes awareness, NDT Awareness
- Preparatory for API (510, 570, 653, 580, 577,571,936,1169, SIFE)
- AWS CWI & CWEng Seminar & Exam
- Computerized mock exams for API and ASNT Level III modules

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Themes for the Special Issues of Journal of Nondestructive Testing and Evaluation (JNDE)

The issues of Journal of Non Destructive Testing and Evaluation (JNDE) are published quarterly and the special issues are focused on specific theme. Each of the special issue features articles and research papers on the latest developments and advancements in the specific theme.

For the current special issue, the theme is "Infrared Thermography". The issue editor for this issue is Dr Ravibabu Mulaveesala, who is a leading expert in the field of IR NDT. He has curated a selection of articles that highlight the latest advancements in this area.

In the same line, the upcoming special issues will feature leading experts as issue editors who will select articles and papers on the following different themes that will be of great interest to researchers, practitioners, and industry professionals alike.

Issue	Theme	Issue Editor
June 2023	Radiological NDE	Dr Debashish Mishra, GE Research
September 2023	NDE of Civil Infrastructure	Dr Surendra Beniwal, IIT Jammu Dr Debdutta Ghosh, CBRI-CSIR
December 2023	NDE 4.0	Dr Shyamsunder Mandayam, Azareri Pvt Ltd

Interested authors are requested to submit articles in these areas by visiting the online portal of the journal at https://jnde.isnt.in/index.php/JNDE/about/submissions. Authors need to register with the journal prior to submitting or, if already registered, can simply log in and begin the five-step process to submit article. The submissions are accepted throughout the year.

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- Sohm Hitech Systems (I) Pvt Ltd
- Betz Engineering & Technology Zone
- Subikaar NDT Engineers
- Technofour
- Omega Inspection
- DCMS Engineering Co.
- Electronic & Engg Co(I) Pvt.ltd
- Kub Quality Services Pvt Ltd
- Amet University
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- Annasaheb Dange College of Engineering & Technology
- Electro Magfield Controls & Services
- L.G. Inspection Services
- Usui Susira International Pvt Ltd
- Ordnance Factory
- Government Polytechnic College Kolhapur
- Roshan Instrumentation
- Advanced Training Institute
- Insight Quality Services
- International Radiography Services
- Saksham Industries
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- Lucid Software Ltd
- Q Tech Inspection Services
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- NDT International (India) Private Limited
- Enmas O & M Services Private Limited
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- Royal NDT Services
- Alco Inspections
- Eagle Industrial Inspection Services
- Vibrant NDT Services Pvt Ltd
- Emerson Process Management Chennai Pvt Ltd
- Lloyd's Register Asia
- Tractor and Farm Equipment (TAFE)
- MM Forgings Limited
- Government Engineering College Barton Hill
- Karmar International Pvt Ltd
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- Chadalawada Ramanamma Engineering College-Autonomous,
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Patent Landscape on Non-destructive Testing in Gas Turbine Applications

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Abstract

Patent analytics is a useful tool to derive insights from publicly available patent data and leverage it to organize the intellectual property (IP) strategy for an organization. The current study describes the use of Derwent Data Analyzer, a patent analytics tool commercialized by Clarivate Analytics. The tool is used to extract patent data on non-destructive testing (NDT) modalities applied to gas turbine applications including aviation, power generation among others for various industrial applications. Within the scope of search, it was observed that aviation players have relatively higher filings compared to the power industry players. Ultrasonic inspection has seen high filing focus with X-ray inspection and thermal imaging not far behind. However, the patent space for microwave and Terahertz inspection has also been expanding. A deep dive patent study is also conducted on X-ray Inspection related filings. Boeing and General Electric have filings across most of the technology segments while Safran has a relatively higher filing count on image processing techniques. Canon and Nikon also have good filing presence focusing on the X-ray scanning system. It is observed that aspects such as inspection data sharing across multiple systems, licensing among others have seen relatively lower focus and could present themselves as potential filing opportunities.There could also be potential opportunities in applying machine learning algorithms to analyze large inspection datasets. The study is a representative example of leveraging patent data towards shaping the innovation strategy of an organization.

Keywords: *NDT; Patent analytics; Patent landscape; Derwent Innovation; Patent Database; Derwent Data Analyzer*

1. INTRODUCTION

Non-destructive testing (NDT) is a vital cog in the process flow of several industries ranging from aerospace, and power to automotive and manufacturing. NDT is a process to detect defects in materials and components without causing damage or destroying the specimen. NDT is employed in several applications to ensure and improve product quality and safety. With the advances in science and engineering proceeding at a rapid rate, there is a fervent need to keep pace with the various developments in the industry.

Patent analytics is a powerful tool and is a process of generating insights based on collating and analyzing publicly available patent data. The patent data is bounded by specific metrics such as technological keywords, patent timeline, patent filing jurisdiction and other related patent parameters. Patent analytics provides directional insights on innovation trends, key competitor focus areas, general market focus, potential filing, and market opportunities. It is a tool that can be leveraged by any company to not only analyze competitor data but also evaluate their own IP position. It can provide directions to the business with respect to investment in research and development activities, chart competitive strategy and explore technology licensing opportunities, which could be a potential avenue for revenue generation for the company. IP investment is a significant monetary commitment for the company and patent analytics is a valuable tool that can be leveraged to provide a sound basis to make these decisions. There is available literature on patent analytics in various applications, relative to the overall application of the methodology and specific instances. Oleg [1] presents a novel usage of patent analytics on a corporate level by adopting a combination of knowledge modelling techniques, technical analysis followed by 'insight-driven analytics' approach to facilitate its implementation in the company's technology management process. OuYang et al. [2] present a

patent analytics approach which combines the patent family with patent citation analysis in a new product design process. Grimaldi et al. [3] presents a framework to analyze and assess strategic patent information to help manage and leverage the value of patent portfolios. These publications serve to present the breadth of patent analytics in deriving useful insights.

NDT is a rapidly evolving field with increasing demand for improved techniques demonstrating high accuracy, repeatability, and efficiency. Patent analytics can serve as a powerful tool to cater to this growing industry and identify the latest trends and innovations in the field. There are several patent databases available commercially and they are usually supplemented with search and analytics tools such as Derwent Innovation, Innography, Patbase and Relecura. Derwent Innovation [4] is a patent research application that provides patent data information as well as tools to perform various analytics activities including tracking innovation trends, perform competitive landscapes and providing resources to make informed Freedom to Operate (FTO) opinions, patent licensing in addition to other features. The licensed user is allowed access to Derwent World Patents Index (DWPI), which is essentially an expert curated patent database with curated title, abstract and subject matter classification, coding, and indexing. The application also provides a family grouping methodology referred to as DWPI(Derwent World Patent Index) family. Derwent Innovation has several integrated features such as “Smart Search” which also utilize machine learning algorithms in patent searches while their “Themescapes” feature provides visualization of smart segregation of patent data. Using advanced data science algorithms, Derwent Data Analyzer [5] is a data-mining tool that converts patent data into actionable insights through intuitive workflow processes, some of which involved machine learning algorithms, and powerful visualization functions.

The current study leverages Derwent Innovation to conduct a patent search on the technology topic of interest using keywords combined as a search string. The dataset obtained is subjected to patent analytics using Derwent Data Analyzer, a licensed tool from Clarivate Analytics. The analysis is done to study innovation and competitive trends in NDT modalities applied to gas turbine applications with limitations on the filing jurisdictions as well as the patent application filing date post 2012. The study presents a deep dive utilizing the X-ray inspection modality and attempts to provide a perspective on the role of patent analytics in driving strategic innovation.

2. PATENT ANALYTICS – PROCESS FLOW

The current section lists the basic process flow used in the current study and a schematic is provided in Figure 1.

Step 1: In the current study, the initial search scope covers patent data which relate to NDT without any limitation on the end application. However, due to the large data-size, the study is restricted to patents and applications filed on or after January 1st, 2013 (i.e., filed in the past 10 years). A further restriction is made to the jurisdictional coverage and the search is limited to filings in US, Europe (EP), WIPO PCT Filings (WO), Germany (DE), England (GB), France (FR), Canada (CA) and Japan (JP). China and other Asian jurisdictions are considered “out-of-scope” in the current study on account of difficulties in handling machine based English language translations of patents.

Step 2: A search strategy is formulated and is depicted in Figure 2. The search string is supplemented with limitations listed in Step 1.

Step 3: The search string is provided as input to Derwent Innovation and the resulting patent and application data is downloaded inthe prescribed format (.dda). The downloaded file comprises one member per INPADOC (International Patent Documentation Center) patent family. An INPADOC patent family [6] can be defined as comprising all patent documents sharing directly or indirectly (i.e., via a third document) at least one priority. One representative member of the INPADOC patent family is only considered for the current analysis. The search string essentially comprises a list of NDT related keywords in the title, abstract, claims or description section of the patent in addition to other limitations such as the application date of 1st January 2013 onwards and the limitation on jurisdictions as described in the previous steps.

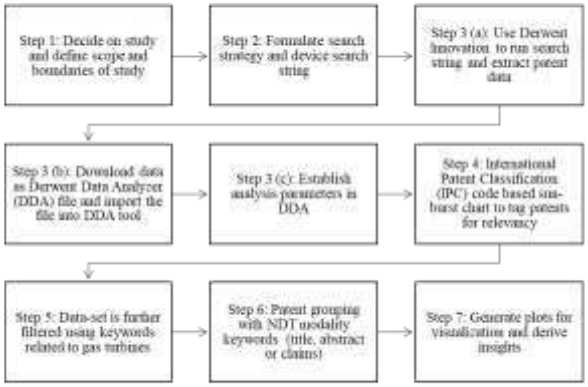

Figure 1. Patent Search and Analysis Process Flow in Derwent Innovation and Derwent Data Analyzer

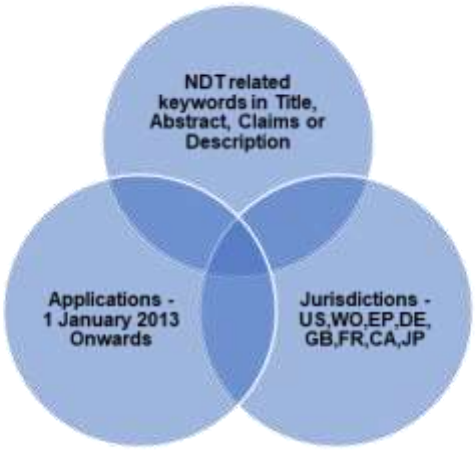

Figure 2. Representative Search string used in Derwent Innovation is the intersection region of the three circles

Step 4: International Patent Classification (IPC) codes available for each patent are used to produce an IPC code-based sun-burst chart. IPC codes are a hierarchical system of language-independent symbols for the classification of patents and utility models according to the different technical fields to which they belong [7]. Symbols are arranged in a hierarchical, tree-like structure [7,8]. Figure 3 depicts the sun-burst chart of the IPC classification codes of patent data obtained in the previous step. The width of each sector is a representation of the count of INPADOC patent families under that classification. It can be observed that patents with G class (broadly relates to physics) are relatively higher in number compared to the other codes. Within the G class, the classification G01 appears to have a relatively larger dataset for the current search scope. G01 relates to measuring and testing. There are further definitions on patent code sub-classifications available in [7]. It should be noted that typically every patent or published patent application is tagged with one IPC code and in most cases with multiple codes. Based on the data obtained, the patents tagged with 'A' classification which relates to "Human necessities" [8] have not been included in the current search scope.

Step 5: In the next step, the search results were further restricted to gas turbines (used in aero-engines, power industry, Oil and gas turbo machinery and related examples). This restriction was accomplished by employing keywords related to gas turbines anywhere in the text of the patent.



Figure 3.IPC sun-burst chart of search results

Step 6: The dataset obtained from Step 5 is further analyzed by segmenting patents on the appearance of keywords related to common NDT modalities including ultrasonic, X-ray inspection, acoustic inspection, thermography, visual inspection among others.

Step 7: Based on the above analysis, visualization is adopted to derive insights on the innovation timeline, key players, and their relative position broadly across the NDT modalities. It is noted here that the accuracy of the current analysis is based on the defined search scope (limited due to the large dataset for the present study) and the accuracy of the tool in segmenting patents in the dataset into select groupings. A further example of X-ray inspection is also described.

3. DISCUSSION

The outcome of the patent analytics process flow is provided in the current section. Figure 4 lists the modalities and the associated count of INPADOC patent families. The plot depicts percentage of total filing count.

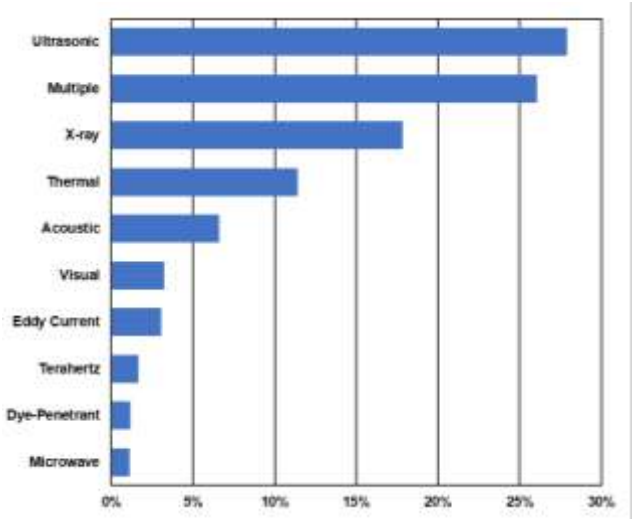

Figure 4.NDT modality and associated INPADOC patent family count

Within the scope of search, the results have been listed in terms of percentage coverage of the total dataset obtained. Ultrasonic inspection as well as radiographic inspection, independently have the highest filing presence. In the figure, multiple modalities relate to patents where multiple NDT modalities have been listed. A typical example would relate to an application where the surface irregularities could be assessed by eddy current inspection and defects present deeper in the sample could be evaluated using ultrasonic inspection. There is lower filing focus on modalities such as microwave inspection and dye-penetrant inspection.

Figure 5 depicts the count of INPADOC patent families as percentage coverage of the total dataset for the listed NDT modalities applied to gas turbines against the application year. The application year for a filing relates to the date when the application is filed with the patent office. The filing trends for NDT modalities can be visualized for patent data that is publicly available. Typically, it takes eighteen months for a patent application to become public from the time of filing the application. There isgood possibility for an increase in the filing counts, particularly in 2021 and 2022. Within the scope of search, the filing trends across all modalities are reasonably consistent. There is no distinct spikein the filing count. It can also be seen that relative to the individual modalities, the segment “Multiple” which relates to either a combination of modalities or the concept applicability to more than one NDT modality, is typically higher. This trend, based on the current search scope, is suggestive of higher filing focus on inspection image processing, data analytics and data transfer which could be leveraged across multiple modalities. Though there are a few filings which relate to the combination of multiple modalities, there could be potential filing opportunities in employing data fusion to drive desired results by combining the data from multiple modalities.

Figure 6 depicts the INPADOC patent family count of select patent assignee/ applicant against the application year. The assignees with relatively higher filing count have been selected for the plot.

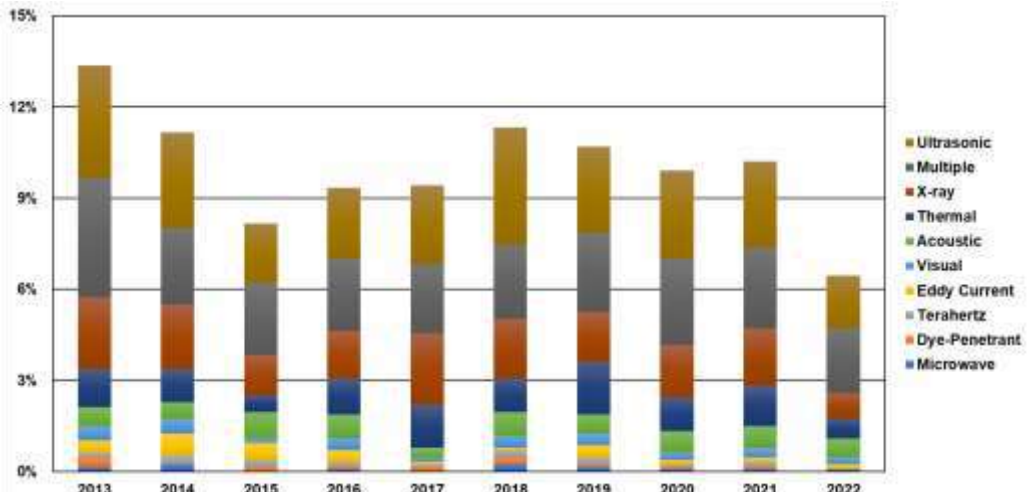

Figure 5. Plot of NDT modality patent family count Vs Application Year

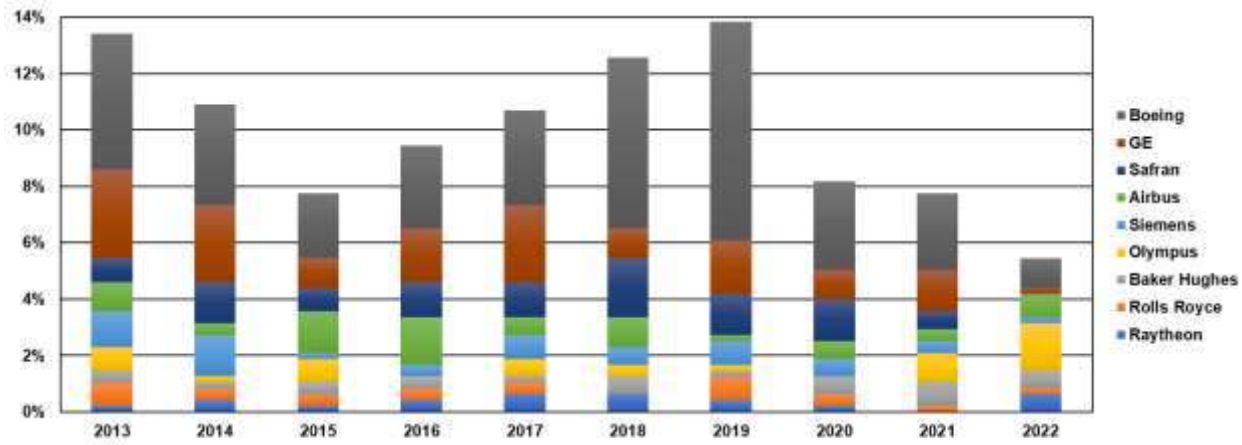

Figure 6. Assignee/Applicant patent family count Vs Application Year

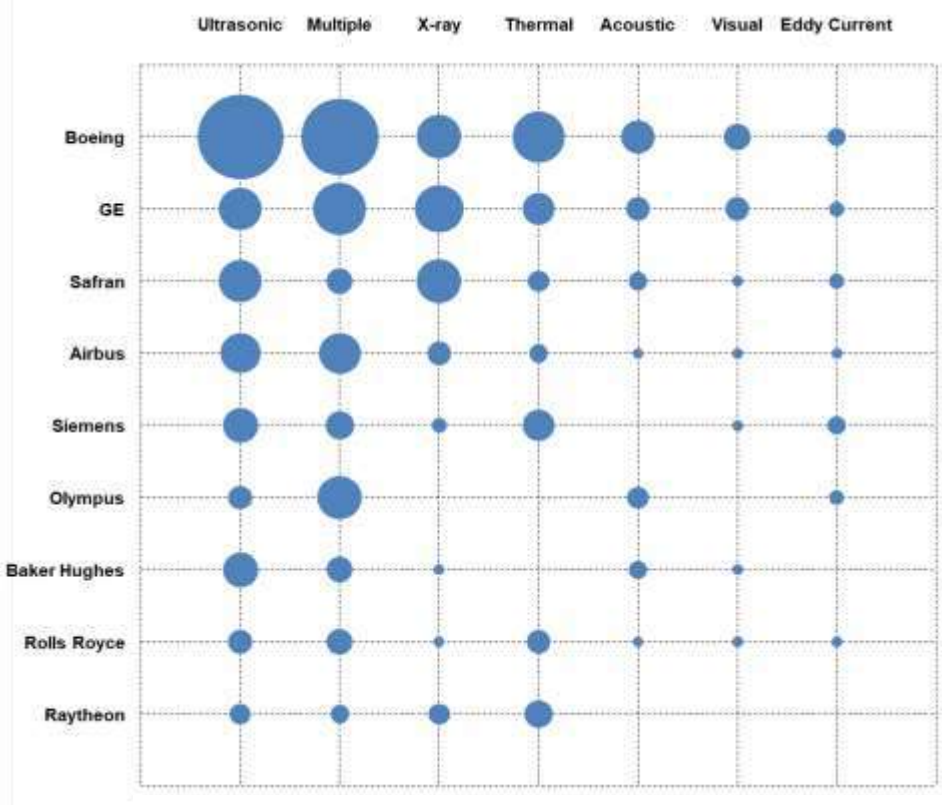

Figure 7. Assignee/Applicant patent family count Vs NDT modality

The assignee refers to the owner of the patent rights for the respective patent. It can be an individual or an organization. Within the scope of search, Boeing and General Electric (GE) have sustained their filing activity across NDT modalities. Olympus has increased its filing activity in the past two years. However, for the rest of the assignees listed in the plot, the filing trend has been maintained with no noticeable peaks in filing activity.Figure 7 depicts the patent family count of select NDT modalities plotted against select assignee/applicant.

The size of the bubble is representative of the INPADOC patent family count for the select assignee and NDT modality. Select players have been identified, particularly from the Aviation and Power industry including airframer such as Boeing and Airbus as well as aircraft engine OEM's. Boeing leads the count followed by GE and Safran. Boeing's filings in the current search scope have high focus on ultrasonic inspection, in most cases, for composite

component inspection and data analytics and multiple modality inspection. The general trend across the select assignees in the plot is suggestive of higher filing focus in ultrasonic inspection as well as multiple modality inspection followed by X-ray radiography/computed tomography. Other modalities such as Terahertz, Microwave and dye-penetrant inspection have not been included in the bubble chartas they have relatively lower filings compared to the other listed modalities. Airframers and engine manufacturers are primarily focused on ultrasonic inspection, X-ray radiography and thermal imaging techniques for their select applications. Olympus and Baker Hughes also have a relatively high filing focus on ultrasonic inspection and multiple modality inspection. A few filings from Baker Hughes also cover inspection data report generation and sharing. Though two representative examples of plots have been provided, it is possible to analyze the dataset further to generate insights on assignee timeline and broad innovation focus areas for a specific modality or a specific industry player.

To illustrate an example for a specific NDT modality, the dataset for X-ray inspection is chosen for further analysis. The dataset is filtered to include only those records which relate to X-ray based inspection, either as an independent modality or in combination with other NDT techniques. The data is then subject to a manual analysis to segment each record in the dataset into one of eight segments (listed below) based on the independent claim.

(a) **Machine:** Filing relates to describing machine aspects including X-ray inspection system layout or portable systems.
(b) **Machine-Source / Source:** Filing relates to the X-ray source assembly or their construction.
(c) **Machine-Detector / Detector:** Filing relates to the X-ray detector configuration.
(d) **Machine-Scanner / Scanner:** Filingrelates to the X-ray scanner system.
(e) **Application:** Filing relates to the end-application (specific component being inspected) such as composite fan blade, composite components, in-situ inspection in additive manufacturing and component repair.
(f) **Image processing:** Filing relates to image processing.
(g) **Analytics:** Filing relates to analytics on the inspection data obtained to derive the parameter of interest. It also includes instances where machine learning algorithms are used in defect detection.
(h) **Others:** Filing relates to data sharing, fleet management, signal processing and other related aspects.

The segmented data is further plotted against application year and assignee. Figure 8 depicts the variation of filing count based on the above listed technology segments with application year. It is evident that the innovation timeline is suggestive of increasing focus on data analytics as well as image processing algorithms for defect detection. There is also interest in applying machine learning algorithms for defect detection. Besides analytics, it can be observed that there is also an increasing focus on the X-ray detector configurations, the related delivery optics arrangement as well as other related features for improved durability.

Figure 9 depicts a bubble chart mapping INPADOC patent family count of select assignees to pre-defined technology segments. Boeing's filings are focused on X-ray inspection system layouts, innovations in the scanner and detector systems, primarily to handle composite inspection. Furthermore, Boeing and GE have filings across most of the technology segments while Safran has a relatively higher filing count on image processing techniques. In addition to Aviation and Power generation players, Canon and Nikon also have filing presence focusing on the X-ray scanning system. Within the scope of the current search, aspects such as inspection data sharing across multiple systems, license sharing among other features have seen relatively lower filing focus. Though there are filings from several players utilizing data analytics for NDT, there are potential opportunities to explore machine learning algorithms to improve the detection speed without compromising on detection accuracy. The example presented is also a relatively broad study and can be further explored to derive useful insights on specific aspects of X-ray inspection. It can thus be seen that the information obtained from patent analytics could be leveraged to understand competitor activity. This information is useful in formulating the innovation strategy for the organization.

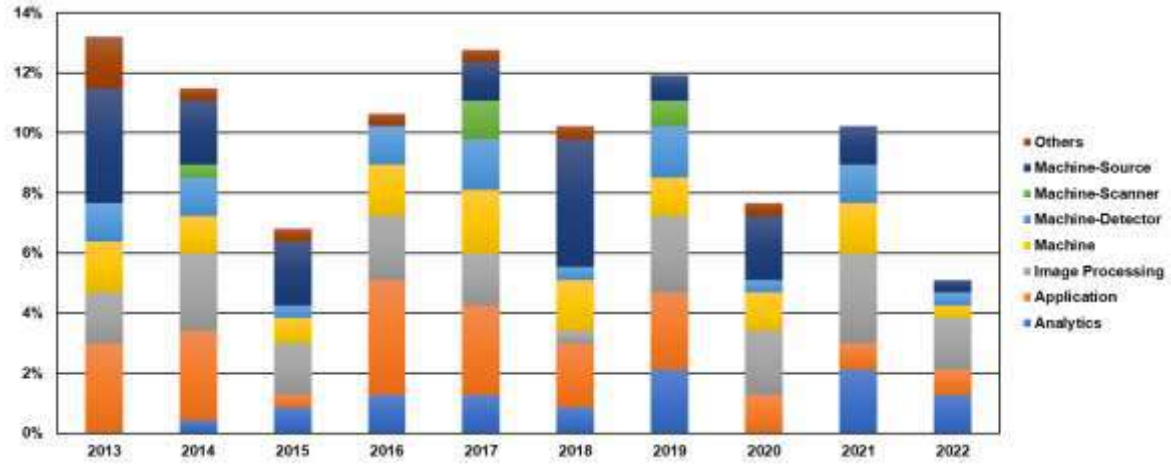

Figure 8.X-ray Inspection: Technology Segment plotted against application year

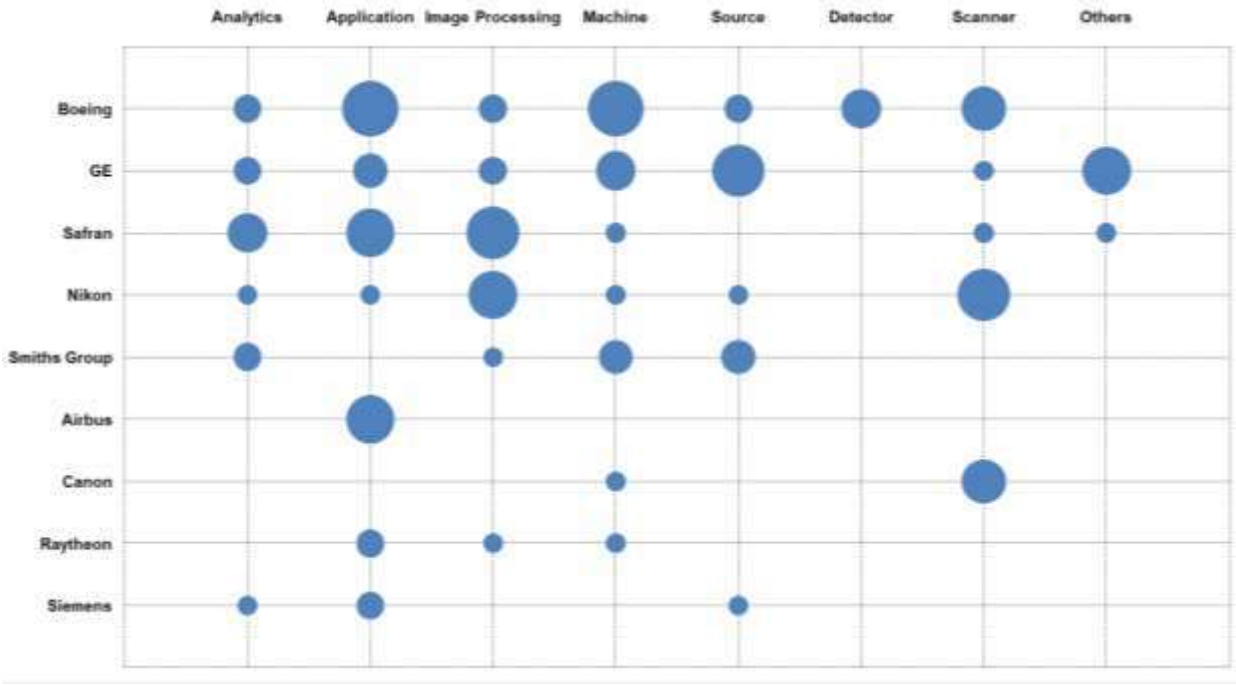

Figure 9. Bubble chart of Assignee/Applicant and technology segment

4. CONCLUSION

The study focused on understanding the patent landscape with application to gas turbines along with jurisdiction and application year restrictions. Within the scope of search, the key observations are listed below.

- Broadly, across all modalities, ultrasonic inspection as well as radiographic inspection, independently have the highest filing presence.
- There is relatively lower filing focus on modalities such as microwave inspection and dye-penetrant inspection.
- Within the scope of search, Boeing and GE have sustained their filing activity across NDT modalities. Olympus has increased its filing activity in the past two years.
- Potential filing opportunities exist in employing data fusion to drive desired

results by combining the data from multiple modalities.

- Boeing has high filing focus on ultrasonic inspection, in most cases, for composite component inspection and data analytics and multiple modality inspection.
- Airframers and engine manufacturers are primarily focused on ultrasonic inspection, X-ray radiography and thermal imaging techniques for their non-destructive inspection needs. Olympus and Baker Hughes also have a relatively high filing focus on ultrasonic inspection and multiple modality inspection. A few filings from Baker Hughes also cover inspection data report generation and sharing.
- A further study has been conducted on X-ray inspection related filings. Boeing and GE have filings across most of the technology segments while Safran has a relatively higher filing count on image processing techniques.
- In addition to aviation and power industry players, Canon and Nikon also have filing presence focusing on the X-ray scanning system.
- Within the scope of the current search, aspects such as inspection data sharing across multiple systems, license sharing among other features have seen relatively lower focus and could present themselves as potential filing avenues.

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[8] Classification code definitions https://is.espacenet.com/classification?locale=en_IS

Application of Terahertz Pulses to Non-Destructive Testing

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Abstract

For the past twenty years, TeraView has been a world leader in the application of terahertz pulses to solve problems for industry.Terahertz technology provides the opportunity of remote, safe, fast and accurate sensing. In recent years, there has been a growing interest from industry in applying terahertz pulses to process control.In this paper, there is a brief review of the generation and detection of terahertz waves (0.1 THz to 6THz) using photoconductive antennas.The applications of time-domain spectroscopy to gas, liquid and solids are discussed.Then, a number of industrial applications ofterahertz pulsed imagingsuch as solar cells, pharmaceutical, battery production and automotive industries are highlighted.

Keywords: *NDT;terahertz, spectroscopy, imaging, coating*

1. INTRODUCTION

Over the last few years, there has been a growing increase in the use of terahertz time-domain spectroscopy or imaging in the non-destructive testing looking at thin coatings on materials. This is due to terahertz advantages properties over other in-line and offline techniques. For example,off-line trial-and-error approach canlead to much additional wastage and equipment downtime. On the other hand, in-line techniques such as laser callipershave difficulty to be implemented with opaque coatings and their accuracy depend on regular calibration. X-ray, beta and gamma sensorssuffers from safety concerns and, in case of betta sensors the time scale required to collect accurate data is long which is a drawback in high-speed industrial applications. Ultrasound imaging relies on stable and accurate calibration. It's a contact technique and doesn't support remote sensingbenefits.Terahertzoffers the prospect of inline remote sensingthat it not harmful and its ultrafast dynamic allows for its application in places that rapid inline measurement is necessary. Previously, we have reviewed several of terahertz applications in industry (1).In this paper,different application areas of terahertz pulsesare explored.The paper is broken down into three sections.The first section very briefly reviews the generation and detection of terahertz pulses.The second is a brief review of terahertz time-domain spectroscopy.The third is time-domain imaging and looking intoseveralcase studies on the application of measuring coating thicknesses in solar cells, pharmaceutical, battery production and automotive industries.

2. TIME DOMAIN TERAHERTZ DETECTION AND EMISSION

Normally, to generate terahertz pulses, light from an ultrashort pulsed laser is focused onto a photoconductive switch (known as an Auston Switch(2)) which manufactured on a semiconductor.The laser operates at wavelengths (or photon energies) that is greater than the bandgap of the semiconductor used in the manufacture of the switch.Typically, 790 nm lasers are used for GaAs and 1550 nm laser are used for InGaAs materials(3).The pulse duration of the laser should be around 100 fs.A voltage is applied across a pair of electrodes in the photoconductive switch, see figure 1, causing an acceleration of electrons and holes in the semiconductor resulting in the emission of a short terahertz pulse of duration less than 1ps.The detectors are also based on a photoconductive switch (4).Again; some of the ultrashort laser is focused between the electrodes generating electrons and holes.However, no accelerating voltage is applied to the electrodes the driving voltage is obtained from the terahertz pulse, which is simultaneously focused onto the switch, as shown in figure 2.This generates an instantaneous of the terahertz electric field.By varying the time arrivals of the terahertz pulse and the optical pulse you can sample a terahertz waveform, shown in figure 3(a).The delay between these pulses

is known as the "optical delay".Taking the terahertz waveform and undertaking a fast Fourier transform (FFT) allows us to acquire frequency information about a sample, shown in figure 3(b).

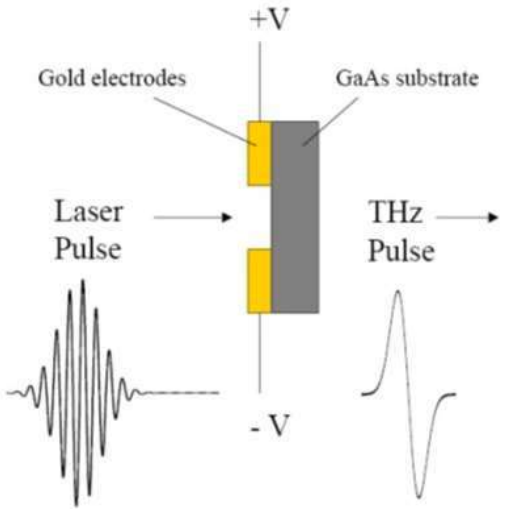


Figure 1: Schematic diagram of the operation of a photoconductive emitter switch that generates THz pulse from a laser pulse source.

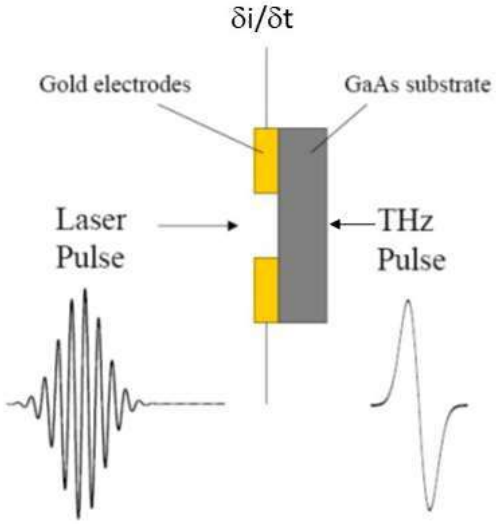
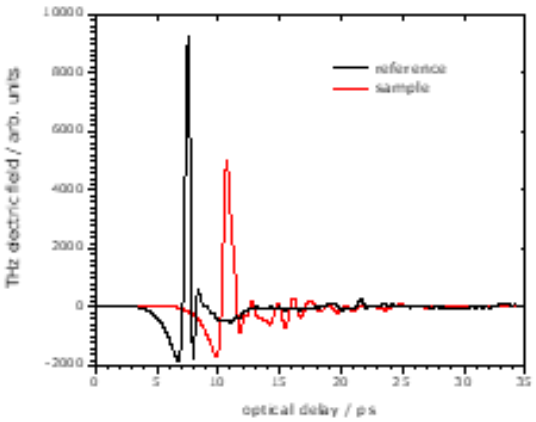


Figure 2: Schematic diagram of the operation of a photoconductive detector switch.

3. TIME-DOMAIN TERAHERTZ SPECTROSCOPY

Time domain terahertz spectroscopy is a single beam measurement where a reference is initially taken, this provides the terahertz electric field, $E_r(t)$ as afunction of time.The reference material is placed into a sample chamber and the sample waveform is measured, $E_s(t)$.As noted in the previous section, a FFT is computed, and the frequency information is recovered. The real part of the FFT provides information about the absorption of the material andimaginary part gives information about the phase of sample, thus the refractive index.

(a)



(b)

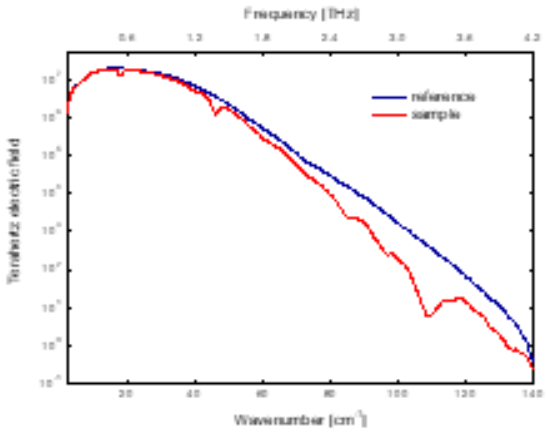


Figure 3: TeraView's TeraPulse Lx single beam spectral data for reference (black line in (a) and blue line in (b)) and sample (red line) is shown.Applying FFT techniques to the terahertz electric field in (a) yields the frequency domain data in (b).

The absorption coefficient is given by

$$\alpha(f) = -\frac{2}{d} ln\left(\frac{E_s(f)}{E_r(f)} \frac{(n(f)+1)^2}{4n(f)}\right)$$

where d is the thickness of the sample, *n(f)* is therefractive index of the sample, $E_r(f)$ is the strengthof the electric field with the reference and$E_s(f)$ is the strength of the electric field with a sample in the beam.
The refractive index, *n(f)* is given by

$$n(f) = 1 + \frac{c}{2\pi f d}(\emptyset_s(f) - \emptyset_r(f))$$

where c is the velocity of light, f is frequency, $\emptyset_s(f)$ is the phase of sample and$\emptyset_r(f)$is the phase of the reference material.

3.1 Gas-phase spectroscopy

Gas phase spectroscopy is convenient to investigate with terahertz pulses.A gas cell is placed between the emitter and receiver and the absorption due to sample molecule is measured.The transitions observed are the results of the rotation of molecule in free space.However, to generate any transitions lines the molecule must be small and have a dipole moment.For example, carbon monoxide (CO) will generate a sequence of rotational lines (5) in the terahertz region while carbon dioxide (CO_2) does not exhibit rotational lines in this region.By way of example, the terahertz absorption spectrum of water

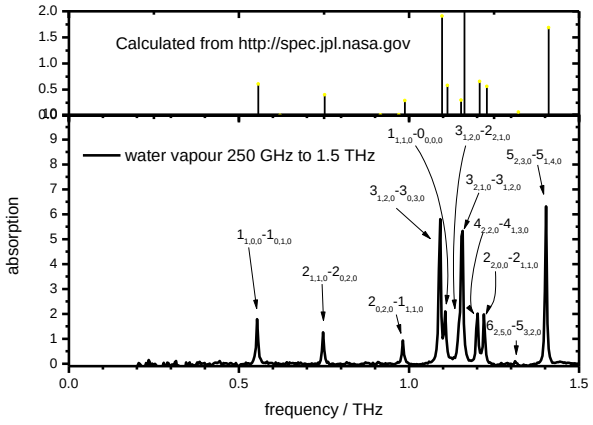


Figure 4: Terahertz absorption spectrum in the region 0.3-1.5 THz.The upper stick spectrum is calculated spectrum from the JPL website.

vapour has been reported in the literature that the observed values are in good agreement (6, 7) with theoretical values.Figure 4 shows the rotational line spectrum in the 0.1 to 1.5 THz together with their associated assignments from the NASA, JPL catalogue at http://spec.jpl.nasa.gov. A stick diagram of the theoretical intensities is also shown in figure 4.All features in the spectrum can be assigned to the rotation of the water molecules in free space.

3.2 Spectroscopy of liquids

The absorption in the terahertz region is dominated by collective, low frequency intermolecular modes of the materials.These tend to lead to broad featureless spectra with absorption increasing with frequency as shown in figure 5 for a range of alkyl alcohols from

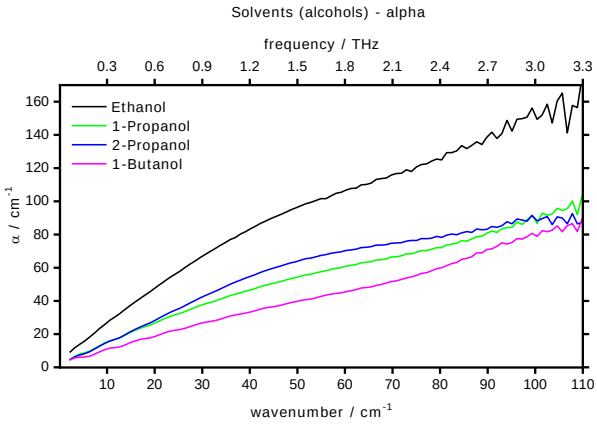


Figure 5: Terahertz absorption spectra of a series of alkyl alcohols

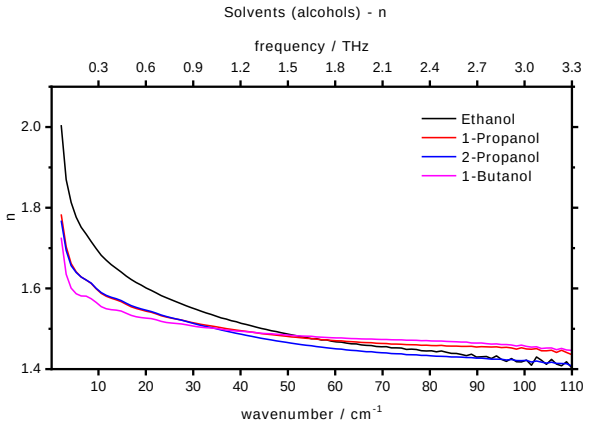


Figure 6: Terahertz refractive spectra of a series of alkyl alcohol derived from terahertz absorption spectra and prior knowledge of the cell thicknesses.

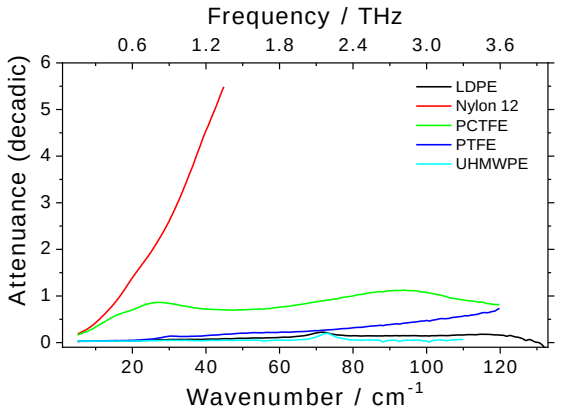


Figure7: Terahertz absorption of five windows materials in the 0.2 – 3.6 THz region.Small absorption features observed around 2 THz in UHMWPE and LDPE due to their crystalline nature.

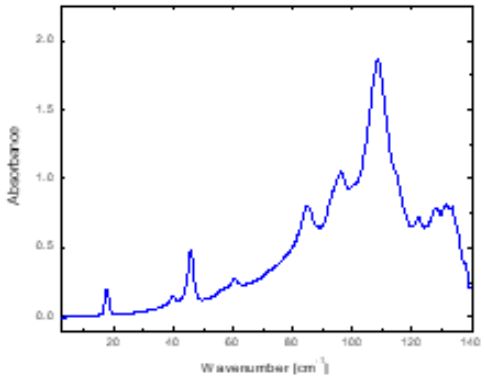


Figure 8: Terahertz absorption spectrum ofcrystalline α- lactose monohydrate that is in contrast with featureless spectrum of windows materials.

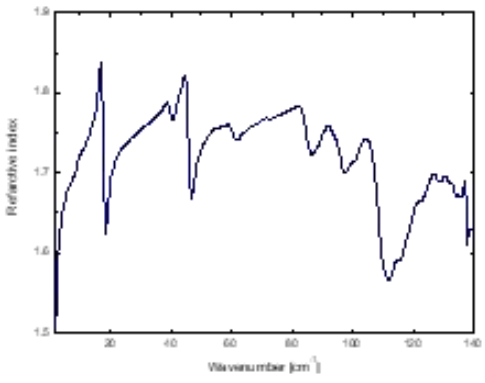


Figure 9: Terahertz refractive index spectrum of α-lactose monohydrate derived from absorption spectrum.

from ethanol to 1-butanol.These liquids were purchase from Sigma Aldrich and used without any additional sample preparation in a liquid cell with a 200 μm spacer. The broadband absorption decreases with the polarizability of the liquid. As the thickness of the cell is known then the refractive index of the liquid can be calculated as shown in figure 6.

3.3 Spectroscopy of solids

To undertake terahertz spectroscopy of solids in the terahertz region you can place the material in the sample chamber or mix the sample with the polyethylene or polytetrafluoroethylene (PTFE).The particle size must be less than 75 μm, if, the size gets greater thanthis,Mie or Rayleigh scattering will be observed from the particulates(8,9) in the sample, and in extreme,this scattering can cause artifacts in the measured spectra.Organic and some inorganic materials show spectral fingerprints in the terahertz region.These fingerprints originate from crystalline structure of the substrates rather than intramolecular modes that dominate at frequencies greater than 10-THz.Crystals allow the propagation of phonon vibrations, also known as lattice vibrations and can be thought of as collective vibrations constructed from the interaction of many intermolecular vibrations. This leads to unique signatures for polymorphic formsof drug substances (10, 11) and hydrates of organic materials(12). If a material is amorphous, the lack of long-range order prevents propagation of the phonon vibration and the energy associated with the vibration is diffusely dissipated within the material and shows broad featureless spectra which contains a surprising amount of information about the stability of these materials(13, 14).Figure 7 shows the terahertz absorption of five window materials showing in broad featureless absorptions, however, small absorption features maybe observed around 2 THz in Ultra-high-molecular-weightpolyethylene(UHMWPE) andLow-density polyethylene(LDPE) as these materials are crystalline in their nature.Both PTFE and LDPE are ideal materials for windows in the terahertz region due to their low absorption.These materials can be contrastingwith the spectral rich crystalline α-lactose monohydrate shown in figure 8 and its corresponding refractive index is shown in figure 9.
The absorption spectrum shows series of phonon vibration with the feature at 17 cm^{-1}having a linewidth of less than 0.35 cm^{-1} which is unusually narrow for the terahertz regional long-lived

vibration. For a complete review of band assignments in the terahertz region the authors suggest the reader to review the excellent work by the Ruggiero group at University of Vermont (15,16).

4. TIME-DOMAIN TERAHERTZ IMAGING

In the previous section, the terahertz pulse generated from the semiconductor was used to understand spectroscopy of materials.In this section, the application of terahertz in imaging is explored.Most non-conducting dielectric materials are semi-transparent to terahertz pulses.Which means if a sample is illuminated by a terahertz pulse,E_0, then some of pulse will propagate into the material and wherever there is a change of refractive index with density of the material a reflection, R_0 and R_1, will occur as shown in figure 10. As terahertz time domain imaging is time-gated, we can monitor pulses coming back from the sample at different times. Knowing the refractive index, *n*, of the material enableto calculate the depth of any feature from inside a product or the thickness of the coating, *d*.

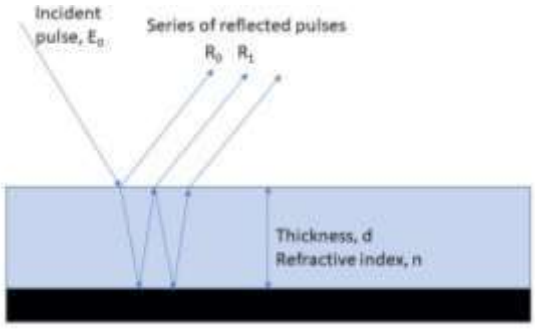


Figure 10: Schematic diagram of the interaction of a terahertz pulse with a material. Thickness can be derived by prior knowledge of refractive index and reflected terahertz pulses.

4.1 Non-destructive testing of tablets

One of the first examples investigated by TeraView was solid dosage forms or tablets or pills(17-20). Tablets made by the pharmaceutical industry are normally coated with a thin layer to disguise the taste or control the release of the pharmaceutical product of the active pharmaceutical ingredient.TeraView was the first company to use a six-axis robot to move the tablet in front of a terahertz focus to generate a 3-d map of the coating thickness.Figure 11 shows the schematic diagram of the interaction of a terahertz pulse with a tablet.The terahertz pulse is illuminated onto the tablet's surface, some of the light is reflected from the front surface, theremaining light propagates into the tablet itself and whenever it sees a change in density or refractive index. Portion of the light is reflected to the detector with a time delay. Waveform from an enteric coated tablet is shown in figure 12. This tablet was coated with an active first layer and a sub-coat between the tablet core and enteric coat. The first peak (at 0.0 mm) is from the remaining light propagates into the tablet itself and whenever it sees a change in density or refractive index, portion of the light is reflected to the detector with a time delay. The strength of the reflection can be related to the effective refractive index of the material and thus the density of coating (21). The next peak is at about 0.15 mm. The distance between the two peaks divided by the refractive index is the thickness of the first enteric coating. There is a third negative peak at about 0.2 mm, this is the enteric coat/sub coat interface.The direction of the peak indicates the relative change in refractive indexbetween the coating. In this case, the change is from high refractive index to low opposite the changes that lead to positive peaks.

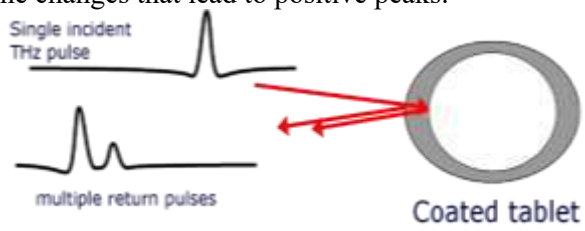


Figure 11: Schematic diagram of the interaction of a terahertz pulse and a coated tablet.The beam partially propagates into the sample and some of the beam reflects.

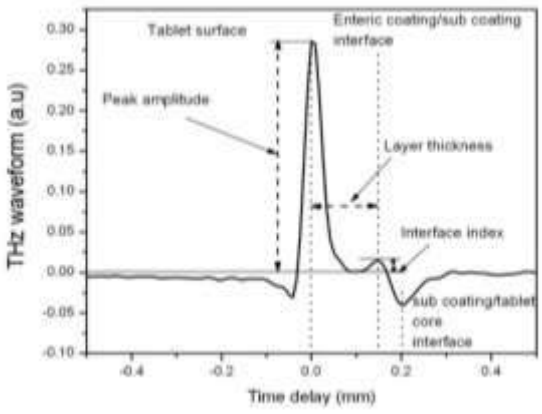


Figure 12: The reflected terahertz pulse from an enteric coated tablet.

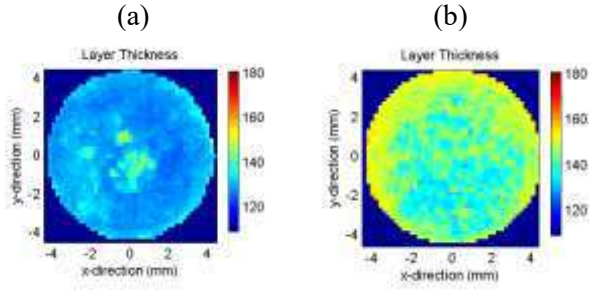


Figure 13: Layer thickness of two tablets from the same batch plotted on the same colour scale. It is possible to see large variation within a process on tablets. The coating thickness uniformity over two samples can be observed. Also, coating on sample (b) is thicker than coating on sample (a).

The data shown in figure 12uses the deconvoluted waveform(20) given by

$$S_{Dec}(t) = iFFT\left[FFT\,(f(t)\frac{FFT\big(s(t)-b(t)\big)}{FFT\big(r(t)-b(t)\big)}\right]$$

where *b(t)* is the baseline pulse, *r(t)* is the reference pulse and *s(t)*are the sample pulse. A filter function of the form

$$f(t) = \left(\frac{e^{-\left(\frac{f}{HF}\right)^2-\left(\frac{f}{HF_2}\right)^8}}{HF}\right)\left(1-e^{-\left(\frac{f}{LF}\right)^2}\right)$$

is used. The parameters *HF* and HF_2 are the high-frequency cut-off and *LH* is a low frequency cut-on filter and *f* is frequency.All parameters are in units of terahertz.HF_2 is the brick-wall cut-off frequency.This would be usually set high say to 4 THz and HF is typically about 2 THz but can be varied to optimise the quality of the waveform. The deconvolved waveform gives rise to an easierunderstand of an else complex waveform.Using the robot to move the tablet, the variation of coating thickness(22) around the tablet can be ascertained.Figure 13 shows two tablets ((a) and (b)) from the same coating batch, their coating thicknessesare plotted on the same colour scale to highlight the variation of coating thickness within the coating process not only inter tablet but also intra tablet. The uniformity of the coating can be inspected form these terahertz images. Also, it can be seen that the coating on sample (b) is thicker than sample (a).

Recent progress has also been made on implementing a terahertz sensor within the coating process itself(23,24).Figure 14 shows a terahertz sensor inside a production coater. The sensor can provide process information over the 5-hour coating run (23).



Figure 14: TeraView's terahertz sensor looking into the back of a coating drum during coating process.The sensor was used through-out the 5-hour coating run.



Figure 15: Crucible scanning unit designed to measure the coating thickness of the silicon nitrate power coatings using terahertz pulses.

4.2 Non-destructive testing of coated crucible walls used in solar cell manufacture

In manufacture of multi crystalline silicon ingots for solar cell industry silicon is melted at high temperature in silica-based crucibles.To improve the yields of the silicon ingots a silicon nitrate power coating is strayed onto the crucible walls.The uniformity of these walls can be investigated by

terahertz pulses.Figure 15 show the scanning developed by TeraView to scan each of the walls of the crucible.The unit is designed to map of the crucible first with a laser gauge to understand the morphology of the crucible and then later with the terahertz pulses to understand the coating thickness.Figure 16 shows the thickness uniformity of each of the walls of the crucible.It shows that the coating is thicker on the floor of the crucible and to each of the edges of the walls. The terahertz measurement can then be used in the modifying the algorithm controlling the robot in the spray of the silicon nitride powder onto the crucible.

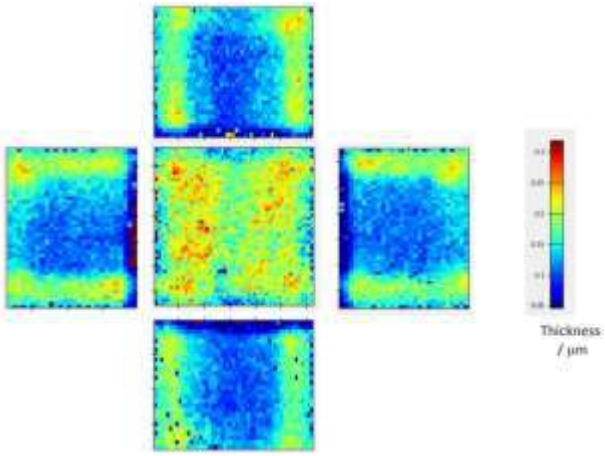


Figure 16: Thickness map derived from the terahertz measurement.The thickness uniformity of each of the walls of the crucible is inspected.

4.3Non-destructive testing of cathodes for EV battery production

Over the next two decades countries around the world will be banning the sale of new fossil fuel-based automobiles. This requires a large expansion of giga factories around the world to manufacture they the required demand for EV batteries. There are currently of the order 200 giga factories that have been built or are in the planning stage.One key factor in battery manufacturing process is electrode productions. The quality of a battery pack is determined by the consistency and quality of the coating on the electrodes. Time-domain terahertz pulses can over other techniques byits ability to simultaneously measure the real (n_o) and imaginary (k) parts of the refractive index of the coating, $n=n_o+ik$ as well as the thickness of the coating. This unique capability of terahertz pulses provides important information on key performance indicators for the coating in battery manufacturing process. The measurements can be done in the laboratory or on-line with webbing moving at serval 10's of metres per minute.For these applications TeraView has develop algorithms that do not require prior knowledge of the cathode properties. Also, in industrial environment, taking reference signals could be inconvenient. TeraViewdeveloped anovelsensor to tackle this challenge by self-referencing mechanism (25-28).

Figure 17 illustrates an example how terahertz enable coating inspection in electrode production process.The measured terahertz signals from two separate cathodes are shown. Since both samples are fabricated from the same material, the difference in time of flight in two waveforms($\Delta t_2 > \Delta t_1$) interpreted sample 2 is thicker than sample 1 and their thickness can be extracted. That helps to evaluate the deviation of the manufactured cathode from initial design.

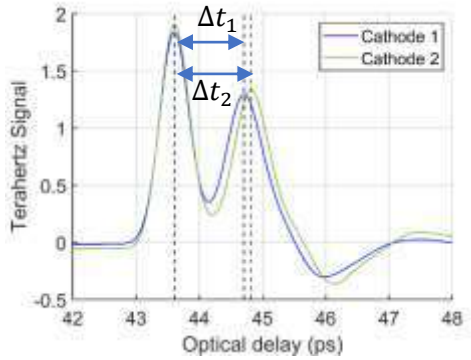


Figure 17: Terahertz measurement for battery cathodes with different thicknesses. As two cathodes are manufactured from same material, the difference in their peak separation interpreted as their thickness difference.

4.4Non-destructive testing of paint on automobiles

A rapidity evolving area of terahertz pulsed applications is the inspection of paint layers on newly painted automobiles. The current techniques of ultrasound and eddy currents are both contact methodswhich in the case of ultrasound requires coupling fluids.The terahertz technique is non-contact and thus a sensor can be placed on the end of a robot arm and moved to different area of a vehicle for paint inspection(29).Unlike, the previous examples in this paper where layers are most likely to be single or at most two layers, car paint are complex multilayer structures. The paint structure on cars normally consists of an electrocoat (about 20 µm thick), a primer (between 10-30 µm thick), a basecoat (about 30 µm thick) and a protective clear coat (between 20-

40 μm thick).Each of layers will generate a reflection if there is a change of refractive index between the layers.Figure 18 shows the terahertz waveform of a car paint sample.There are multiple peaks associated with each of the paint layers, the negative peaks to the right of the electrocoat/substrate interface (at 0.0 mm) are a result of multiple reflections within the sample.To recover the thickness of each layer algorithms have been developed based in the interaction of terahertz pulses with layer and requires knowledge of the complex dielectric function of the materials, n_o+ik, an example of which is by Krimi *et al.*(30)and van Mechelen *et al.*(31)
Shown in figure 19 is TeraView's TeraCota terahertz sensor head.Associated with this head is a control unit based on a 19-inch rack format that can be placed several metres from the robot. The control unit contains a computer server for interfacing in the local production environment and providing information about the paint thickness over the car body.

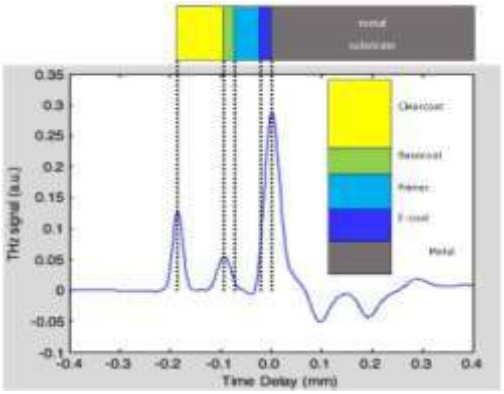


Figure 18: The terahertz waveform from a car paint sample. There are four layers including electrocoat, primer, basecoat and clearcoat.The negative peaks after the metal surface are multiple reflections within the sample.



Figure 19: The TeraCota sensor head on the end of a robotic arm in a test environment.The robot is able to move with six- or seven-axis depending on the application.

5. CONCLUSIONS

Over the last twenty years, TeraView has been at the front of the application of terahertz pulses to industrial applications. In this paper, terahertz generation and detection concisely are explained, and terahertz spectroscopy and imaging applications in industry are outlined. Additionally, terahertz applications in the areas of pharmaceutical, silicon production in solar cells, EV battery and automotive paint inspection are described. Terahertz technology finds its place in non-destructive sensing and promises a wealth of applications wherever safe, remote, fast and accurate sensing is required.

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Emissivity Related Correction Approaches for Temperature Monitoring Using Infrared Thermography

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Abstract

Accurate estimation of the spatio-temporal temperature evolution of material aids in understanding the thermal characteristics of materials and indentifying anomalies (if any). Infrared thermography is a popularly used technique for temperature measurement, which is non-contact in nature. The efficiency of this technique for estimating temperature depends directly on the emissivity, which is a material surface property. The lack of information on emissivity or variability in emissivity is likely to affect the temperature estimation. This paper discusses the importance of emissivity in temperature estimation followed by the illustration of various factors that may affect temperature estimation using infrared thermography. In addition to that, various temperature correction approaches related to unknown and variable emissivity has also been discussed.

Keywords: *Emissivity, temperature monitoring, infrared thermography, correction approaches*

1. INTRODUCTION

Temperature monitoring can be defined as the process of measuring, recording, and analyzing the spatio-temporal temperature evolution of a material. The monitoring of temperature is important in various fields of science and engineering like medicine [1], manufacturing [2], condition monitoring [3], material characterization [4] etc. Any abnormality in the temperature evolution of the material indicates some underlying issues, for instance, abnormal human skin temperature indicates health concerns [5], a high temperature in an electrical circuit may indicate some fault in circuitry [6], unusual temperature evolution during characterization may signify variation in material properties [7] etc. Hence, accurate estimation of the temperature is necessary for ensuring the efficient and safe operation of varied applications.

Temperature monitoring is done using temperature sensors which can measure temperature either using a contact approach or a non-contact approach [8]. In the contact approach, the temperature is sensed by establishing physical contact between the sensor and the material under investigation (MUI). Some commonly used contact temperature sensors are thermocouples, thermopiles, thermometers, resistive temperature detectors (RTD) etc. Most of the contact temperature sensors are inexpensive and have a rugged design. However, it is capable of only single point measurement and the measured value is likely to be influenced by contact resistance. While, in the non-contact approach, no physical contact needs to be established between the sensor and the MUI for temperature monitoring. Infrared detectors are popularly used non-contact sensors. The technique of temperature measurement using an infrared detector is referred to as infrared thermography (IRT) or simply thermography. The main advantage of infrared thermography over any contact sensor-based measurement is that it is non-intrusive in nature. Secondly, it is capable of large area surface temperature monitoring, which yields temperature information of the entire surface via surface maps [9].

The true temperature estimated by infrared thermography is a function of the magnitude of infrared radiation emanating from the surface of MUI [10]. The ability of a material to emanate infrared radiation depends on a surface property referred to as emissivity. Hence, the accuracy of the temperature estimation by infrared thermography is also dependent on the emissivity of the MUI. The temperature estimation using infrared thermography for a material with high emissivity is better than that

of a material with low emissivity when both materials are at the same temperature. Many a time, the emissivity of MUI is either unknown or varying spatio-temporally, in such situations the temperature estimation using infrared thermography may result in some erroneous value. To deal with such situations, researchers working in the area of infrared thermography have come up with different correction approaches for estimating the temperature close to the true value. In this paper, an effort has been made to broadly discuss different temperature correction approaches. The paper is organized as follows. The subsequent section covers the basic principle of temperature monitoring using infrared thermography. Followed by a discussion on some emissivity related temperature correction approaches.

2. TEMPERATURE MONITORING USING INFRARED THERMOGRAPHY

A basic infrared thermography setup for temperature monitoring includes an infrared detector (infrared camera), MUI, a data acquisition system, and an excitation source (optional only in case of active infrared thermography [11]). Fig. 1 shows the infrared thermography setup for temperature monitoring.

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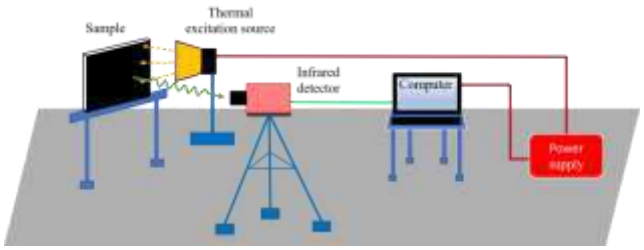

Fig 1. Basic infrared thermography setup

The infrared radiation (I) emanating from the surface of the MUI and detected by the infrared detector (depicted by the green wavy arrow in figure 1) broadly comprises of three components i.e., absorbed, reflected, and transmitted (Fig. 2), as shown in eq.(1).

$$I = (I_{MUI})_A + (I_{MUI})_R + (I_{MUI})_T \quad (1)$$

Where $(I_{MUI})_A$, $(I_{MUI})_R$ and $(I_{MUI})_T$ refer to the absorbed, reflected and transmitted component of the energy emanating from the MUI surface respectively. For an opaque MUI, $(I_{MUI})_T$ is considered to be negligible and subsequently eq. (1) simplifies to eq. (2).

$$I = (I_{MUI})_A + (I_{MUI})_R \quad (2)$$

As per Kirchhoff's law, at thermal equilibrium, the absorbed energy is considered to be equal to the emitted energy (i.e.,$(I_{MUI})_A = (I_{MUI})_E$) [12] and hence eq. (2) can be rewritten as eq. (3).

$$I = (I_{MUI})_E + (I_{MUI})_R \quad (3)$$

The true temperature of a material is majorly a function of the absorbed component ($(I_{MUI})_A$) of the energy emanating from the MUI surface [13]. In an ideal scenario, the infrared radiation detected by the infrared detector is composed of only the emitted (or absorbed) component, which subsequently yields the true temperature. However, in a real scenario, as the detected radiation also has a stray component (i.e., $(I_{MUI})_R$) in addition to the emitted component, the estimation of temperature using infrared thermography is not straightforward. The stray component or $(I_{MUI})_R$ is the reflected radiation that comes from different surrounding media. The contribution of $(I_{MUI})_R$ results in the variation of the estimated temperature from the true temperature. In order to minimize the deviation of the estimated temperature from the true temperature, the contribution of $(I_{MUI})_E$ should be significant in the radiation detected by the infrared detector. This is possible either by increasing the contribution of $(I_{MUI})_E$ in Ior by reducing the contribution of $(I_{MUI})_R$ in I. Both increasing or decreasing the contribution of $(I_{MUI})_E$ and $(I_{MUI})_R$ is related to the emissivity of the MUI. As already mentioned, emissivity is a material surface property, which explains the ability of a surface to emit radiation. Mathematically, emissivity is defined as the ratio of the actual amount of infrared energy emitted by MUI to the theoretically perfect amount that could be emitted [14] and is expressed as follows

$$\varepsilon = \frac{(I_{MUI})_E}{(I_{MUI})_{Eb}} \quad (4)$$

where $(I_{MUI})_{Eb}$ refers to the theoretically perfect amount that could be emitted as in the case of blackbody. A blackbody is an ideal body, which

emits radiation equal to absorbed and has an emissivity value equal to 1. All the real bodies have an emissivity value of less than one. A relation between the emissivity of a material and the ability of a material to reflect (i.e., reflectivity) can be deduced by dividing both sides of eq. (3) with *I*, which can be written as follows

$$\varepsilon + \rho = 1 \qquad (5)$$

where$\varepsilon = \frac{(I_{MUI})_E}{I}$ and $= \frac{(I_{MUI})_R}{I}$.

As already mentioned, the material surface temperature depends upon the emitted component, hence it is imperative to have knowledge of material emissivity. The emissivity of material can be obtained directly from material handbooks or by conducting the task mentioned in ASTM standard E1933-97 [15]. However, it is not always possible to carry out tasks declared in ASTM standard E1933-97 in many industrial applications, which face emissivity related concerns. In such situations, it is necessary to resort to correction approaches for approximating the true temperature of the material. In the next section, some emissivity related temperature correction approaches will be discussed.

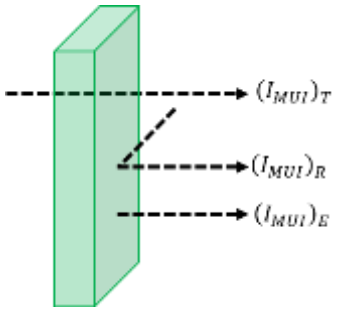

Fig 2. Components of infrared radiation detected by infrared detector

3. TEMPERATURE CORRECTION APPROACHES

Knowledge of the emissivity is crucial for accurate temperature estimation. However, in many practical scenarios despite the knowledge of the material emissivity, it is not possible to determine the true temperature accurately due to the spatio-temporal variation of the emissivity. As emissivity is a surface property, any kind of degradation or change to the surface of the MUI will affect the emissivity, which will subsequently influence the estimation of the temperature [16]. The most common approach to deal with emissivity variation during temperature measurement is coating the material with matt finish black paint. Painting the surface of MUI black ensures good absorption as well as good emission of infrared radiation and eliminates non-uniformity of surface emissivity. However, painting the surface of MUI black for enhancement of emission may not always be an appropriate solution, in the first place because the MUI may be at a remote location, and secondly the coating may interfere with the heat transfer process of the MUI and ultimately alter the temperature [17]. In order to take advantage of infrared thermography, it is necessary to overcome the limitations caused due to unknown or variable emissivity. In the following subsections, some approaches which have been developed for correcting temperature due to the variation in emissivity will be discussed.

3.1Single wavelength infrared thermography

Single wavelength thermography is otherwise also referred as monochromatic infrared thermography. This is a conventional approach of estimating the surface temperature, wherein the infrared radiation emanating from the surface of MUI is detected over a single wavelength range for inferring the temperature [18]. A typical setup of single wavelength thermography is similar to as shown in Fig. 1. This approach will yield satisfactory results as long as the $(I_{MUI})_E$ component is significant in the infrared radiation emanating from the surface. In situations, when the magnitude of infrared energy from background sources is significant (like, when the MUI is near too hot or too cold object), this technique is likely to yield erroneous results as the magnitude of stray infrared energy i.e., $(I_{MUI})_R$ becomes predominant. In order to make the single wavelength thermography suitable for such situation, researchers have developed correction approaches.

The emissivity related correction for temperature estimation using infrared thermography is nothing but solving a radiometric heat transfer problem. As the radiometric equation is ill-posed in nature, the solution approaches are non-analytical. Some approaches based on iterative algorithms have been developed to be used along with the radiometric models to correct the estimated temperature. Methods based on iterative algorithms can be used for varied types of material (i.e. low emissivity [19], or high emissivity [20]), however each developed method is applicable for only narrow range of material and hence not universal. Also, iterative methods are a bit

time consuming. Some methods have been developed which are based on artificial neural network (ANN). The use of ANN for emissivity temperature correction has exhibited very promising results in applications which are complex in nature like nuclear fusion process, biological process etc. The only challenge with this approach is that the network needs to be trained using large representative data set and therefore is data intensive. Correction approaches can also be developed using indirect methods, wherein the emissivity is determined based on estimated reflectivity and subsequently, the temperature is determined [21].

3.2 Multi-spectral infrared thermography

At high temperatures, the emissivity is likely to vary with time and space, hence the use of the single wavelength method is unlikely to yield accurate estimation. For such cases, multi-spectral infrared thermography techniques have been developed for temperature estimation. In multi-spectral infrared thermography, the infrared radiation emanating from the surface of MUI is measured over two or more spectral bands, which is used along with different data processing methods to extract information related to material emissivity and true temperature. This technique is based on the gray body assumption. A gray body is an ideal body, which has a constant emissivity over all wavelength and temperature ranges [22]. Multi-spectral infrared thermography is established on the understanding that clutter (clutter is responsible for abnormality in measured temperature) is the only component which is varying during temperature measurement in different spectra. Hence, a proper analysis of the measured spatio-temporal temperature information in different spectra can aid in distinguishing between the useful information (i.e. radiation emitted from MUI, which corresponds to true temperature) and clutter. Multi-spectral infrared thermography is carried out by splitting the radiation emanating from the MUI surface into different spectral bands. Some methods of splitting the emanating radiation are the use of a beam splitter with multiple detectors [23], a rotating filter wheel with detectors [24] etc.

Amongst the various multi-spectral techniques, the technique that is based on two spectral bands has gained significant acceptability. This is also referred to as dual-wavelength infrared thermography or two-color infrared thermography. This technique was developed at Lawrence Livermore National Laboratory in the year 1977 [25]. In this method, the temperature is estimated as a function of the ratio of radiant energy measured in two different wavelength ranges and hence sometimes is also referred to as the ratio method [26]. The most important factor, which influences the success of this method, is the choice of the two wavelengths [27]. The chosen wavelength should be such that the distance between the central values of the filter should be sufficiently close to fulfill the graybody assumption and distant enough to improve the temperature estimation [28]. The two-color method is advantageous over the conventional single wavelength method, as it does not require the knowledge of emissivity for temperature estimation. The temperature estimation using the two-color method can also be done either using direct approach or an indirect approach. In the direct approach optical measurements and data processing techniques are used along with radiometric models to estimate the temperature and emissivity, while in the indirect method optical measurements and data processing techniques based on reflectivity models [29]. For situations where the gray body assumption is difficult to satisfy, many researchers have proposed alternative methods, wherein a compensation factor is used with the dual-wavelength technique for temperature estimation [30]. Some multi-spectral methods, which are based on three [31], four [32], and even eight spectral bands [33], have also been developed to cater to the need for temperature estimation for different applications.

4. CONCLUSIONS

This paper discusses the importance of emissivity in temperature monitoring using infrared thermography. The various factors, which influence the temperature monitoring process, were highlighted followed by a discussion on different temperature correction approaches to deal with concerns related to emissivity (like unknown emissivity, and variable emissivity). The basic principle of single wavelength infrared thermography and multi-spectral infrared thermography along with the application of these techniques for developing temperature correction approach has been elucidated. The multi-spectral method based on two wavelengths, i.e., dual-wavelength infrared thermography has been illustrated in particular owing to the widespread usage of this method in varied industrial applications. Though there are ample of emissivity-related temperature correction approaches, most of them do not have universal applicability. The choice of correction approach and development of new

correction approaches depends on the type of material under investigation, the degree of accuracy required by the end-user, and the availability of the resources.

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Flare Control Based on Sound Speed Measurement by Ultrasonic Flow Meters

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Abstract

The molecular weight of a vent gas can be derived from an online measurement of the speed of sound (SOS) performed by an ultrasonic flow meter. The Net Heating Value (NHV) inferred from this molecular weight measurement provides critical real-time feedback for flare control. This inferential NHV measurement overcomes latency problems caused by an online Gas Chromatograph (GC) typically used to monitor vent gas NHV. Flare operation based on the calculated vent gas NHV can be used for real-time control of the Net Heating Value in the flare combustion zone (NHVCZ) and smokeless combustion to achieve high combustion efficiency as required by US Environmental Protection Agency (EPA) regulations. The working principle of this control scheme and field performance data from refinery flares equipped with online GCs, Mass Spectrometers (MS) and Calorimeters are presented in this paper.

Keywords: *Flare control; Ultrasonic flow meter; Speed of sound; flare gas NHV*

1. INTRODUCTION

New regulations from the United States Environmental Protection Agency (EPA) for the petroleum refinery sector 40 CFR §63.670 (Requirements for flare control devices, December 1, 2015), require all new and existing flare systems in refineries to be compliant by January 30, 2019 [1]. Under these regulations, the key requirements for flare operation are to maintain a minimum net heating value in the combustion zone (NHV_{cz}) of 270 BTU/SCF and smokeless combustion. This ensures the desired minimum combustion efficiency (CE) of 96.5% and hydrocarbon destruction and removal efficiency (DRE) of 98% can be achieved. Currently, flare operations in North America are mainly based on using an online GC to measure vent gas composition, and hence, its NHV content, and a fixed vent gas to assist gas (steam or air) ratio to control assist gas flow for flaring.

The main challenge in this method of flare combustion control is the latency in the GC measurement, which typically has a response time of 6 to 15 minutes depending on the sampling configuration and gas analysis columns employed. The slow response of GC poses practical problems during flaring events when the vent gas composition changes dramatically from nominal flow conditions. The GC may fail to detect this change during short flaring events and this could result in black smoke, as the fixed vent gas-to-steam ratio used is insufficient to maintain smokeless combustion. Providing the proper amount of steam assist is critical in efficient flare operation, as too much steam is obviously a waste. Excessive steaming could also result in a "white smoke" condition wherein vent gas CE is greatly reduced due to reduced NHVcz, hence releasing un-combusted volatile organic compounds (VOCs) into the air. Conversely, too little steam would result in a "black smoke" condition wherein vent gas combustion efficiency would suffer and form particulate contaminants. US EPA regulations attempt to prevent both these incomplete combustion conditions by mandating that proper flare operation includes maintaining a minimum Net Heating Value of 270 BTU/SCF in the combustion zone (NHV_{cz}), invisible combustion and flare tip velocity limitation etc.

Ultrasonic flow meters have been in the market for over 5 decades since they were first developed by Panametrics in the 1970s [3]. This technology is especially suitable for flare flow measurement

because of its accuracy, high turndown ratio and insensitivity to gas composition variations. The common "transit time" configuration of an ultrasonic flow meter compares propagation of sound waves both against and with the flow stream, known as upstream and downstream, respectively. It determines the flow velocity from the time difference of these two waves. Sound speed in gaseous phase is determined by properties of the media, such as pressure, temperature, molecular weight, and compressibility of the gas. Molecular Weight (MW) of a gas mixture can then be derived from the sound speed measurement as demonstrated by Hammond [2].

In this paper, an automated flare control system based on the real-time measurement of the speed of sound (SOS) in flare vent gas using the ultrasonic flare flow meter is presented. From the SOS measurement, the molecular weight and hence the NHV of vent gas can be derived for flare control to maintain the minimum NHVcz and the optimal steam-to-vent gas ratio. A brief description of the technology is given, followed by a discussion of field performance data from multiple flare configurations that utilize either an online GC, MS or Calorimeter to measure the BTU content of the vent gas. The NHV inferred from the SOS measurement is compared with online NHV measurements using different analyzers, clearly demonstrating the superior speed of response, simplicity, and robustness of the SOS method for flare control. A brief description of flare control is given with field application data showing steam savings based on the control scheme.

2. METHODOLOGY

2.1 Molecular Weight Determination from Speed of Sound

Flare flow measurement, especially mass flow measurement, is challenging even for a refinery or petrochemical plant with simple refining processes or limited gas feedstocks due to the complex gas composition and large variations in it. A common approach to handle this problem is to combine a volumetric flow device such as an ultrasonic flow meter with a gas composition analyzer, usually a GC, to measure the mass flow rate. In 2009, Hammond developed an empirical method using gas virial equation of state to derive the total molecular weight based on speed of sound in the gas [2]. The virial equation of state for sound speed is shown in equation (1) below:

$$c^2 = \frac{\gamma_0 \cdot R \cdot T}{M} \cdot \left[1 + \frac{1}{\bar{V}}\left[2 \cdot B + 2 \cdot (\gamma_0 - 1) \cdot T \cdot \frac{dB}{dT} + \frac{(\gamma_0 - 1)^2}{\gamma_0} \cdot T^2 \cdot \frac{d^2 * B}{dT^2}\right]\right] \quad (1)$$

where γ_0 is the ideal gas ratio, C_p/C_v, R is the gas constant, M is the molecular weight, T is the temperature, $\bar{V}$ is the molar volume, and B is the second virial coefficient, in units of volume per mole. Since the second virial coefficient B can be well approximated from the critical temperature, critical pressure, and the acentric factor ω for non-polar molecules such as hydrocarbons, and most organic molecules [4]. Hammond demonstrated in his patent that for hydrocarbons, the critical temperature, critical pressure and acentric factor can be described as functions of molecular weight. Using virial coefficient mixing rules, the second virial coefficient can be estimated from the mix of hydrocarbons and inorganic molecules such as N_2, CO_2, etc. if the molecular weight of the hydrocarbons is known. Hence, the overall sound speed can be calculated from the derived virial coefficient. The flow chart in **Error! Reference source not found.**illustrates the r egression process used to estimate MW from the measured SOS.

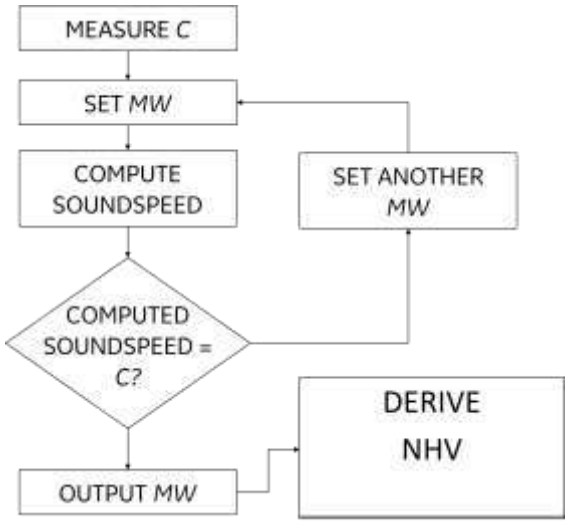

Fig. 1: Estimation of MW from SOS

For a typical ultrasonic flow meter used in flare gas applications, MW derived from SOS measurement

can achieve very high accuracy. With known concentration of inorganic molecules, the average error in MW estimation is within 1.8% for all the test cases, with the worst error of 6.8% observed when mixing 85% H_2 with 15% Hexane, a very rare combination for flare vent gas [2].

2.2 NHV Derived from Molecular Weight

Flare vent gas in refineries consists mostly of hydrocarbons and common inorganic gases such as CO_2, N_2, H_2O and CO, and high concentrations of N_2 and CO_2 are likely. For hydrocarbons, including H_2, the NHV is strongly correlated to its MW, as shown in Fig. 2. Using the NHV and corresponding MW of various hydrocarbon compounds, a linear fit would generate a satisfactory result with an error of less than 2% for most molecules. Hence, based on the MW derived from the SOS measurement, the NHV of flare vent gas can be calculated with a typical error of ~3–5% depending on the vent gas composition. This in-situ continuous NHV and MW measurement can then be utilized for real-time flare control to avoid the latency problem caused by the GC.

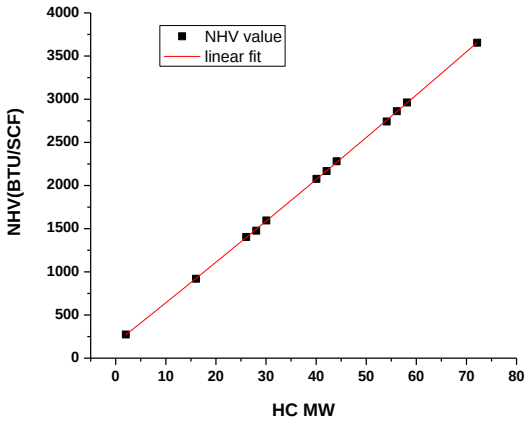

Fig. 2: Correlation between hydrocarbon MW and NHV.

3. RESULTS AND DISCUSSIONS

3.1 Field Performance Results of NHV from SOS Method vs. MS

The key requirements of this new MACT regulation in flare control are to maintain a minimum NHV in the combustion zone and invisible combustion. To achieve smokeless combustion, usually steam can be provided to assist the combustion process as recommended in the API 521 model, where the ratio of steam-to-vent gas flow required is determined by the molecular weight of hydrocarbons in the vent gas [5]. The NHV data from several refineries using online MS, GC or calorimeter for vent gas monitoring are compared to those derived from the online SOS measurement to demonstrate the advantages of this real-time NHV measurement method for optimal flare control.

Mass Spectrometry (MS) is an EPA approved method for flare vent gas composition and NHV measurement with accuracy of better than 1% [6]. Process MS has recently gained popularity due to its fast response compared to the traditional process GC. Fig. 3shows the NHV measurement during normal operation in a refinery equipped with both an online MS and an ultrasonic flow meter. As shown in the plot, the overall error in NHV measurement using the SOS method is less than 3% compared to that of the MS. The dropouts visible in the MS measurement are due to daily calibration of the MS as required by EPA regulations.

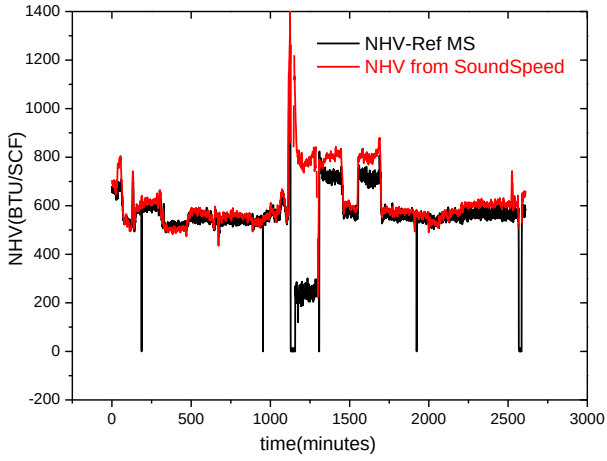

Fig. 3: Comparison of online vent gas NHV measurement from MS vs. SOS.

The mass spectrometer is a fast flare gas analyzer requiring only 6 seconds per sample. The overall system response can vary from site to site due to differences in the number of gases analyzed, sampling line length and sample conditioning requirements. Fig. 4 shows the NHV measurement during several flaring events. The NHV derived from SOS matches that from MS measurement during both normal operation and upset conditions. As shown in the inset plot inFig. 4, the overall system response of

the process MS for this flare is 2 minutes, which is slower than the real-time in-situ SOS measurement. Proper control of steam flow to assist flare combustion can eliminate smoking during the onset of such flaring events if the control is based on the NHV and MW measurements using SOS rather than the MS.

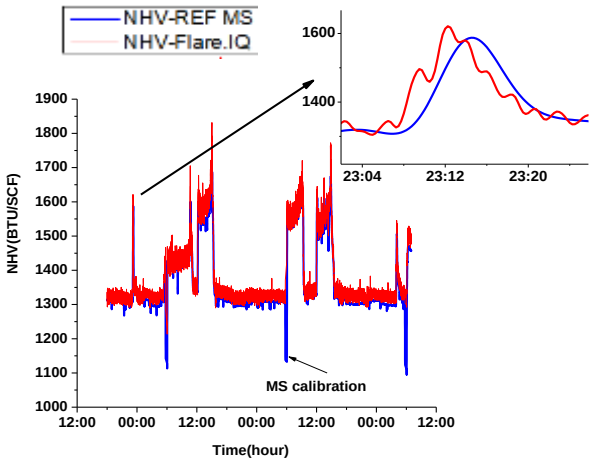

Fig. 4: Comparison of vent gas NHV measurement from MS vs. SOS during flaring events.

3.2 Field Performance Results of NHV from SOS vs Calorimeter

The calorimeter has a very fast response with a typical measurement cycle time of 30 seconds. As shown inFig. **5**, the NHV measured by the Calorimeter matches the value calculated from the SOS measurement. For this field test, the inorganic gas content of the vent gas, especially N_2 concentration, was set to a static value. The overall error is less than 5% during the test. For cases where N_2 concentration deviates from the set-point, additional error would arise due to N_2 variation. Also shown in the plot is a sporadic reading dropout from the calorimeter. This would potentially cause flare system instability if this NHV value is used for flare control. Hence, NHV measurement from SOS can be used as a complementary method in flare control during the dropout.

3.3 Field Performance Results of NHV from SOS vs GC

GC is the most common refinery gas monitoring method due to its technical maturity and capability of analyzing VOC pollutants emitted from refinery processes. It is straightforward to calculate flare vent gas NHV from the measured concentration and NHV of each component. This system typically takes 6 to 15 minutes to generate a reading depending on sample conditioning required and the number of components that need to be analyzed. The EPA accepts reporting NHV of the vent gas in 15-minute block averages. However, this significant latency in the GC response will cause problems in flare control.

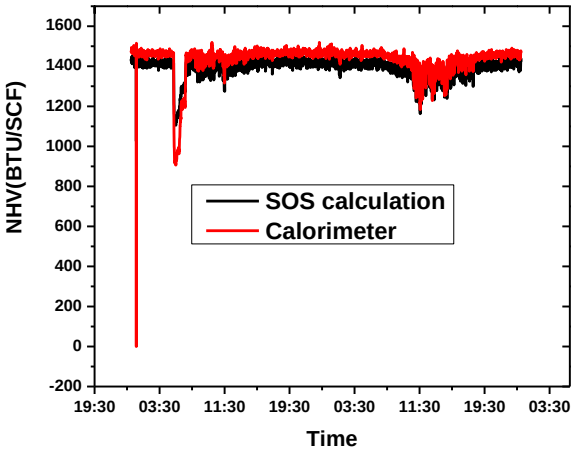

Fig. 5: Comparison of online vent gas NHV measurement from Calorimeter vs. SOS.

Providing proper steam/air assist flow to suppress smoke or supplemental fuel to maintain the minimum NHV in the combustion zone requires much faster feedback from the online analyzer. As shown inFig. **6**, NHV from the GC measurement matches that from the SOS quite well during nominal, i.e. non-flaring conditions. In the plot, there are two short flaring events with each one lasting under 10 minutes. The sudden change in vent gas NHV content requires an adequate increase in the steam-to-gas ratio to prevent smoking. The GC missed both these flaring events due to a system response time of 14 minutes. This would normally have resulted in an improper control of steam provided to assist the combustion, and hence, the formation of black smoke during these flaring events. With the real-time measurement of NHV and MW derived from the ultrasonic flowmeter, a real-time response and control of the flare assist has been realized, thus preventing smoking.

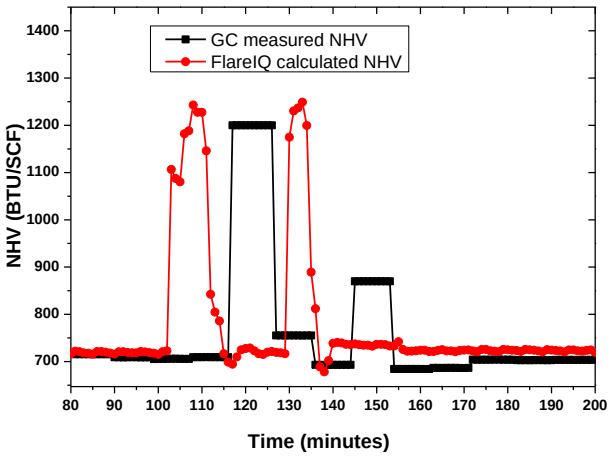

Fig. 1: Comparison of online vent gas NHV measurement from GC vs. SOS.

3.4 System Design

Flares are designed to safely and efficiently destroy waste gases released during normal plant operation or as safety devices during emergency situations. To ensure that the vent gas, usually a mixture of hazardous air pollutants such as volatile organic compounds, is completely destroyed or converted to CO_2 and H_2O, proper operation of the flare system is critical. This involves maintaining a minimum NHV in the combustion zone and the right amount of assist gas (steam/air). Calculation of supplemental fuel and/or assist gas demand using real-time MW and NHV derived from vent gas sound speed measurement enables fully automated control of flare operation.

Fig. **2**illustrates schematically the flare control logic based on vent gas sound speed measurement. The MW of the vent gas can be calculated using the vent gas SOS. The NHV can then be inferred from the calculated MW. Based on the vent gas MW, assist steam required to maintain invisible combustion can be set per API 521 model [5]. Combining the vent gas flow rate and NHV, steam flow rate and fuel flow rate, NHV in the combustion zone (NHVcz) can be calculated. By comparing this calculated NHVcz with the setpoint of minimum NHVcz, for example 270 BTU/SCF required by US EPA regulation, supplemental fuel flow rate can then be determined. All the setpoints for steam flow rate and fuel flow rate can be fed back to the central flare control system, known as distributed control system(DCS).DCS would set the control valve to provide the steam and fuel according to the set-points.

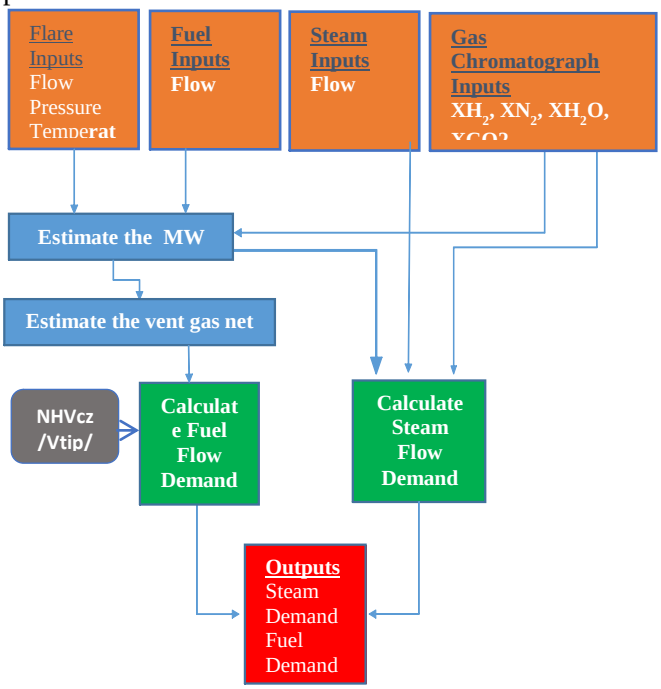

Fig. 2: Flare control logic schematics based on vent gas sound speed measurement.

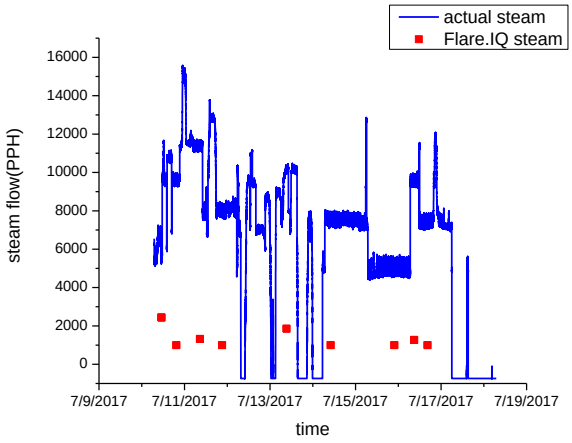

Fig. 3: Steam flow: SOS flare control setpoint vs actual steam.

This control scheme has been implemented and tested in the field, where full automation of flare operation according to EPA regulations has been realized with

major savings in steam consumption. It is common for plant operators to over-steam their flares to prevent smoking. As shown in **Error! Reference source not found.**, the average steam saving for this plant was about 80% with installation of the real-time flare control system. The average savings of 6000 pounds/hour steam would correspond to about $310,000 per year in savings.

4. CONCLUSIONS

In this paper, a method of deriving MW and NHV from vent gas speed of sound measurement has been described. Flare control using the derived MW and NHV of the vent gas has been developed and tested at refineries using either GC, MS or calorimeter as online gas speciation and NHV analyzers. The advantages of measurement accuracy, real-time response and system simplicity in flare control based on SOS measurement have been demonstrated with field performance data. Although this flare control system was developed to enable compliance with the US EPA refinery sector rules, it can be configured for any site-specific requirements to achieve high combustion efficiency and reduce VOC emission, as well as assist steam savings.

Acknowledgment: The authors would like to thank Dr. Baskaran Ganesan, Principal Engineer at Panametrics for his support.

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NDE of Non-metallic Components Using Microwave Based NDE Methods and Techniques

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Abstract

The capability to inspect complex, non-metallic components is being developed. The use of these non-metallic components has grown exponentially in recent years, due to advantages over metallic components more traditionally used. Use of these components is limited to a significant extent by an inability to perform meaningful inspections for quality both during manufacture of these components and during their service life. The establishment of accepted inspection methods for these components has expanded their use enabling technological progress to be made that would otherwise be impossible. Future developments in NDE will enable further progress in material science.Inspection of non-metallic materials is often not practical, or even possible, using traditionally accepted inspection methods. Specifically, eddy current methods, magnetic particle methods and other methods which rely on either bulk electrical conductivity or magnetism are entirely ineffective on many non-metallic materials. Additionally, many such materials are reinforced using fibers or fabric which reflect and scatter ultrasonic beams, rendering that method ineffective.

What is needed is a method which can be used to penetrate and provide volumetric information for these non-metallic components. One such method is microwave NDE. Microwave NDE has been in development since the last quarter of the last century. Advances were made in the 1980's which proved that inspection of industrial components was possible, leading to further advancements in the 1990's making practical microwave NDE a reality. Challenges to application of microwave NDE are many, including a general lack of standardization of the materials and processes used in the manufacture of the non-metallic components in need of inspection.

This paper will provide the technical details of the challenges to implementation of microwave NDE, the history of how many of these challenges have been overcome and the current state of remaining challenges and the paths to their elimination.

Keywords: NDT, NDE, Non-metallic, Microwave

1. INTRODUCTION

The use of non-metallic materials in construction, specifically the use of such materials in piping, tanks and fluid processing pressure boundaries has grown dramatically in recent years. This is due to progress in materials research, resulting in plastics, rubbers and other man-made materials with properties superior to more traditional construction materials. Plastic pipe, such as high density polyethylene (HDPE), is corrosion-resistant, erosion-resistant and can now be joined successfully to build pipelines stretching for hundreds or even thousands of kilometers. Fiber-reinforced plastics (FRP), wherein structural fibers are

held within a resin (typically thermoplastic) matrix is becoming extremely common for both piping and tankage. Rubber products, both fiber reinforced and non-reinforced, are finding substantial applications in materials handling (primarily material conveyors) as well as in flexible piping pressure boundary (primarily rubber expansion joints). All of these new construction materials present challenges to the more traditional NDE methods.

1.1 Microwave NDE – Basic Principles

Microwave NDE is applicable to any structure which is not electrically conductive. The structure to be inspected can have conductive constituents but must be "bulk non-conductive". Examples of this will be discussed later. As with the more traditional ultra-sonic inspection method, the microwave method exploits changes in critical parameter values in the specimen under test. In ultra-sonic testing, the changes in the speed of sound in the material, sometimes referred to as acoustic impedance, are detected because at an interface between 2 regions with different sonic velocity, some of the sound is reflected and some of it is transmitted. These interfaces are often important, perhaps representing a weld, an overlay of different material or a defect. This reflection of a part of the ultra-sonic beam at that interface permits detection of these features in a part under inspection.

The propagation of electromagnetic energy in a non-conductor, referred to as a dielectric, is analogous. When the electromagnetic energy encounters an interface between different dielectric constants (the dielectric constant is related to the real part of the complex permittivity of a material), some fraction of the energy is reflected, and some fraction is transmitted. In ultra-sonic inspection, the ratio of the part that reflects to the part that transmits is a function of the change in sonic velocity and beam angle. Since the index of refraction in a dielectric material is the square root of the dielectric constant and since the index of refraction is the ratio of the speed of light in a vacuum to the speed of light in the dielectric material, it is again the change in beam propagation speed which results in the reflections. As with ultra-sonic inspection, the ratio of transmitted to reflected energy is also a function of the beam angle, relative to the interface. It is interesting that two phenomena as different as sound waves (simple harmonic motion of atoms and molecules in a material) and electromagnetic radiation would behave similarly.

2. MICROWAVE NDE TECHNIQUES

Within the microwave NDE Method, many different techniques are available.

2.1 Single Emitter with Fixed Frequency and Multiple Discrete Detectors

Several of the commercially available techniques use microwaves of a constant frequency and several detectors, generally configured in an arrangement staggered in the propagation direction. Using several detectors and a single emitter of constant frequency, it is possible to extract both the amplitude (used here in the classical sense) and phase of the reflected beam signals.

2.2 Multiple Frequency with a Single Detector

Again, if several frequencies are available, it is possible to extract both the amplitude and phase of reflections from response of a single detector.

2.3 Swept Frequency and a Vector Network Analyzer

Using a VNA it is also possible to extract the amplitude and phase information from the reflected beam energy.

3. COMMERCIAL APPLICATIONS OF MICROWAVE NDE

Microwave NDE is being used commercially to inspect many different product forms made of many different materials in many countries.

3.1 Fiber Reinforced Plastics (FRP)

FRP is used for piping systems and tanks, as well as for some structural building materials, boat hulls, automotive parts and other applications. Most products consist of a glass reinforcing fiber, either in the form of individual fibers or as woven fabric, surrounded by a resin "matrix". The reinforcing fibers generally have a different index of refraction than the matrix and as such, the entire system can be imaged using microwave NDE. Below in Figure 1 is an image of an FRP pipe coupon made using commercially available microwave NDE. As can be seen in the image, very fine detail is available and special resolution is generally not limited by the wavelength of the microwave energy used. The provided image was made using a single emitter, fixed frequency, multiple detector system.

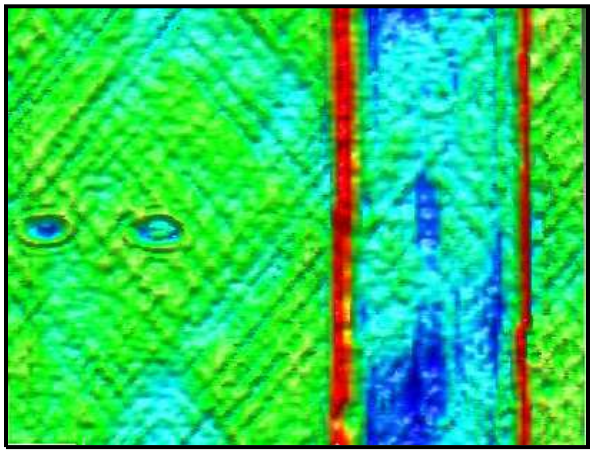

Figure 1. FRP pipe coupon image

3.2 HDPE Thermal Butt Fusion Weldments

HDPE thermal butt fusions are used extensively across the world. The fusions are created by melting the ends of two HDPE pipe sections and then forcing them together, axially, in a very controlled way. Many defects are possible, probably the most important of which is caused by insufficient melt volume and a failure of the joint to contain entangled polymer molecules from the two ends. This defect can appear to have integrity, perhaps even passing a hydro-static test, but then failing in service subsequently. It is interesting to note that this defect, called a cold joint or cold fusion presents no change in the speed of sound, making it extremely difficult to detect using ultra-sonic techniques. Due to the dielectric anisotropy of extruded HPDE, the defect does present a change in the speed of light and is therefore detectable using microwave NDE. Example images of both a good and poor HDPE thermal butt fusion appear in Figures 2 and 3, below.

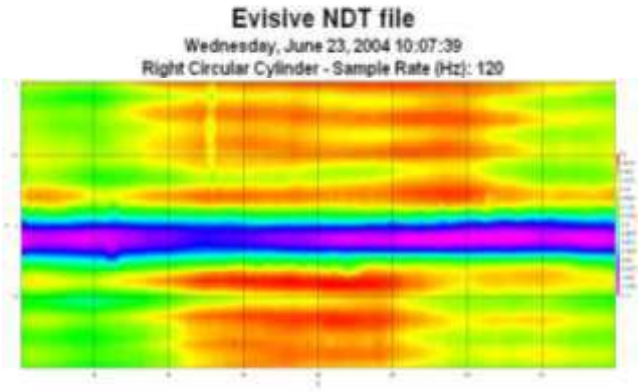

Figure 2. Microwave scan image of a good HDPE thermal butt fusion

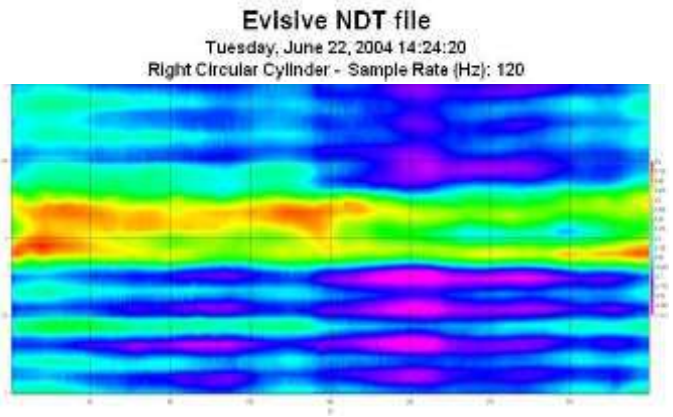

Figure 3. Microwave scan image of a poor HDPE thermal butt fusion (contaminated)

3.3 HDPE Electro-Fusion Weldments

Due to the constraints of construction, it is often necessary to make the last field weld on HDPE using a completely different approach. Though less popular

than thermal butt fusions, electro-fusion fittings are also used to join HDPE pipe sections in such circumstances. Electro-fusion fittings utilize resistance heating wires in the inner walls of the fittings. A special electronic controller is used to provide power to the wires, again under very controlled conditions, such that the pipe outer surface and fitting inner surface become melted, intermingle, and join. Again, many defects are possible and the inspection is complicated by the presence of the electrical heating wires in the weld melt zone. This is an example of a case where the pipe and fitting are dielectric, but the wires are electrical conductors. In such a case, the microwave inspection technique must be designed to permit inspection of the region of interest in the presence of the conductive components. Details of the technique are beyond the scope of the current discussion, but the technique involves controlling the polarization properties of the microwave beam and orienting it properly with respect to the conductive components. Below, in Figures4 and 5, are images of an acceptable and unacceptable HDPE electro-fusion weldment.

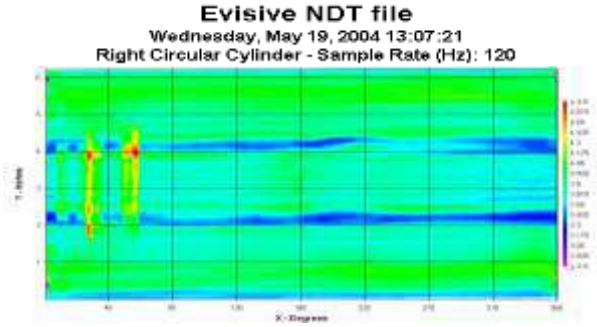

Figure 4. Microwave scan image of a good HDPE Electro-fusion

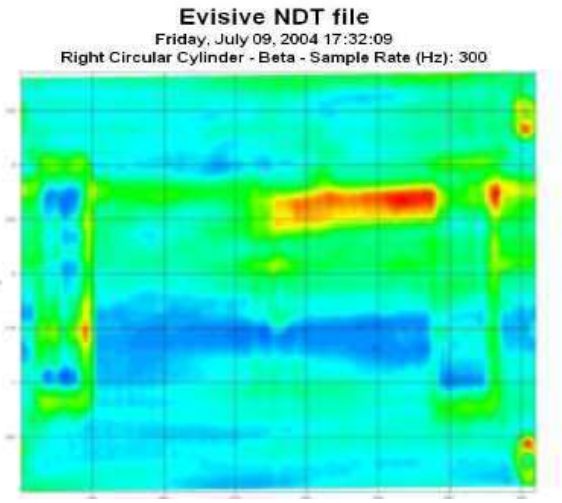

Figure 5. Microwave scan image of a section of a poor HDPE Electro-fusion

3.4 Rubber Expansion Joint in Piping System

There are cases when full two dimensional (C-Scan) images of an inspected component are not required. Such is generally the case for the inspection of rubber expansion joints. These joints are included in otherwise rigid piping systems to permit flexibility and/or minor misalignment during operation without failure. These joints typically have diameters many times their length and present the opportunity to perform adequate inspections using only 1 dimensional, or line scans. The reasons that this approach provides adequate inspection detail relates to the in-service failure mechanisms for these joints and is beyond the scope of the current discussion. Suffice it to say that beam width (i.e. beam divergence) is used to integrate the inspection data such that only circumferential location is needed to detect and characterize a defect of interest. An example of an acceptable and unacceptable rubber expansion joint line scan appear in Figures 6 and 7, below.

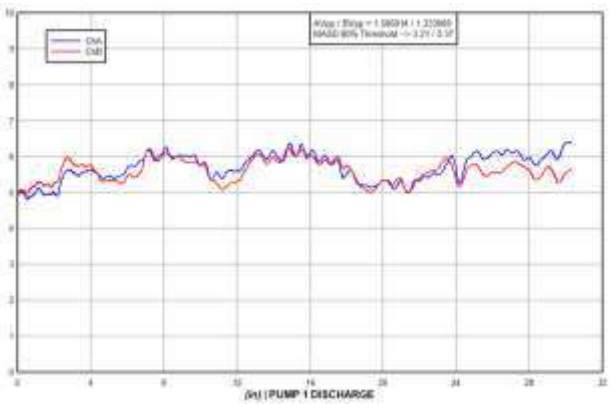

Figure 6. Microwave line scan of an acceptable rubber expansion joint

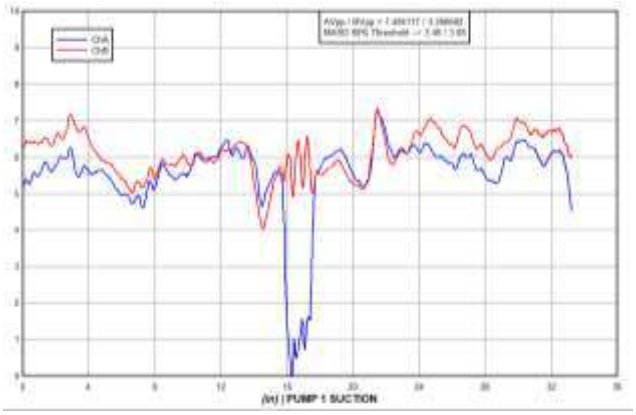

Figure 7. Microwave line scan of an unacceptable rubber expansion joint

3.5 Various Other Applications for which Microwave NDE Might be Chosen

In applications for which the geometry is complicated by multiple layers, complex angles, different materials or a combination, microwave NDE can be an excellent choice.

For example, when inspecting sandwich structures such as plastic foam or wood surrounded by thin laminate, microwave NDE is capable of simultaneously imaging both sides of the encapsulating laminate and the inner core. Such structures appear often in aerospace applications, as well as in wind turbine blade manufacturing. In such structures, it is also possible to focus on a specific depth in such a structure, to permit detection of defects associated with a particular material interface. Data from such inspections is typically proprietary and an example will not be provided here.

Another example of an inspection to which the microwave method is particularly amenable is the detection of defects in ceramic dielectric materials. Examples of this can be found in the references for this paper.

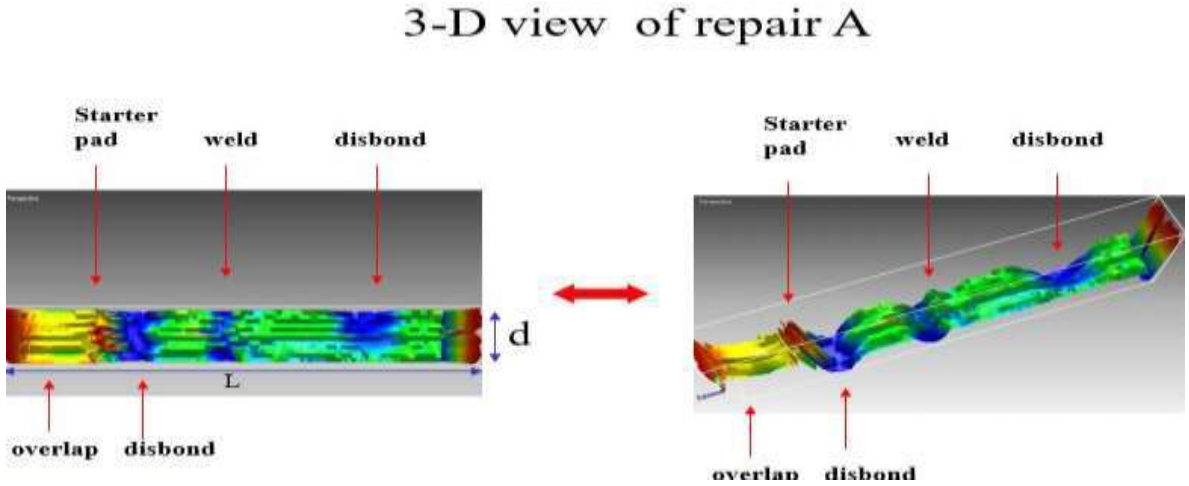

Figure 8. Microwave image of pipe "wrap repair", showing dis-bond

One additional application is inspection of a multi-layered structure such as is sometimes used to repair metallic pipe. In such a repair, multiple layers of fiber-reinforced plastic are wrapped around the pipe such that the FRP carries the piping hoop stress and thinning of the actual metallic pipe wall can be tolerated. An example of microwave scan images for such a "wrap repair" can be seen in Figures 8, below.

4. LIMITATIONS OF MICROWAVE NDE

Microwave NDE has strengths when compared to more traditional methods as has been explained already in this paper. There are several important limitations to the method, particularly when applying it to materials for which the detailed properties are not entirely known.

4.1 Unknown Index of Refraction

It is typical in the manufacture of FRP piping and tanks to manufacture the product without documenting (or even knowing) the dielectric properties of the constituent parts or final whole. Clearly, from the previous discussion, the phase information for the reflections within the part under inspection relies on the distance between the reflectors, measured in wavelengths. As discussed previously, the index of refraction is roughly the square root of the dielectric constant, which is related to the real portion of the complex electrical permittivity of the material. Index of refraction is the phase velocity in a vacuum divided by the apparent phase velocity in the material and is therefore, generally greater than unity. Since at constant frequency, the wavelength of the radiation varies as the speed of propagation for a time varying wave, the wavelength of the microwaves in the part is proportional to the reciprocal of the index of refraction. Lack of information about the detailed dielectric properties necessarily leads to ambiguity about the information contained in the phase relationship between the emitted and reflected waves.

4.1.1 Solution

It is often possible to obtain a section of the pipe or tank to use as a calibration standard. With access to this it is possible to eliminate the ambiguity described above. If no such sample exists, but it is possible to inspect a pipe or tank section for which the precise thickness is known, it is also possible to eliminate the ambiguity. If neither is possible, then an inspection can be made of the pipe or tank which is geared towards establishing how uniform the microwave NDE response is across the part and performing additional inspection in areas for which anomalous response exists.

4.2 Attenuation

As with any NDE method which relies on the response of a part under inspection to energy being used to inspect it (i.e. a "beam"), there exists a limitation due to the absorption or attenuation of the beam energy by the part. When using microwave NDE, the attenuation of an inspection beam by a part is related to a dielectric property referred to as the loss tangent. The loss tangent is related to the imaginary part of the complex permittivity, and it rises as the inspection frequency rises. This leads to a maximum frequency which can be used to inspect any given part material. For some materials the attenuated fraction of the beam is so small as to be insignificant and present no practical inspection limitations. Such is the case with HDPE. Even at relatively high inspection frequencies, the loss tangent is sufficiently small so as not to limit the maximum part thickness from which a "back wall" reflection can be obtained (a "back wall" reflection is essential to ensure that a full volumetric inspection is being performed).

With most rubber materials, the loss tangent is sufficiently high so as to limit the inspection frequency for parts of reasonable thickness. While the resolution is not strictly limited to the wavelength of the radiation used, the resolution is proportional to it and higher frequency inspections are generally possible by using higher frequencies. Therefore,

materials with very high loss tangents will generally produce lower resolution scans images owing to the lower frequencies needed.

5. ACCEPTANCE – CODES AND STANDARDS

Microwave NDE has gained substantial acceptance in recent years. Microwave NDE was first included in the American Society for Non-destructive Testing (ASNT) recommended practice ASNT SNT-TC-1A in 2016 (now in its 2020 revision).

There are ASTM International (formerly American Society for Standards and Materials) Standard Practices for microwave NDE of HDPE thermal butt fusions (ASTM E3101) as well as for HDPE electro-fusions (ASTM E3102).

Microwave NDE has been included in several American Society of Mechanical Engineers (ASME) codes, specifically sections III (new nuclear build) and XI (maintenance of nuclear power plants).

6. THE FUTURE - CONCLUSIONS

As deployment of products manufactured from dielectric materials continue to advance, microwave NDE will almost certainly become increasingly important in quality monitoring of those structures and components. Advances in microwave NDE are being made continuously across the world and new techniques within the method are being developed by many advanced practitioners.

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State of Artificial Intelligence (AI) in Thermographic Non-Destructive Evaluation (NDE) and its role in NDE 4.0

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Abstract

This paper discusses the current trends and state of the art in using artificial intelligence (AI) for analyzing thermographic inspection data. Several articles aimed at automating the process of dispositioning parts/components using thermography were reviewed and presented. In addition, the challenges and path forward for achieving the deliverables of NDE 4.0 in the context of thermography were discussed and elaborated.

1. INTRODUCTION: NDE 4.0

Non-destructive evaluation (NDE) 4.0 is a phenomenon coined by NDE researchers, practitioners, and professionals following the footsteps of the fourth industrial revolution (Industry 4.0) which calls for development and integration of several emerging technologies like 5G, blockchain, cloud storage, cloud computing, artificial intelligence (AI), big data, quantum computers, and extended reality for a purpose that was not achievable previously. Although there is no standard definition for NDE 4.0, there is a consensus among the NDE community about what the NDE 4.0 phenomenon entails [1–4]. NDE 4.0 calls for development and integration of autonomous/semi-autonomous inspection technologies in an industrial workflow with feedback from findings learnt while inspecting assets (components, specimens, or parts) into the design and production processes. The technologies required to achieve this goal overlap with the technologies that must be developed/matured and integrated to achieve the goal envisioned for Industry 4.0. Traditionally, NDE has been used in the industry to ensure quality and safety. Although this approach ensures that the inspected components are following design specifications, it has not been a revenue generating part of the supply chain, unless you own/operate an NDE firm. The advent of NDE 4.0 redefines the role of NDE in the industry to not just ensure safety and quality of parts/components in a self-regulating fashion but to also use findings from inspecting these parts/components to optimize/improve design and production processes making it a revenue generating aspect of the workflow. Artificial Intelligence (AI)and machine learning are key technology areas that can drive autonomous decision making in the workflow. It is important that the NDE community embraces AI to (1) analyze inspection data, (2) disposition parts/components based on findings from the inspection data, and (3) help optimize the production processes in-line with expectations from the NDE 4.0 revolution. In this paper, a brief overview of the current state-of-the-art in AI for thermography is laid out and the path forward for this modality in the context of NDE 4.0 is discussed.

Supervised machine learning architectures have evolved exponentially in the last decade starting with the traditional fully connected neural networks (FCN), followed by shallow and deep convolutional neural networks (CNN), generative adversarial networks (GAN), physics informed neural networks (PINN), recurrent neural networks (RNN), auto encoders, transformers and other large language models. NDE researchers have leveraged almost all

these architectures to improve the speed, and reliability of inspection techniques. In the next few sections, we will briefly discuss how different machine learning architectures have been leveraged in thermographic NDE.

2. INFRARED THERMOGRAPHY AND AI

Thermographic NDE of a scene/part/component can be performed in two ways (1) active, and (2) passive thermography. In active thermography, the part is heated/cooled to induce a thermal gradient using an external source like heat lamp (for example, flash thermography), induction coil(for example, induction thermography), laser, and forced air[5–7]. After inducing a thermal gradient, the changes in surface temperature of the component are monitored using an infrared camera. Defects in a part can be localized with this approach because the thermal signature of a defective portion in the component would be different compared to a defect free location. In passive thermography, no external source is required to induce a thermal gradient. The part under inspection has its own heat signature which can be captured using an infrared camera to identify defects or anomalies.

Infrared (IR) cameras are classified into three types depending on the wavelength of the IR spectrum they are sensitive to (1) short-wave (0.9-1.7 μm), (2) mid-wave (3-5 μm), and (3) long-wave (8-14 μm). Typically, mid-wave and long-wave IR cameras are used for thermographic NDE. Long-wave IR cameras are more economical compared to mid-wave IR cameras. This is because most mid-wave IR cameras consist of cryogenic coolers. The detectors (focal plane arrays) in the mid-wave cameras must be cooled to cryogenic temperatures to minimize the detector's own radiation so the detector records the radiation from the scene. Mid-wave IR cameras are more sensitive to changes in temperature and can typically reach high frame rates; on the other hand, most commercially available long-wave cameras are not as sensitive and have a fixed frame rate (typically 30 or 60 fps). Hence mid-wave IR camera are used for applications requiring high frame rates (>60 fps) and low integration times (for example, flash thermography).

Because the data available from an infrared camera are like images from a typical visual camera (for example, webcams, and machine vision cameras); classic segmentation, object detection and object tracking frameworks (with a CNN backbone) can be directly used or optimized using transfer learning to identify anomalies. However, unlike visible light images, infrared images collected during thermographic inspections are sensitive to indications like delaminations, and sub-surface cracking that don't manifest on the surface of the component. In an industrial setup, both thermal images and visible light images can be used in tandem to autonomously disposition parts or provide an operator with initial assessment using AI and machine learning so the operator can disposition part. This advantage makes thermographic NDE an attractive modality to spearhead the NDE 4.0 campaign.

Unlike point based inspection modalities like ultrasound (UT), and eddy current (EC); thermographic NDE covers a broad area of the component at once hence reducing the time involved in collecting inspection data.

2.1 Current state of the art in application of AI for thermography

Many researchers have explored the applicability of supervised machine learning frameworks to analyze thermography data. Yang et al. [8]annotated 3000 thermal images of steel plates with locations of surface breaking and sub surface cracks. A region proposal network (RPN), and a Faster R-CNN[9] network were trained to detect the presence of surface breaking and non-surface breaking cracks using thermal images collected by heating the surface of steel plate with a rolling heater. Jang et al. [10] generated hybrid images of concrete surfaces by fusing images from a traditional optical/visual camera and thermal images from an IR camera. A GoogLeNet architecture[11] was

retrained via transfer learning using about 20,000 annotated images. The trained network was able to identify micro- and macro-cracks with low false positives. Jaeger et al. [12] retrained several CNN architectures (pretrained on the ImageNet dataset) to identify cracks in turbine blades. Turbine blades were excited using an induction heater and the surface temperature was monitored using an IR camera. Each CNN architecture was trained on approximately 590 thermal images (540 with crack and 50 without crack) to detect cracks. Liu et al. [13] like [12] trained several CNN frameworks to predict crack locations in asphalt pavements. Three types of images were used to train the CNN networks (1) visible light images, (2) thermal images, and (3) fusion image obtained by combining the visible and thermal images. The networks were both trained from scratch and using pretrained weights obtained from the ImageNet dataset. It was observed that, when CNN architectures were trained from scratch, using fusion images resulted in better accuracy compared to raw visible light and thermal images. However, when pretrained CNN architectures were used to retrain for this task using transfer learning, traditional visible light images outperformed thermal and fusion images. Buongiorono et al. [14] trained different machine learning frameworks like Support vector machine (SVM), nearest neighbor clustering, and CNNs to predict if a weld was defective or healthy using thermal images/video collected during the welding process. For training each of these models, approximately 2300 thermal images were collected during welding without an external heat source. Thermal gradient induced in the parts by the process of welding was sufficient for the inspection. Each image was annotated by an operator as ‘defective’ or ‘healthy’ by analyzing electrical properties of the weld using a high precision milliohmmeter. The CNN architecture trained on this data could predict a damaged weld with close to 99% accuracy.

Ma et al. [15] developed a thermal imaging technique to detect gas leak using a wide-band thermal camera and auxiliary excitation like an external heat pulse. SVM was used to predict the presence or absence of a gas leak. The model was able to predict gas leaks with 94% accuracy. Wang et al. [16] trained 2-, 3-dimensional CNN, and a long short term memory (LSTM) model to predict gas leakage using passive IR images/videos recorded by an IR camera. Approximately 700,000 images (with and without gas leaks) were recorded and annotated to train the deep learning models. 2-D CNN networks were trained using individual images whereas 3-D CNN networks were trained using consecutive frames captured in a thermal video. It was observed that the prediction accuracy (presence/absence of gas leak) was close to 100% for the 3-D CNN networks.

Ren et al. [17] developed a super-resolution network model to reconstruct thermal images with better subject definition by leveraging both visible light and thermal images from an IR camera. The proposed CNN framework consisted of a feature extraction block, information extraction block and reconstruction module to obtain a thermal image with better edge and texture features compared to the input thermal image.

Wei et al. [18] developed a polyvinyl chloride (PVC)-Infrared dataset which consists of pulsed thermography data collected on PVC blocks with indications/holes at different locations with different sizes and depths. This work was aimed at (1) generating an open-source dataset for thermographic NDE that can be leveraged by other researchers, and (2) to demonstrate the ability of CNN frameworks to detect indications using flash/pulsed thermography. Different CNN frameworks like VGG-Net [19] and U-Net [20] were trained on this dataset to accurately identify the location of anomalies. Like Wei et al. [18], Fang et al. [21] developed a flash/pulsed thermography dataset only this dataset consists of synthetic thermography data from finite element simulations in addition to experimental data. CNN architectures like Mask-RCNN were trained to detect anomalies in this work

Unlike the previously described applications of AI in thermography where IR data are typically only considered like visible light images where we can visualize damage by physically looking at the images/videos, a sub-section of the AI community focuses on physics informed neural networks (PINN) where the optimization/loss function(s) used to train neural networks consists of the partial differential equations (PDEs) and boundary conditions (BCs) that govern the underlying physics. Lim et al. [22] used a physics informed loss consisting of the 3-D heat diffusion equation and boundary conditions while training the NN to predict the presence of defects from pulsed thermography data collected from a carbon fiber reinforced polymer sample. Limited articles are available in the literature that address using PINNs to solve thermographic NDE problems. This sub-section of AI must be explored in the context of thermography because, (1) the PDEs governing heat transfer are well defined, (2) considering them while training the NN will help address boundary effects and noise resulting from a simple 1-dimensional assumption, (3) analyzing thermal images without considering the underlying physics typically results in overestimation of size of identified defects or indications.

3. CLOSING REMARKS AND THE PATH FORWARD

It is clear from the brief review of literature described in this document that NDE researchers have embraced the AI revolution and adapted it to analyze thermographic inspection data to give the modality a certain level of autonomy. Having said that, most AI work reported in the literature in the context of thermography (or any other modalities) are proof of concept studies restricted to (1) controlled laboratory environments, and/or (2) specific material properties/geometry. We still have a long way to go before this can be integrated into an industrial environment. To accomplish this, AI techniques must be (1) *accurate* in identifying defects, (2) *reliable* (few/no false positives), (3) *fast* requiring fewer computational resources, and (4) *robust* to changes in environmental and material properties of the component.

Most of the previous work focuses on using CNN architectures to analyze images (2-D CNN) and videos (3-D CNN) for detecting indications. In addition to directly inputting thermographic video to the CNN architecture, several studies used traditional dimensionality reduction/unsupervised learning methods to preprocess thermal videos which reduces the number of training examples to obtain decent accuracy without overfitting. It is however important to also develop other capabilities to address the following challenges if thermographic inspection and AI were to be integrated to an industrial workflow:

1. Limited training data: Most AI applications for thermography suffer from unavailability of training data. Researchers are only able to generate few images/videos for training AI models because thermal images must be collected in a controlled experimental environment with multiple variables like heat source, and component geometries. This is unlike visible image datasets which typically contain hundreds of thousands to a few million annotated images for training AI models to perform tasks like object detection, tracking, and segmentation. There is a need to develop/create an open-source thermography dataset with contributors from academia and industry across the globe. Availability of such dataset(s) will help NDE researchers train AI models that are robust, accurate and most importantly will make AI models more generalizable. In other words, the model can be leverage to analyze thermographic data collected on parts/components with different geometry and material properties compared to the geometry and properties of the parts used for collected the training data. Leveraging synthetic data generated using fine difference and finite element simulations will also help improve the volume of training data.
2. Considering the physics of heat transfer: Most AI applications for thermography consider infrared images collected during inspection (especially during active thermography) like

traditional visible light images. It is important to remember that data collected in this process follows the laws of heat transfer for e.g. the heat diffusion equation in the case of pulsed thermography. Augmenting this information into the loss functions while training will make the AI model robust to presence of boundaries, changing material properties and component geometries. In this regard focusing on developing PINNs to analyze thermographic data is key.

3. Low resolution of thermal images: Thermal images collected using commercially available IR cameras typically have a low resolution (less than or equal to 512x640 pixels). Such low-resolution images might limit applicability of the method especially for cases where it is important to measure the size of indications accurately. This calls for an (1) improvement in hardware capabilities (from IR camera vendors side), and (2) artificially improving the resolution, edge features and texture by fusing thermal images with visible light images.

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NDE PATENTS

Dr.Shyamsunder Mandayam

Through this feature every quarter, we intend to provide you a snapshot of some latest and important patents in the world of NDE. We also intend to use this feature to encourage the Indian NDE community to file more patents based on your innovations. We will be happy to provide guidance and assistance in different ways – Answering queries, Conducting Tutorials and webinars, One-on-one discussions, Networking with Intellectual property experts, etc.

Need help understanding, What are Patents? Why to Patent? When to Patent? What is the Patenting Process? …… Please feel free to reach out to me by email at mandayam.shyamsunder@gmail.com

Here we list below a few interesting patents related to a mix of different modalities in ***NDE and Inspection.***

United States Patent 2023/0152278 Al

In-Process Quality Assessment for Additive Manufacturing

Inventors: Neil J. Goldfine,Todd M. Dunford

Assignee: JENTEK Sensors, Inc., Marlborough, USA

Disclose is a system and method for real-time measurement and feedback of metrology and metallurgical data during additive manufacturing (AM) part fabrication. This solution promises to provide higher performance, lower cost AM parts. A sensor is placed either in the rake/roller or following the rake/roller so that it has no impact on the process efficiency and can be used to provide real-time feedback and an archived digital map of the entire part volume. The solution provides non-contact sensing of AM layer's electrical conductivity in a high-temperature environment, metallurgical property verification, porosity imaging, local defect detection and sizing, local material temperature monitoring, and grain anisotropy imaging. Part geometry, the AM powder, and the laser/material interface are monitored in real-time. Dual mode sensing using magnetoquasistatic and optical sensors enhance results. Real-time nonlinear control of the AM fabrication process is performed based on the sensor data.

United States Patent 11650183

System and method for real-time degree of cure evaluation in a material

Inventors: David A Jack, TX, USA

Assignee: VERIFI Technologies LLC, TX, USA

The present disclosure provides a system and method for real-time visualization of a material during ultrasonic non- destructive testing. The system includes a graphical user interface (GUI) capable of showing a three-dimensional (3-D) image of a composite laminate constructed of a series of two-dimensional (2-D) cross sections. The GUI is capable of displaying the 3-D image as each additional 2-D cross section is scanned by an ultrasonic testing apparatus in real time or near real time, including probable defect regions that contain a flaw such as a hole, crack, wrinkle, or foreign object within the composite. Furthermore, in one embodiment, the system includes an artificial intelligence capable of highlighting defect areas within the 3-D image in real time or near real time and providing data regarding each defect area, such as the depth, size, and/or type of each defect.

NDE PATENTS

United States Patent11,573,192

Enhanced guided wave thermography inspection systems and methods of using the same

Inventors: James F. Landy, Paul J. Zombo, Cody J. Borigo, Joseph L. Rose,

Steven E. Owens

Assignees: Siemens Energy, Inc., Orlando, FL (US); FBS, Inc., State College, PA (US)

Non-destructive inspection systems and methods for inspecting structural flaws that may be in a structure based on guided wave thermography. The method may include sweeping a frequency-phase space to maximize ultrasonic energy distribution across the structure while minimizing input energy, e.g., via a plurality of actuators. The system may include transducer elements configured to predominantly generate shear horizontal-type guided waves in the structure to maximize thermal response from any flaws.

United States Patent 11,480,517

Heat exchanger fouling determination using thermography combined with machine learning methods

Inventors: Ali Al Shehri,VincentCunningham, Ayman Amer, Wei Xu, Faisal Melibari

Assignee: Saudi Arabian Oil Company, Dhahran (SA)

Disclosed is a methodology for determination and prediction of heat exchanger fouling, such as polymer fouling in the circulation loop that forms part of the heat exchanger system. The buildup of a polymer or other undesired mate- rial deposit in the heat exchanger provides a distinctive temperature signature (thermal gradient) on the surface of the heat exchanger asset, which is visualized using a thermographic camera. Coupling images (thermograms) from the camera with a machine learning algorithm identifies fouling and, with knowledge of the historical data of the asset and operating and ambient conditions, enables prediction of future fouling. The thermal images provide several types, or orders, of temperature information that are indicative of locations vulnerable to fouling. In one case, the method uses machine learning applied to time-based temperature change/gradient information to detect hidden polymer fouling in areas that form part of the heat exchanger.

United States Patent 11,603,593

Systems and methods for automatic detection of coating defects

Inventors: Venkata VijayaraghavaNalladega, Bernard Patrick Bewlay, MajidNayeri, MichaelHoward Rucker

Assignee: General Electric Company, Schenectady, NY (US)

Systems and methods for automatic detection of defects in a coating of a component are provided. In one aspect, a coating inspection system is provided. The coating inspection system includes a heating element operable to impart heat to the component as it traverses relative thereto. An imaging device of the system captures images of the com- ponent as the heating element traverses relative to the component and applies heat thereto. The images indicate the transient thermal response of the component. The system can generate a single observation image using the captured images. The system can detect and analyze defects using the generated single observation image.

Indian Society for Non-destructive Testing (ISNT)
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CIRCULAR

No: ISNT/2023/01 **Date: 2nd January 2023**

Schedule of ISNT meetings
YEAR: 2023

Month	Meeting	Day/Date of mtg.	Timing	Mode / Venue
JANUARY 2023	Past President's Meeting	Sunday, 8th January	03:30 pm–05:30 pm	ONLINE
	Finance / Treasurers Meeting	Saturday, 21st January	03:30 pm–05:30 pm	ONLINE
FEBRUARY 2023	Byelaw Enforcement & Advisory and RA Committee	Saturday, 4th February	03:30 pm–05:30 pm	ONLINE
MARCH 2023	Chapter Chairmen Meeting	Saturday, 4th March	03:30 pm–05:30 pm	ONLINE
	PFMB	Saturday, 11th March	10.00 am– 11.30 am	HYBRID Online / ISNT HO, Chennai
	TMB		11.45 am – 1.30 pm	
	NCB		2.30 pm – 4.30 pm	
	NGC	Sunday, 12th March	10.00 am – 3.30 pm	
MAY 2023	Finance / Treasurers Meeting	Saturday, 20th May	03:30 pm–05:30 pm	ONLINE
JUNE 2023	PFMB	Saturday, 10th June	10.00 am– 11.30 am	HYBRID Online / ISNT HO, Chennai
	TMB		11.45 am – 1.30 pm	
	NCB		2.30 pm – 4.30 pm	
	NGC	Sunday, 11th June	10.00 am – 3.30 pm	
JULY 2023	Past President's Meeting	Sunday, 9th July	03:30 pm–05:30 pm	ONLINE
AUGUST 2023	Byelaw Enforcement & Advisory and RA Committee	Saturday, 5th August	03:30 pm–05:30 pm	ONLINE
SEPTEMBER 2023	Chapter Chairmen Meeting	Saturday, 2nd September	03:30 pm–05:30 pm	ONLINE
	PFMB	Saturday, 9th September	10.00 am– 11.30 am	HYBRID Venue to be decided by March NGC
	TMB		11.45 am – 1.30 pm	
	NCB		2.30 pm – 4.30 pm	
	NGC	Sunday, 10th September	10.00 am – 3.30 pm	
	Finance / Treasurers Meeting	Saturday, 16th September	03:30 pm–05:30 pm	ONLINE
OCTOBER 2023	Award Committee	Saturday, 14th October	03:30 pm–05:30 pm	ONLINE
DECEMBER 2023	PFMB	Wednesday, 6th December NDE 2023	02.00 pm– 03.00 pm	PHYSICAL NDE 2023 Venue, Pune
	TMB		03.00 pm - 04.00 pm	
	NCB		04.30 pm– 0530 pm	
	NGC		05.30 m - 07.30 pm	

Notes: 1. Separate notifications will be sent to the members of the committee / Board for each meeting
2. Each meeting should be attended only by the members and invitees

Bikash Ghose
Hon Gen Secretary, ISNT

The First International Conference on NDE 4.0 - April 2021 in Virtual Mode



The Second International Conference on NDE 4.0 – October 2022 at Berlin, Germany



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