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CSNI/R(2014)1**
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Non-destructive Evaluation of Thick-walled Concrete Structures

Proceedings of an
OECD/NEA WIAGE Workshop
Prague, Czech Republic
17-19 September 2013

OECD
BETTER POLICIES FOR BETTER LIVES

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Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **30-Jan-2015**

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

NEA/CSNI/R(2014)1
Unclassified

Cancels & replaces the same document of 15 October 2014

Proceedings of OECD/NEA WGIAGE Workshop on the Non-Destructive Evaluation of Thick-walled Concrete Structures

Prague, Czech Republic, 17-19 September 2013

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English text only

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Republic of Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

THE COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

"The Committee on the Safety of Nuclear Installations (CSNI) shall be responsible for the activities of the Agency that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations, with the aim of implementing the NEA Strategic Plan for 2011-2016 and the Joint CSNI/CNRA Strategic Plan and Mandates for 2011-2016 in its field of competence.

The Committee shall constitute a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It shall have regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee shall review the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensure that operating experience is appropriately accounted for in its activities. It shall initiate and conduct programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It shall promote the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings, and shall assist in the feedback of the results to participating organisations. The Committee shall ensure that valuable end-products of the technical reviews and analyses are produced and available to members in a timely manner.

The Committee shall focus primarily on the safety aspects of existing power reactors, other nuclear installations and the construction of new power reactors; it shall also consider the safety implications of scientific and technical developments of future reactor designs.

The Committee shall organise its own activities. Furthermore, it shall examine any other matters referred to it by the Steering Committee. It may sponsor specialist meetings and technical working groups to further its objectives. In implementing its programme the Committee shall establish co-operative mechanisms with the Committee on Nuclear Regulatory Activities in order to work with that Committee on matters of common interest, avoiding unnecessary duplications.

The Committee shall also co-operate with the Committee on Radiation Protection and Public Health, the Radioactive Waste Management Committee, the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle and the Nuclear Science Committee on matters of common interest."

FOREWORD

The Committee on the Safety of Nuclear Installations (CSNI) Working Group on Integrity and Ageing of Components and Structures (IAGE) has as a general mandate to advance the current understanding of those aspects relevant to ensuring the integrity of structures, systems and components, to provide for guidance in choosing the optimal ways of dealing with challenges to the integrity of operating as well as new nuclear power plants, and to make use of an integrated approach to design, safety and plant life management.

The Working Group has three subgroups dealing with (a) integrity and ageing of metal structures and components, (b) integrity and ageing of concrete structures, and (c) seismic behaviour of components and structures.

Over the last two decades, the IAGE Concrete Sub-group has convened a series of workshops and published reports on integrity and aging of thick-walled concrete structures, primarily aimed at containment structures. The last workshop was "Ageing Management of Thick Walled Concrete Structures, including ISI, Maintenance and Repair – Instrumentation Methods and Safety Assessment in view of Long Term Operation" held in Prague, Czech Republic, on 1-3 October 2008. One of the conclusions from that workshop was that further meetings or workshops should be held every few years to review progress on non-destructive examination (NDE) of concrete, and to provide a forum for information exchange.

With developments in NDE methodologies over the intervening 5 years, the IAGE working group considered it was timely to host a follow-on to the 2008 workshop in 2013, with the objective to present and discuss the state-of-the-art techniques for the integrity assessment of concrete structures, and to recommend areas where further research is needed. This report documents the proceedings for the 2013 workshop on "Non-Destructive Evaluation of Thick Walled Concrete Structures".

Overall, the workshop demonstrated there has been significant development in NDE methodologies for thick-walled concrete since 2008. There is still substantial work to be done before fully qualified techniques can be deployed on a regular basis to determine the overall health of a concrete structure. The workshop concluded with recommendations for areas that would benefit from further study, and from international cooperative programmes. These include: i) appropriately capturing the information on effects of irradiation in standards or guidance documents, ii) following up on the state-of-the-art report on concrete NDE methodologies, iii) undertaking development of standard specimens and using round-robins for intercomparisons, and iv) holding a subsequent meeting or workshop to review progress after a few more years.

ACKNOWLEDGMENTS

Gratitude is expressed to the Nuclear Research Institute Rez in the Czech Republic for hosting the Workshop, and in particular, to Dr. Ladislav Pecinka for his help, and excellent organisation of the meeting.

Thanks are also expressed to the Workshop Technical Committee, the Session Chairpersons and the workshop participants for their effort and cooperation.

Organizing Committee

Ladislav Pecinka (NRI Rez, Czech Republic)
Workshop Chairperson

Dan Naus, ORNL, USA
Herbert Wiggenhauser, BAM, Germany
Jean Mathieu Rambach, IRSN, France
Jean Salin, EdF, France
Neb Orbovic, CNSC-CCSN, Canada
Madhumita Sircar, US NRC, USA
Pentti Varpasuo, FORTUM, Finland
Silvio Sperbeck, GRS, Germany
Alejandro Huerta / Andrew White, OECD-NEA

SUMMARY AND CONCLUSIONS

1. Introduction

This report documents the proceedings for the workshop on "Non-Destructive Evaluation of Thick Walled Concrete Structures", held in Prague, Czech Republic on 17-19 September 2013. A total of 34 specialists from 15 countries and international organisations attended. The Meeting was sponsored by the OECD Nuclear Energy Agency Committee on the Safety of Nuclear Installations and hosted by the Nuclear Research Institute Rez.

The objective of this workshop was to present and discuss the state of the art techniques for the integrity assessment of concrete structures, and to recommend areas where further research is needed. The workshop was structured in 4 technical sessions, with papers covering degradation mechanisms, application of NDE methodologies, and test rigs for determining NDE effectiveness.

2. Background of the Workshop

Concrete structures are essentially passive components under normal operating conditions, but play a key role in mitigating the impact of extreme or abnormal operating and environmental events. Structural components are somewhat plant specific, may be difficult to inspect and the limiting factor for plant life since they are mostly irreplaceable. Structures are subject to time-dependent changes that may impact their ability to perform safety functions. As NPPs age, assurance is needed that the capacity of concrete structures to mitigate extreme events has not deteriorated unacceptably.

Of particular importance to most nuclear facilities are concrete containment structures whose main purposes are to provide the final physical barrier to the release of fission products to the environment and to protect the reactor and other safety related structures, systems and components.

Although, it was thought that concrete was maintenance-free with a design life of hundreds of years, this has proved to be optimistic. Experience has demonstrated that concrete structures can exhibit the first signs of degradation after 20 years or even earlier. Concrete containments of the nuclear facilities are subjected to many types of environmental effects that can, over time, initiate a variety of degradation mechanisms.

The safety significance of containment combined with the current trend towards life extension and the regulatory authorities' demands for even higher levels of safety assurance, means that ageing degradation mechanisms must be effectively understood and monitored, and the recognised ageing mechanisms should be continuously controlled. An important element of this control is inspection and monitoring to assess and determine the condition of the concrete structures and associated components. Modern NDE methods and instrumentation are providing useful techniques for the detection and measurement of the extent of internal damage and providing information on the quality of construction. Nevertheless, further work is required to provide standardized and qualified inspection techniques.

3. Summaries for the Workshop Sessions

Session 1

Herbert Wiggenhauser summarized the “State-of-the-Art of non-destructive methods and technologies for application to nuclear power plant safety-related concrete structures”. This state-of-the-art report provides a comprehensive assessment of the various available NDE techniques (e.g. ultrasonics, radiography, radar, etc.) and their strengths and limitations for various applications (thickness, cover depth, detection of rebar, detection of defects, etc.). Recommendations are for further research to develop:

- validation and reference specimens
- software for data analysis and modelling
- combined techniques and automation
- improvements to equipment and techniques.

Georgios Michaloudis presented “Applying numerical simulations for the non-destructive evaluation of concrete structural components subjected to high-dynamic loading”. Numerical simulations were used to assess the damage induced in a concrete structure from a high-dynamic load (e.g. explosion). The complex energy propagation through air and then into a structure was modelled and compared well with actual results. The models can be used to determine the residual load capacity of the structure following an impact event.

Brian Hohmann presented “Inspection of Containment Liners and Shells Utilizing Advanced Nondestructive Examination Techniques”. Some areas of containment liners and shells are not readily accessible for inspection, but can have installation defects and can degrade in-service. Ultrasonic techniques have been developed to detect flaws in a liner or shell, and applied to full-scale mock-ups. The techniques were able to detect flaws introduced in the mock-ups, but require further work to provide reliable defect sizing and characterization. It was noted that discontinuities in a liner or shell, such as a butt weld, can seriously attenuate the NDE signal.

Session 2

Jiri Zdarek presented “Temperature and Radiation Effects on the RPV Concrete Cavity: Project Description on Irradiation, Testing and NDE Development”. Long term exposure to radiation and thermal loading can result in degradation of mechanical properties of concrete structures such as RPV cavities. An experiment is being conducted to determine the effects of high-radiation fields on concrete behaviour (described further in a presentation in Session 3). In addition, NDE techniques using Non-linear Elastic Wave Spectroscopy are being developed and applied to a sample of concrete from a biological shield from a mothballed VVER. One possible opportunity is to use the ionization penetrations in the VVER biological shield as access points for NDE probes in an operational VVER.

Fahim Al-Neshawy presented “Monitoring of hygrothermal performance of thick-walled concrete structures”. Exposure of concrete structures to variations in temperature and humidity can lead to deterioration. Dr. Al-Neshawy described a technique for collecting data on the effects of temperature and humidty on concrete, and using neural networks to forecast hygrothermal performance.

Brian Hohmann provided a summary of “The Effect of Irradiation on Thick Walled Concrete Structures in Nuclear Power Plants with Respect to Long Term Operation”. Mr. Hohmann presented the available data on the effects of irradiation on concrete, and showed that the data of most relevance to reactor containment structures indicates there is not likely to be any deterioration for fast neutron fluences up to ~10^{19}n/cm^2. Thus there is no indication that containment concrete will deteriorate due to irradiation, but additional data (as is being sought in the experiment described in Sessions 2 and 3) will be useful to confirm the lack of effect at high fluences.

Session 3

Sontra Yim presented “The Use of Digital Image Correlations for Detection of Degradation in Concrete Structures”. The digital image correlation (DIC) - that combines photogrammetry and image correlation - is an effective non-contact non-destructive evaluation (NDE) technique to quantify changes in shape, deformation, displacement and strain. This method was successfully validated 2011 during a structural integrity test (SIT) period in the framework of pressurization, hold and depressurization on inner concrete surfaces (~1m^2) of a NPP containment. The quantitative data that was recorded will provide a basis for comparison to future tests (e.g. at 10 years interval). DIC can be used to detect, track and trend concrete degradation.

Milan Marek presented “Projects Dealing with Radiation Damage of Concrete at the LVR Research Reactor”. This contribution is a complement to the presentation “Temperature and Radiation Effects on the RPV Concrete Cavity: Project Description on Irradiation, Testing and NDE Development” of the 2nd session. An experiment to determine the effects of irradiation on concrete using the LVR-15 reactor was described. Concrete cylindrical samples (5 cm diameter, 10 cm height) will be irradiated with a neutron flux of 1.5E+20 n/cm^2 (E>0.1 MeV) below 90°C temperature. The samples will be investigated by means of post irradiation examination (PIE) and NDE. The data will be useful in assessing the safety of NPP concrete structures since they will provide information regarding degradation (material changes and influence of chemical parameters) of irradiated concrete.

Sontra Yim presented “Use of Fiber Optic Sensors for Monitoring Loads in Post-Tensioned Tendon”. Fiber optic sensors were selected due to their expected stable performance over long time periods, accuracy, immunity to electromagnetic interferences as well as electrical noise, and environmental stability. The resulting fiber optic sensing system (FOSS) was installed in a NPP with a post-tensioned tendon systems and provides real time tendon monitoring in order to detected tendon wire breaks, wire relaxation, local concrete failure under tendon anchorage or loss of rock anchor. FOSS holds promise to be an alternative to lift-off testing. It has worked robustly for over two years, and is anticipated to perform over a long-time period (e.g. more than 10 years).

Session 4

Josef Machac presented his work on a “Hydraulic Vibration Exciter.” In this study numerical simulation of the response of structures to a dynamic vibration load was performed and compared with the experimental measured values. Experimental case studies included dynamic load test of bridges, the Orlik dam, the tallest exhaust stack in Europe, and a power plant turbine and generator basemat. The technique shows promise for monitoring degradation through systematic repeated measurements over long time periods, e.g. 5-10 years.

Ladislav Pecinka presented the topic "Experimental Stend UJV Rez for Probability of Detection (POD) Assessment." He provided background on a methodology for quantifying the detection capability of a NDE technique. A POD demonstration test is typically conducted using a set of standard specimens of the same geometry and material that have a known number and distribution of indication sizes. An important consideration is that the size distribution should go beyond the NDE technique's detection capability to establish the POD. Dr. Pecinka also elaborated on a set of four specimens of dimension 2mx2mx1m, UJV has constructed with known defects and internal components (rebar, tendon ducts). UJV has examined the specimens with ultrasound, ground penetration radar and impact echo NDE methods and identified which method is suitable and successful to detect the particular types of defects. Although not a complete spectrum of indication sizes, the set of specimens should be valuable for comparison testing by other organizations.

4. Discussion

The workshop provided ample opportunity for discussion amongst participants on various aspects of degradation of concrete structures, and use of NDE to monitor concrete performance. Key areas of discussion are captured here.

Since the last workshop in 2008, there has been significant development of NDE methodologies for concrete. The application of various ultrasonic techniques continues to be expanded and refined. Digital Image Correlation is showing promise as a technique for monitoring deformation and tracking degradation. The use of fiber optics is enabling reliable NDE measurements over an extended time period, and could potentially avoid costly and dangerous direct measurement such as post-tensioning tendon lift-off. Hydraulic exciters can be used to look at the mechanical response of large structures, and monitor for changes over time.

Nevertheless, we are far from having a comprehensive set of qualified techniques that can be standardized and applied by certified contractors. We are still at the stage of much of the work being performed in research centres and universities, prior to standardization and commercialization. As techniques move from the laboratory into regular application, there will be a need for appropriate training to ensure the techniques are used properly and consistently. Given the complex and expansive nature of thick-walled concrete structures, it is anticipated that multiple techniques will be required to assess the full-range of potential indications, and to probe the entire volume of a structure.

A big challenge is posed by the lack of standardization in concrete. While there can be specifications for mix ratios, aggregate size distribution, rebar arrangement, etc., key aspects of concrete can change with location and time. For example, cement and aggregate composition can vary. The effects of these differences are not well understood nor well characterized, and could influence properties enough to make prediction of aging effects difficult.

In terms of aging, the work underway at UJV Rez should go a long way toward resolving the effects of irradiation. Nevertheless, the challenges to integrity posed by environmental exposures (temperature, moisture, contaminants, etc.) can stem from a wide range of phenomena, and continued investigation is required to ensure the phenomena of importance to nuclear structures are well understood and characterized.

Advances in computer technologies are helping to improve NDE methodologies. Post-processing software can be used to turn NDE measurements into 3-D representations of a structure, its internals, and any flaws or defects. Finite-element and mechanical modelling is being used to supplement NDE methodologies in determining the nature of discontinuities and defects, and in determining the consequences of detected anomalies on mechanical properties. Statistical analysis and reliability methodologies are likewise showing promise in extrapolating from NDE findings to the consequences for a structure.

5. Conclusions and Recommendations

1) There is a clear need for means of ensuring concrete structures meet their design criteria. During and immediately following construction, NDE can provide quality control and verification. After being subjected to aging degradation, NDE can be used to characterize material properties and ensure adequate performance. It is therefore recommended that there be a follow-on workshop or meeting in few years to allow for further exchange of information.
2) The state-of-the-art report [ORNL/BAM] provides a valuable assessment of the current applicability and limitations of available concrete NDE methodologies. The IAGE Concrete subgroup should review the recommendations in the report and identify areas that can benefit from international collaboration.
3) Methodologies for concrete NDE continue to evolve, and there are, as yet, no standardized and qualified techniques. As a result, international standard specimens should be developed to allow direct comparisons between various techniques, with consideration given to ensuring a broad range of defects to ensure the Probability of Detection (POD) for a method can be properly determined. Test rigs such as those developed at UJV Rez and LPI could provide a starting point for such inter-comparisons. In addition, samples should be removed from plants under decommissioning. A round-robin study could be valuable in comparing between NDE techniques, and in determining variability in the application of the same technique. The highest priority testing tasks should be determined to ensure that resources are appropriately focussed.
4) Once the experiments on the effects of irradiation are completed, it is recommended that the results be captured in standards and / or regulatory guides. This will likely require radiation effects to be included in constitutive models for concrete used in finite-element modelling and used in fracture mechanics assessments.

OECD/NEA WGIAGE Workshop on the Non-destructive Evaluation of Thick-walled Concrete Structures – Prague, Czech Republic 17-19 September 2013

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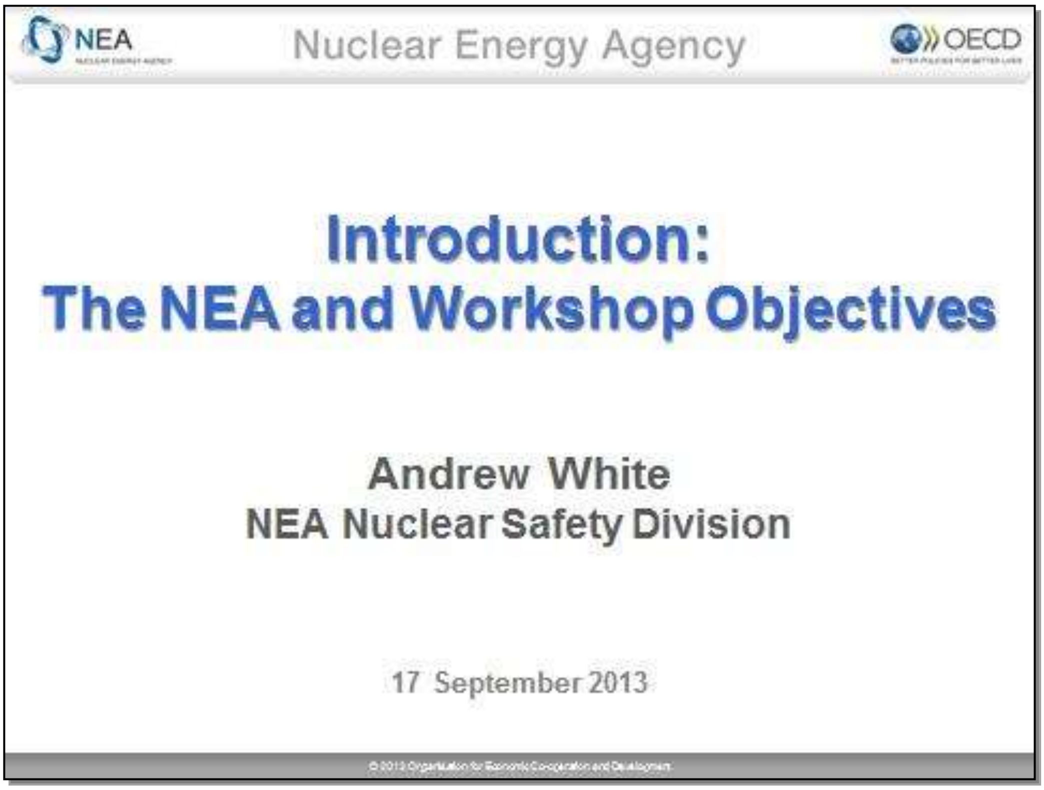
Presentation on NEA and WGIAGE
Andrew White

Welcome and Overview of UJV Rez
Vladimir Stratil


NEA
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Introduction:
The NEA and Workshop Objectives
Andrew White
NEA Nuclear Safety Division
17 September 2013


NEA
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The NEA Mission
• To assist its member countries in maintaining and further developing, through **international co-operation, the scientific, technological and legal bases** required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes.
• To provide authoritative assessments and to forge **common understandings** on key issues, as **input to government decisions on nuclear energy policy**, and to broader OECD policy analyses in areas such as energy and sustainable development.
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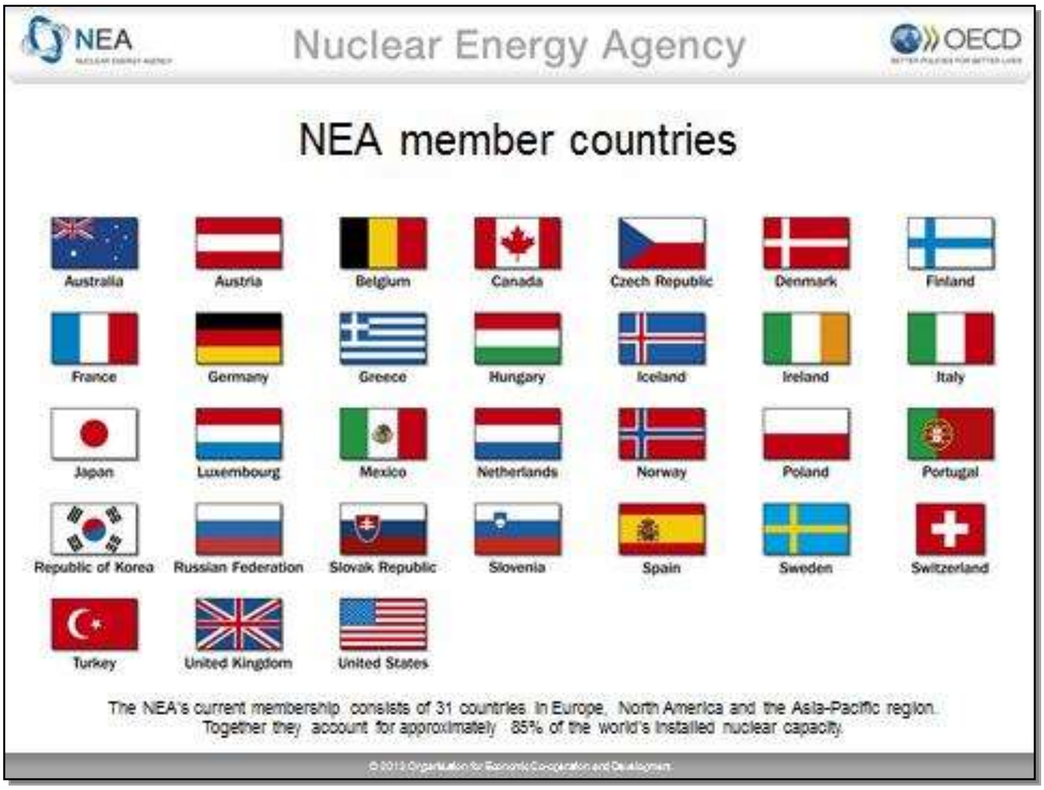
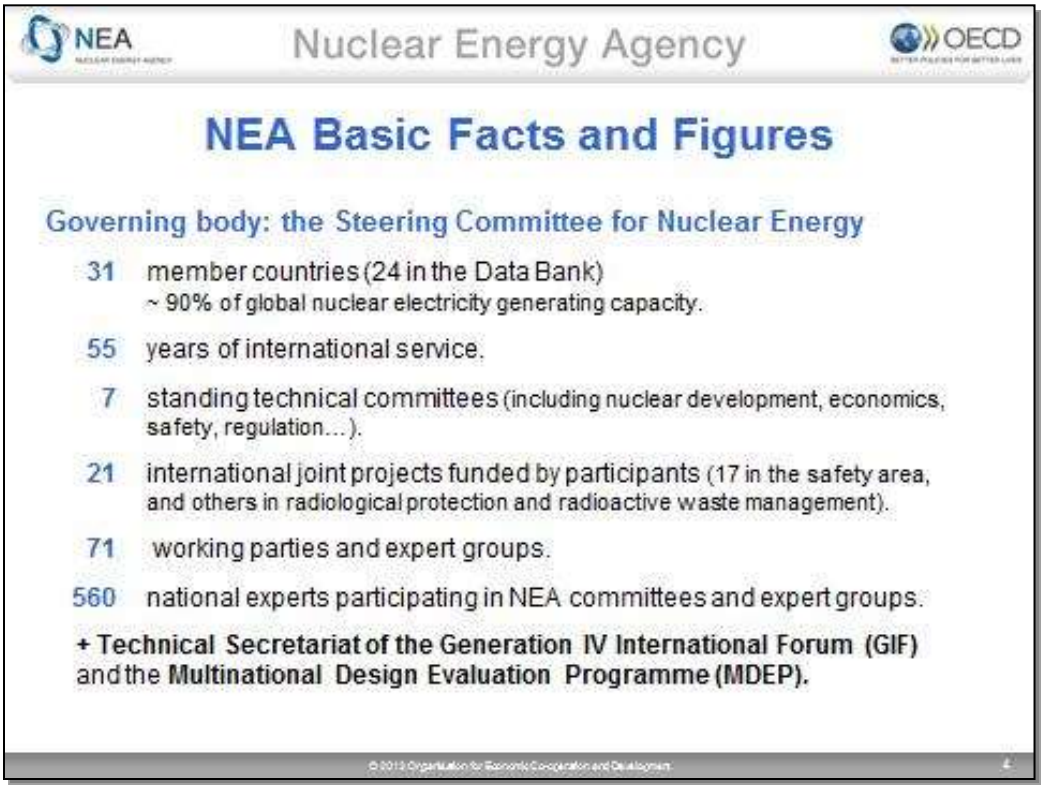

NEA
Nuclear Energy Agency
OECD
NEA member countries
Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Japan
Luxembourg
Mexico
Netherlands
Norway
Poland
Portugal
Republic of Korea
Russian Federation
Slovak Republic
Slovenia
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States
The NEA's current membership consists of 31 countries in Europe, North America and the Asia-Pacific region.
Together they account for approximately 85% of the world's installed nuclear capacity.


NEA
Nuclear Energy Agency
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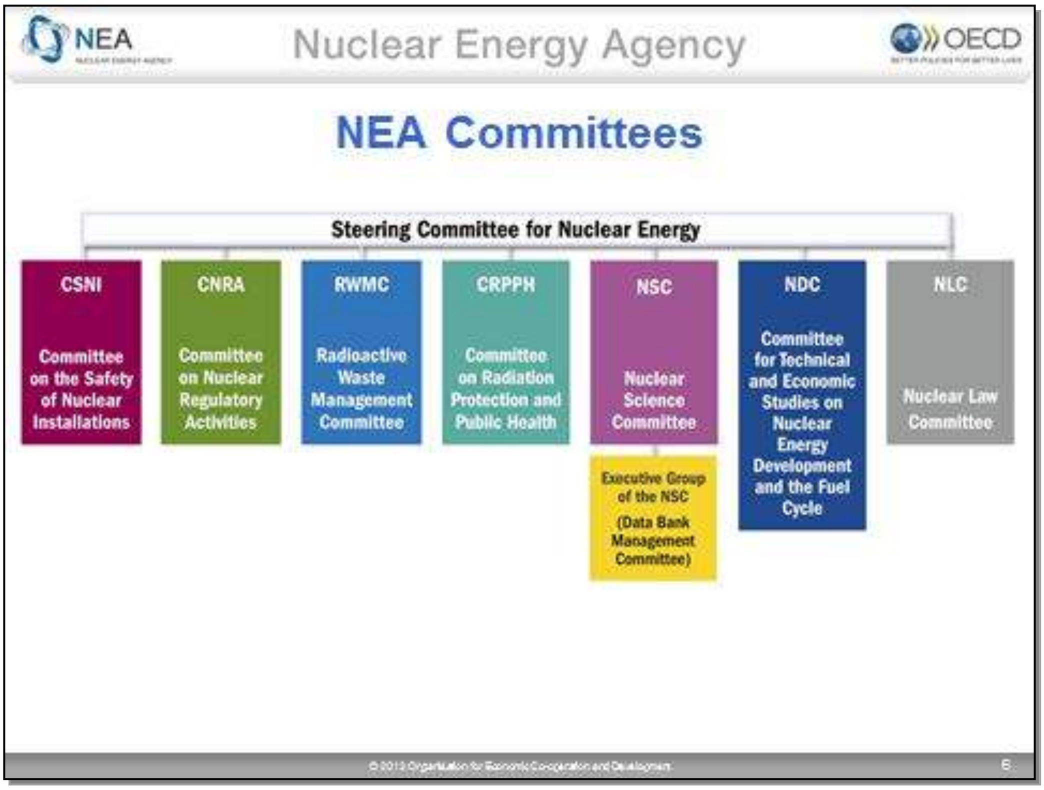
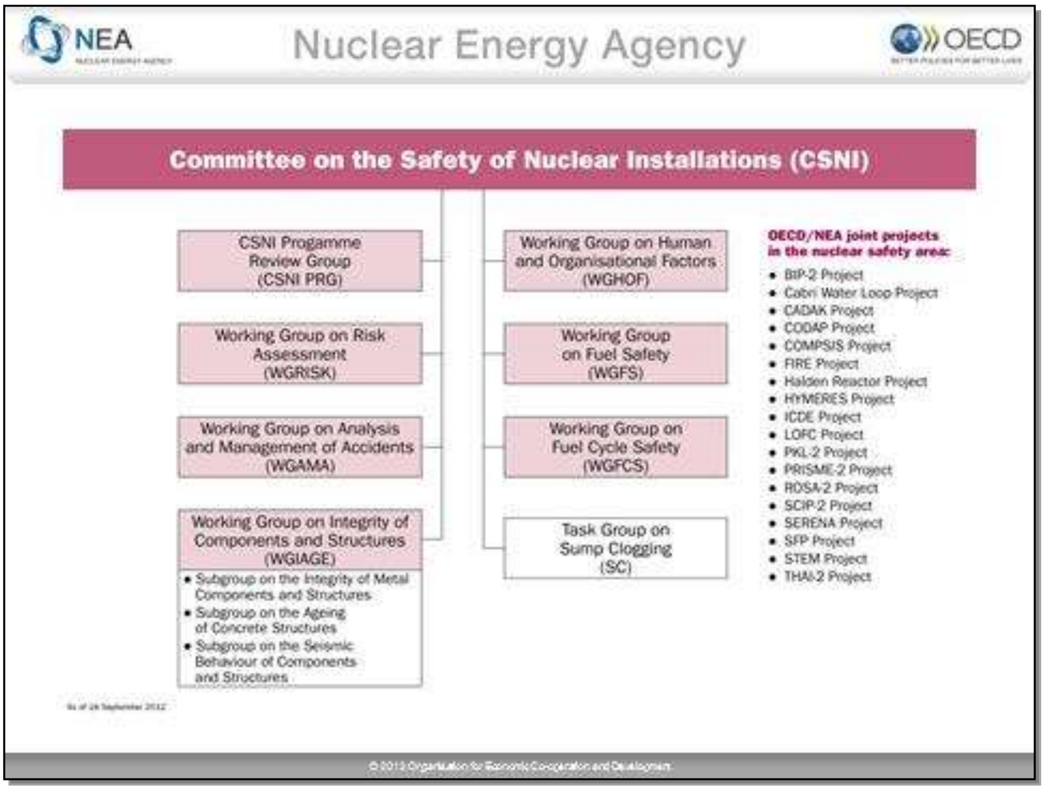
NEA Basic Facts and Figures
Governing body: the Steering Committee for Nuclear Energy
31 member countries (24 in the Data Bank)
~ 90% of global nuclear electricity generating capacity.
55 years of international service.
7 standing technical committees (including nuclear development, economics, safety, regulation…).
21 international joint projects funded by participants (17 in the safety area, and others in radiological protection and radioactive waste management).
71 working parties and expert groups.
560 national experts participating in NEA committees and expert groups.
+ Technical Secretariat of the Generation IV International Forum (GIF) and the Multinational Design Evaluation Programme (MDEP).


NEA
Nuclear Energy Agency
OECD
NEA Co-operation and Interactions
• International Energy Agency (IEA): OECD family,
• International Atomic Energy Agency (IAEA): agreement,
• European Commission (EC): full participant,
• China: Joint Declaration on Co-operation approved,
• India: expert invitations,
• Ad hoc observers (national governments),
• Industry input to selected studies.


NEA
Nuclear Energy Agency
OECD
NEA Committees
Steering Committee for Nuclear Energy
CSNI
Committee on the Safety of Nuclear Installations
CNRA
Committee on Nuclear Regulatory Activities
RWMC
Radioactive Waste Management Committee
CRPPH
Committee on Radiation Protection and Public Health
NSC
Nuclear Science Committee
Executive Group of the NSC
(Data Bank Management Committee)
NDC
Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NLC
Nuclear Law Committee


NEA
Nuclear Energy Agency
OECD
Committee on the Safety of Nuclear Installations (CSNI)
CSNI Progamme Review Group (CSNI PRG)
Working Group on Risk Assessment (WGRISK)
Working Group on Analysis and Management of Accidents (WGAMA)
Working Group on Integrity of Components and Structures (WGIAGE)
• Subgroup on the Integrity of Metal Components and Structures
• Subgroup on the Ageing of Concrete Structures
• Subgroup on the Seismic Behaviour of Components and Structures
Working Group on Human and Organisational Factors (WGHOF)
Working Group on Fuel Safety (WGFS)
Working Group on Fuel Cycle Safety (WGFCS)
Task Group on Sump Clogging (SC)
OECD/NEA joint projects in the nuclear safety area:
• BIP-2 Project
• Cabri Water Loop Project
• CADAK Project
• CODAP Project
• COMPSIS Project
• FIRE Project
• Halden Reactor Project
• HYMERES Project
• ICDE Project
• LOFC Project
• PKL-2 Project
• PRISME-2 Project
• ROSA-2 Project
• SCIP-2 Project
• SERENA Project
• SFP Project
• STEM Project
• THAI-2 Project
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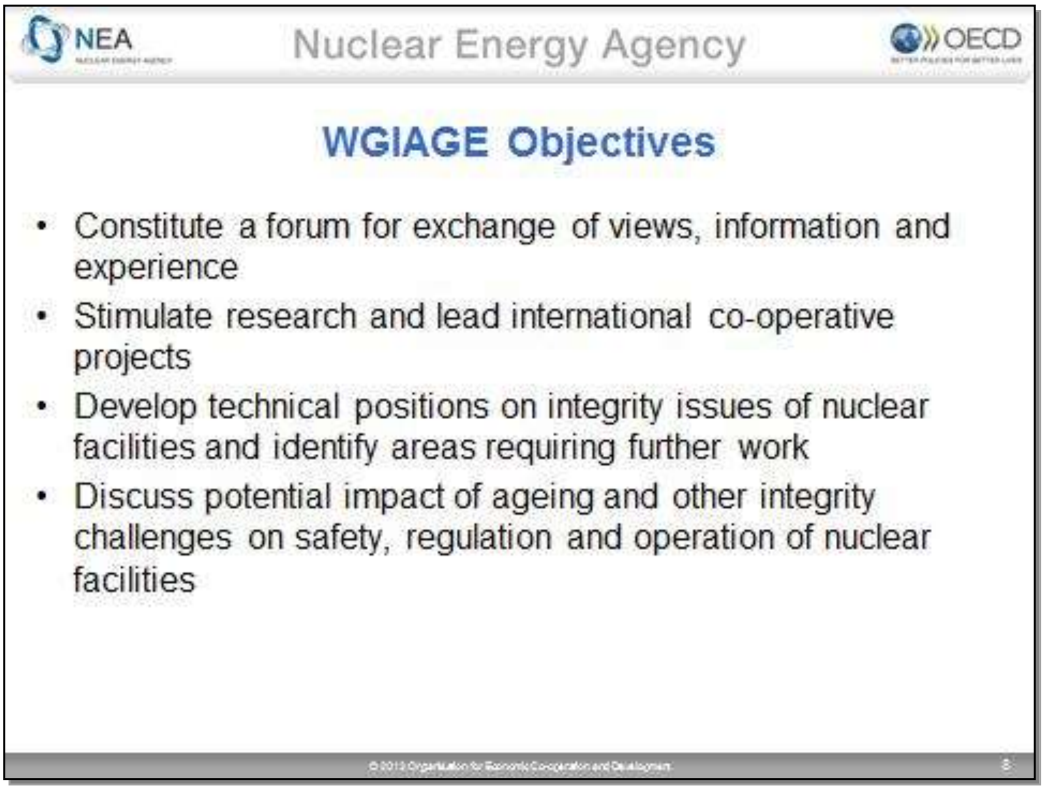
NEA
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WGIAGE Objectives
• Constitute a forum for exchange of views, information and experience
• Stimulate research and lead international co-operative projects
• Develop technical positions on integrity issues of nuclear facilities and identify areas requiring further work
• Discuss potential impact of ageing and other integrity challenges on safety, regulation and operation of nuclear facilities
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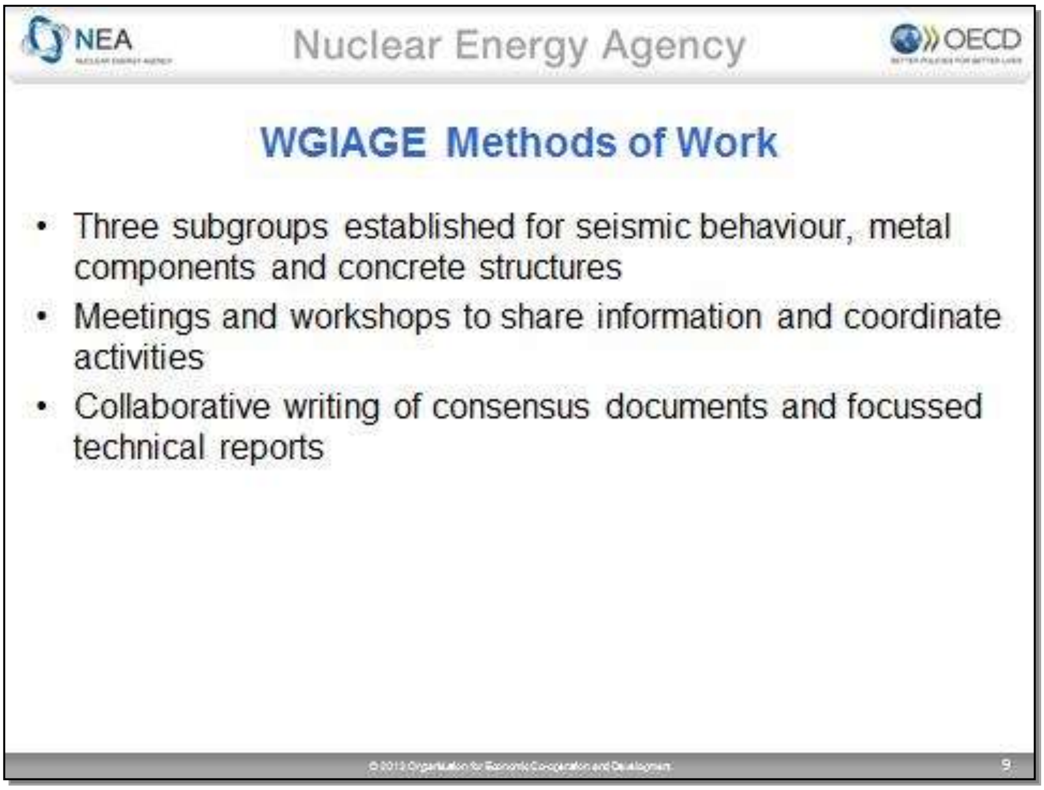
NEA
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WGIAGE Methods of Work
• Three subgroups established for seismic behaviour, metal components and concrete structures
• Meetings and workshops to share information and coordinate activities
• Collaborative writing of consensus documents and focussed technical reports
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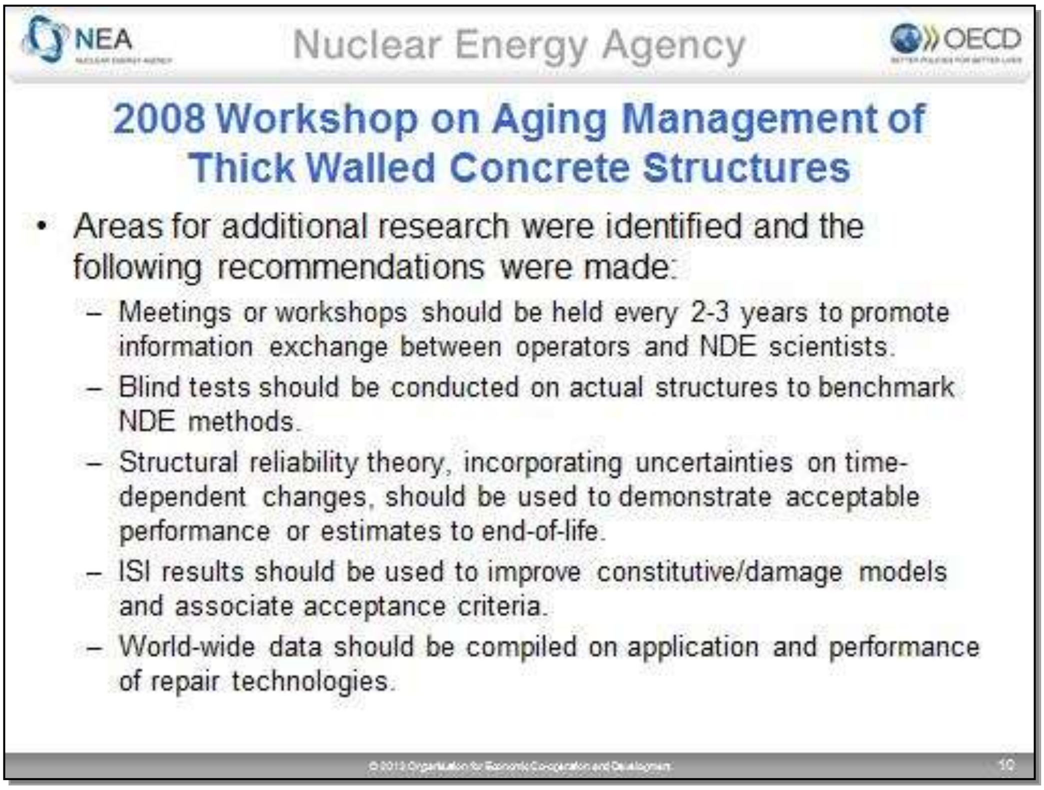
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2008 Workshop on Aging Management of Thick Walled Concrete Structures
• Areas for additional research were identified and the following recommendations were made:
– Meetings or workshops should be held every 2-3 years to promote information exchange between operators and NDE scientists.
– Blind tests should be conducted on actual structures to benchmark NDE methods.
– Structural reliability theory, incorporating uncertainties on time-dependent changes, should be used to demonstrate acceptable performance or estimates to end-of-life.
– ISI results should be used to improve constitutive/damage models and associate acceptance criteria.
– World-wide data should be compiled on application and performance of repair technologies.
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2013 Workshop Objectives

- Review existing methods for NDE of NPP's thick-walled concrete structures.
- Present state-of-the-art techniques for integrity assessment of concrete structures and for detection of
  - Voids and cracks
  - Liner corrosion
  - Loss of pre-stress in tendons
- Recommend areas for further research.

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2013 Workshop Scope

- More than 30 participants from a number of different countries and diverse organizations
- Variety of presentations on concrete degradation mechanisms and NDE in 4 different sessions

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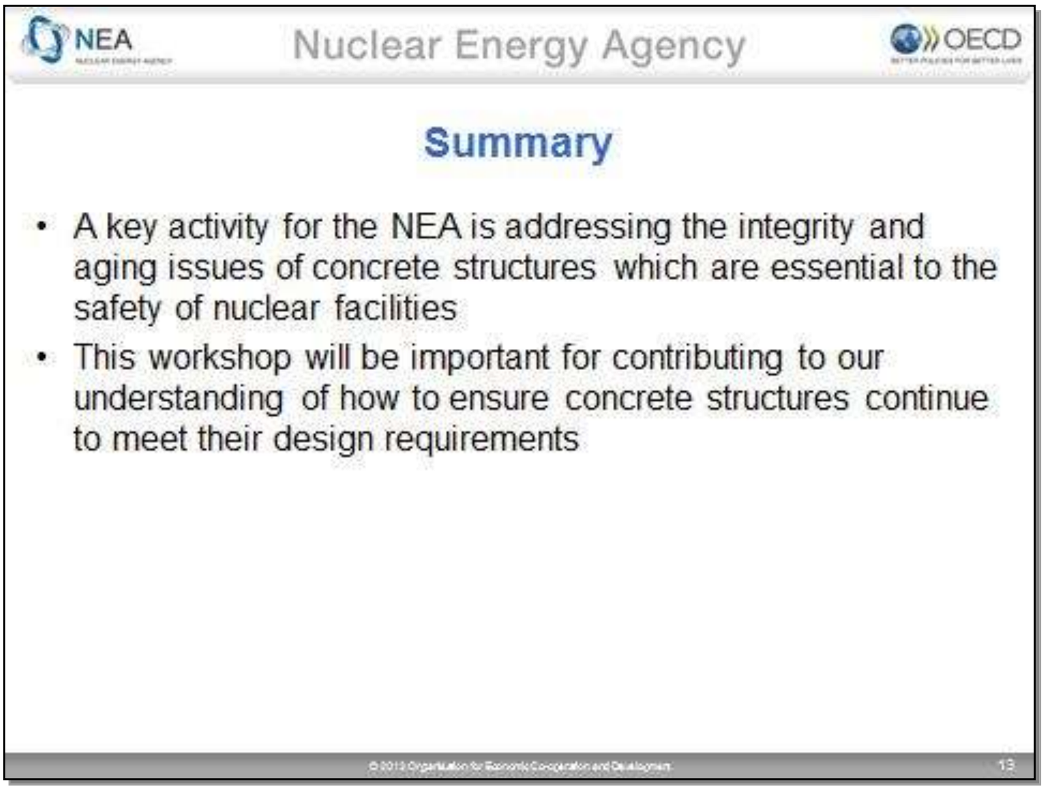
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Summary
• A key activity for the NEA is addressing the integrity and aging issues of concrete structures which are essential to the safety of nuclear facilities
• This workshop will be important for contributing to our understanding of how to ensure concrete structures continue to meet their design requirements
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ÚJV Řež, a. s.
IAGE workshop
AMBASSADOR - Prague

Vladimir Stratil
September 18th, 2013

Who we are

- We are a company operating in the area of research and development on the top national and global level more than 58 years.
- More than 1,000 persons employed by the ÚJV Group represent the potential from scientific capacities through technology specialists, designers to experienced production workers.

2

Who we are

- Our divisions, departments and daughter companies employ 62% of university-educated specialists, 26% of secondary-educated specialists and 12% of technically skilled persons.
- We are in possession of unique research, production and process facilities in the Central and Eastern Europe.
- We belong among the recognized and respected members of many of international and national organizations and companies.

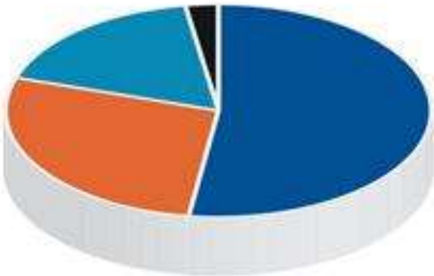
3

History and milestones

- 1955 Foundation of the Nuclear Physics Institute in Rez
- 1957 VVR-S research reactor start-up
- 1972 The original Institute was separated into the Nuclear Physics Institute and the Nuclear Research Institute
- 1993 The Nuclear Research Institute Rez was privatised to joint-stock company
- 2000 Scientific leadership of the commissioning of Temelin NPP
  - Purchase of Institute of Applied Mechanics Brno, Ltd. (IAM)
  - 2002 Research Centre Rez Ltd. (CVŘ)
  - Purchase of part of ENERGOPROJEKT PRAHA a.s. – formation of the Division ENERGOPROJEKT
- 2009 Acquisition of
  - Research and Testing Institute Plzen (VZÚ Plzeň)
  - EGP INVEST, spol. s r.o. (EGPI)
- 2011 Formation of UJV Group
  - ÚJV Řež + CVŘ Řež + VZÚ Plzeň + ÚAM Brno + EGPI Uhersky Brod

4

Shareholders



- ČEZ, a. s. – 52,46%
- Slovenské elektrárne, a.s. – 27,77%
- ŠKODA JS a.s. – 17,39%
- Municipality Husinec – 2,38%

Company strategy

To provide

- Engineering, design, analytical and scientific support in operating and constructing new energy facilities including nuclear facilities.
- Comprehensive and system R&D services, especially in the area of use of nuclear energy and ionizing radiation sources.

To be

- Professional authority and promoter in the area of nuclear energy and utilization of ionizing radiation.
- A transparent company with clear management, well-arranged finance and open information about implemented projects.
- Good neighbor in all places where we implement our oobjectives and projects.


International cooperation I.
ÚJV
An inherent part of activities of the Institute from its foundation in 1955.
Multilateral cooperation
International Atomic Energy Agency (IAEA), Vienna
Nuclear Energy Agency (NEA), Paris
Participation in framework programs of EURATOM, Brussels
Member of the European Nuclear Education Network (ENEN)
Member of the European Technical Safety Organizations Network (ETSON)
The Electric Power Research Institute (EPRI)
Key player in founding process of NUGENIA
7


International cooperation II.
ÚJV
Bilateral cooperation
Commission at Energy Atomic (CEA), France
Institute for Radiological Protection and Nuclear Safety (IRSN), France
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany
Czech-Russian Work Group for Nuclear Energy, MPO/ROSATOM
State Scientific & Technical Centre for Nuclear and Radiation Safety (SSTC NRS), Ukraine
Cooperation with US institutes through agreements concluded between the regulatory bodies (USNRC–SÚJB) and ministries (USDOE–Ministry of Industry and Trade)
Bhabha Atomic Research Centre (BARC), India
Centrum of Nuclear Research (NCBJ),Poland
8

Certificates

ÚJV

- EN ISO 14001:2004, valid until: 2014-06-23
- EN ISO 9001:2008, valid until: 2014-06-23
- BS OHSAS 18001:2007, valid until: 2014-06-23
- Certificate of Facility Security Clearance

TÜV NORD

9

ÚJV Group

ÚJV

ÚJV

VZÚ PLZEŇ

EGP INVEST

IAM BRNO

10

Subsidiary companies

- **Research Centre Rez**
  - Founded in 2002; Director: Martin Ruščák
  - Research and development organisation focused on technologies in energy; Operator of research reactors LVR-15 and LR-0
- **Research and Testing Institute Plzen**
  - Founded in 1907, from 2006 owned by ÚJV Řež,a.s., Director: Václav Liška
  - Research, development and accredited testing; Research of materials and mechanical engineering; Computer modelling
- **EGP INVEST, spol. s r.o.**
  - Founded in 1991 in Uherský Brod, from 2009 owned by ÚJV Řež, a. s., Director: Petr Sláčala
  - Design activities, surveys; Engineering activity
- **Institute of Applied Mechanics Brno, Ltd.**
  - Founded in 1959, from 2004 owned by ÚJV Řež,a.s. Director: Lubomír Junek
  - Comprehensive analyses of strength, service life and seismic resistance of steel structures, pressure vessels; Advisory services in the area of mechanical engineering, metallurgy and energy

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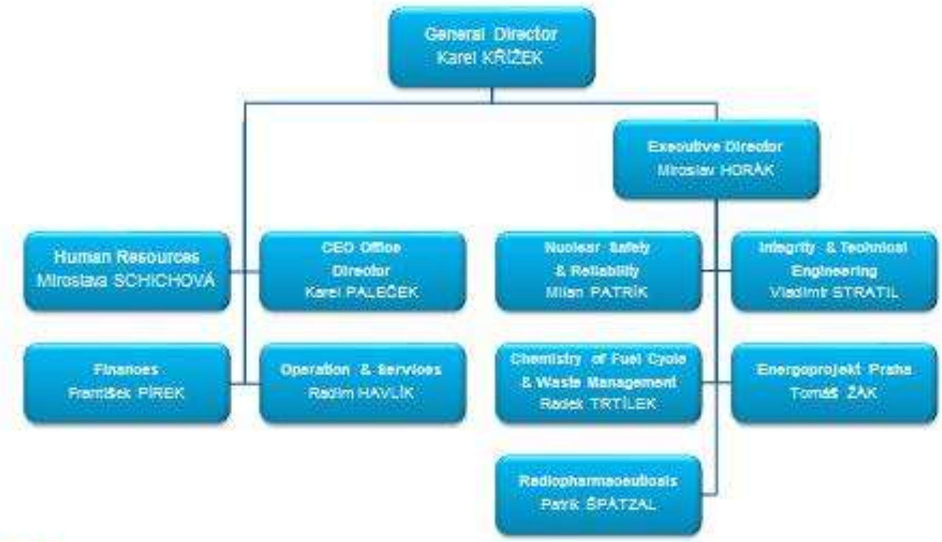
Divisions and their main services

Organization Chart



13

Nuclear Safety and Reliability Division

- Reactor physics and fuel cycle
- Safety analyses, including
  - Severe accidents
  - Probabilistic safety assessment
  - Emergency preparedness
- Diagnostics and reliability of existing and new reactor technologies
- Non-nuclear activities
  - Hydrogen technologies in energy and transportation
  - Support to reliability and risk management of industrial technologies, gas transport, electric power transmission, aviation

14

Integrity and Technical Engineering Division

- Structural and life time assessment of syseterns, structures and components (RPV including surveillance programme, piping systems, valves, ...)
- PLIM/ LTO programmes including specific AM programmes
- Technical support and maintenance of NPP
- Tests and analyses of material properties
- Equipment qualification
- Non-destructive testing, in-service inspection (ISI) and ISI qualification
- Design and construction of experimental and customer-requested equipment

16

Chemistry of Fuel Cycle and Waste Management Division

- Radioactive waste management
  - Services and technologies of processing, treatment and conditioning of radioactive waste
  - Radiochemical analyses, characterization of radioactive waste, radiation monitoring
  - Transport of spent nuclear fuel
- Research and engineering support to the Deep Geological Disposal Project and for L&ILW Repositories
  - Barriers, safety assessment, WAC development, design, monitoring
- Decommissioning of nuclear facilities, fragmentation and decontamination

18

ENERGOPROJEKT PRAHA Division

- Design and engineering services
  - General designer or designer – all phases and areas of investment process mainly in energy sectors: electric power production and heating
- Data processing and associated services
- Database graphics
  - Preparation of technical documentation in the environment of graphic and relation databases
  - Development of applications to support designing and operation of energy and industrial projects – GAMED and GADUS application systems

17

Radiopharmaceuticals Division

- Production of PET radiopharmaceuticals
  - „In the place of the application"
  - FDG (glucose marked ^{18}F)
- Production of SPECT radiopharmaceuticals and kits
- Research and development of radiopharmaceuticals
  - Mainly for diagnostic, but potentially also therapeutic use in the treatment of tumour diseases, neurodegenerative diseases
- Biological testing laboratory

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Significant references

Area of nuclear safety and reliability

- Development and applications of advanced algorithms for optimisation of fuel loading in NPPs
- Significant participation in power uprating projects for Czech NPPs Dukovany and Temelin
- Application of advanced knowledge of severe accident phenomenology during NPP safety enhancement
- SCORPIO
  - Measurements in the core, including calculations (EDU, ETE)
  - Non-nuclear technologies
  - Development & Operation of hydrogen bus
  - Accumulation of energy in hydrogen

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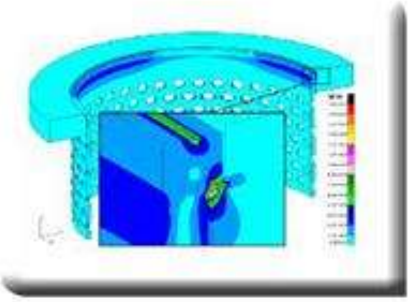
Area of integrity and technical engineering



- Development of the long-term operation and plant life management strategy for the Ukrainian nuclear power plants
  - European Commission project
  - Leading consortium member
    - ÚJV Řež, a. s.; NPP OSI Kiev; ENERGORISK Kiev; VÚJE, a.s. (SR)
- Evaluation of the technical conditions and lifetime extension of the reactor pressure vessel and internals for two units of Ukrainian NPPs
- Participation in EPRI (Electric Power Research Institute) activities
  - Successful and efficient transfer of "know-how" with unique safety and economic benefit
- Membership in NUGENIA association
  - ÚJV Řež,a.s. is one of 7 founders

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Area of chemistry of fuel cycle and waste management

- Global Threat Reduction Initiative(GTRI)
  - Transports of fresh and spent nuclear fuel from research reactors (projects RRRFR,RERT)
  - Executed transports: Czech Republic, Poland, Ukraine, Belarus, Serbia, Hungary, Bulgaria
- Decommissioning and radwaste treatment
  - Area „Velké zbytky", Řež,project of ecological solution of the past activities
- Deep Geological Repository Development
  - Provides technical support and analyses for RAWRA
- Radioactive Waste Regulatory Autority (RAWRA)
  - Barriers, safety assessment, WAC development, conceptual design

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Area of NPP Design

- Feasibility Studies
- All levels of Detail Design (studies, permit documentation, etc.)
- Safety reviews and analyses
- Author's supervision
- Participation in the commissioning and evaluation of defined success criteria fulfilment
- Customers:
  - Dukovany NPP (4x VVER 440 MWe)
  - Temelín NPP (2x VVER 1000 MWe)
  - Bohunice NPP (4x VVER 440 MWe)
  - Mochovce NPP (2x VVER 440 MWe)

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Area of radiopharmaceuticals

- PET Centres operation
  - Prague, Brno, Řež
- Supplier of PET radio-pharmaceuticals into six Czech hospitals
- PET Centre Řež constructed on the premises of the company (2010-2012)
  - with cyclotron for the production of positron emitters intended mainly for R&D PET radiopharmaceuticals
  - producing the new generation of radiopharmaceutical characterized by ultra-short lived radionuclides for diagnostics

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Contacts
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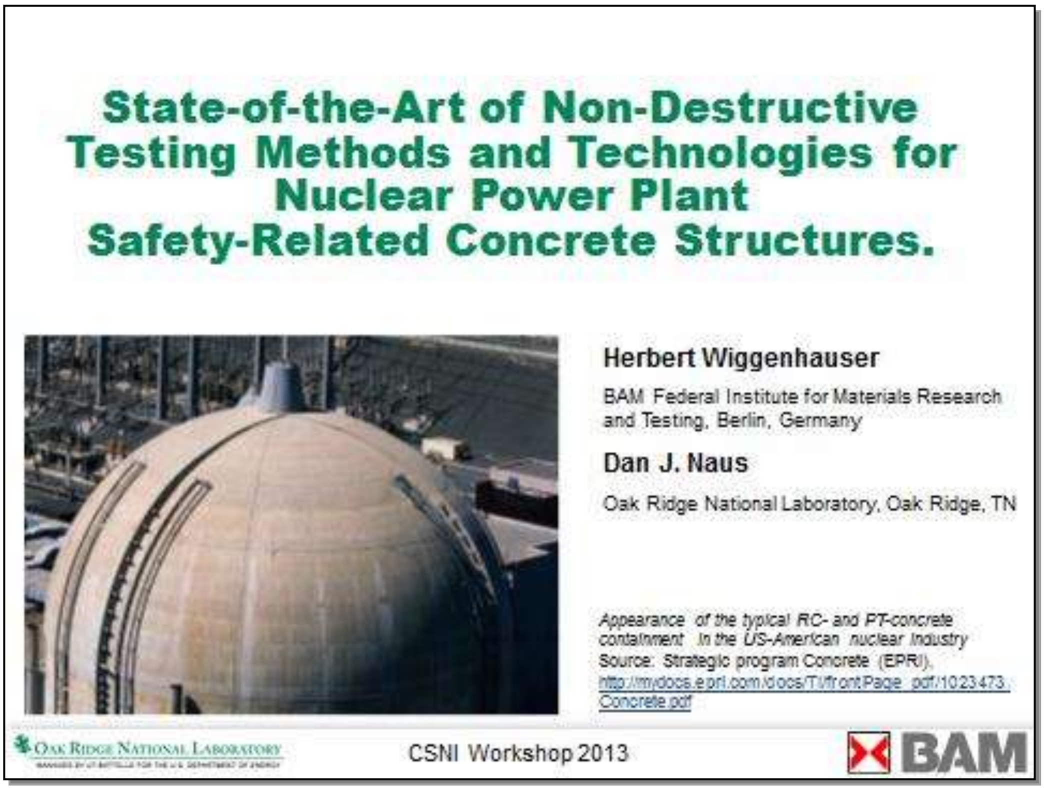
SESSION ONE


State-of-the-Art of Non-Destructive Testing Methods and Technologies for Nuclear Power Plant Safety-Related Concrete Structures.
Herbert Wiggenhauser
BAM Federal Institute for Materials Research and Testing, Berlin, Germany
Dan J. Naus
Oak Ridge National Laboratory, Oak Ridge, TN
Appearance of the typical RC- and PT-concrete containment in the US-American nuclear industry
Source: Strategic program Concrete (EPRI).
http://mydocs.epri.com/docs/TI/frontPage_pdf/1023473_Concrete.pdf
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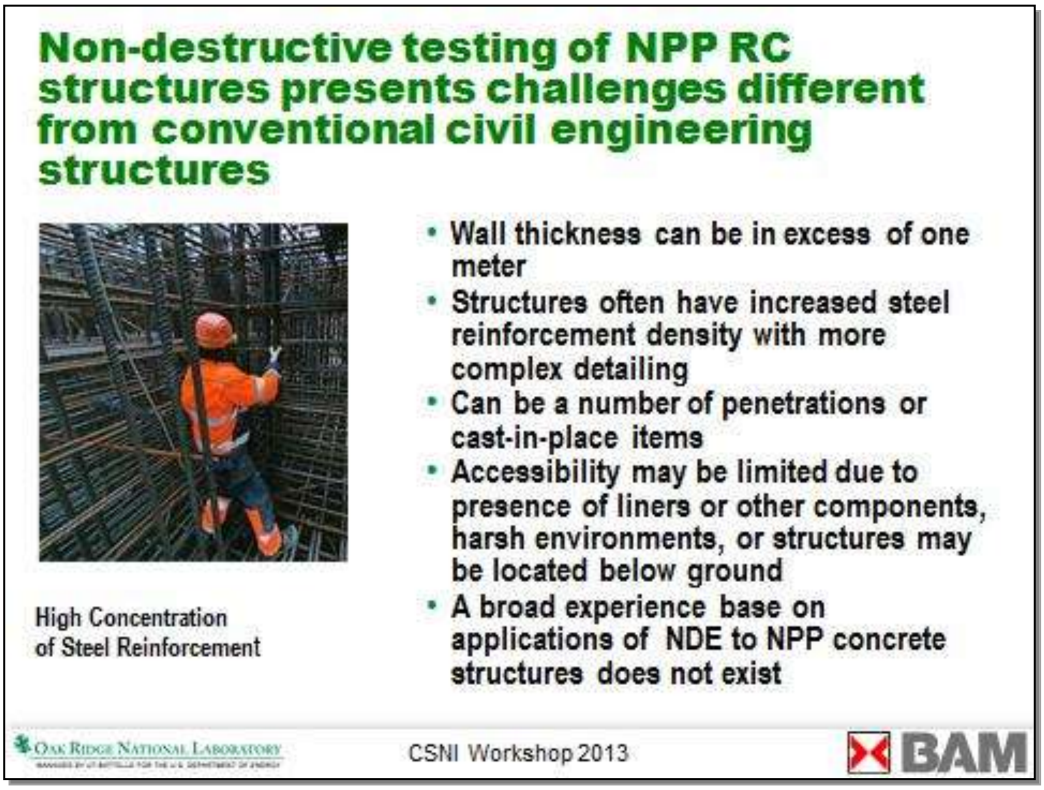
Non-destructive testing of NPP RC structures presents challenges different from conventional civil engineering structures
High Concentration of Steel Reinforcement
• Wall thickness can be in excess of one meter
• Structures often have increased steel reinforcement density with more complex detailing
• Can be a number of penetrations or cast-in-place items
• Accessibility may be limited due to presence of liners or other components, harsh environments, or structures may be located below ground
• A broad experience base on applications of NDE to NPP concrete structures does not exist
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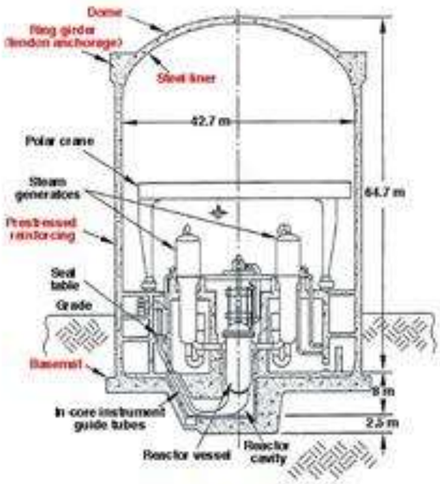
Several areas have been identified where improvements in NDT methods are desired



PWR Large Dry
Prestressed Concrete Containment

- Thick, heavily reinforced concrete sections
  - As-built or current structural features
  - Flaw detection and characterization
  - Honeycomb and embedded items
  - Voids adjacent to liner
- Basemats and other inaccessible areas
  - Based on indirect approach (i.e., environmental qualification)
- Liners –
  - Global inspection methods
  - Inaccessible areas
- Prestressing tendons
  - Real-time techniques to monitor post-tensioning systems for tendon wire failures and level of stressing

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General comments on application of NDT methods to thick, heavily-reinforced concrete structures

http://energy.gov/ne/downloads/light-water-reactor-sustainability-lwrs-program-rd-roadmap-non

Ultrasonic Shear-Wave Tomography

- Use of NDT techniques is required for compliance testing, collection of specific data or parameters, condition assessments, and damage assessments
- Quality of results is directly related to quality of concrete
- Combination of methods is often the most effective approach with first method used to detect and locate suspect areas followed by use of second method to provide high quality images to permit assessment of condition of area in question
- Acoustic (UPV, UPE, SASW, I-E, and AT), radar, and radiography appear to have greatest potential
- Inaccessible structures (i.e., foundations) are assessed through opportunistic inspections or indirectly through environmental qualification
- Development of standards to quantify capabilities of NDT for NPP safety-related concrete structures is desirable
- As NPP concrete structures age, NDT is likely to gain an increasingly important role in their aging management
- New designs should give consideration to providing improved accessibility for application of NDT techniques

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A SOA report summarizing available data and information on NDT methods and recommendations for research has been completed

- Recent operating experience has identified several areas of interest
  - Detection of cracking, voids, delamination, and honeycombing
  - Detection of inclusions of different materials or voids adjacent to concrete side of liner
  - Methods capable of identification of corrosion occurrence on the concrete side of the containment liner
  - Applicability of laser-induced breakdown spectroscopy to assess occurrence of concrete degradation in form of alkali-silica reactions, sulfate attack, irradiation, and elevated temperature
  - Locating steel reinforcement and identification of its cover depth
  - Locating tendon ducts and identification of the condition of grout materials

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Task (1) locating steel reinforcement and identification of its cover depth

Methods very well suited for the described task:

- inductive method with low frequency excitation (< 10 cm cover max 2 layers)
- inductive method with high frequency excitation (eddy-current) (< 10 cm cover max 2 layers)
- radar (< 30 cm cover diameter not measurable)

Methods well suited for the described task:

- Ultrasonic (> 5 cm cover)
- radiography (multi-angle technique) (< 60 cm two sided access)
- magnetic flux leakage (< 20 cm)

Methods partially suited for the described task:

- active thermography (< 10 cm cover; n/a for depth > 10 cm)

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Task (1) locating steel reinforcement and identification of its cover depth

The combination of radar and magnetic methods – mentioned already in the 1980ies – is still a very powerful tool for cover depth, rebar location and bar-sizing. Several devices exist; strategies how to apply both methods in combination and software for data assessment and imaging of both methods are of great interest for further development.

Research Needs

The inductive methods, both with high or low frequency excitation as well as the Radar method have to be validated to a large extent. Although commercial devices are available, the application is still not well established for the described tasks and particularly not in the needed thickness range. For radiography (e.g. Betatron) the time consumption is very high and and safety precautions have to be strictly followed.

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Task (2) locating tendon ducts + identification of the condition of the grout materials

Methods very well suited for the described task:

- ultrasound echo imaging (MIRA)
  locate (< 80 cm), cover (< 80 cm), grouting condition
- radar locate (< 50 cm) cover (< 50 cm)

Methods well suited for the described task:

- ultrasound echo (A-scan) locate (< 50 cm), cover (< 50 cm)
- radiography (x-ray, gamma, betatron, linear accelerator),
  locate: (< 60 cm), cover: (< 60 cm), grouting
- ultrasound transmission, locate (< 10 cm)

Methods partially suited for the described task:

- radiography (x-ray, gamma, betatron, linear accelerator)
  cover: + (< 60 cm),
- ultrasound echo (A-scan) for grouting condition

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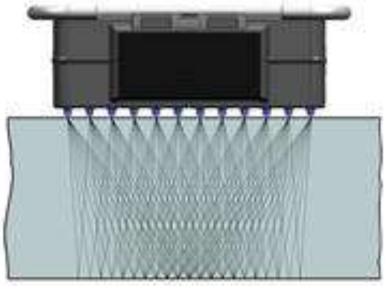
Task (2) locating tendon ducts + identification of the condition of the grout materials

Ultrasonic equipment and scanner system in BAM laboratory



Acsys MIRA A1040

Acsys A1220

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Task (2) locating tendon ducts + identification of the condition of the grout materials

Research Needs

Linear array (ACSYS MIRA A1040) should be tested in comprehensive experiments at new specimens.
Improvement of the ultrasonic echo imaging technique with SAFT including phase evaluation.

Special evaluation algorithms with back propagation and RTM (reverse time migration).

Hardware: development of transducers with adapted focusing range.
Size and area of synthetic aperture should be extended.

To improve the performance, the development of larger automated equipment to scan the surfaces should be done.

New vision: air coupled ultrasound application with new types of nano sensors.

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Task (3) detection of cracking, voids, delamination and honeycombing in concrete structures

Methods very well suited for the described task:

- none

Methods well suited for the described task:

- imaging ultrasonic echo (delaminations, cracks, voids) in a depth range < 100 cm
- impact echo (delaminations) in a depth range < 50 cm

Methods partially suited for the described task:

- imaging ultrasonic echo (honeycombs) in a depth range < 100 cm
- ultrasound, surface + lamb + diffracted waves (delaminations, cracks, voids) in a depth range < 50 cm
- impact echo (cracks, voids) in a depth range < 50 cm

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Task (3) detection of cracking, voids, delamination and honeycombing in concrete structures

Research Needs

It would be beneficial to do a comprehensive analysis of inspection records to collect information about the most typical defects in containments and related NPP-structures. Following this, the design of a mock-up for the typical NPP-containments with typical artificial defects (vertical cracks surface, near surface crack, irregular crack or deep delamination, honeycombing) can be made.

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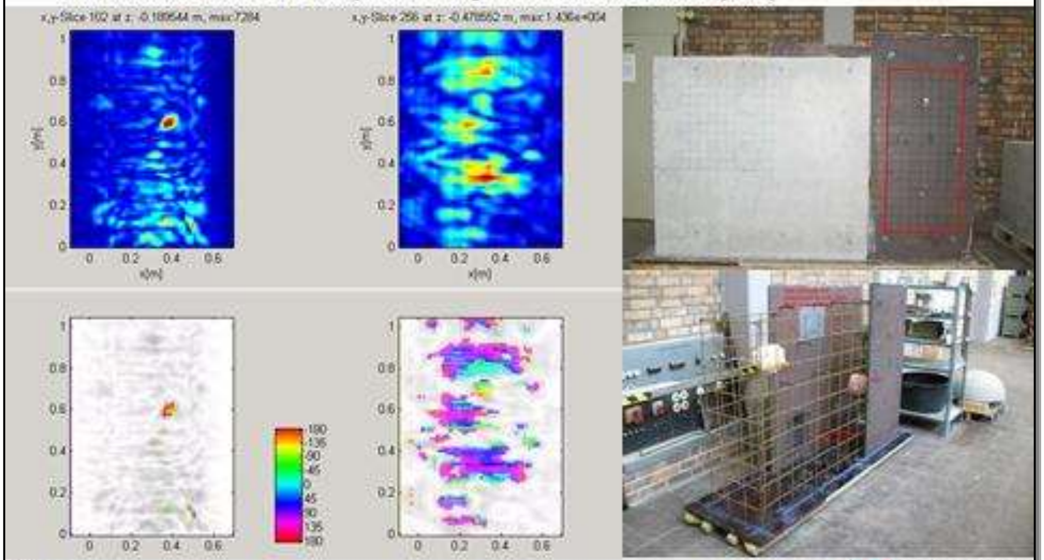
Task (3) detection of cracking, voids, delamination and honeycombing in concrete structures

Identification of voids and honeycombs using the ACSYS A1040 MIRA (BAM)



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Task (4) detection of inclusions of different materials or voids adjacent to the concrete side of the containment liner

Methods well or very well suited for the described task:

- none

Methods partially suited for the described task:

- imaging ultrasound with large aperture (location, material), depth range ~ 2 m

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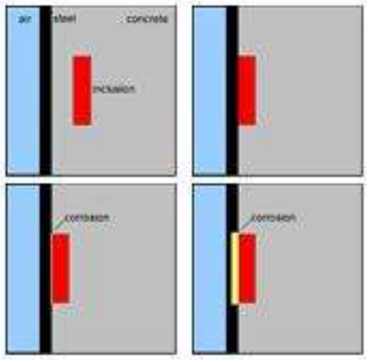
Task (4) detection of inclusions of different materials or voids adjacent to the concrete side of the containment liner

Four different scenarios may be of interest:

- Concrete layer between liner and inclusion
- Direct contact between inclusion and liner
- Early stage liner corrosion
- Significant liner thickness loss



Research Needs

To assess the ability of the techniques mentioned above to detect inclusions of anomalous material properties it is recommended to perform a series of test at full scale mockups, including all scenarios described above. In a first phase existing techniques should be assessed. Further research and development has to be discussed after evaluating the results.

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Task (5) methods capable of identification of corrosion occurrence on the concrete side of the containment liner

Methods well or very well suited for the described task:

- none

Methods partially suited for the described task:

- ultrasound echo large aperture (delamination),
- ultrasound echo high frequency (indirect measurement of corrosion by determination of liner thickness)
- acoustic emission (active corrosion)

Only indirect measurements can eventually point out that corrosion in one of the above described forms has happened. While ultrasound echo with large aperture might be able to identify delaminations (which might be an indication for corrosion and loss of contact near the liner), ultrasound echo high frequency can measure the remaining liner thickness (access to liner).

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Task (5) **methods capable of identification of corrosion occurrence on the concrete side of the containment liner**

Research Needs

This task needs fundamental research.
Detection of corrosion through the steel liner or through highly reinforced thick concrete.
Has any research in this area been tried?

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Conclusions (contd.)
Biggest impact on research into NPP related NDE

- The biggest impact on research into NPP related NDE of reinforced concrete structures may be found in improvement of the **research infrastructure** and support of synergy effects.

- **Combination** of methods is one of the key areas for finding solutions to the testing tasks

- **Automation** and scanning is vital for producing high quality data which is the basis for any subsequent data analysis.

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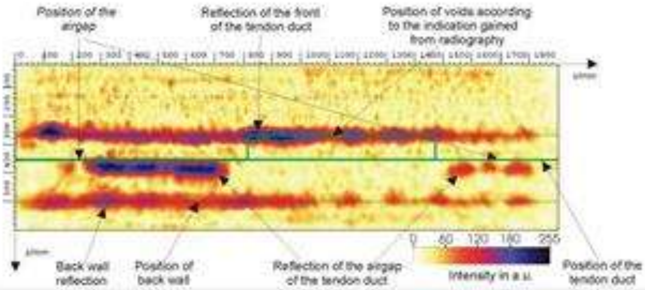
Conclusions (contd.)
Biggest impact on research into NPP related NDE

- A major role in any research is **software** for **modelling**, **simulation** and **data analysis**. It is necessary to be able to simulate a testing scenario as close as possible to reality to be able to choose the appropriate equipment and parameters for the test and the subsequent data analysis.
- A **common data format** would be a significant step towards more **collaboration** between research groups and comparability of results

Result of imaging tendon duct in a specimen with shear waves: B-scan above the tendon duct from 3D-SAFT reconstruction.



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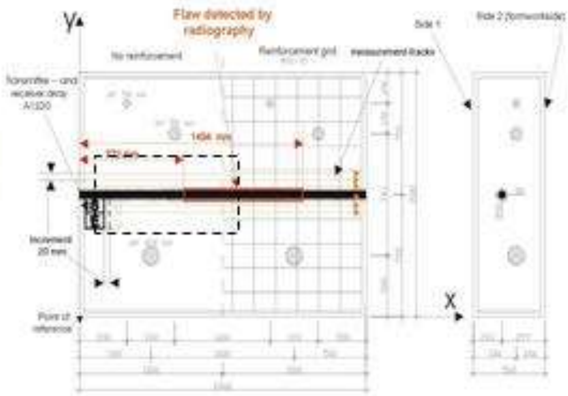
Conclusions (contd.)
Biggest impact on research into NPP related NDE

- A **software pool** with dedicated numerical routines for data analysis, **visualization**, modeling, simulation and **validation** - as it is common in other areas of research, e.g. geophysics or medicine - would be very supportive for any NDE research and application.
- **Reference specimens** and **validation** are key elements for a streamlined research effort. Comparability of experiments and results should be assured.



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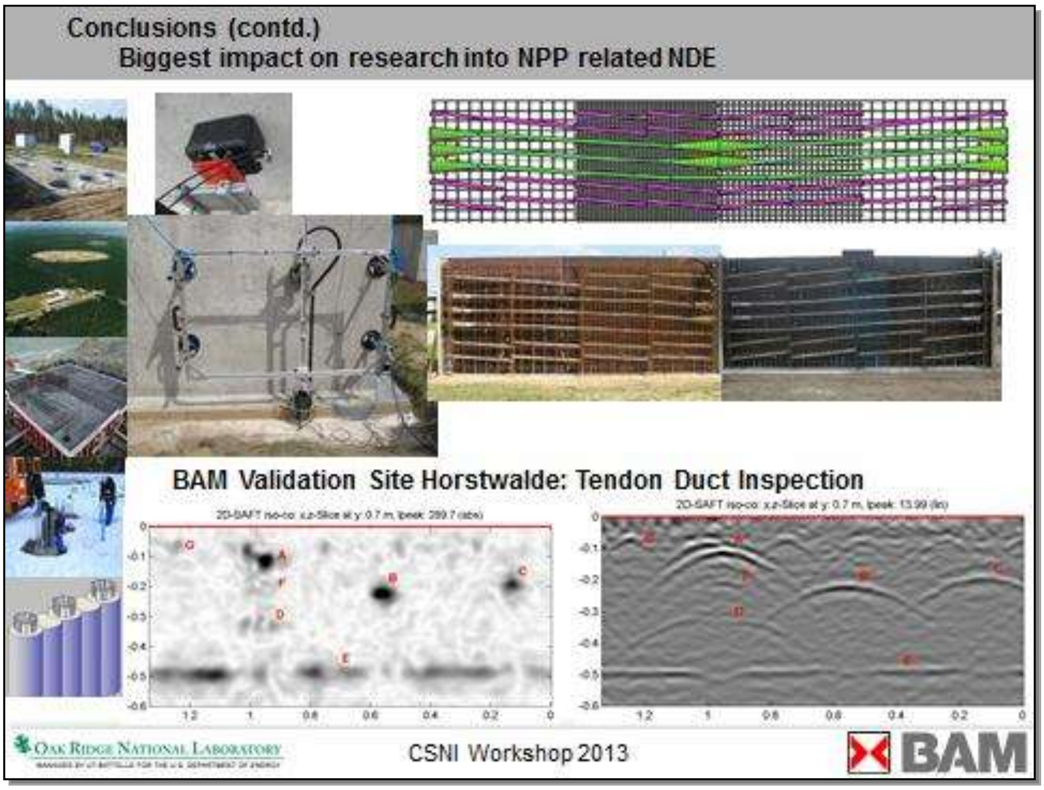
Conclusions (contd.)
Biggest impact on research into NPP related NDE
BAM Validation Site Horstwalde: Tendon Duct Inspection
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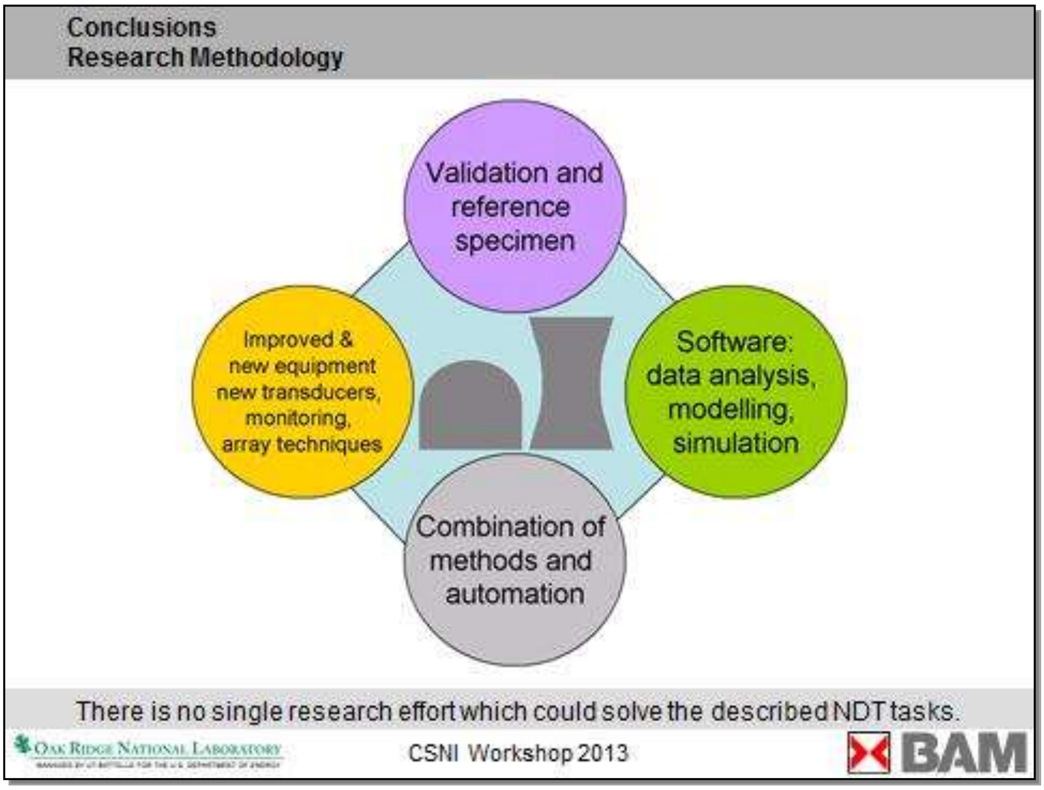
Conclusions
Research Methodology
Validation and reference specimen
Improved & new equipment new transducers, monitoring, array techniques
Software: data analysis, modelling, simulation
Combination of methods and automation
There is no single research effort which could solve the described NDT tasks.
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Thank you!

ORNL
E.M. Schilling

BAM
Dipl.-Ing. Rosemarie Helmerich
Dr. Martin Krause
Dr. Frank Mielentz
Dr. Ernst Niederleithinger
Dr. Alexander Taffe
Dipl.-Phys. Gerd Wilsch
Dipl.-Ing Christian Köpp

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NDT candidate methods for foundations/piles

- Candidate methods
  - Sonic echo
  - Impulse-response (mobility)
  - Impedance logging
  - Crosshole sonic logging
  - Parallel seismic
  - Gamma-gamma logging
- NPP basemats either partially or totally inaccessible
- Indirect methods related to environmental qualification often utilized

Item Measured	Candidate Methods or Reference
Air	
Acidity	ASTM D 1654, G 60, G 92
Carbon dioxide content	Sensors
Humidity	ASTM D 4230 and E 337
Temperature	Sensors
Soil	
Corrosivity/pH	ASTM G 51; BS 1377-3(9); BR 279
Sulfate ion concentration	ASTM D 4542; BS 1377-3(5); BR 279
Chloride ion concentration	ASTM D 4542; BS 1377(3); BR 279
Resistivity	ASTM G 57
Moisture content	ASTM D 2216, D 3017; DIN 18121-1, -2
Nitrate	BR 279
Permeability	ASTM D 2434; DIN 18130-1; prEN 1997-2; BS 8004, 5930
Groundwater	
Water table elevation/sampling	ASTM D 512, D 1293, D 4448; wells, piezometers
Corrosivity/pH	ASTM D 1067, D 1293, E 70; BR 279; BS 1377-3(9)
Hydrostatic pressure	Sensors
Dissolved oxygen content	ASTM D 888
Soluble sulfate	ASTM D 516, D 4327, D 4130, D 4327; BR 279, BS 1377-3; DIN 38406-5
Nitrate ion	ASTM 4327; BR 279
Chloride ion	ASTM D 4458, D 4327, D 512; BR 279; BS 1377-3(7)
Carbon dioxide content	EN 13577
Microorganisms/bacteria	ASTM D 4412

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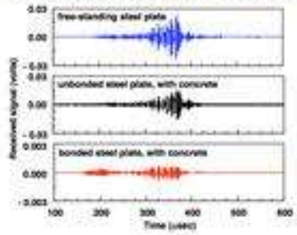
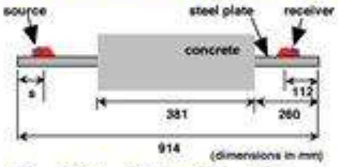
General comments on NDT techniques addressing containment metallic pressure boundaries

High-frequency acoustic imaging – effect of concrete and bond



Effect of Concrete and Bond on Signal



Steel Plates 914 x 203 x 25.4 mm³
w and w/o flaws Embedded in Concrete

- Inaccessible portions of containment metallic pressure boundary have experienced corrosion
- Available NDT techniques are time-consuming and costly because they generally examine only a small area at a time
- Concrete bonded to metallic pressure boundary can result in significant signal attenuation
- Techniques utilizing guided waves that interrogate specimen cross-section appear promising
- Additional activities are required to develop global inspection system as well as to characterize defects and assess flaw significance
- Lucius Pitkin/EPRI/DOE is looking at feasibility of tandem- synthetic aperture focusing technique and magnetostrictive sensors to detect corrosion in inaccessible areas

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Maintaining the post-tensioning system components in good working order is essential for prestressed concrete members

Example of multistrand tendon system

PT system examination

- Force determinations
- Mechanical tests
- Grease tests
- Anchorage inspections

- Current examination programs adequate for determining condition of PT tendon materials and evaluating effects of conventional degradation
- Conventional material degradation has not been a significant aging concern, but isolated incidences of wire failure due to corrosion have occurred
- Leakage of tendon sheathing filler (except for loss of corrosion protection) appears to be primarily an aesthetic problem
- Tendon forces at most plants are acceptable by a significant margin, but larger than anticipated loss of force has occurred in a few older plants
- What is the exact relationship between end-anchorage force measured by lift-off test and change in mean force along tendon length?
- Estimation of time-dependent loss of prestressing force is based on limited duration relaxation tests (e.g., 1000 h) and concrete creep results (e.g., 6 mo). What is validity of extrapolation of these results by time factors of ~ 500 and 120 (60 yr life)

Post-tensioning system degradation affects when concrete cracks and steel reinforcement yields

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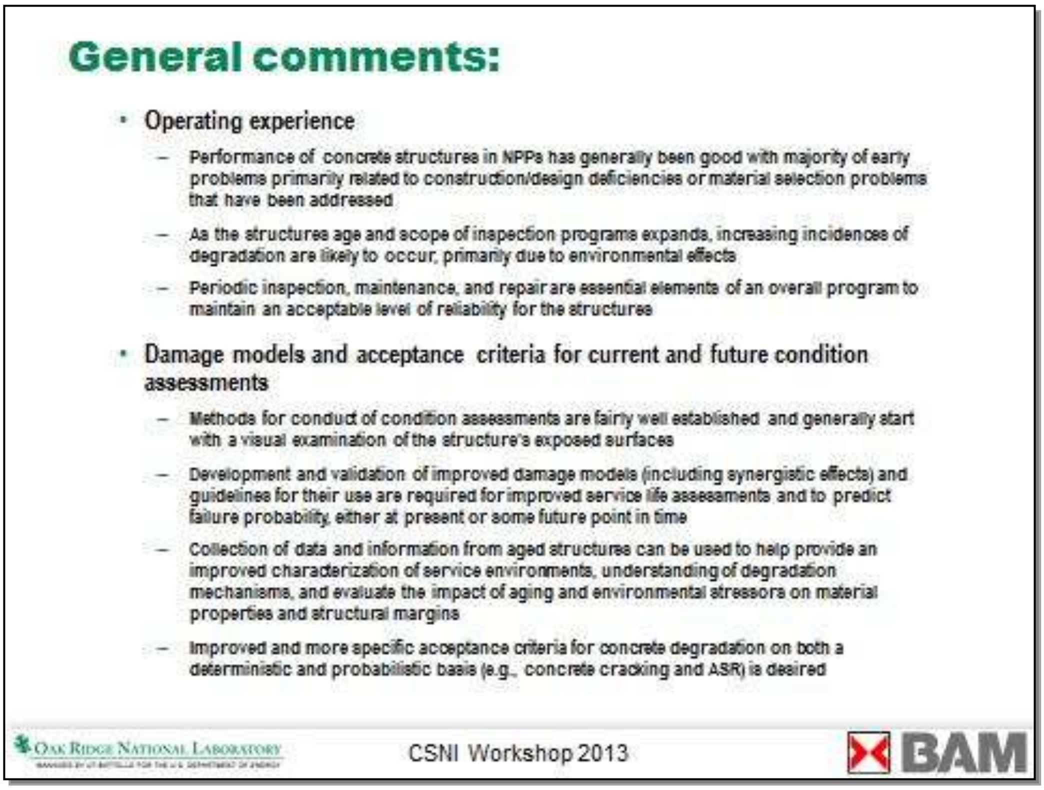
General comments:
• Operating experience
– Performance of concrete structures in NPPs has generally been good with majority of early problems primarily related to construction/design deficiencies or material selection problems that have been addressed
– As the structures age and scope of inspection programs expands, increasing incidences of degradation are likely to occur, primarily due to environmental effects
– Periodic inspection, maintenance, and repair are essential elements of an overall program to maintain an acceptable level of reliability for the structures
• Damage models and acceptance criteria for current and future condition assessments
– Methods for conduct of condition assessments are fairly well established and generally start with a visual examination of the structure's exposed surfaces
– Development and validation of improved damage models (including synergistic effects) and guidelines for their use are required for improved service life assessments and to predict failure probability, either at present or some future point in time
– Collection of data and information from aged structures can be used to help provide an improved characterization of service environments, understanding of degradation mechanisms, and evaluate the impact of aging and environmental stressors on material properties and structural margins
– Improved and more specific acceptance criteria for concrete degradation on both a deterministic and probabilistic basis (e.g., concrete cracking and ASR) is desired
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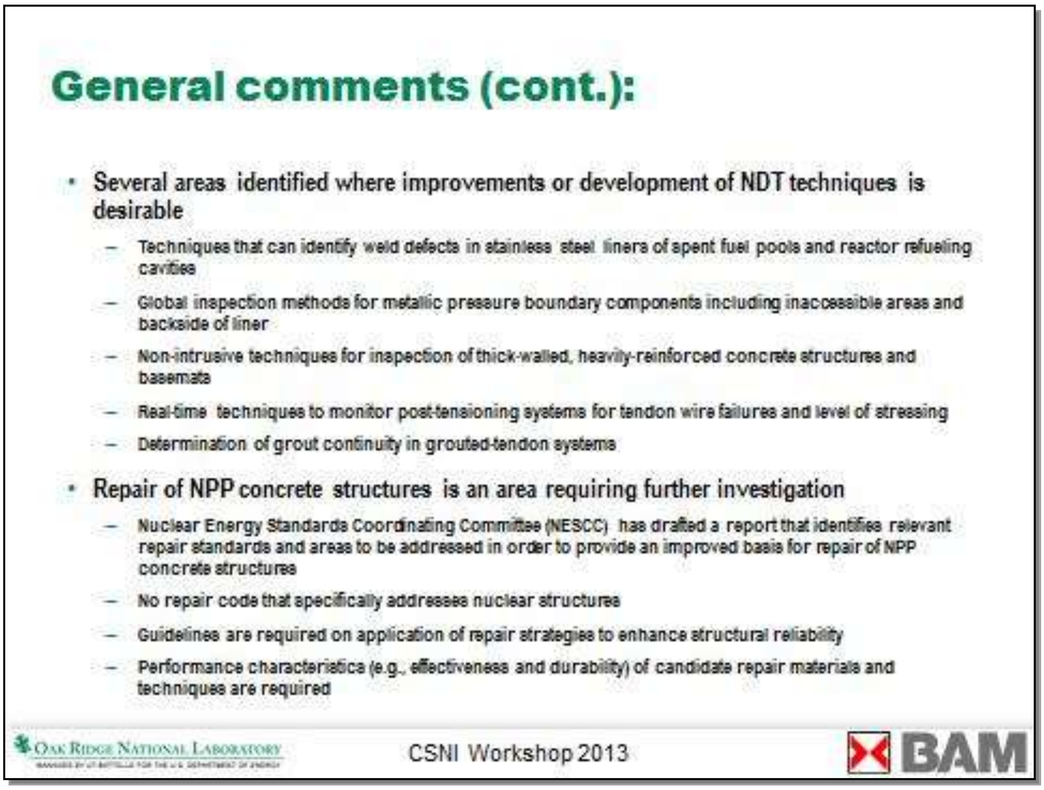
General comments (cont.):
• Several areas identified where improvements or development of NDT techniques is desirable
– Techniques that can identify weld defects in stainless steel liners of spent fuel pools and reactor refueling cavities
– Global inspection methods for metallic pressure boundary components including inaccessible areas and backside of liner
– Non-intrusive techniques for inspection of thick-walled, heavily-reinforced concrete structures and basemats
– Real-time techniques to monitor post-tensioning systems for tendon wire failures and level of stressing
– Determination of grout continuity in grouted-tendon systems
• Repair of NPP concrete structures is an area requiring further investigation
– Nuclear Energy Standards Coordinating Committee (NESCC) has drafted a report that identifies relevant repair standards and areas to be addressed in order to provide an improved basis for repair of NPP concrete structures
– No repair code that specifically addresses nuclear structures
– Guidelines are required on application of repair strategies to enhance structural reliability
– Performance characteristics (e.g., effectiveness and durability) of candidate repair materials and techniques are required
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General comments (concl.):

- Extend application of time-dependent reliability-based approach
  - Evaluation of structures for continued service should provide quantitative evidence that their capacity is sufficient to withstand future demands within the proposed service period with a level of reliability sufficient to ensure public health and safety
    - Structural aging may cause the integrity of structures to evolve over time
    - Uncertainties that complicate the evaluation of aging effects arise from a number of sources and any evaluation of the reliability or safety margins of a structure during its service life must take these sources into account
    - Structural reliability analysis methods provide the framework for dealing with uncertainties
  - Assess the current and future performance of degraded structures
    - Hazard function [conditional probability of failure within the time interval (t,t+Dt) given that the component has survived up to t] is used to analyze structural failures due to aging
    - Fragility analysis (depicts the role of uncertainties in response of structures to specified challenges) provides a structured framework to:
      - Identify aging factors important to safety;
      - Identify areas where the potential for degradation to impact safety is important;
      - Focus in-service inspection, maintenance, and repair;
      - Guide acquisition of additional data; and
      - Make risk-informed service decisions regarding continued service
    - Develop risk-informed condition assessment guidelines for evaluating the performance of aging structures
    - Formulate in-service inspection/maintenance strategies aimed at ensuring that structures maintain a desired performance level

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Applying numerical simulation for the non-destructive evaluation of concrete components subjected to high dynamic loading

G. Michaloudis, N. Gebbeken

NON-DESTRUCTIVE EVALUATION OF THICK WALLED CONCRETE STRUCTURES, PRAGUE, CZECH REPUBLIC, 17.-19.09.2013

Outlook

1. Motivation
2. Characteristics of explosions
3. Description of conducted experiments
4. Applying numerical methods for the evaluation of damage
5. Conclusions – Future work


Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Motivation
Load carrying capacity tests of RC-plates
55/P5
[WTD 52]
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Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Motivation
Load carrying capacity tests of RC-plates
[Mangerig 2002]
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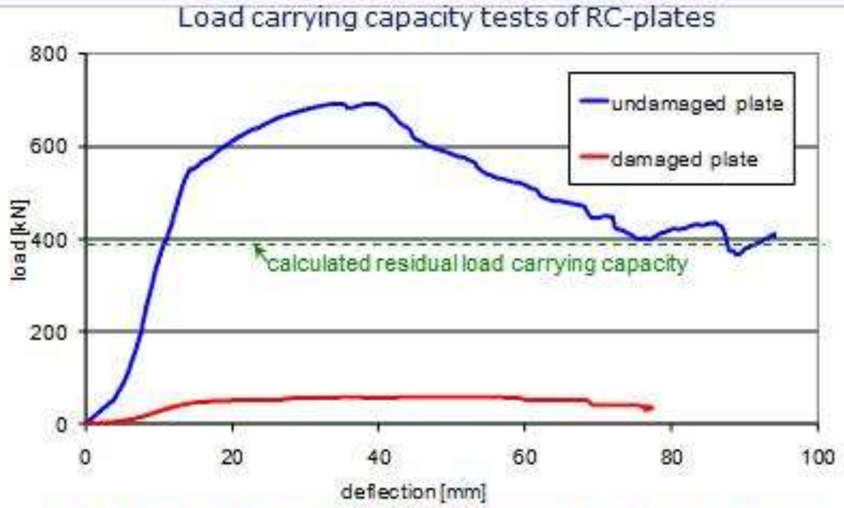
Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Motivation



Goal: Calculate the load carrying capacity of concrete structural members, partially damaged due to blast loading

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Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Characteristics of Explosions

Categorization of Explosions with respect to its:

a) Velocity of Propagation through the air

- Deflagration (subsonic propagation)
- Detonation (supersonic propagation)

b) Distance from the target (Scaled Distance $z = R/W^{1/3}$, R=distance, W=Mass of explosive material):

- Contact Explosion
- Close Range Explosion (z<0.5)
- Wide Range Explosion (z>0.5)

- Explosion → Propagation of large amounts of energy within microseconds
- Typical detonation velocities: 8000-10000 m/s
- Creation of a shock wave

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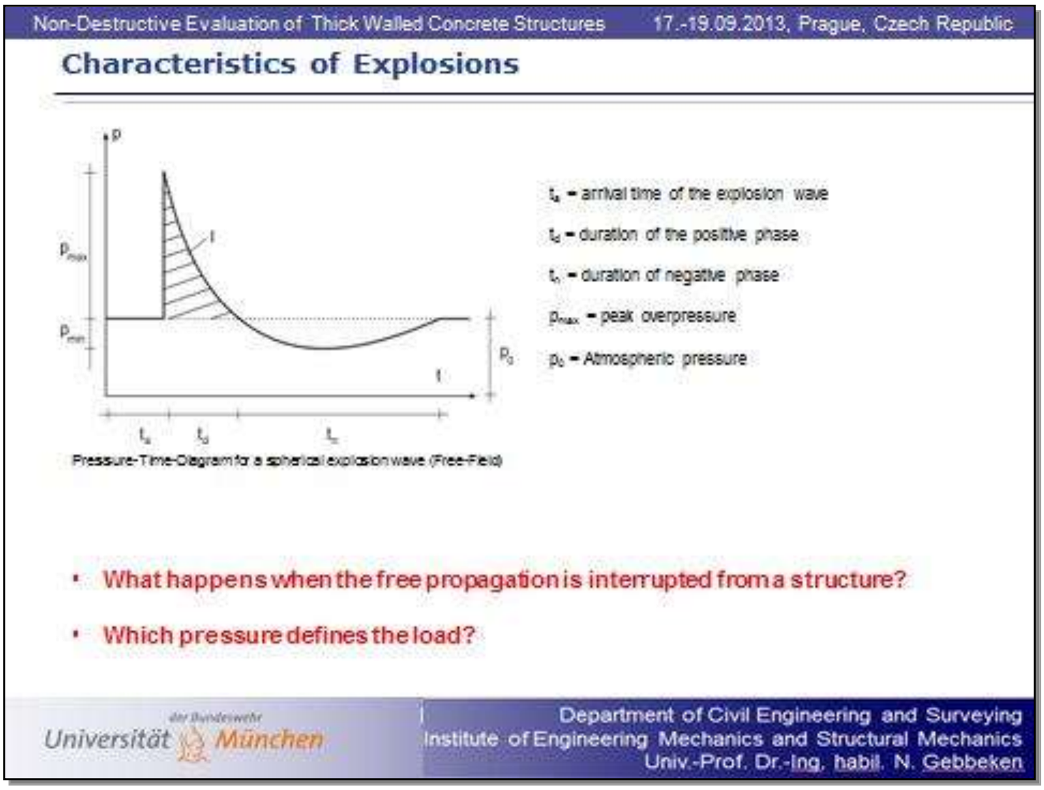
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Characteristics of Explosions
p
p_{max}
p_{min}
I
t
p_0
t_a
t_d
t_n
Pressure-Time-Diagram for a spherical explosion wave (Free-Field)
t_a = arrival time of the explosion wave
t_d = duration of the positive phase
t_n = duration of negative phase
p_{max} = peak overpressure
p_0 = Atmospheric pressure
• What happens when the free propagation is interrupted from a structure?
• Which pressure defines the load?
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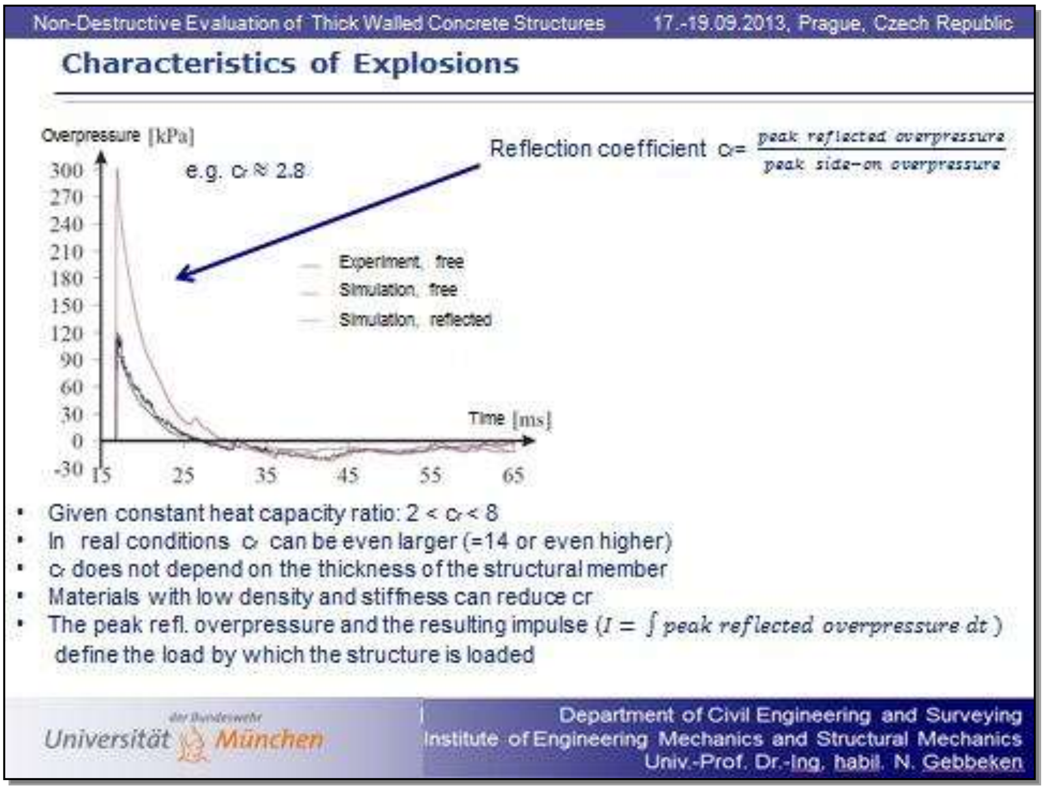
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Characteristics of Explosions
Overpressure [kPa]
e.g. $c_r \approx 2.8$
Reflection coefficient $c_r = \frac{peak\ reflected\ overpressure}{peak\ side-on\ overpressure}$
Experiment, free
Simulation, free
Simulation, reflected
Time [ms]
300
270
240
210
180
150
120
90
60
30
0
-30
15
25
35
45
55
65
• Given constant heat capacity ratio: $2 < c_r < 8$
• In real conditions c_r can be even larger (=14 or even higher)
• c_r does not depend on the thickness of the structural member
• Materials with low density and stiffness can reduce cr
• The peak refl. overpressure and the resulting impulse ($I = \int peak\ reflected\ overpressure\ dt$) define the load by which the structure is loaded
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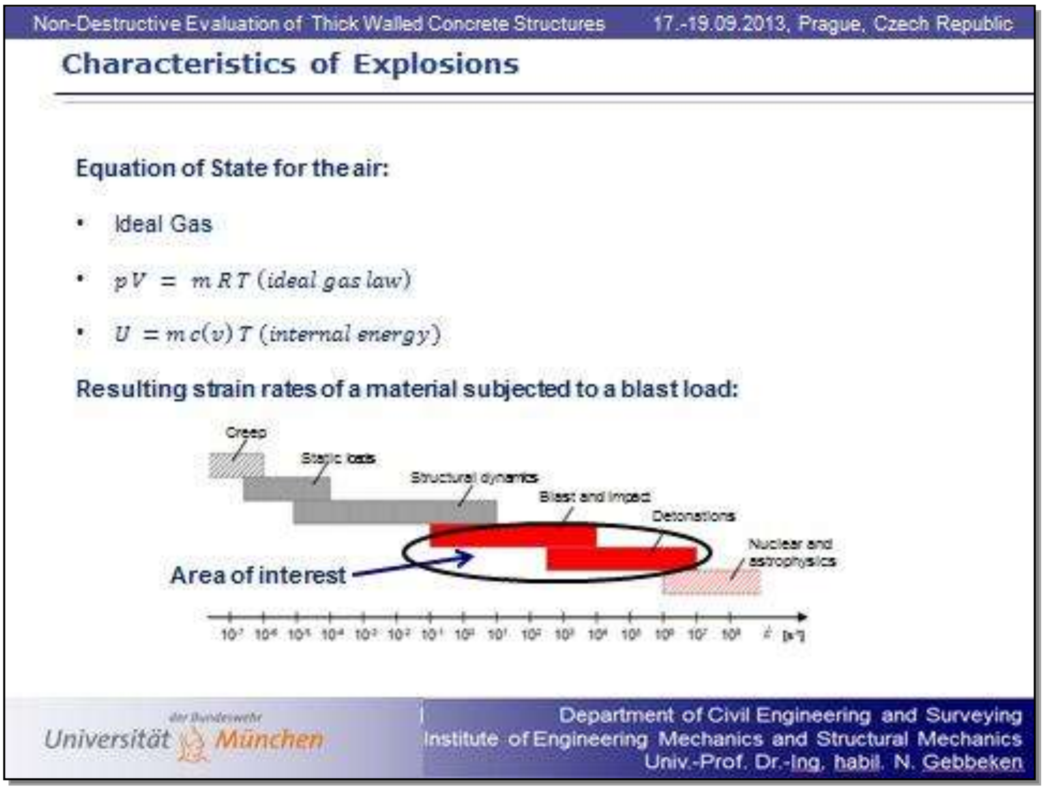
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Characteristics of Explosions
Equation of State for the air:
• Ideal Gas
• $pV = mRT$ (ideal gas law)
• $U = m\,c(v)\,T$ (internal energy)
Resulting strain rates of a material subjected to a blast load:
Creep
Static loads
Structural dynamics
Blast and impact
Detonations
Nuclear and astrophysics
Area of interest
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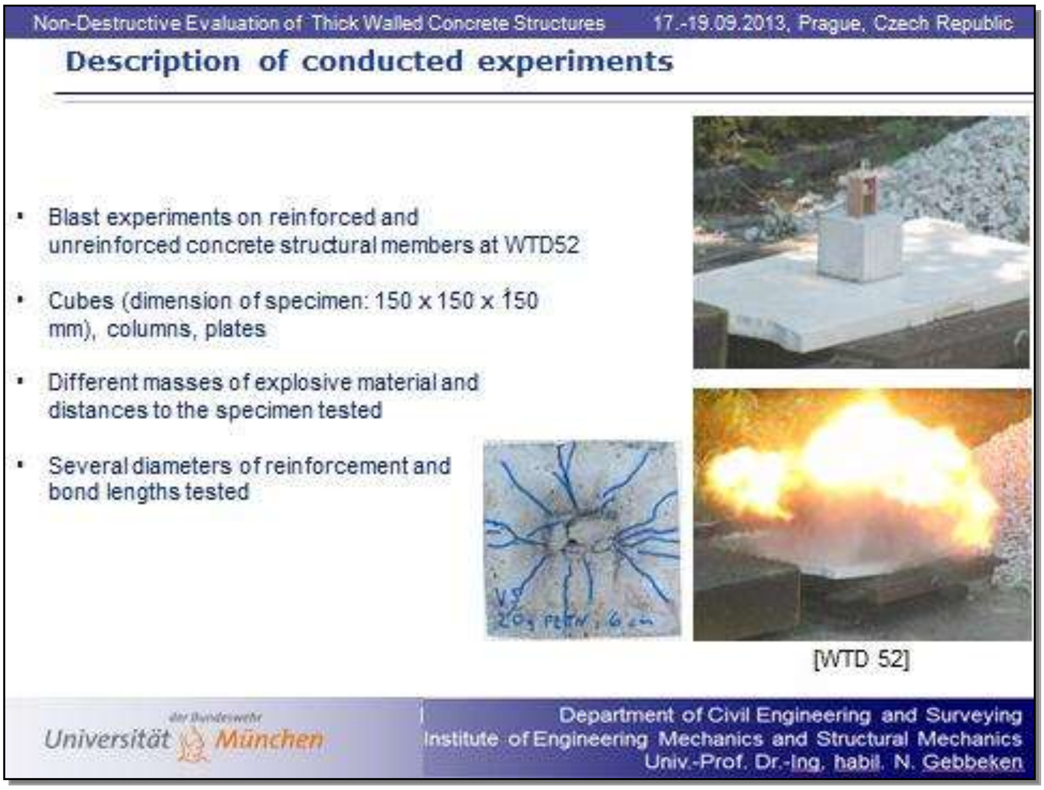
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Description of conducted experiments
• Blast experiments on reinforced and unreinforced concrete structural members at WTD52
• Cubes (dimension of specimen: 150 x 150 x 150 mm), columns, plates
• Different masses of explosive material and distances to the specimen tested
• Several diameters of reinforcement and bond lengths tested
[WTD 52]
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Universität der Bundeswehr München

Description of conducted experiments

- Scenarios leading to

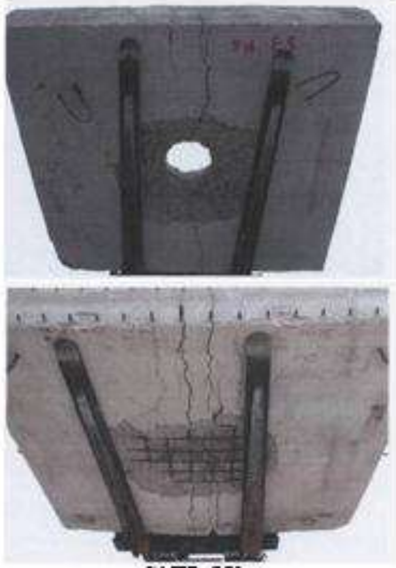
a) negligible damage

b) severe damage

c) total damage

are tested

- In a second phase the structural members are tested regarding their residual loading carrying capacity → Static tests



[WTD 52]

Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Description of conducted experiments

[Institute of Structural Engineering, Universität der Bundeswehr München]

- Compression tests
- Pull-out tests
- Bending tests

} Evaluation of the residual load carrying capacity of the damaged structural members

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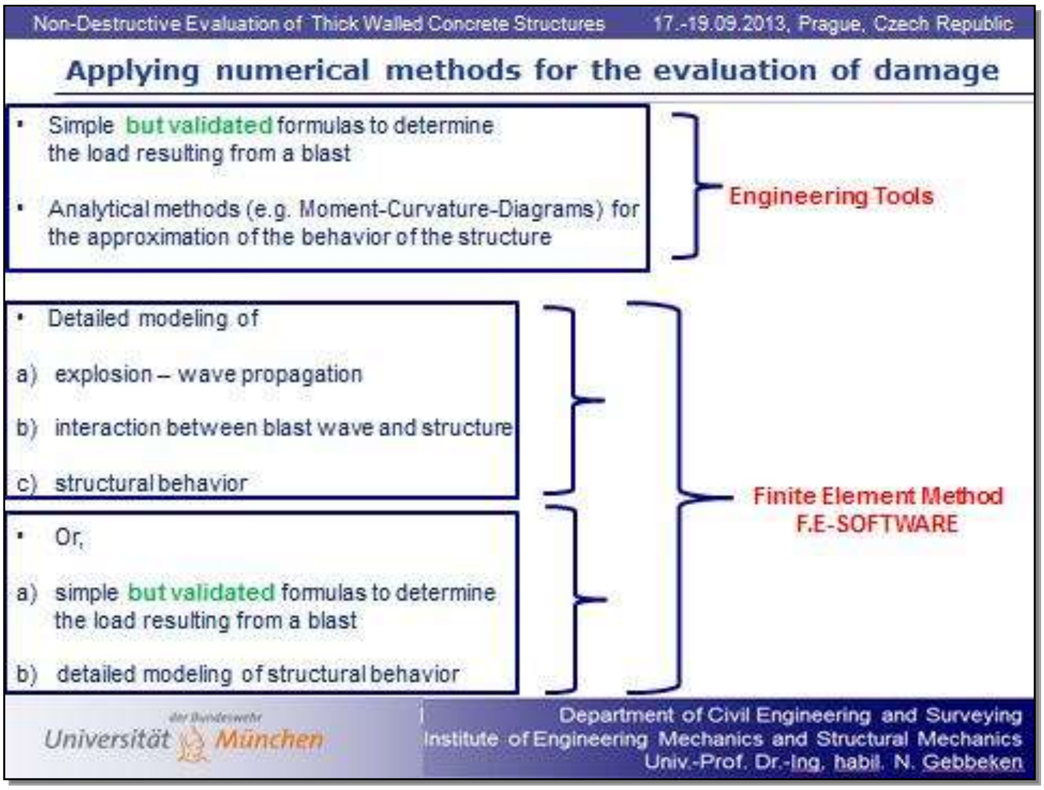
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Applying numerical methods for the evaluation of damage
• Simple but validated formulas to determine the load resulting from a blast
• Analytical methods (e.g. Moment-Curvature-Diagrams) for the approximation of the behavior of the structure
Engineering Tools
• Detailed modeling of
a) explosion – wave propagation
b) interaction between blast wave and structure
c) structural behavior
• Or,
a) simple but validated formulas to determine the load resulting from a blast
b) detailed modeling of structural behavior
Finite Element Method
F.E-SOFTWARE
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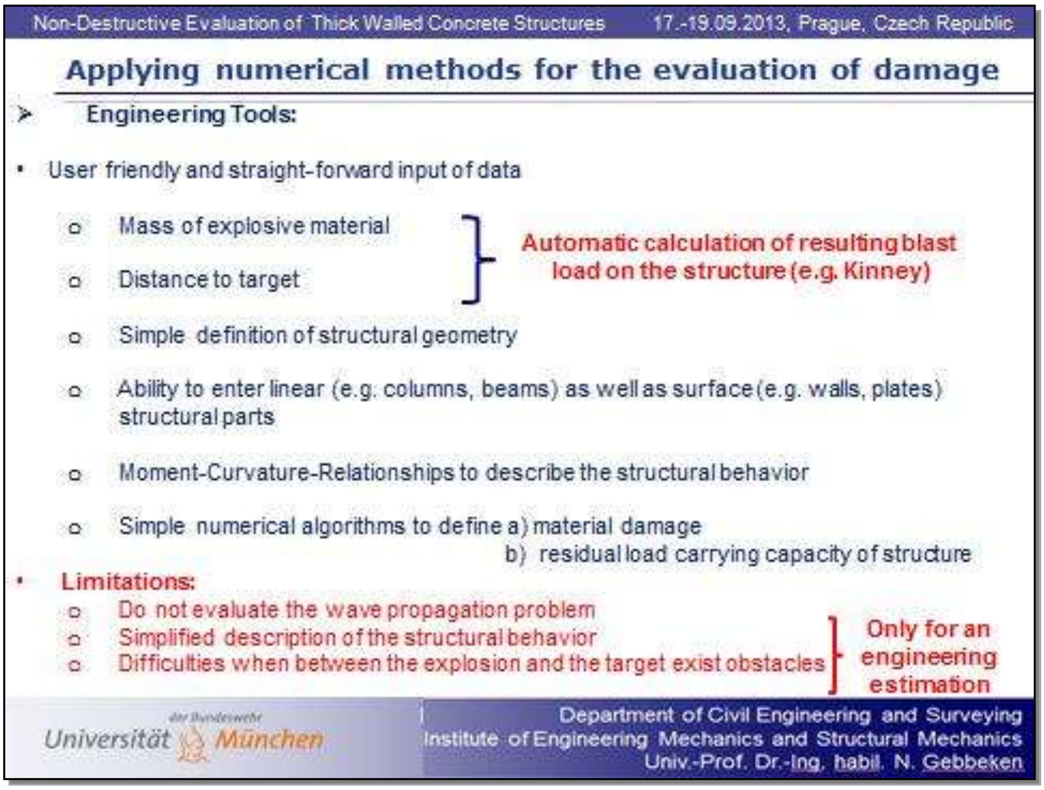
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Applying numerical methods for the evaluation of damage
Engineering Tools:
• User friendly and straight-forward input of data
Mass of explosive material
Distance to target
Automatic calculation of resulting blast load on the structure (e.g. Kinney)
Simple definition of structural geometry
Ability to enter linear (e.g. columns, beams) as well as surface (e.g. walls, plates) structural parts
Moment-Curvature-Relationships to describe the structural behavior
Simple numerical algorithms to define a) material damage
b) residual load carrying capacity of structure
• Limitations:
Do not evaluate the wave propagation problem
Simplified description of the structural behavior
Difficulties when between the explosion and the target exist obstacles
Only for an engineering estimation
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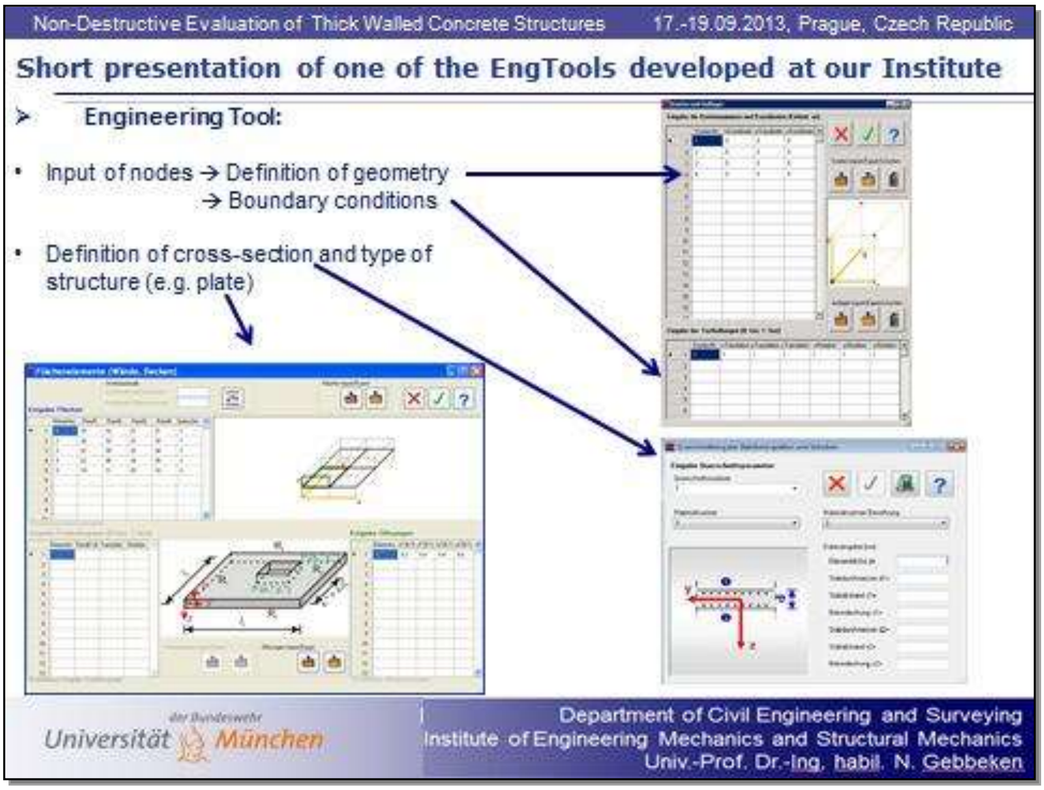
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Short presentation of one of the EngTools developed at our Institute
Engineering Tool:
Input of nodes → Definition of geometry
→ Boundary conditions
Definition of cross-section and type of structure (e.g. plate)
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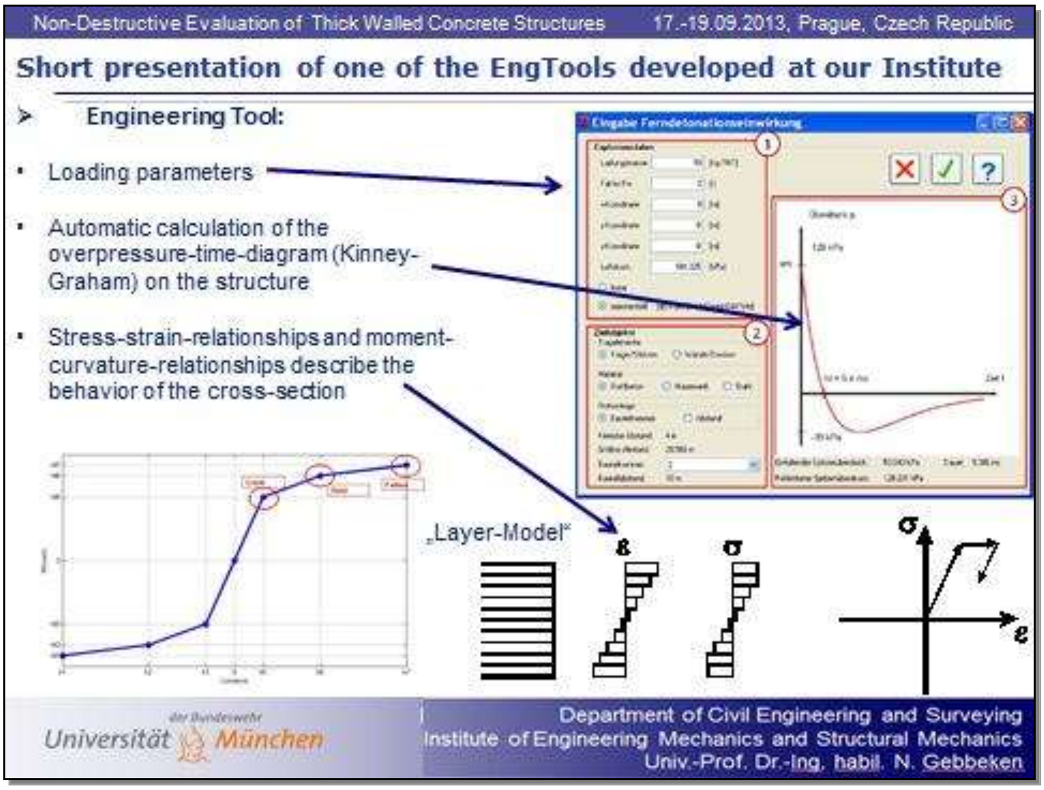
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Short presentation of one of the EngTools developed at our Institute
Engineering Tool:
Loading parameters
Automatic calculation of the overpressure-time-diagram (Kinney-Graham) on the structure
Stress-strain-relationships and moment-curvature-relationships describe the behavior of the cross-section
Eingabe Ferndetonationseinwirkung
„Layer-Model"
ε
σ
σ
ε
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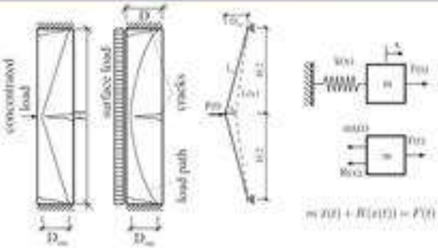
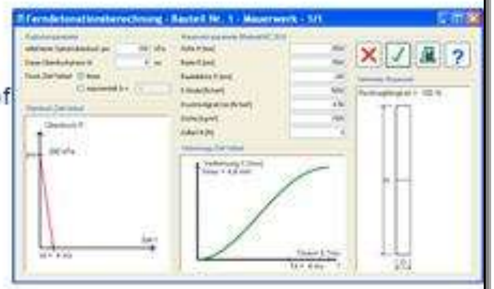
Short presentation of one of the EngTools developed at our Institute



➢ **Engineering Tool:**

- Simplified models, e.g. Single-degree-of-freedom system describe the behavior of the structural part
- The EngTool calculates the deformation-time-diagram for the structural part and also the moment-time-diagram for the cross-sections
- Delivers as final result the residual load carrying capacity of the part and also the strain condition of the different layers of the cross section. It categorizes them in 3 conditions:

a) Totally elastic
b) Plastic-partly damaged
c) Totally damaged



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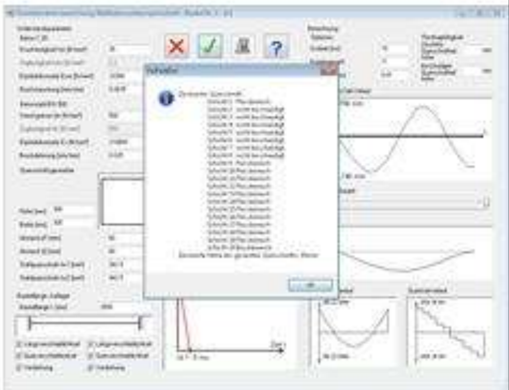
Short presentation of one of the EngTools developed at our Institute



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Applying detailed FE-Models

Goal: Simulation of the entire experimental procedure – Describe all occurring phenomena

1. Simulation of the explosion
2. Capture the wave propagation phenomenon
3. Calculate the resulting strain and stresses of the structural part
4. Evaluate the damage of the material
5. Take into account the computed damage in order to evaluate the new condition of the structura part
6. Calculate its Residual Load Carrying Capacity (R.L.C.C.)

Up to now within this research project have been tested:

- Cubic specimens, with and without reinforcement
- Reinforced concrete plates

The numerical models are created and computed with:

- ANSYS-AUTODYN + SOFISTIK (one computational scheme), or/and
- LS-DYNA (second computational scheme)

Applying detailed FE-Models

- **General aspects of the numerical simulation**

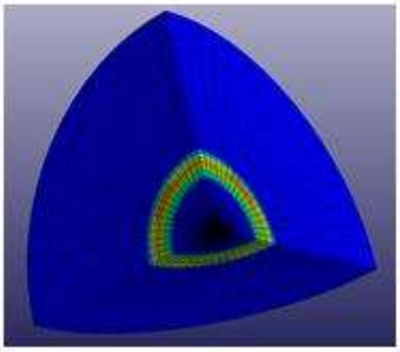
1. Create an appropriate Euler mesh for the wave propagation (convergence study – meshes in the of mm up to 2-3 cm in the areas of high pressures)
2. Choose the parameters of the explosive material (explosion velocity, internal energy etc.)
3. Describe the complicated interaction between the shock-wave and the structure (ALE algorithms)
4. Create an appropriate Lagrange mesh for the structure
5. Choose appropriate material models for the structure

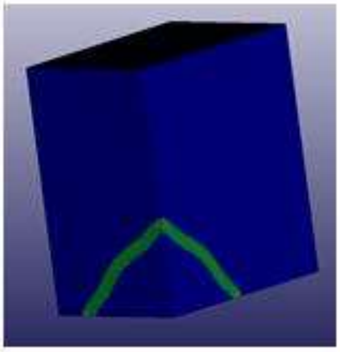
- Modern F.E Codes provide adequate solutions to all these aspects
- Parallel computing allows the use of complicated algorithms and models with large numbers of degrees of freedom per model

Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Applying detailed F.E Models

- **Case of explosion of a spherical shaped explosive with an expected spherical propagation: Does the geometry of the Euler mesh matter?**
- This symmetrical problem remains symmetrical only if it is described in spherical coordinates
- If Cartesian coordinates are used, the equations are no more symmetrical → artificial phenomena





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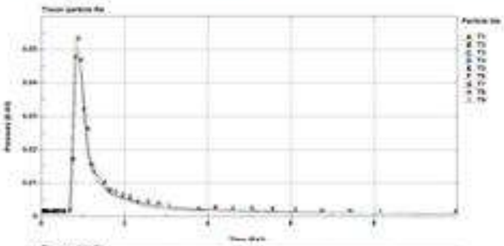
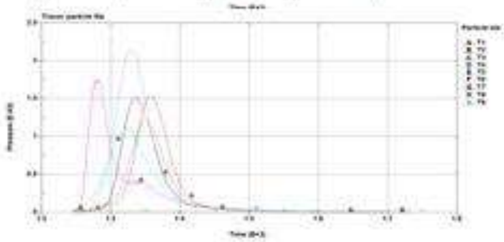
Applying detailed F.E Models

- Expected: Time of arrival and resulting pressure at equal radial distances from explosion to be equal → Symmetric problem
- Time of arrival and pressure are measured on radial distances of 1,5 m from the explosion



- Spherical coordinates



- Cartesian coordinates

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Applying detailed F.E Models

- Spherical coordinates: very similar pressure and identical times of arrival
- Cartesian coordinates: error imposed due to the cancelation of the symmetry condition

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Applying detailed F.E Models

- **Cubic specimens – Simple models to validate complicated numerical algorithms**
- General simulation strategy:

Goal: Simulation of the entire experimental procedure – Describe all occurring phenomena

1. Simulation of the explosion
2. Capture the wave propagation phenomenon
3. Calculate the damage of the material
4. Transfer the values of damage to the F.E-Model – Input for the material model
5. Calculate the Residual Load Carrying Capacity (R.L.C.C.) of the specimen

Steps 1-3: Explicit dynamic computation → AUTODYN

Step 5: Static F.E computation → SOFISTIK

Detailed models necessary – As consistent as possible

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Applying detailed F.E Models

AUTODYN: Explicit Hydrocode

- Appropriate for mixed-domain, multi-physics modeling
- Tool for simulating dynamic high velocity events:
  - High speed impacts
  - Mine explosions
  - Blasts in and around buildings
- Coupling of Lagrangian-Eulerian meshes possible
- Solvers for computational structural dynamics (computation of: deformations, stresses, damage etc.)

Powerful tool for solving numerical problems with large deformations on short time scales

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Applying detailed F.E Models

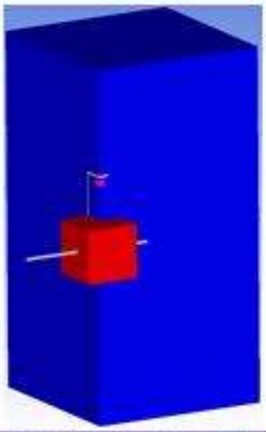
Euler-Mesh

- Air
- Explosion material
- Wooden box (Consideration of inertia phenomena)

Euler-Lagrange Interaction

Lagrange-Mesh

- Concrete specimen
- Steel



Material models in AUTODYN:

- Air: Ideal gas
- Explosion Material: AUTODYN PETN 1.5
- Wooden Box: Polynomial EOS
- Concrete: AUTODYN CONC -35MPA
- Reinforcement: Linear elastic behavior

Meshes created:

- Unreinforced specimen: 1.25 mm – 1.728.000 Elements
- Reinforced specimen : 1.875 mm ≈ 700.000, 1.25 mm ≈ 2.200.000 Elements

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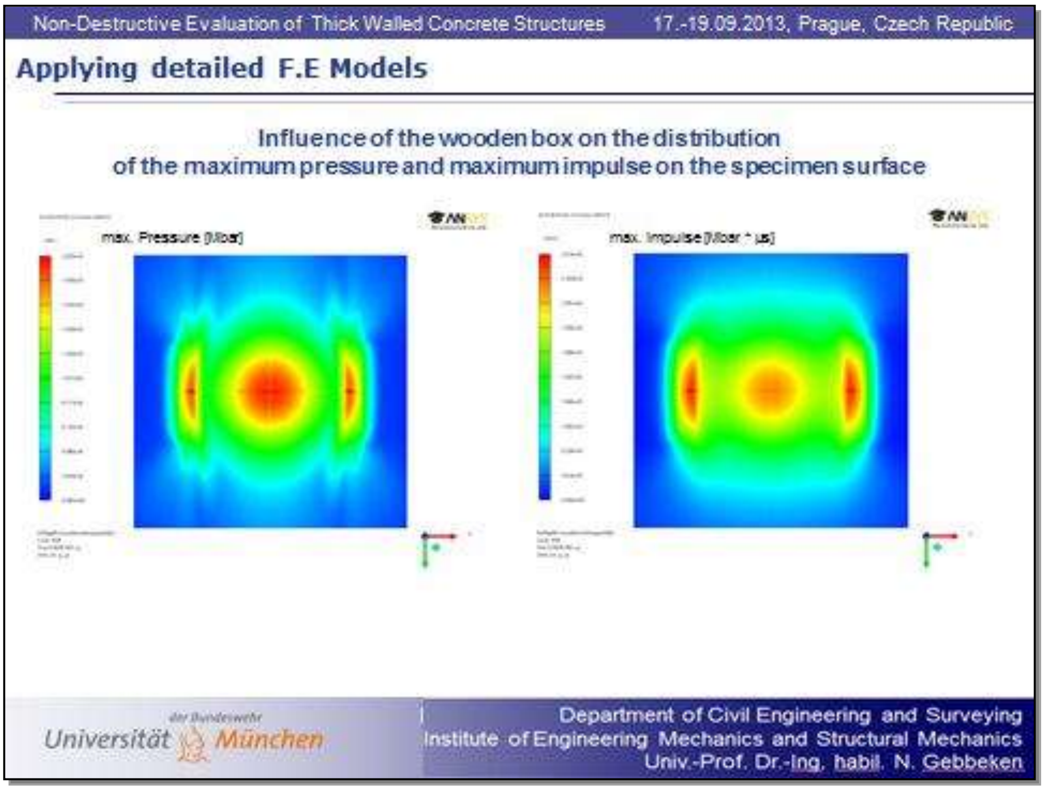
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Applying detailed F.E Models
Influence of the wooden box on the distribution
of the maximum pressure and maximum impulse on the specimen surface
max. Pressure [Mbar]
max. Impulse [Mbar * µs]
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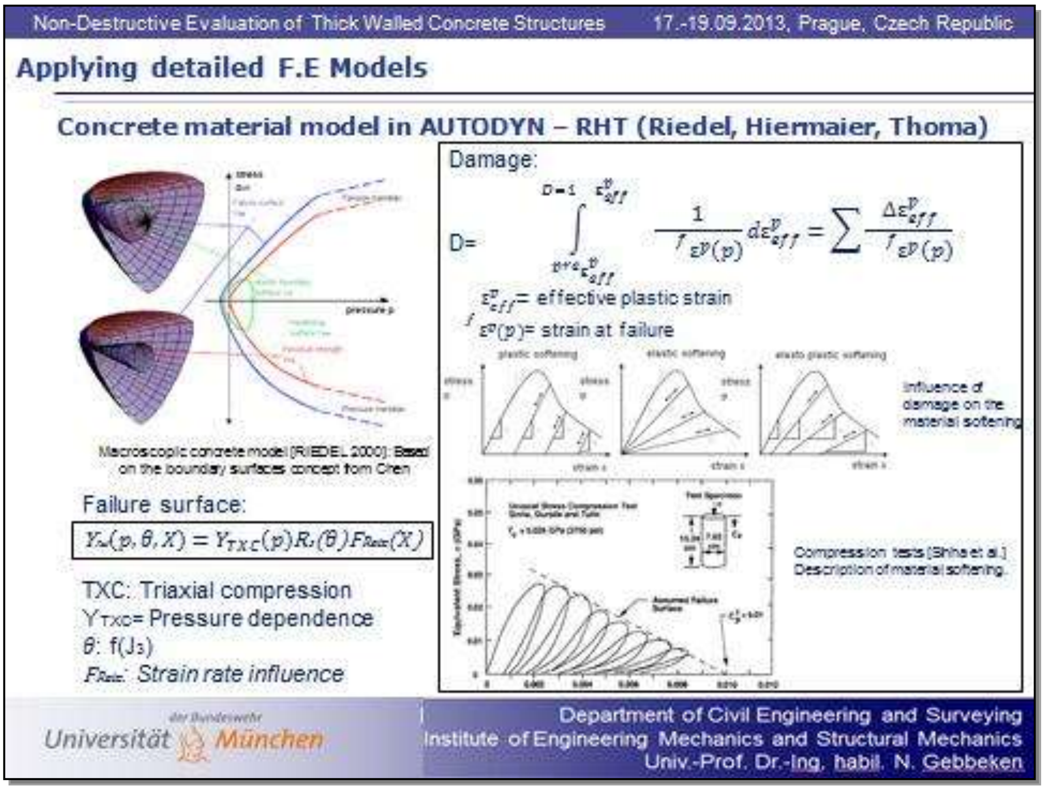
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Applying detailed F.E Models
Concrete material model in AUTODYN – RHT (Riedel, Hiermaier, Thoma)
Damage:
D= ∫ 1 / f εp(p) dεpeff = Σ Δεpeff / f εp(p)
εpeff = effective plastic strain
f εp(p) = strain at failure
plastic softening
elastic softening
elasto plastic softening
Influence of damage on the material softening
pressure p
Macroscopic concrete model [RIEDEL 2000]: Based on the boundary surfaces concept from Chen
Failure surface:
Yfail(p, θ, X) = YTXC(p)R3(θ)FRate(X)
Compression tests [Sinha et al.] Description of material softening
TXC: Triaxial compression
YTXC= Pressure dependence
θ: f(J3)
FRate: Strain rate influence
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Applying detailed F.E Models

Concrete material model in SOFISTIK – LADE

$$f = I_1^3 - \left(27 + p_1 \cdot \left(\frac{p_a}{I_1}\right)^m\right) \cdot I_3 = 0$$

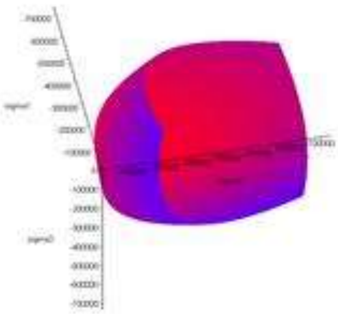
p_a – atmospheric pressure
m – shape factor

$$I_1 = -f_t - f_t - (f_t + f_c)$$

$$I_3 = (-f_t) \cdot (-f_t) \cdot (-f_t - f_c)$$

$$f_c(D) = f_{c,0} - D \cdot (f_{c,0} - f_{c,dam})$$

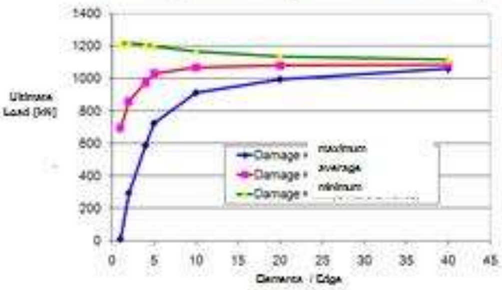
$$f_t(D) = f_{t,0} - D \cdot (f_{t,0} - f_{t,dam})$$



Lade, P.V., Failure Criterion for Frictional Materials, Mechanics of Engineering Materials, pp. 385–402 (1984)

Applying detailed F.E Models

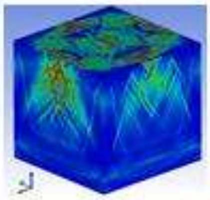
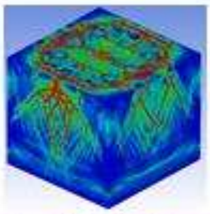
- Transfer the damage values from AUTODYN to SOFISTIK model → Input parameters for the material model
- Coarser mesh for the static analysis in SOFISTIK applicable
- Search algorithm: which AUTODYN elements belong to each SOFISTIK element
- Element wise calculation of damage in SOFISTIK
  →Average of damage values of corresponding AUTODYN elements



Bond:
- Rigid connection between concrete and steel elements on the interface
- Carrying capacity of bond = Carrying capacity of concrete
- Excess of the carrying capacity of concrete → Failure of the bond

Applying detailed F.E Models

AUTODYN – Unreinforced specimens – Mesh size: 1.25mm

Explosion Material [g PETN]	Distance [cm]	Damage picture
30	8	
40	10	

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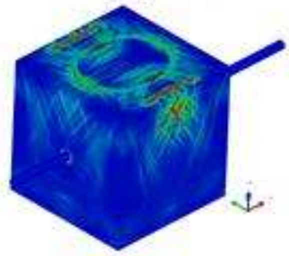
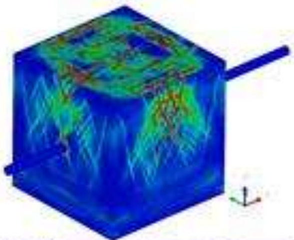
Applying detailed F.E Models

AUTODYN – Reinforced specimens – Mesh size: 1.25mm

Reinforcement diameter d_s Bond length l_b	Explosion material [g PETN]	Distance [cm]	Damage picture
d_s = 10 mm, l_b = 100 mm	20	6	
	30	8	

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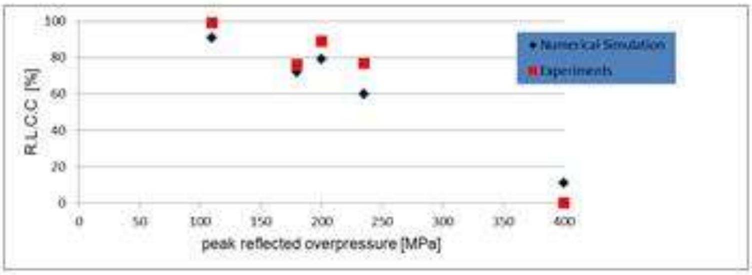
Applying detailed F.E Models

SOFISTIK– Unreinforced specimens

	Numerical results	Experiments
	R.L.C.C [%]	R.L.C.C [%]
undamaged	100	100
13g - 6cm	91	96
20g - 6cm	72	76
30g - 8cm	79	89
40g - 10cm	60	77



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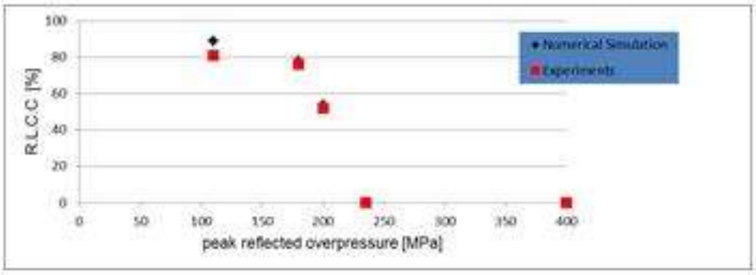
Applying detailed F.E Models

SOFISTIK– Reinforced specimens

d_s=10mm l_s=100mm	Numerical results	Experiments
	R.L.C.C [%]	R.L.C.C [%]
undamaged	100	100
13g - 6cm	89	81
20g - 6cm	88	73

d_s=10mm l_s=50mm	Numerical results	Experiments
	R.L.C.C [%]	R.L.C.C [%]
undamaged	100	100
20g - 6cm	78	77
30g - 8cm	54.5	54
40g - 10cm		



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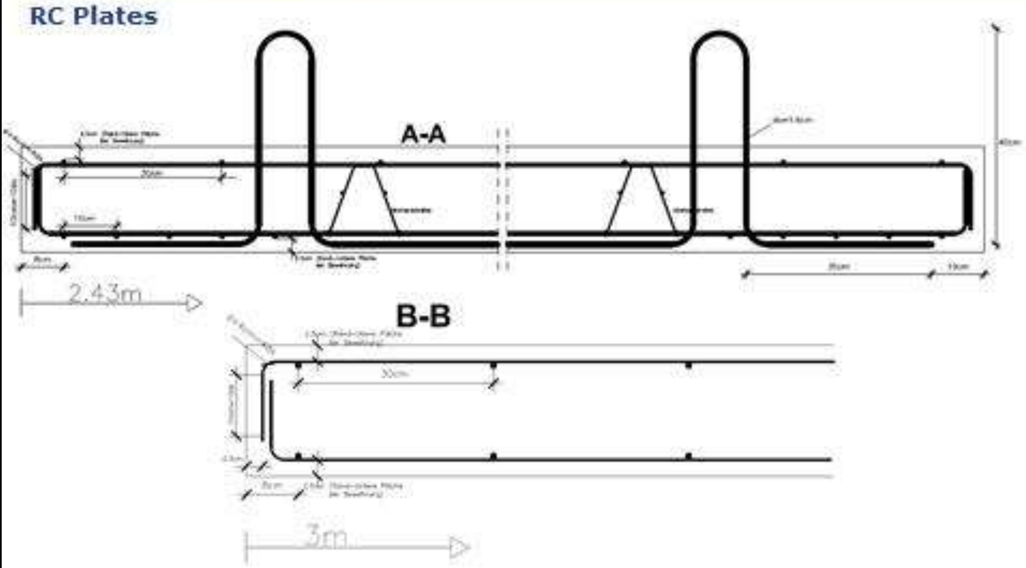
Applying detailed F.E Models

RC Plates



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Applying detailed F.E Models

Goal: Use the algorithms which have been validated with the smaller models

1. The RHT model describes the behavior of the concrete
2. Linear, hexahedral, reduced integrated with appropriate Hourglass stabilization finite elements to model the plate
3. Beam elements with elastic material assumption for the reinforcement
4. The model consists of three independent meshes: a) Lagrange for the plate, b) Lagrange for the reinforcement and c) Euler for the air
5. ALE algorithms for the interaction between air and plate
6. Special coupling between the plate and the reinforcement in order to describe the influence of the reinforcement on the behavior of the concrete
7. A large number of appropriate material models for concrete are nowadays implemented and available in commercial SOFTWARE (e.g. LS-DYNA)

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Applying detailed F.E Models

- LS-DYNA–> very efficient parallel computing algorithms: Wall times reduces from days to hours →Possible to create and compute very detailed models
- The entire experimental procedure (Explosion + Static test) can be modeled and computed within LS-DYNA → No additional SOFTWARE required → Consistent simulations

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Applying detailed F.E Models

Alternative strategy within LS-DYNA:

1. Avoid the simulation of air
2. Explosion is not modeled directly
3. Validated empirical formulas calculate the blasting load
4. Reduces strongly the number of finite elements used → Wall times reduced to minutes
5. Tests show that tends to underestimate the resulting pressures
6. Very attractive alternative due to reduced wall times
7. Adequate for cases of large distances between explosion and target

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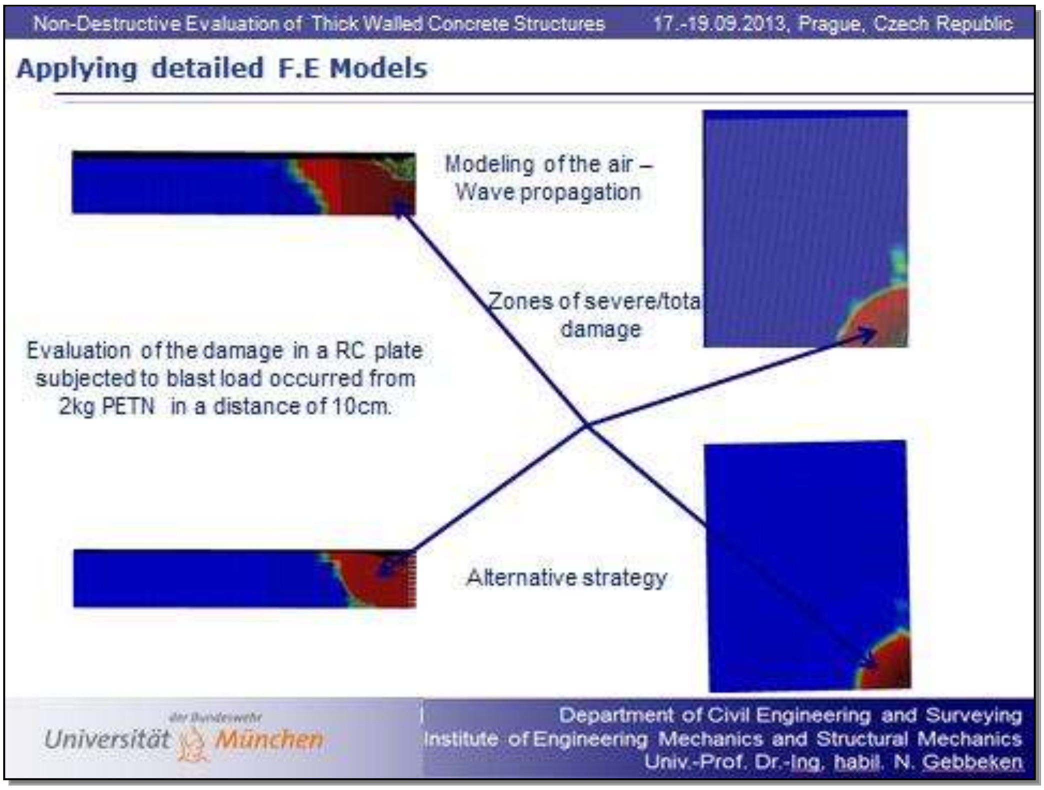

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Conclusions – Future work

- EngTools: User friendly SOFTWARE – Combines simplified assumptions of structural behavior and validated formulas for the determination of the load resulting from an explosion.
- Within minutes the user can define and calculate the problem.
- Provide a good engineering solution which has limitations.
- With the Finite-Element-Method one can create detailed numerical models which describe all the aspects of the dynamic problem: explosion, wave propagation, structural response.
- A number of issues must be taken into account: reasonable meshes, appropriate material parameters, good description of interactions.
- Detailed finite element models can reach several millions degrees-of-freedom → Parallel computing is essential
- The numerical results deliver information about the **total stress-strain condition of the structural part, the developed damage, the post-damage behavior of the part → Numerical methods are a powerful modern tool for the evaluation of local and global structural response**

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Conclusions – Future work

Future work:

- Testing more material models which are available in the material libraries of modern SOFTWARE
- Implement in LS-DYNA the material model HPG which was developed at our Institute and is appropriate for describing the behavior of concrete subjected to blast loads
- Assumption of rigid connection of the bond: too coarse → refinement of the contact descriptions: Segment-based penalty formulation on the interface with an embedded failure criterion
- Development of a "bond finite element" for the modeling of the bond

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EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Inspection of Containment Liners and Shells Utilizing Advanced Nondestructive Examination Techniques

September 17, 2013
Brian Hohmann, Thomas Esselman,
Theodore Taylor (Lucius Pitkin, Inc.),
James J. Wall (EPRI)

Lucius Pitkin, Inc.
Consulting Engineers

1

INTRODUCTION

- Discussion of Operational Experience.
- Design and Construction of the Mockups.
- Flaw Map and Inspection Procedure.
- Advanced NDE techniques.
  - Magnetostrictive Sensor (MsS) Guided Wave
  - SAFT UT
- Results of inspections and Discussion of Data.
- Conclusions.

2

Operational Experience – Containment Liners and Shells

- Susceptible to ID and OD corrosion.
- Through-wall at Brunswick 2 (1999) North Anna 2 (1999), DC Cook 2 (2001), Beaver Valley 1 (2009).
- Some OD corrosion noted during concrete removal for SG replacement at Beaver Valley 1.
- Liner corrosion from the ID was noted at twenty three PWRs – all caused by coating failures or moisture barrier degradation.
- Shell corrosion noted at Oyster Creek and other BWR drywells.

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Degradation Mechanisms

- Pitting
- Uniform Corrosion
- Other forms of corrosion may contribute

D. Dunn, A Pulvirenti, and M. Hiser, "Containment Liner Corrosion Operating Experience summary, Technical Letter Report, Revision 1", US Nuclear Regulatory Commission, Office of Nuclear regulation Research, August 2, 2011.

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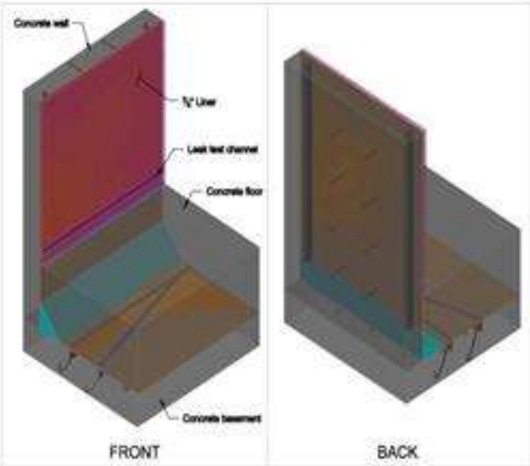
PWR Containment Liner Mock-Up

- The liner is ⅜" (9.5mm) thick with the liner thickness decreasing to ¼" (6.3mm) at weld location below the basemat region. Mock-up was full size.
- The liner had butt welds and channels welded over the welds. Studs were on the concrete side.
- Concrete is poured on the outside of the shell to represent the containment and on the the inside to represent a floor.



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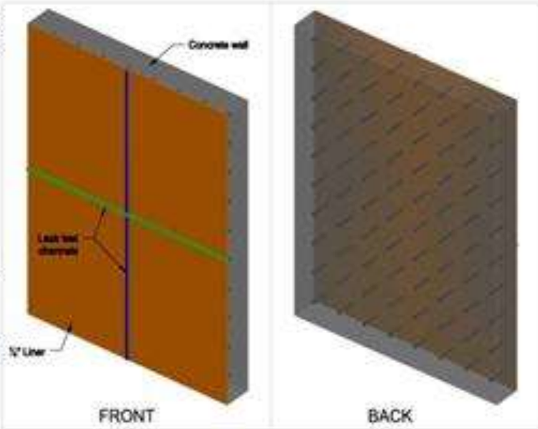
PWR Containment Liner Mock-Up

6

PWR Containment Flat Wall Liner Mock-Up

- The mock-up simulates a large area of flat accessible liner wall. Liner is ¼" (6.3mm) thick.
- The liner has butt welds, studs on the concrete side, and channels covering the butt welds.
- Concrete is poured on one side of the liner to a thickness of 12 inches (30.5 cm).



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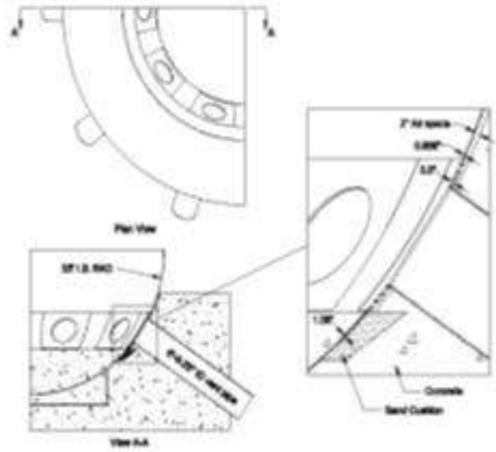
PWR Containment Flat Wall Liner Mock-Up

8

BWR Drywell Shell Mock-Up

- The drywell shell is approximately 1⅛" (28.6 mm) thick. Mock-up was full size.
- The shell section selected has no welds or studs.
- Concrete is poured on the outside of the shell near the location of the sand cushion and on the inside to represent a floor.



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BWR Drywell Shell Mock-Up

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Construction of Mockups–PWR Liner
11


Fully constructed mockups
12

FLAW PLAN FOR MOCK-UPS

Objective:

- Determine the ability to detect and size flaws in a liner or shell in a generally accessible region of liner.
- Determine the ability to detect and size flaws in a liner or shell that are inaccessible, like beneath poured concrete.
- "Flaws" are loss of material due to corrosion.
  - Various flaw types placed in mockups, including pitting, scalloped, cluster, and flat bottom hole (FBH)
- Define the confidence in accuracy of detecting flaws.
- Provide basis to differentiate between normal features of the liner or shell, including studs, brackets, butt welds, leak detection channels, weld strikes, and other features that are not indicative of degradation and actual corrosion damage.

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Flaw Map Development

- A Flaw Map was generated so the exact location of every flaw in each mockup could be determined following concrete placement.
- Each mockup given a designated origin (0,0,0) and flaws inserted at specific (x,y,z) locations.
- Same coordinate system used for ID and OD side
- Full description of test procedure available in EPRI Technical Report No. 000000003002001720 – *Synthetic Aperture Focusing Technique and Guided Wave Examination of Containment Liners and Shells.*

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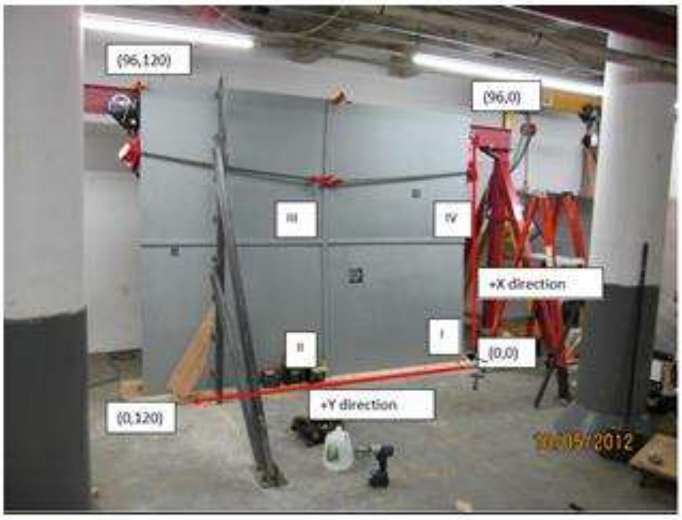
Coordinate system for flaws – PWR Flaw Wall Liner



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Inspection Procedure

- Assemble mock-ups without concrete and without flaws
  - Generate a baseline for evaluation of NDE signal attenuation due to flaws and concrete
- Perform Guided Wave and SAFT-UT
- Install flaws
  - Replication samples taken on all flaws to quantify flaw depth more accurately and keep for future testing
- Perform Guided Wave and SAFT-UT
- Material was placed in flaw to maintain space between steel and concrete to simulate wall loss that has occurred in-service
- Pour concrete and let it cure for 30 days
- Perform Guided Wave and SAFT-UT
- Evaluate flaw detection, flaw sizing, and signal attenuation of complete dataset

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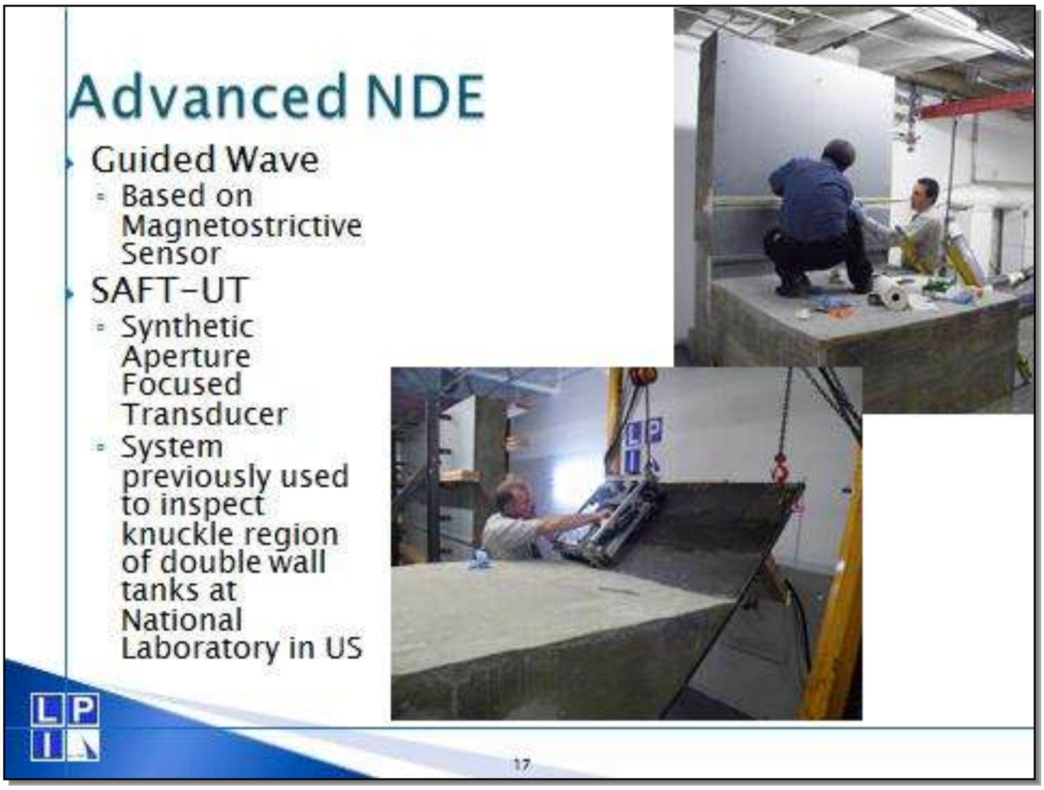
Advanced NDE
Guided Wave
Based on Magnetostrictive Sensor
SAFT-UT
Synthetic Aperture Focused Transducer
System previously used to inspect knuckle region of double wall tanks at National Laboratory in US
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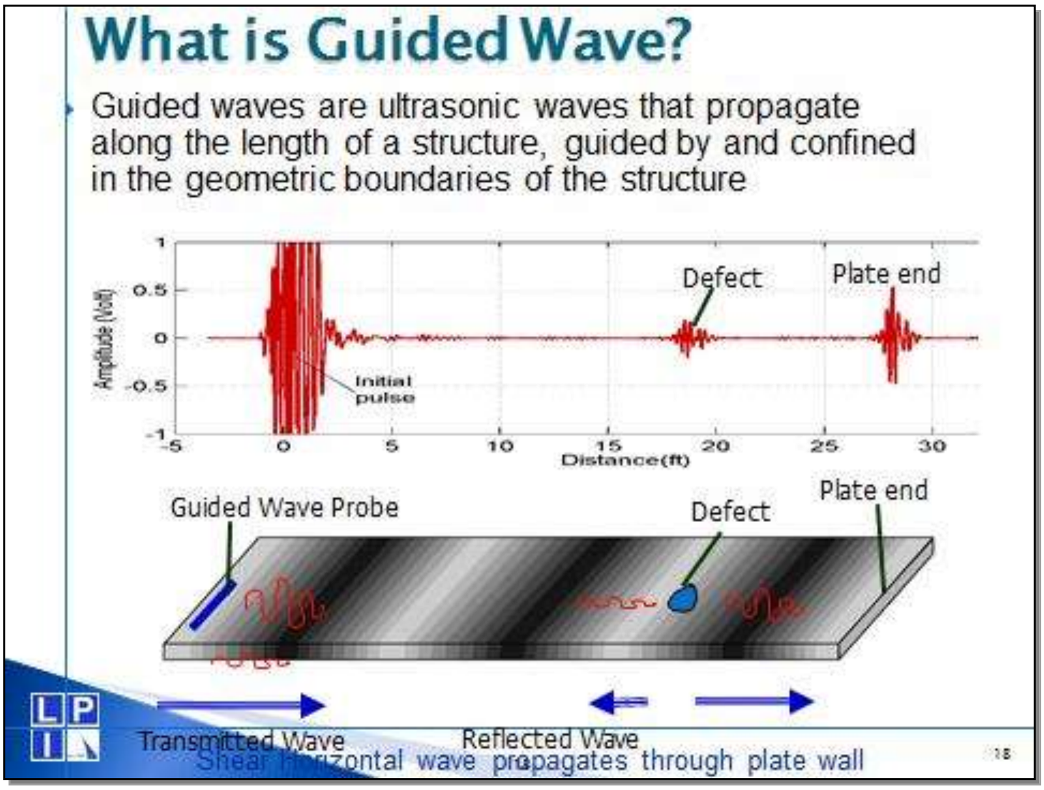
What is Guided Wave?
Guided waves are ultrasonic waves that propagate along the length of a structure, guided by and confined in the geometric boundaries of the structure
Amplitude (Volt)
Distance(ft)
Initial pulse
Defect
Plate end
Guided Wave Probe
Defect
Plate end
Transmitted Wave
Reflected Wave
Shear Horizontal wave propagates through plate wall
18

MERITS OF GUIDED WAVE INSPECTION

- Rapidly provides comprehensive condition information on large areas of structure
- Requires minimal preparation
  - Insulation removal, scaffolding, excavation, coating removal, etc.
- Inspects inaccessible areas remotely
- Pinpoints where to use quantitative follow-up
  - Reduces inspection cost and enhances overall inspection efficiency
  - 100 % of volume is inspected

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MsS Guided Wave Testing System for Generating Shear Horizontal Wave

MsSR3030R

FeCo Strip

MsS plate probes

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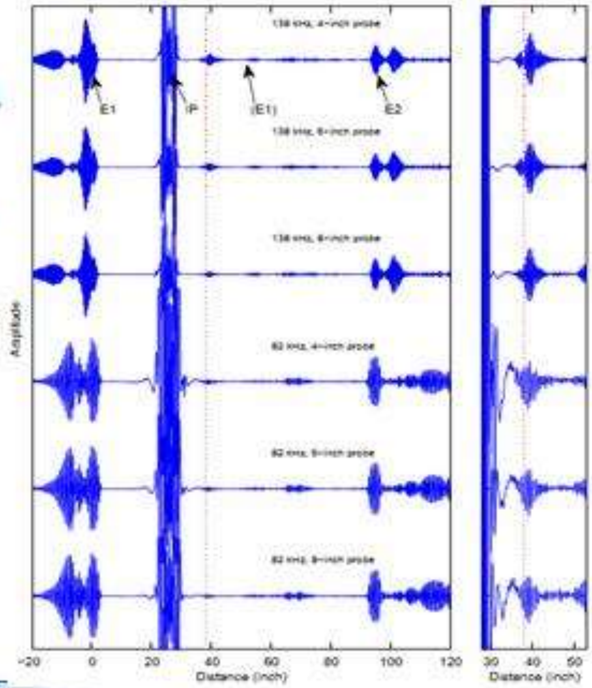
Inspection Data of BWR-ID-1 at (-38, 18.8) with MsS Probe at (-26, 19)



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SAFT/TSAFT Technology

- "Synthetic aperture focusing" refers to a process in which the focal properties of a large-aperture focused transducer are synthetically generated from data collected over a large area using a small transducer with a divergent sound field.
  - For more information the see: Busse et al. 1984 or Hall et al. 1988
- The processing required to focus this collection of data has been called beam-forming, coherent summation, or synthetic aperture processing.

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Status of TSAFT Technology

- The Current TSAFT system was configured to detect and size flaws in the double shelled tanks at Hanford
- The current system is used in two modes
  - Detection of Vertical Through-wall cracks
  - Through-wall sizing of Cracks
- SAFT/TSAFT was originally used to improve the detection and sizing of vertical defects
- SAFT/TSAFT was not designed to detect corrosion in Containments of BWRs and PWRs – it has been adapted for this purpose

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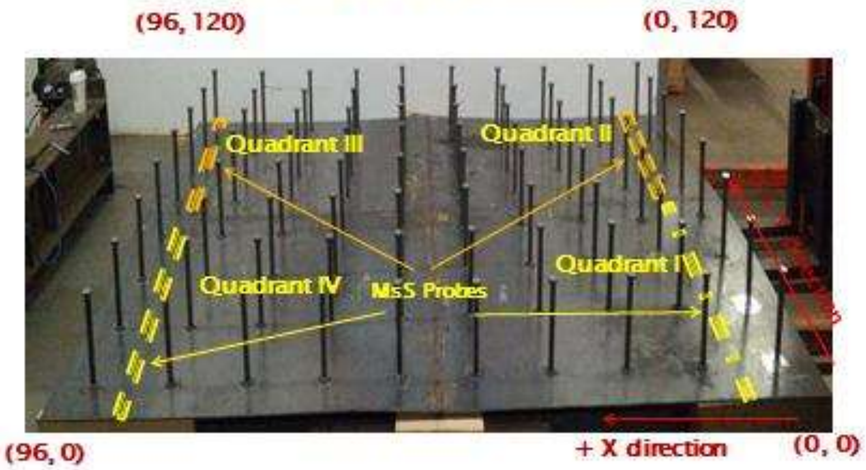
PWR Flaw Wall Liner Mockup MsS Probe placement



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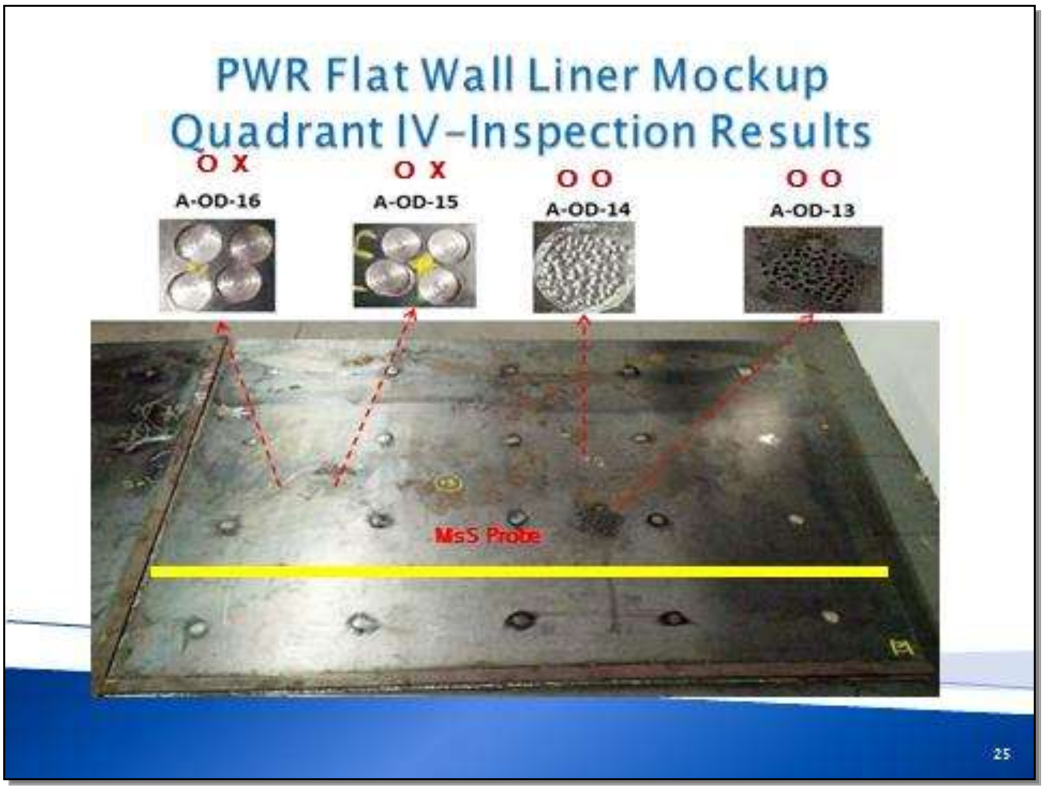

PWR Flat Wall Liner Mockup Quadrant IV – Defect Description

FLAW No.	LOCATION* (in.)	DESCRIPTION
A-OD-13	(66, 23.5)	"Pitting" flaw; approx. 3in. diameter with 1/4 in. through-wall depth pits
A-OD-14	(74.5, 23.5)	"Pitting" flaw; approx. 3in. diameter and 1/8 in. depth
A-OD-15	(72.5, 45)	"Cluster" flaw; four 0.5 in, diameter FBHs of 1/32 in. depth
A-OD-16	(72.5, 51)	"Cluster" flaw; four 0.5 in, diameter FBHs of 1/16 in. depth

LPI

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Results from MsS Inspections

- MsS system and plate probe works well for finding defects
- BWR Drywall Shell Mockup
  - 11 defects tested (9 defects detected, 2 defects were not detected)
  - Reduce inspection range for minimizing dispersion of SH1 mode
- PWR Containment Wall Liner Mockup
  - 13 defects tested (8 defects detected, 5 defects were not detected)
  - Install MsS probe in the tested plate instead of sending wave through U-shaped channel
- PWR Flat Wall Liner Mockup
  - 19 defects tested (17 defects detected, 2 defects were not detected)
  - Geometric features (stud, U-shaped channel) make difficult to detect defects. Recommend 1) to perform monitoring, 2) to use high frequency and one cycle for increasing spatial resolution, and 3) to compare the acquired data with data acquired at similar condition (geometric feature)

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Inspection results for BWR shell mock-up ID side

Flaw ID #	Location ID/OD Coordinates Y, X, Z	Flaw Type and Trough Wall Depth	Guided Wave Pre-Concrete Detected (Yes/No)	Guided Wave After Concrete Detected (Yes/No)	T-SAFT System Pre-Concrete Detected (Yes/No)	T-SAFT System After Concrete Detected (Yes/No)
BWR-ID-1	(-56, 16.75)	"Pitting" flaw; approx. 2in. diameter and 1/4 in. depth	Yes	Yes	Yes	No
BWR-ID-2	(-45.75, 11.5)	"Corrosion" type flaw; Scalloped flaw appearance 1.5 in. diameter and 1/4 in. depth	Yes	No	Yes	Yes
BWR-ID-3	(-31.5, 6.25)	"Pitting" flaw; approx. 2in. diameter and 1/8 in. depth	Yes	Yes	Yes	Yes
BWR-ID-4	(-49.25, 57)	"Cluster" flaw; four 0.5 in. diameter FBHs of 1/4 in. depth	Yes	Yes	No	No
BWR-ID-5	(-76.75, 58.5)	FBH; 1in. diameter and 1/4 in. depth	Yes	Yes	No	No
BWR-ID-6	(-65, 19.75)	"Cluster" flaw; four 0.5 in. diameter FBHs of 1/4 in. depth	Yes	Yes	No	No

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Status of TSAFT Technology

- Detection of Corrosion in the PWR Containment Mockup

Flaws 1, 2 and 4 that were fabricated in the PWR Containment mockup

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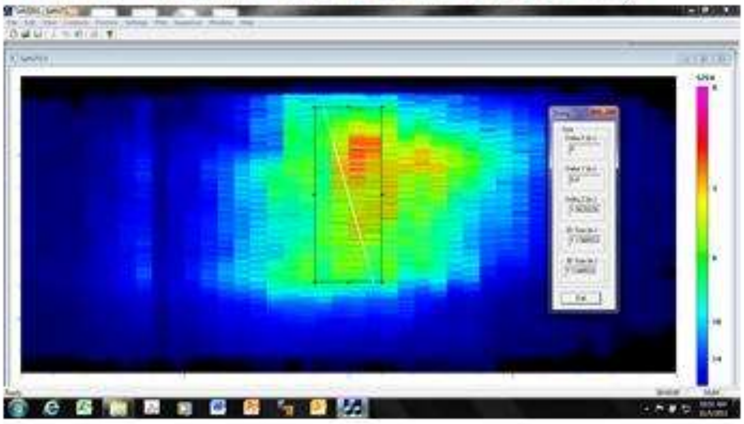
Process of Sizing a Flaw in BWR Mockup (25% Thru-Wall Flat Bottom Hole)



- The SAFT-UT estimate is 0.39 inches (9.9 mm) in Depth
- The Actual Depth is 0.28 inches (7.1 mm) based upon 25% wall loss of 1.125 inches (28.6 mm) total thickness

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Conclusions

- It is possible to detect defects such as corrosion in visually inaccessible areas of containment liners and shells.
- Guided Wave detected most flaws under each set of conditions.
- No ID versus OD differentiation provided.
- Geometric features, such as channels over butt welds, affected sensitivity.
- SAFT-UT detected most implanted flaws for conditions prior to concrete installation.
- SAFT-UT lost some sensitivity after concrete pour
- The SAFT system performed better on thicker components such as the drywell.
- The SAFT system was originally configured to detect cracks in welds and not round corrosion-like defects. Optimization would improve SAFT results.
- Neither system was sufficiently accurate at sizing defects.
- Additional development required regarding flaw characterization and acceptance criteria.

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SESSION TWO

Temperature and radiation effect on the RPV concrete cavity. Project description on irradiation, testing and NDE development

ÚJV Řež, a. s.
J. Žďárek, L. Horáček, P. Brabec
17. 09. 2013

NPP containment ageing

- More than 10 concrete degradation mechanism with influence on containment building
- RPV concrete cavity exposed to temperature and radiation loading as most critical damage mechanism
- No effective validated inspection procedure proposed for RPV cavity until now!

2

RPV cavity damage mechanisms

- Neutron and gamma rays irradiation has effect on concrete
- Changes of the concrete properties depend primarily on aggregates behaviour
- Irradiation exposure can induce volume change of aggregates
- Heat generated from radiation absorption (attenuation) in concrete may have detrimental effect on physical, mechanical and nuclear properties of the concrete

Influence of irradiation on mechanical properties

Long term exposure to radiation and thermal loading can result in degradation of mechanical properties of RPV concrete

- Neutron radiation more than 10^{19} n/cm^2 or 10^{10} rads (more than 40 years of operation) of dose for gamma radiation in some cases decreases tensile strengths, compressive strengths and modulus of elasticity and causes marked increase in volume
- High irradiation generates growth of calcite crystals, which decreases both size of pores and the strength of the concrete
- Radiation induced temperature has minor influence on changes of concrete properties

Damage mechanisms in NPPs

- Following table shows ranking of importance for specified concrete damage mechanisms
- Identification of research gaps in three principle areas:
  - Materials
  - Inspection
  - Prediction

Issue	Ranking	Research Gap Analysis		
		Materials	Inspection	Prediction

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Ranking and gap analysis of damage mechanisms

Issue	Ranking	Research Gap Analysis		
		Mate-rials	Inspe-ction	Predi-ction
Chloride diffusion into concrete	High		X	X
Boric acid effects on concrete	High	X	O	X
Corrosion of reinforcing steel embedded in concrete	High		X	X
Radiation damage of reactor cavity concrete	High	X	?	?
Containment liner corrosion-accessible and inaccessible areas	High		X	
Post-tensioning tendon relaxation	High		X	
Leaching of the containment liner	High			X
Bulging of the containment liner	High			X
Freeze-thaw damage	High	X	X	X
Spent fuel pool liner stress corrosion cracking (welds)	High		X	X
Pre- and post-tensioning tendon corrosion/stress corrosion cracking	High		X	X
Concrete carbonation and effects on steel reinforcement	Medium		X	
Swelling due to alkali-aggregate reaction or delayed ettringite formation	Medium	X	X	X
Concrete creep, microcracking	Medium	X	X	X
Concrete dissolution effects on spent fuel pool liners	Medium		X	X
Boric acid attack of steel reinforcement	Medium	X	?	?
Water treatment chemical attack of concrete	Medium	X	?	?
Aggressive groundwater/External sulfate attack	Low		X	X
Thermal cycling/cooling towers (operational temperatures)	Low			X
Containment pressurization/depressurization (integrated leak rate test)	Low		X	X
Hydrogen embrittlement of post-tensioning tendons	Low		O	X
Thermal fatigue at penetrations	Low	X		X
Differential settlement of structures	Low			X
Spent fuel pool channel corrosion	Low		X	

8

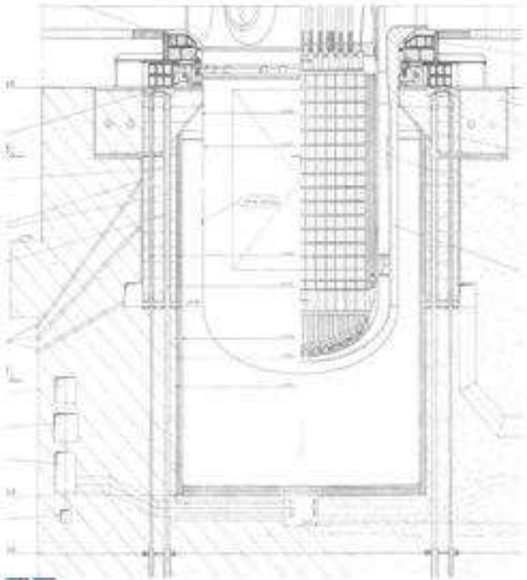
Ranking and gap analysis of damage mechanisms
- radiation damage of reactor cavity concrete -

Issue	Ranking	Research Gap Analysis		
		Mate-rials	Inspe-ction	Predi-ction
Chloride diffusion into concrete	High		X	X
Boric acid effects on concrete	High	X	O	X
Corrosion of reinforcing steel embedded in concrete	High		X	X
Radiation damage of reactor cavity concrete	High	X	?	?
Containment liner corrosion-accessible and inaccessible areas	High		X	
Post-tensioning	High		X	

- High ranking of damage mechanism
- Inspection and Prediction identified with question marks!

7

Design of VVER 1000/320 RPV cavity



- steel frame embedded in heavy concrete construction transfers weight of RPV to the cavity
- serpentine concrete segments, opposite to active core, serve as a biological shield
- ferrite steel cladding (11 mm thickness) on outer surface of biological shield
- structural concrete in the lower part of cavity
- ionization channels around cavity circumference formed by embedded steel pipes

8

Experimental project mock-up

- Irradiation damage simulation of RPV cavity concrete after long term operation of NPPs
- Cylindrical samples (50 x 100 mm) of NPP Temelín type RPV cavity concrete – ferro-serpentine concrete
- Irradiation of samples above neutron fluence 10^{19} n/cm^2
- Post irradiation examination of samples focused on changes of mechanical and microstructural properties
- NDE inspection technique testing on model segment of outer part of reactor cavity with ionization channels

Irradiation experiment

ÚJV

in cooperation with:

Centrum výzkumu Řež s.r.o.
Research Centre Rez
Člen skupiny ÚJV

Irradiation experiment description

- Irradiation of concrete specimens in vertical channels of light water research reactor LVR-15
- Specimens in special aluminium capsules
- Thermocouples controlled temperature, temperature maintenance by passive systems
- Neutron monitors for neutron flux and fluence determination
- Monitoring of gas released from concrete sample during irradiation experiment

11

Post irradiation examinations

ÚJV

in cooperation with:

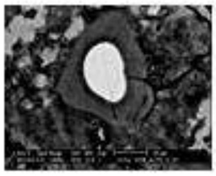
team: **P. Štemberk et al.**

CTU Prague

12

Post irradiation testing

- Optical Polarization Microscopy
- Scanning Electron Microscopy and Microanalysis
- Nano Hardness Testing – Micromechanics
- Thermogravimetry and Differential Thermal Analysis



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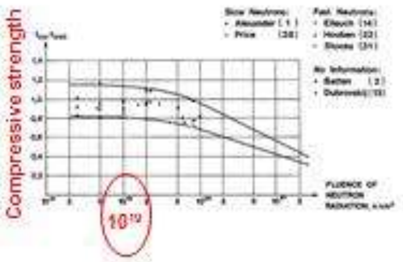
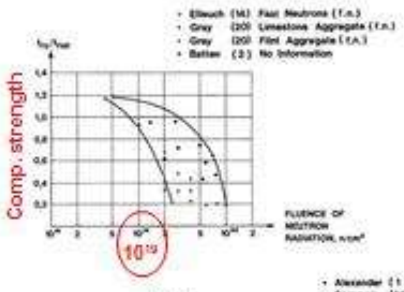
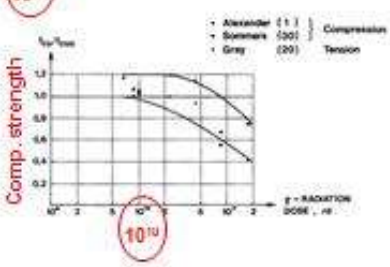
Reasons for post irradiation testing

- Decisive mechanical parameters (strength and stiffness) of concrete decrease under exposure to neutron and gamma radiation.





- Only collection of incompatible experimental data is available. (by Hilsdorf)
- Systematic data for real structural materials is needed. (e.g. on cylindrical 50x100 mm specimens)



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Optical polarization microscopy

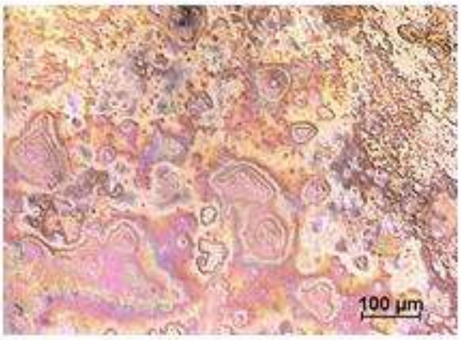
ZEISS Axio Imager

Optical polarization microscopy

- Detection of alteration processes in primary C-S-G gels (loss of bound water). Interpretation of alteration processes in concrete on micro-level
- Changes in structures on micro-level; i.e. occurrence of newly-formed shrinkage in consequence of mineral transformations and flux heat
- Occurrence of newly-formed mineral phases as a products of alteration processes

Optical polarization microscopy

Cross polished section of Portland cement



Partly hydrated Portland cement powder

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Scanning electron microscopy and microanalysis

- EDX – elementary microanalysis & simultaneous element mapping
- WDS microprobe for precise elementary analysis
- BSED – phase and chemical contrast
- EBSD / OIM – electron diffraction & preferential orientation analyses of mineral aggregates
- Resolution 0.8 nm @ 15 kV
- Probe current 10 pA – 300 nA: both for sensitive materials & analysis

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Scanning electron microscopy and microanalysis

- Detection of changes in microstructure from initial stages
- Decomposition of C-S-H gels on sub-micro level
- Phase mineral alterations in all spectra of intensities
- Indication of newly-formed phases in consequence of exposure to radiation energy and heat flux
- Interpretation of changes of mechanical properties on micro-level
- Textural arrangement of crystalline structures – statistical evaluation of prevailed lattice orientation

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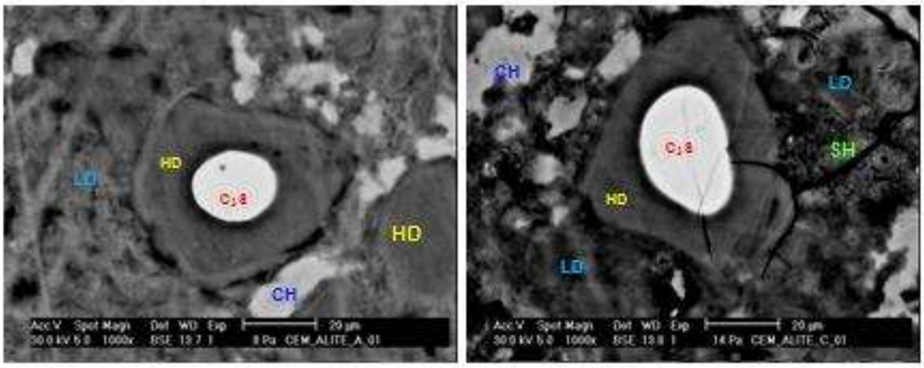
Scanning electron microscopy and microanalysis



C-S-H gel: high density gel (HD), low density gel (LD), portlandite (CH) and ettringite (SH)

20

Nano hardness testing - micromechanics

NANOINDENTER – Nano Test, Micro Materials Ltd., UK

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Nano hardness testing - micromechanics

- Detection of changes in microstructure from initial stages
- Decomposition of C-S-H gels on sub-micro level in elementar clusters
- Phase mineral alterations in all spectra of intensities
- Indication of newly-formed phases in consequence of exposure to radiation energy and heat flux
- Detection and measurement of changes in mechanical properties of exposed material on micro-level
- Interpretation of changes of mechanical properties on micro-level

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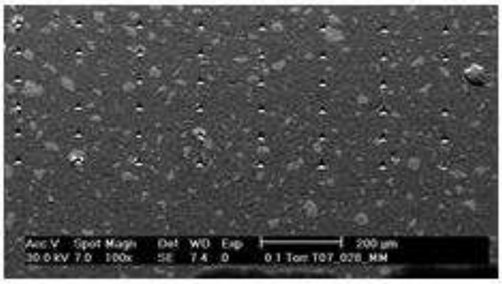
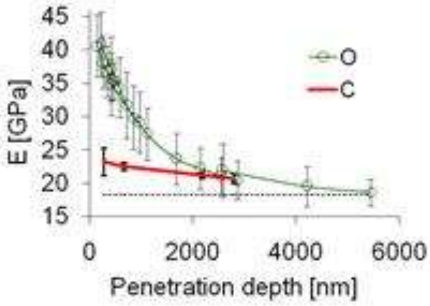
Nano hardness testing - micromechanics



Matrix of nanoindents



Modulus of elasticity

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Thermogravimetry and differential thermal analysis

Quantitative detection of phase transitions during constant heat flux

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Thermogravimetry and differential thermal analysis

- Identification and quantification of changes of phases in dependence on continual heat flux into the sample.
- The technique is based on the fact that when substance is heated, it undergoes reactions and phase changes that involve absorption or emission of heat. In DTA, the temperature of the test material is measured relative to that of an adjacent inert material.
- DTA can clearly identify the phase changes of material in original (intact) state, that is phase transformation in concrete due to irradiation.

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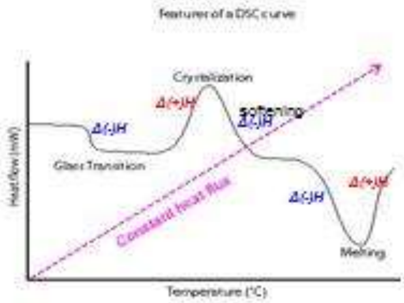
Thermogravimetry and differential thermal analysis



Heat flux vs. temperature of the system as a demonstration of phase and chemical changes in material

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NDE technique development and testing

ÚJV

in cooperation with:

retegate

Institute of Thermomechanics AS CR, v. v. i.
Academy of Sciences of the Czech Republic

Pavel Kudrna, Zdenek Prevorovsky, Milan Chlada, Josef Krofta, Jan Kober

27

Non-linear Elastic Wave Spectroscopy - NEWS

- Objective of RPV biological shielding testing:
  - Original archive material of WWER type biological shielding
  - Developed inspection procedures (IP) based on NEWS methods to be optimized for validation purposes
  - Future final verification to obtain „0" level site feedback before site trials
- Objective to manufacture two (unirradiated) segments:
  - Testing of different concrete compositions,
  - NEWS IP development with repeatable equipment application in clean environment without doses
- Available NEWS methods taken into account: NRUS, NWMS, NLTRM, SSM
- Methods selected for preliminary testing:
  - Non-Linear Wave Modulation Spectroscopy - NWMS
  - Non-Linear Time reversal Method - NLTRM
  - Scaling Substraction Method - SSM

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Two new manufactured model test blocks for NEWS methods testing – concrete composition

Ferro-serpentine concrete	kg/m3
Cement I 42,5	435
Drink water	241
Crushed aggregate (Bernatice quarry)	
0-2 mm	361
2-5 mm	136
4-8 mm	127
8-11 mm	42
11-16 mm	118
Glassfrit	280
Cast-iron L22	2118
Plasticizing admixture Stacheplast	2,26

Serpentine concrete	kg/m3
Cement I 42,5	499
Drink water	190
Crushed aggregate (Bernatice quarry)	
0-4 mm	690
8-16 mm	459
16-22 mm	527
Plasticizing admixture Stacheplast	4,1

Structural concrete	kg/m3
Cement I 42,5	499
Drink water	190
Crushed aggregate (Dobkovičky quarry)	
0-4 mm	800
8-16 mm	100
16-22 mm	776
Plasticizing admixture Stacheplast	4,1

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Non-linear Elastic Wave Spectroscopy – NEWS Method overview

- NRAS / NRUS (Nonlinear Resonant Acoustic / Ultrasonic Spectroscopy)
- SIMONRUS (Single-Mode NRUS)
- ❑ NWMS **(Non-linear Wave Modulation Spectroscopy)**
- SD (Slow Dynamics)
- NDIS (Nonlinear DISsipation / attenuation)
- Travelling Waves (Nonlinear ultrasonic wave transmission)
- ❑ NLTRA **(Nonlinear Time Reversal Acoustics)**
- ❑ SSM **(Scale Subtraction Method)**

S1

Non-linear Elastic Wave Spectroscopy - NEWS

Three main classes of phenomena associated to the non-linear elastic elements in the test-blocks are:

- Amplitude dependence of the elastic constants and, consequently, of the wave speed which causes changes in the phases of the recorded signal
- Non-linear attenuation mechanisms, which influence the amplitude of the recorded signal
- Non-linear coupling in the wave equation, which allows the generation of higher-order harmonics, sidebands, or sub-harmonics

- **Follow some examples of the preliminary result trends:**
  - NWMS (Non-linear Wave Modulation Spectroscopy)
    - Expected trend value can be provided by amplitude growth of the sideband (f_1+2f_0) vs. driving frequency (f_0) amplitude, higher value trend than:
    - Amplitude growth of the 3rd harmonic vs. f_0 driving frequency amplitude, will be compared with:
    - Amplitude growth of the ratio 3rd/2nd harmonic vs. f_0 driving frequency amplitude
  - SSM (Scaling Subtraction Method)
    - tested for ferro-serpentine concrete, serpentine concrete
    - nonlinear energy vs. driving amplitude seems to provide reasonable results

S2

Advantages & Limitations of NEWS techniques:

- Versatile tools for SHM
- High sensitive detection of defects and damaged zones
- Up to 1000x more sensitive than linear ultrasonic methods
- Detection of defects smaller than wavelength
- Distinguishing defects from pseudo-defects (e.g. structural notches)
- NDT/NDE at hidden places in complex structures
- Remote defect sensing relatively far from installed ultrasonic probes
- Material penetration depth (~ 0,01 - 1) m
- Low-amplitude interrogation of tested parts (e @ 10-9 - 10-4)

- Procedures are mostly global, and mostly reflect only presence
- of defects without their precise location ⇒ solution is e.g. multiplexing of transmitting / receiving channels using dependency of nonlinearity on the wave paths ("pseudo-tomography")
- Size of defects cannot be easily determined

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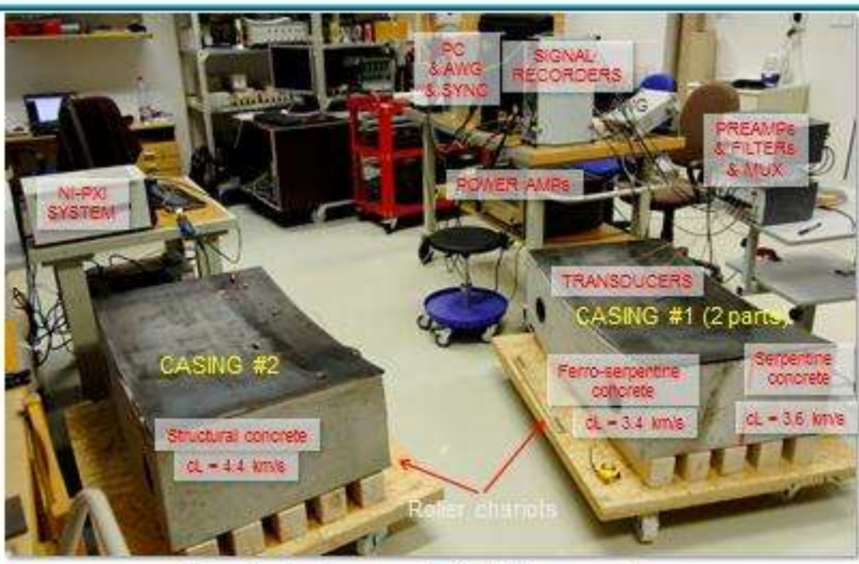
NEWS Equipment



c_L ... measured longitudinal wave celerity in the concrete

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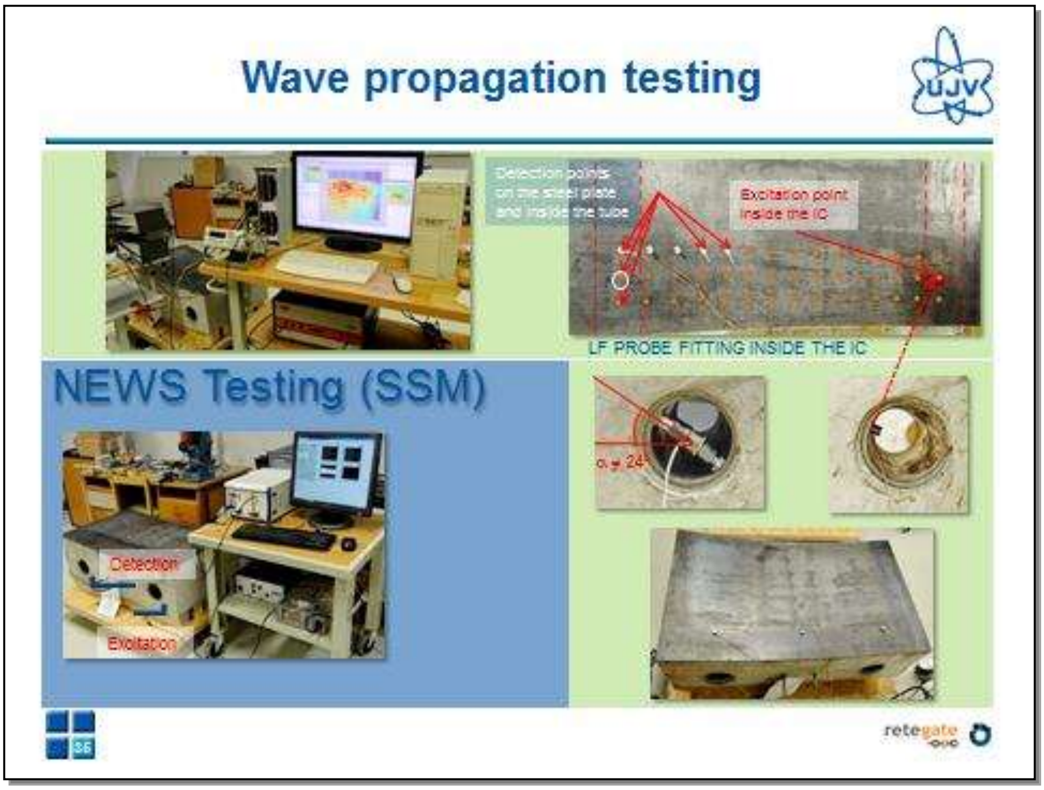
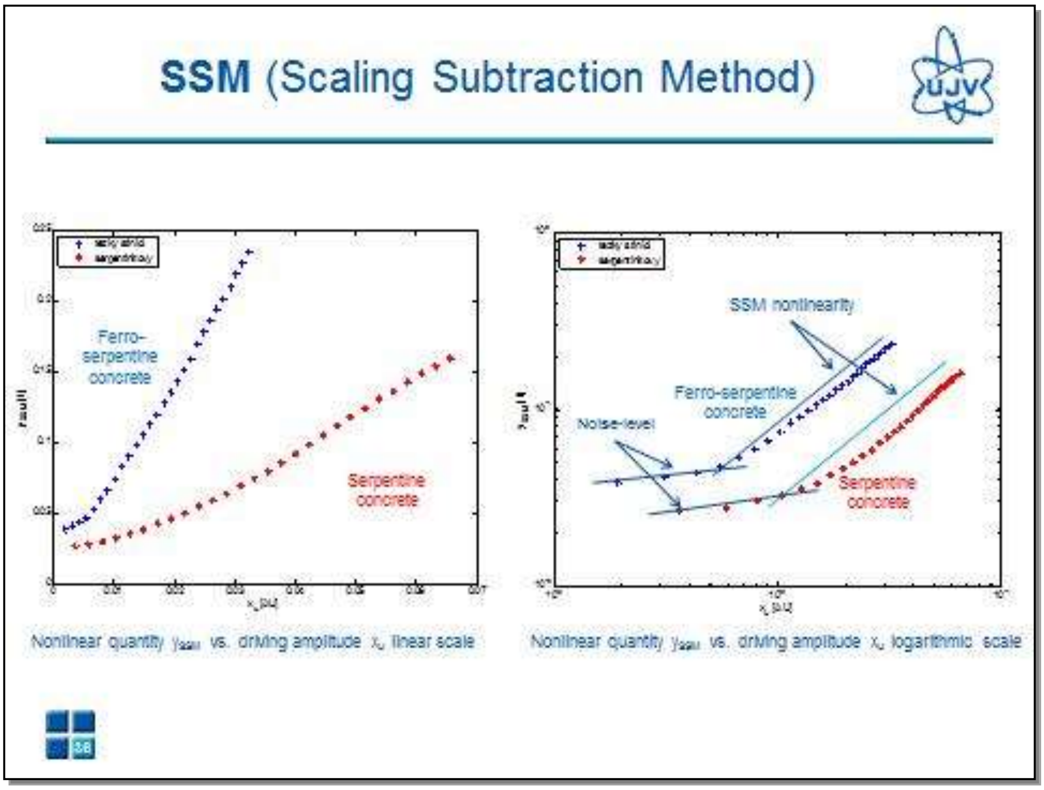
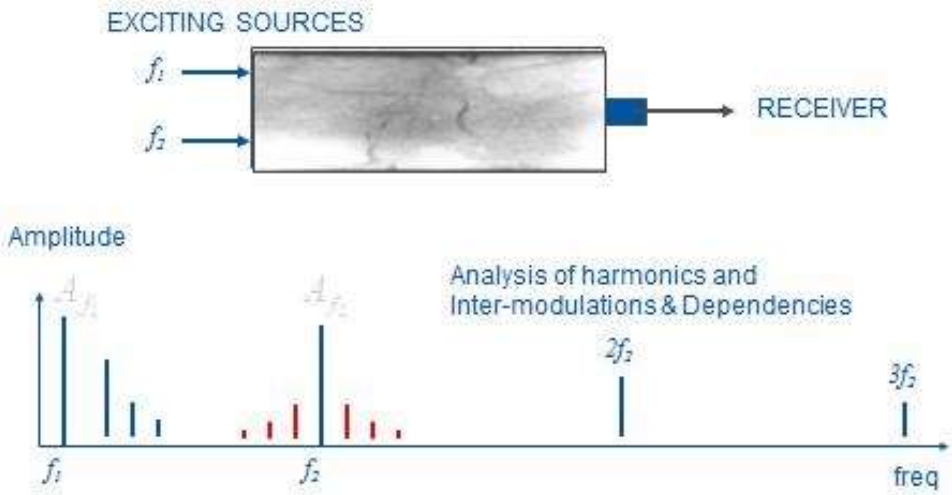
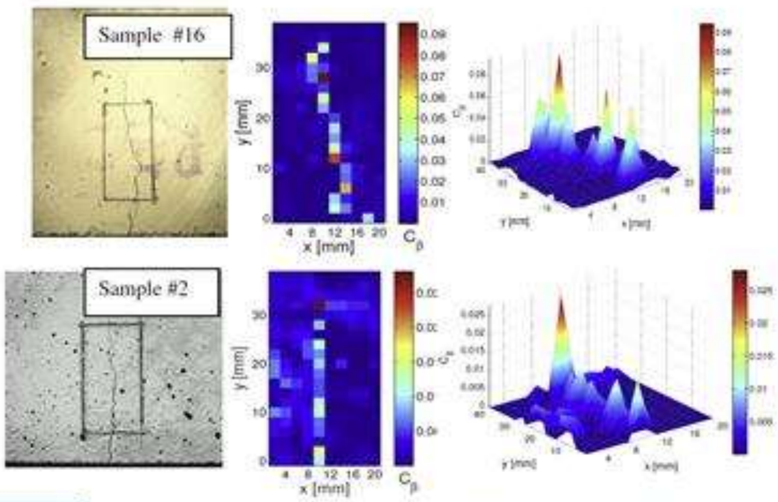

Wave propagation testing
UJV
Detection points on the steel plate and inside the tube
Excitation point inside the IC
LF PROBE FITTING INSIDE THE IC
NEWS Testing (SSM)
Detection
Excitation
retegate


SSM (Scaling Subtraction Method)
UJV
Ferro-serpentine concrete
Serpentine concrete
SSM nonlinearity
Noise-level
Nonlinear quantity γSSM vs. driving amplitude x0 linear scale
Nonlinear quantity γSSM vs. driving amplitude x0 logarithmic scale

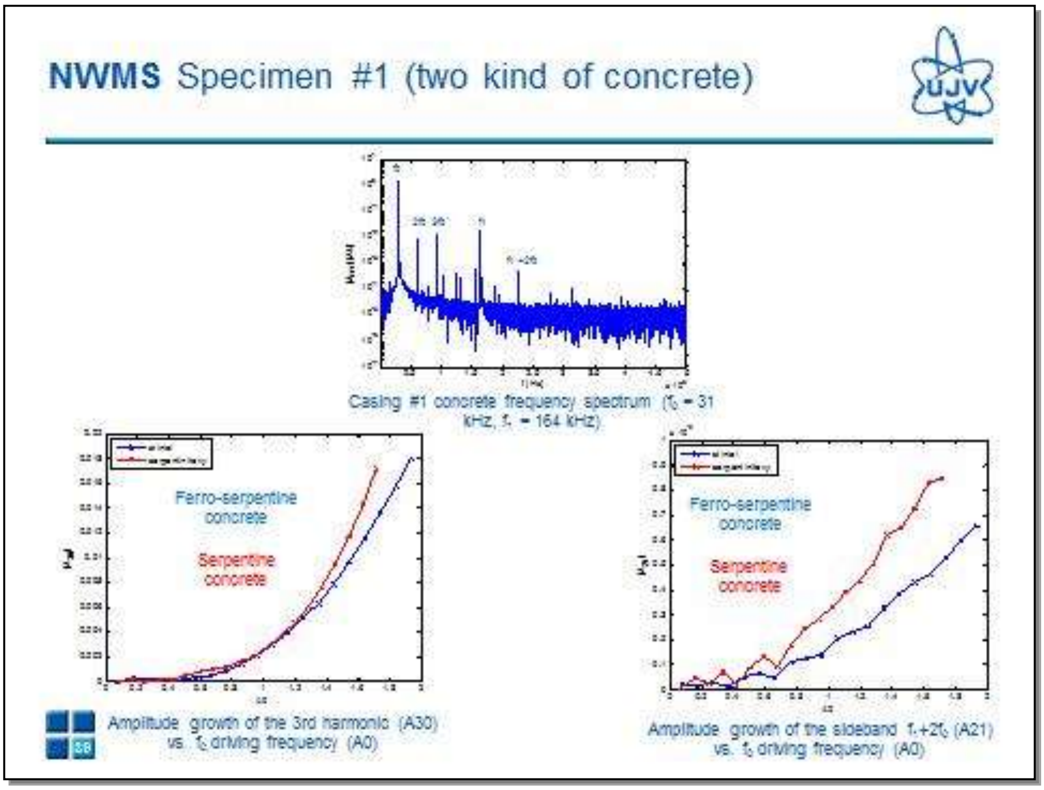
Nonlinear Wave Modulation Spectroscopy (NWMS)

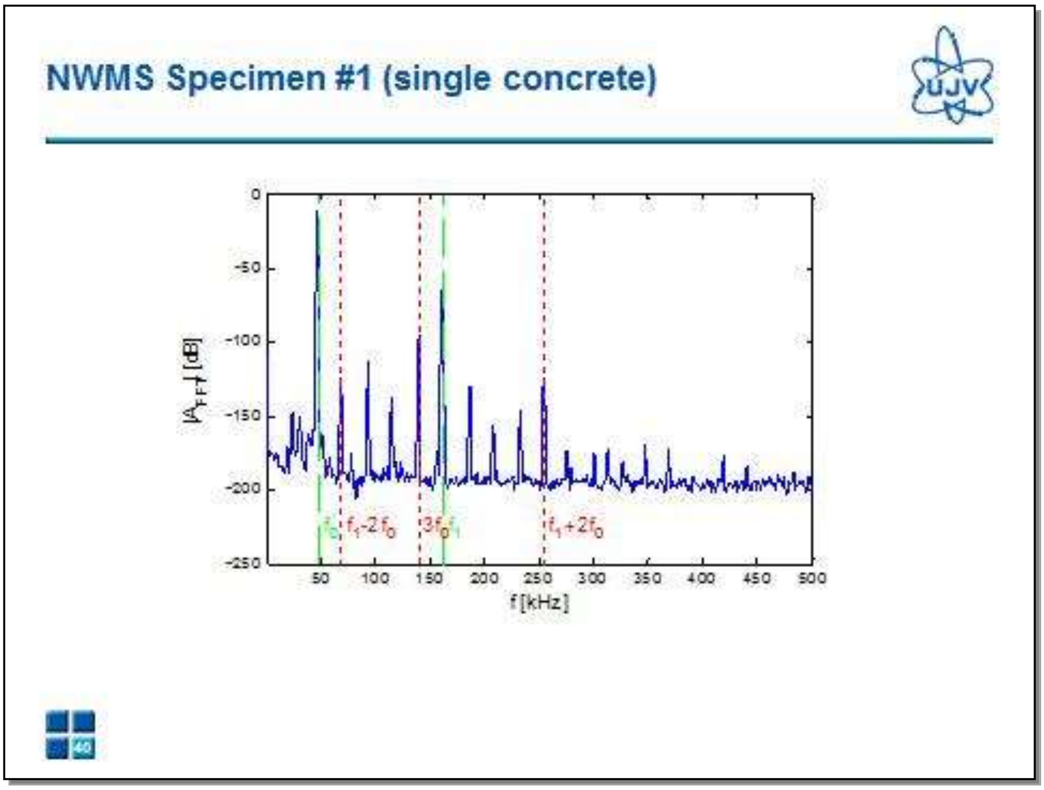


NEWS C-SCAN (previous concrete structure research)

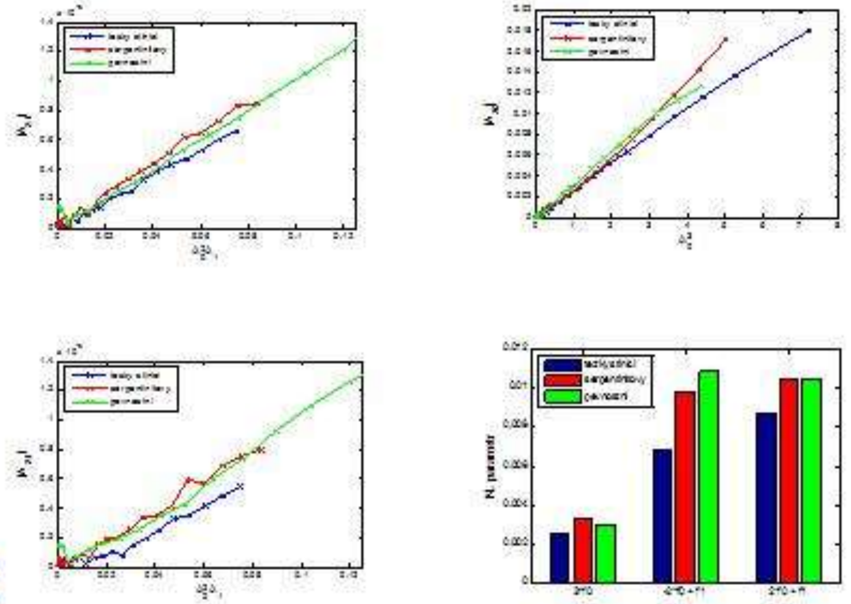


Cracks initiated during 4-point bending tests of slab samples #2 and #16. Crack photos (left) and their NWMS surface images

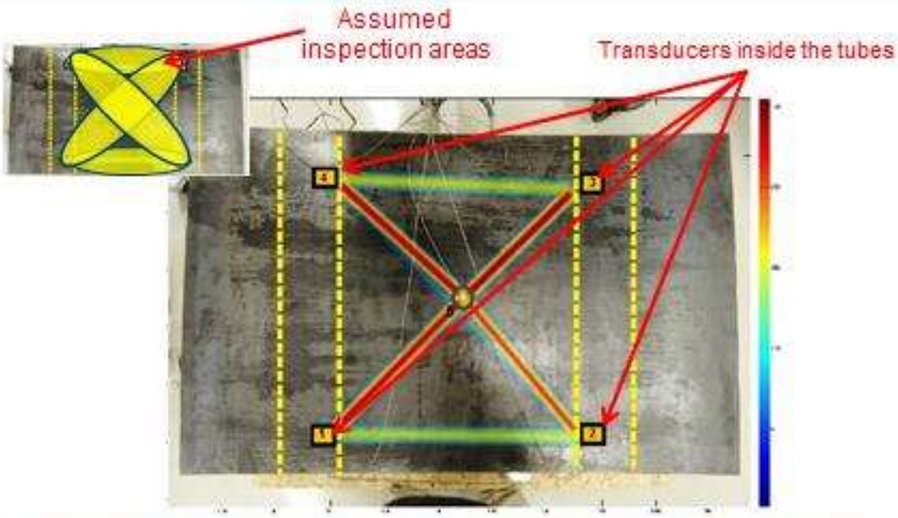

NWMS Specimen #1 (two kind of concrete)
Casing #1 concrete frequency spectrum (f0 = 31 kHz, f1 = 164 kHz)
Ferro-serpentine concrete
Serpentine concrete
Ferro-serpentine concrete
Serpentine concrete
Amplitude growth of the 3rd harmonic (A30) vs. f0 driving frequency (A0)
Amplitude growth of the sideband f1+2f0 (A21) vs. f0 driving frequency (A0)
38


NWMS Specimen #1 (single concrete)
0
-50
-100
-150
-200
-250
|A_FFT| [dB]
f0
f1-2f0
3f0
f1
f1+2f0
50
100
150
200
250
300
350
400
450
500
f [kHz]
40

NWMS – Non-linear parameter (results) Nonlinearities charakter/dependencies clearance



NLTRM (Non-Linear Time Reversal Method)



Heavy concrete (Nonlinearity index N_2 between 5 transducers is represented by color scaling)

Future comparative works on unique segment of biological shielding from decommissioned NPP

- NPP Greifswald Unit 5 (Germany) – trial run stopped in 1990
- WWER 440 type reactor – PWR of Russian construction
- UJV Rez in 2012 purchased a block of biological shielding as a surveillance material for complex testing
- Segment of steel lined serpentine concrete
- Documentation available – plant operation history, recipe of concrete mix, drawings,...

- Segment 1 of RPV biological shielding
  - Represents full construction height (2,78 m) and thickness (0,7 m)
  - In width (1,62 m) separated by parallel cuts from original ring of biological shielding
  - Segment comprise two original neutron flux measuring channels
  - Original construction and composition reference material !

Segment No.	mass [kg]	max. dose rate 0.1 m distance [mSv/h]	max. dose rate 1 m distance [mSv/h]	contamination α [Bq/cm²]	contamination β/γ [Bq/cm²]	mass specific activity [Bq/g]
1	7290	8.500E-01	1.200E-01	<4.000E-02	7.000E-01	1.720E+03

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Movie – Wave propagation

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Thank you for your attention
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Monitoring, evaluation and long-term forecasting of hygrothermal performance of thick-walled concrete structure

Woubishet Zewdu Taffese, Fahim Al-Neshawy Jukka Piironen, Esko Sistonen and Jari Puttonen

Aalto University School of Engineering, Department of Civil and Structural Engineering, Espoo, Finland

Abstract

A thick-walled concrete structure may be considered as a massive, often heavily-reinforced concrete structure with thickness greater than one meter. The main reinforcement consists of steel bars located on the both sides of the concrete wall. Thick-walled concrete structures are extensively used for infrastructures and industrial installations such as nuclear containments, dams, and waste water treatment plants. They are among the biggest structures in civil engineering which demand high level of safety and huge amount of construction budgets.

Thermal and moisture interactions inside thick-walled concrete structures are one of the decisive factors influencing its durability. Hence, long-term, in-service monitoring of thick-walled concrete structures in regular interval is very essential especially those require high level of safety. In addition, long-term hygrothermal interactions in thick-walled concrete structure can result in changes in mechanical properties and may cause serious service failures. Accordingly, knowledge of the long-term hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life.

Several concrete deterioration forecasting models are caused by long-term hygrothermal interactions. However, these models are not based on real-time monitored data and contain assumptions and approximations. Assumptions and simplifications compounded with the dynamic behavior of hygrothermal interaction as well as complexity of thick-walled concrete structure the existing models may inadequate to use for service-life forecasting especially those structures require high level of safety .

In this paper, long-term and in-service hygrothermal monitoring in nuclear containment is discussed. The monitored hygrotermal performance was also analyzed statistically before processing with artificial neural network. Non-linear autoregressive with exogenous inputs (NARX) network was used to model the observed time-series hygrothermal data and to perform long-term hygrothermal performance forecast. The forecasting performance evaluations revealed that the model forecast long-term hygrothermal behaviour inside concrete with good accuracy.

1. Introduction

Thick-walled concrete structures are extensively used for infrastructures and industrial installations such as nuclear containments, dams, and waste water treatment plants. They are among the biggest structures in civil engineering which demand high level of safety and huge amount of construction budgets. Thick-walled concrete structures are often heavily-reinforced, with thickness greater than one meter. Thermal and moisture interactions inside thick-walled concrete structures are one of the decisive factors influencing its durability. Understanding of the foremost deterioration mechanisms caused by hygrothermal interaction inside concrete is vital to extend service-life and insure safety of the structures.

1.1 Moisture effect on durability of concrete structures

The presences of moisture filled pores in the concrete will remarkable influence on the kinetics of transport processes of aggressive substances. High moisture content in concrete hinders those processes that take place easily in the gaseous phase, such as oxygen and carbon dioxide diffusion. On the other hand, it facilitates those processes that occur in aqueous solution, like the diffusion of chlorides, or ions in general [1] and [2]. Consequently, it contributes a significant impact on several physical and chemical deterioration of reinforced concrete structures, including corrosion of reinforcement steel, alkali-aggregate reaction, freezing and thawing, as well as sulphate attack [3], [4], [5], [6], [7], [8] and [9].

Moisture content in the concrete strongly influences on the formation of corrosion products and the rate of corrosion of reinforcement steel [10] and [11]. The amount of moisture content close to saturation makes the departure of corrosion products easier, but it decreases the oxygen diffusivity and makes the supply of oxygen more difficult [12] and [13]. The optimum relative humidity range is between 70% and 80% that allows enough oxygen to diffuse into the concrete and initiate corrosion of reinforcement steel [10].

Moisture content in the concrete can chemically react with harmful substances (e.g. alkali and sulphate ions) penetrated in the concrete. The reactions can form products that are deleterious to concrete because of the volume expansion of the reaction products. The volume expansion is increasing with rising of the moisture content in the concrete. If the relative humidity inside the concrete is above 98%, the damage caused by such reactions is high [14] The amount of moisture content in the concrete also controls damage risk associated with frost. Concrete with high internal relative humidity (85-95%) and saturated (>98%) the damage risk related with frost attack is medium and high, respectively [14].

1.2 Thermal effect on durability of concrete structures

Thermal effects cause expansion or contraction of the concrete structures. There are three types of thermal effects on concrete structures: (i) bulk temperature change, where the entire structural components or segments of the component are subject to a uniform temperature change; (ii) thermal gradient, which is caused by different thermal conditions on two faces of a structure, such as two sides of a wall or the top and bottom of a beam; and (iii) local thermal exposure, which is elevated temperature at a local surface that is caused by an external source such as operating equipment or piping or an abnormal event such as a fire [14].

Thermal interaction inside concrete is also one of the dominant factors in accelerating deterioration processes caused by chemical and physical factors. To mention few, an increment of temperature by 10℃ increases the corrosion rate of reinforcement steel in concrete by two fold. When temperature of pore solution drops below freezing temperature, corrosion of reinforcement steel stops completely since ions cannot move in the pore solution. In carbonated concrete, the corrosion rate is increased logarithmically with temperature in the range between -20℃ and around 30℃. In chloride contaminated concrete, the concentration of chloride in pore solution is increased for temperature above 55℃ while the concentration of hydroxide decreases, in turn it may accelerate chloride associated deteriorations [12].

1.3 Combined effect of moisture and temperature on durability of concrete structures

Based on moisture content changes as well as progressive deterioration of concrete constituent's, the mechanical properties of structure may vary considerably. As temperature increases, water is partly evaporated and generates a pressure in the pore structure. If the stresses applied internally by the induced vapor pressures exceed the tensile strength of the concrete, spalling of concrete or even catastrophic service failures may be caused [15], [16] and [17]. Generally, significant deterioration of concrete strength occurs when the exposure temperature goes above 400℃ at which decomposition of calcium hydroxide occurs. The decomposition process can lead to the increase of porosity and degrade the mechanical properties of concrete. The compressive strength, modulus of elasticity and volume deformation, decrease remarkably upon heating, in turn, jeopardize the structural integrity and load bearing capacity of the structure [15], [16], [18], [19], [20] and [21]. Not only elevated temperature, but also long-term hygrothermal interactions in reinforced concrete structure can result in changes in mechanical properties and may cause catastrophic service failures.

2. Monitoring of hygrothermal performance

Currently, there are several concrete deterioration forecasting models caused by long-term hygrothermal interactions. Nonetheless, the models are not based on real-time monitored data and contain assumptions and approximations. Assumptions and simplifications compounded with the dynamic behavior of hygrothermal interaction as well as complexity of thick-walled concrete structure the existing models may not adequate to use for service-life forecasting especially those structures require high level of safety. Without systematic hygrothermal monitoring and modelling, it is impossible to maintain significant level of reliability over service-life of thick-walled concrete structures. Hence, long-term, in-service monitoring of thick-walled concrete structures in regular interval is very essential Precise knowledge of hygrothermal performance of concrete is also required at the time of performing various non-destructive testing such as ground penetrating radar, ultrasonic pulse velocity and impact-echo because they are very sensitive to hygrothermal conditions [22], [23], [24], [25] and [26].

In this paper, long-term real-time hygrothermal performance monitoring and evaluation in a thick-walled concrete structure is discussed. The case thick-walled concrete structure is containment in power plant situated in Northern Europe. The containment wall consists of an outer and an inner cylindrical wall with thicknesses of 850 mm and 250 mm, respectively, and of a 5 mm thick steel liner between them as shown in Figure 1.

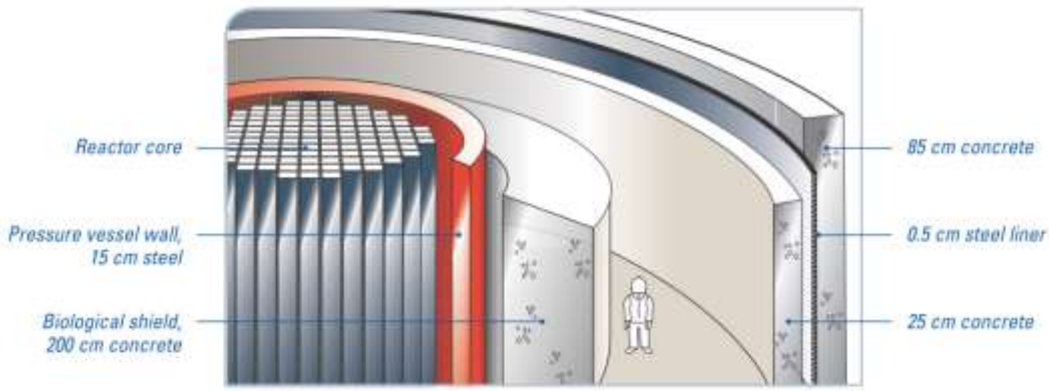
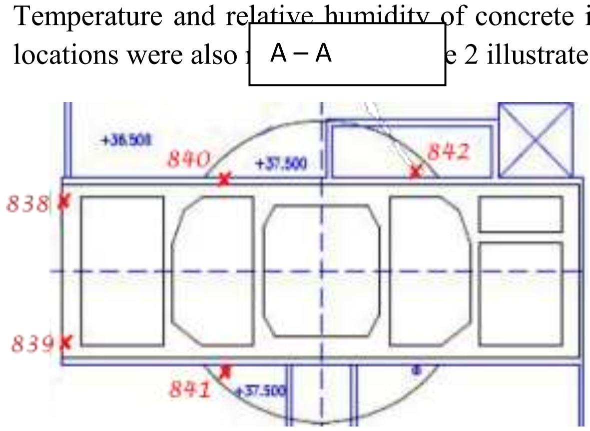
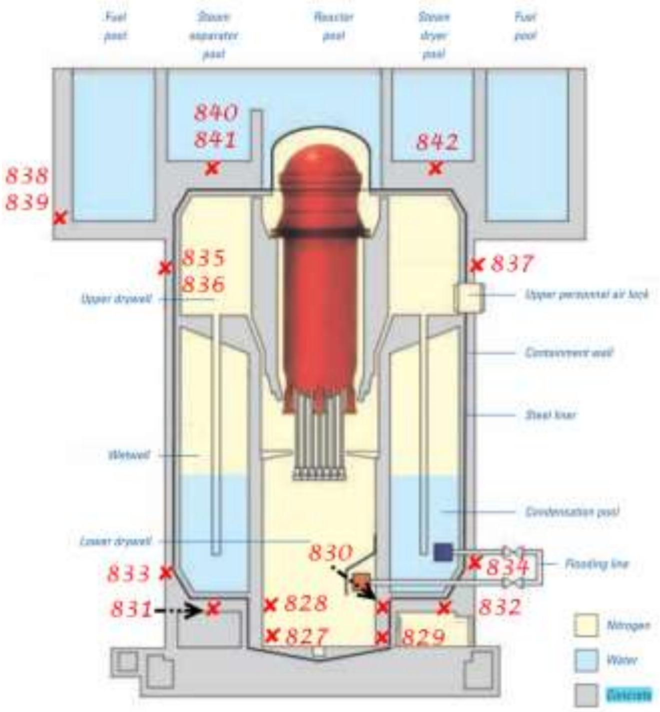


Figure 1. Cross-sections of the containment wall and pressure vessel wall made of concrete and steel.

The containment structure is heavily-reinforced, with a number of liners or cast-in-place items. The hygrothermal interaction among various elements in thick-walled concrete is complex. This makes mathematical analysis of hygrothermal performance in specific positions inside thick-walled concrete structure is challenging. The hygrothermal performance in the nuclear containment was monitored using HMP44L sensors. The sensors were produced by Vaisala Oy (Ltd.), Finland.

The ambient temperature and relative humidity were collected inside containment at elevation of 1000mm. Temperature and relative humidity of concrete inside the containment in the depth of 400mm at various locations were also [illegible] e 2 illustrates the sensors location in the case containment structure.





Elevation (m)	Sensor label
36.6	840 841 842
31.8	838 839
30.0	835 836 837
6.0	833 834
2.5	831 828 830 832
1.0	827 829

Figure 2. Locations of temperature and relative humidity sensors within the containment structure.

The monitored hygrothermal performance is corresponded to about a year period from 4 June 2011 to 24 April 2012 and illustrated in Figure 3 and Figure 4. Measurements were made at regular time intervals of 24 hours. Temperature inside concrete seems to have the same trend with the ambient temperature. In case of relative humidity, the ambient relative humidity measurements do not have the same trend with relative humidity inside concrete. Strong association can be observed among the relative humidity measurements inside concrete. Relative humidity measurements inside concrete, in many cases, are above 80%.

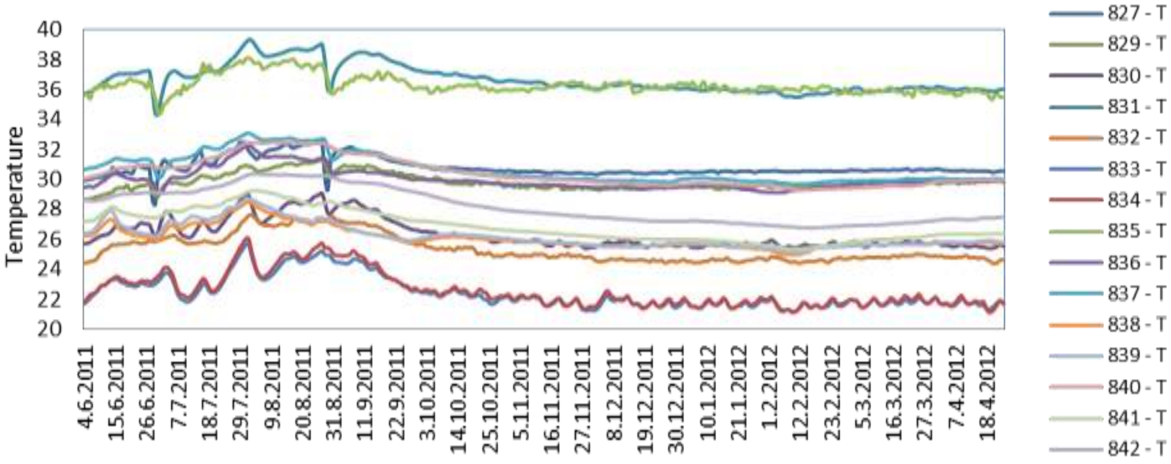


Figure 3.Time-series plot of temperature measurements in nuclear containment.

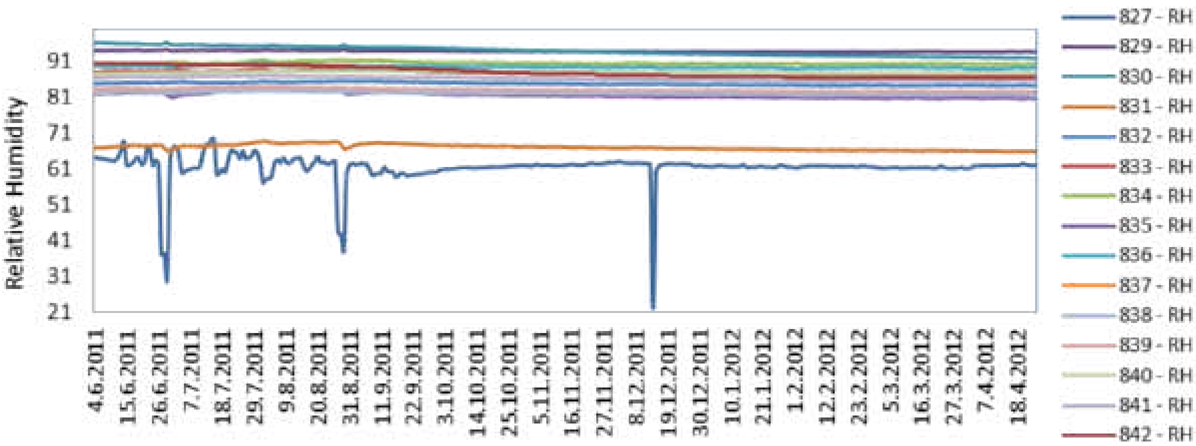


Figure 4.Time-series plot of relative humidity measurements in nuclear containment.

The correlation coefficients between hygrothermal performances at different locations were statistically analyzed and presented in Table 1. Hygrothermal dataset within the same elevation in the containment structure are presented in respective cells. Correlation coefficients of relative humidity and temperature are presented in bottom left triangle - and upper right triangle, respectively. The correlations between ambient temperature and temperature inside concrete at all locations are generally strong and positive. This implies that, when the ambient temperature increases or decreases the temperature inside the concrete increases or decreases accordingly. The temperature correlation coefficients are in the range between 0.66 and 0.88. The ambient temperature is found to be more strongly correlated with temperature inside concrete at a location labelled 829 with correlation coefficient of 0.88. This location is found in lower drywall with the same elevation as that of the ambient temperature monitoring location, labelled 827. This is one of the most probable reasons why location labelled 827 obtained a strong positive relation with the ambient temperature compared with the other locations.

Table 1. Correlation coefficients between temperature and relative humidity measurements in nuclear containment structure.

	827	829	830	831	832	833	834	835	836	837	838	839	840	841	842	T
827		***0.88***	***0.84***	***0.85***	***0.80***	***0.78***	***0.78***	***0.72***	***0.81***	***0.79***	***0.70***	***0.66***	***0.79***	***0.70***	***0.72***	**827**
829	***-0.11***		0.83	0.85	0.84	0.78	0.78	0.70	0.83	0.78	0.64	0.59	0.81	0.68	0.72	**829**
830	***-0.03***	0.93		0.90	0.96	0.98	0.98	0.69	0.84	0.91	0.81	0.78	0.93	0.87	0.91	**830**
831	***0.00***	0.80	0.82		**0.89**	0.86	0.85	0.81	0.88	0.91	0.80	0.77	0.91	0.85	0.88	**831**
832	***-0.09***	0.90	0.90	**0.92**		0.95	0.95	0.68	0.86	0.93	0.83	0.81	0.96	0.91	0.94	**832**
833	***-0.07***	0.93	0.91	0.90	0.98		**1.00**	0.68	0.84	0.90	0.82	0.80	0.92	0.87	0.90	**833**
834	***-0.16***	0.60	0.51	0.78	0.81	**0.80**		0.67	0.83	0.89	0.82	0.80	0.92	0.87	0.90	**834**
835	***-0.02***	0.89	0.85	0.95	0.91	0.93	0.75		**0.83**	**0.81**	0.72	0.68	0.75	0.67	0.67	**835**
836	***0.04***	0.87	0.82	0.82	0.79	0.84	0.57	**0.89**		**0.94**	0.93	0.90	0.91	0.89	0.84	**836**
837	***-0.04***	0.93	0.91	0.95	0.97	0.97	0.77	**0.98**	**0.88**		0.93	0.92	0.97	0.96	0.95	**837**
838	***0.01***	0.92	0.90	0.92	0.95	0.95	0.73	0.95	0.91	0.98		**0.99**	0.89	0.95	0.88	**838**
839	***0.01***	0.93	0.94	0.91	0.95	0.96	0.68	0.95	0.90	0.98	**0.99**		0.87	0.95	0.88	**839**
840	***-0.09***	0.55	0.48	0.81	0.79	0.70	0.88	0.73	0.55	0.75	0.73	0.68		**0.96**	**0.98**	**840**
841	***-0.02***	0.94	0.93	0.90	0.96	0.97	0.71	0.93	0.89	0.98	0.99	0.99	**0.71**		**0.98**	**841**
842	***-0.01***	0.97	0.98	0.82	0.91	0.94	0.56	0.88	0.86	0.93	0.93	0.95	**0.51**	**0.95**		**842**
RH	**827**	**829**	**830**	**831**	**832**	**833**	**834**	**835**	**836**	**837**	**838**	**839**	**840**	**841**	**842**	

It can be also observed that the correlation coefficients between temperature inside concrete (categorized in the same location or elevation) are generally strong and positive. Even there is a perfect positive correlation between sensors labelled 833 and 834. The correlation analysis between relative humidity of ambient and inside concrete showed that the ambient relative humidity do not have any linear correlation, even with the closest location labelled 829. Similar to temperature, positive linear correlation between relative humidity inside concrete within the same group is noticed.

3. Artificial neural network for long-term forecasting of hygrothermal performance

Knowledge of the future hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life. Developing a model to forecast hygrothermal performance in thick-walled concrete structure is a major problem because of its dynamic, complex and nonlinear characteristics. Such a problem requires systems approach where the most essential features of a complex problem with multiple interactions are modelled so that the system behaviour can be forecasted reliably. Thus, the best solution is to learn system behaviour through observations. Artificial neural network (ANN) has been found useful in solving complex time-series problems in different applications as they are modelled after the brain.

ANN is a computational network which attempt to simulate the networks of nerve cell (neurons) of the biological central nervous system [27], [28] and [29]. Artificial neurons form massively parallel networks, whose function is determined by the network structure, the connection strengths between neurons, and the processing performed at neurons [28].

The model of a neuron, which forms the basis for designing artificial neural networks are shown in Figure 5. It basically consists of:

- A set of synapses or connecting links, each of which is characterized by a weight or strength of its own. Specifically, a single x_j at the input of synapse j connected to network k is multiplied by synaptic weight w_{kj}.
- An adder for summing the input signals, weighted by the respective synapses of the neuron;
- An activation function for limiting the amplitude of the output of a neuron.

A neuron k, can be mathematically described by the following equations:

$$u_k = \sum_{j=1}^{m} w_{kj}\, x_j \qquad (1)$$

$$y_k = \varphi(u_k + b_k) \qquad (2)$$

Where:

$x_1, x_2, \ldots, x_m$ are the input signals;
$w_{k1}, w_{k2}, \ldots; w_{km}$ are the synaptic weights of neuron k;
u_k is the linear combiner output due to the input signals;
b_k is the bias;
$\varphi(.)$ is the activation function; and ;
y_k is the output signal of the neuron.

The externally applied bias b_k has the effect of increasing or lowering the net input of the activation function, depending on whether it is positive or negative, respectively.

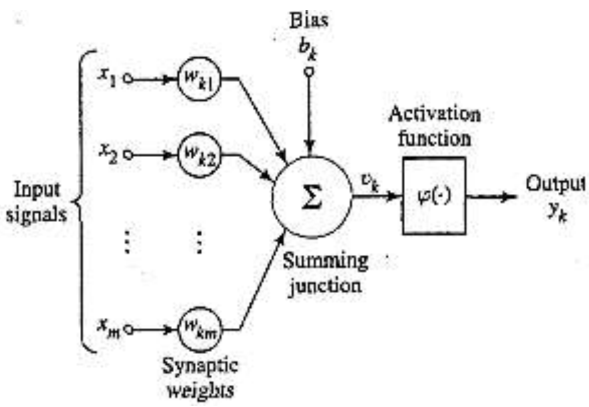


Figure 5. A simplified model of artificial neuron [29].

ANNs are flexible, adaptive learning systems that follow the observed data freely to find patterns in the data and develop nonlinear system models to make reliable forecast of the future [28]. By the help of hygrothermal sensors real-time data can be monitored. The real-time data can be modelled using ANN, in turn makes self-learning smart structure which speaks the future hygrothermal performance for itself. Figure 6, Venn diagram indicates self-learning smart structure by confluence of thick-walled concrete structure, hygrothermal sensors and artificial neural networks.

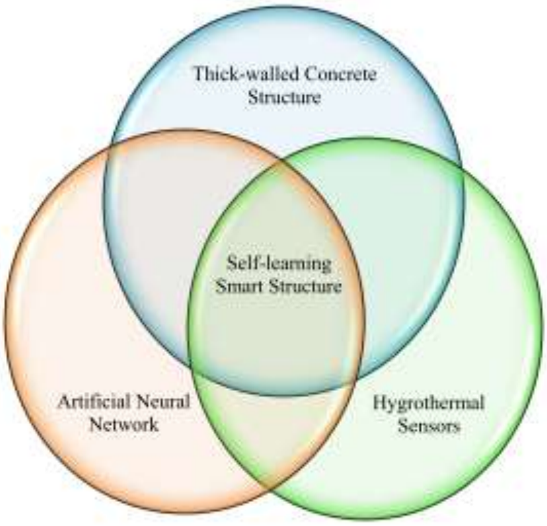


Figure 6. Venn diagram indicates self-learning smart structure by confluence of thick-walled concrete structure, hygrothermal sensors and artificial neural networks.

3.1 Neural Network Architecture

The pattern of connections between the neurons is called the architecture of the neural network [30]. Depending on their architecture neural networks may be classified in a number of different ways which is intimately linked with the learning algorithm used to train the network. Different neural network architectures are widely described in the literature. However, there are three fundamentally different classes of network architectures: Single-layer feedforward networks, multilayer feedforward networks and recurrent networks [29].

Recurrent neural network model have been successfully used for various time-series forecasting tasks. It attempts to incrementally build the autocorrelation structure of a series into the model internally, using feedback connections relying solely on the current values of the input(s) provided externally. The network learn the dynamics of the series over time from the present state of the series, which is continuously fed into it, and then the network uses this memory when forecasting [28] and [29]. The architectural layout of recurrent network takes many different forms. In this study, non-linear autoregressive with exogenous inputs (NARX) model was selected.

3.2 Non-linear autoregressive with exogenous inputs (NARX)

NARX model is recurrent dynamic network and in this model external inputs are presented to the network in addition to those fed back from the output [28]. This model may have input that is applied to a tapped-delay-line memory of q units. The output is also fed back to the input via another tapped-delay-line memory of q units. The contents of these two tapped-delay-line memories are used to feed the input layer of the multilayer perceptron. The present value of the model input is denoted by $u(n)$, and the corresponding value of model output is denoted $y(n+1)$; that is, the output is ahead of the input by one time unit. Thus, the signal vector applied to the input layer of the multilayer perceptron consists of a data window made up as follows:

- Present and past values of the input, namely $u(n)$, $u(n-1)$,..., $u(n-q+1)$, which represent exogenous inputs originating from outside the network,
- Delayed values of the output, namely, $y(n)$, $y(n-1)$,..., $y(n-q+1)$, on which the model output $y(n+1)$is regressed.

The dynamic behaviour of the NARX model is described by Equation 3.

$$y(n+1) = F\big(y(n), \dots, y(n-q+1), u(n), \dots, u(n-q+1)\big) \qquad (27)$$

(3)

where F is a non-linear function of its arguments.

4. Modelling of artificial neural network

4.1 Network structure

Two long-term hygrothermal forecasting models: one is for temperature and the other is for relative humidity was developed. MATLAB® neural network toolbox [31] was used for modelling the data. The models use ambient hygrothermal data as inputs to forecast the hygrothermal performance inside nuclear containment structure. The dependency of the hygrothermal behaviour inside the containment with the ambient hygrothermal performance is somewhat identical in all locations of the structure as proofed by the correlation analysis. Accordingly, in this paper, forecasting performance of hygrothermal behaviour in nuclear containment structure only for the location labelled 829 is presented.

Non-linear autoregressive with exogenous inputs (NARX) network with two layers was used to model the data. The fundamental architecture of the network is the same as shown in Figure 7. The model has two inputs, one is an external input (e.g monitored ambient temperature), and the other is a feedback connection from the model output. The feedback connection from the model output at future time-steps (which are then used as inputs) are forecasted hygrothermal data. The model must recursively make forecasts for the n required time-steps of $(t+1)$, $(t+\ 2)$,..., $(t\ +\ n)$ using only the inputs at time t. As a consequence, long-term forecasting performance depends on its own prediction in a single-step to recursively predict the outcome for the next step.

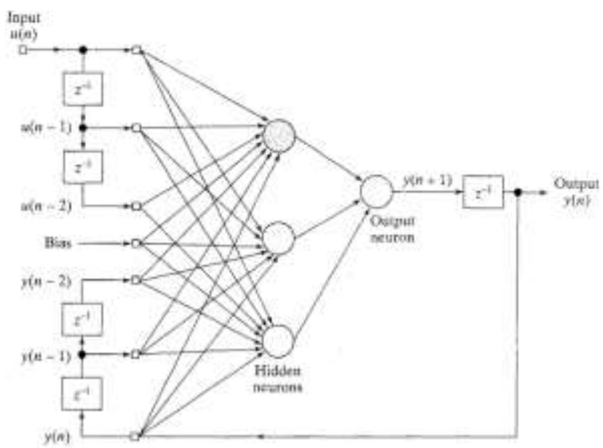


Figure 7. NARX model with three hidden neurons [29].

The time-steps of the inputs were equals to the whole hygrothermal time-steps minus n size of required future time-steps. The subtracted n size of required time-steps is monitored hygrothermal data which are used to evaluate the model forecasting performance since they were not used for network training. A tapped-delay-line memory of two units was assigned for both input and feedback. The network obtained five hidden neurons and one output neuron. The optimal number of neurons in the hidden layer and a tapped-delay-line memory was based on the generalization error and found after several trainings. The activation functions selected for the layers were hyperbolic tangent transfer function in the hidden layer and linear transfer function in the output layer. The input and target outputs were randomly divided to 70% for training, 20% for validation and 10% for testing. The training hygrothermal dataset was used to train the network. Training begins with the third data point since a tapped-delay-line memory of two units was assigned. Validation dataset was used to measure the network generalization, and to halt training when the generalization stops improving. Test dataset used to measure network performance during and after training. The applied training algorithm was the Levenberg-Marquardt. This algorithm is an iterative technique that locates the minimum of a multivariate function that is expressed as the sum of squares of non-linear real-valued functions and is the fastest method for training.

4.2 Result analyses

Training performance of the NARX model for long-term (90-steps-ahead) forecasting of hygrothermal behaviour inside containment structure is shown in Figure 8. It illustrates training, validation and testing performance functions versus the iteration number. The error on the validation set is monitored during training, and the training is stopped when the validation error stop decreasing further. As indicated by the dashed line in the performance plot, the best model generalization for temperature was obtained at epoch 23 where minimum mean square error of validation is dropped to 6.82e-03. In case of relative humidity, best validation performance was occurred at epoch 54 with minimum mean square error of 9.1e-04. The error in case of temperature is a bit higher compared to relative humidity.

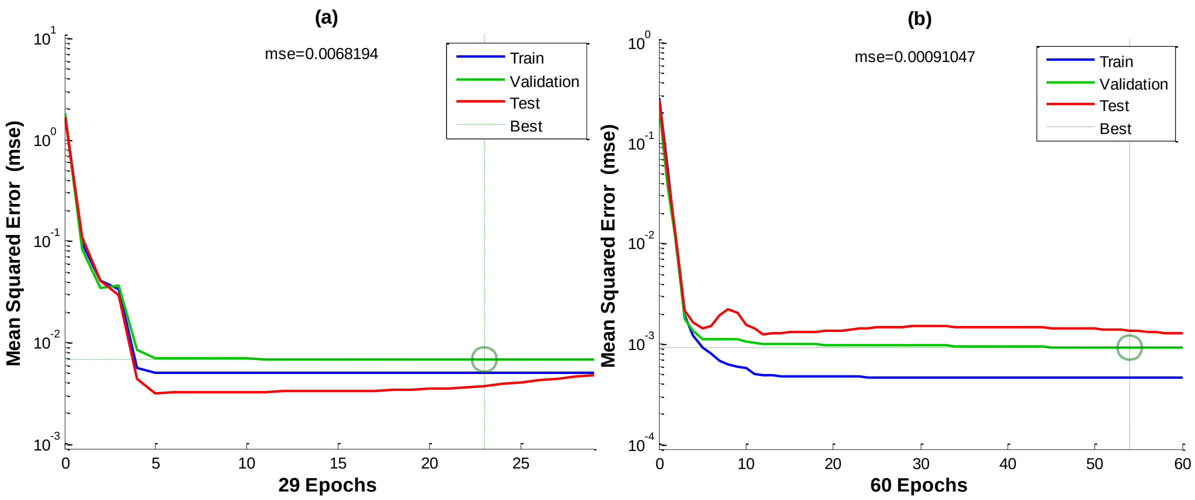


Figure 8. Plot of training of the NARX model for long-term forecasting of hygrothermal performance inside containment concrete a) temperature b) relative humidity.

A linear regression between the network outputs and the corresponding targets were conducted and shown in Figure 9. The R-value for temperature response was 0.99321 and for relative humidity was 0.99053. In both cases the R-values are above 0.99 which indicates the model outputs tracks the targets (observed hygrothermal behaviour inside concrete) very well.

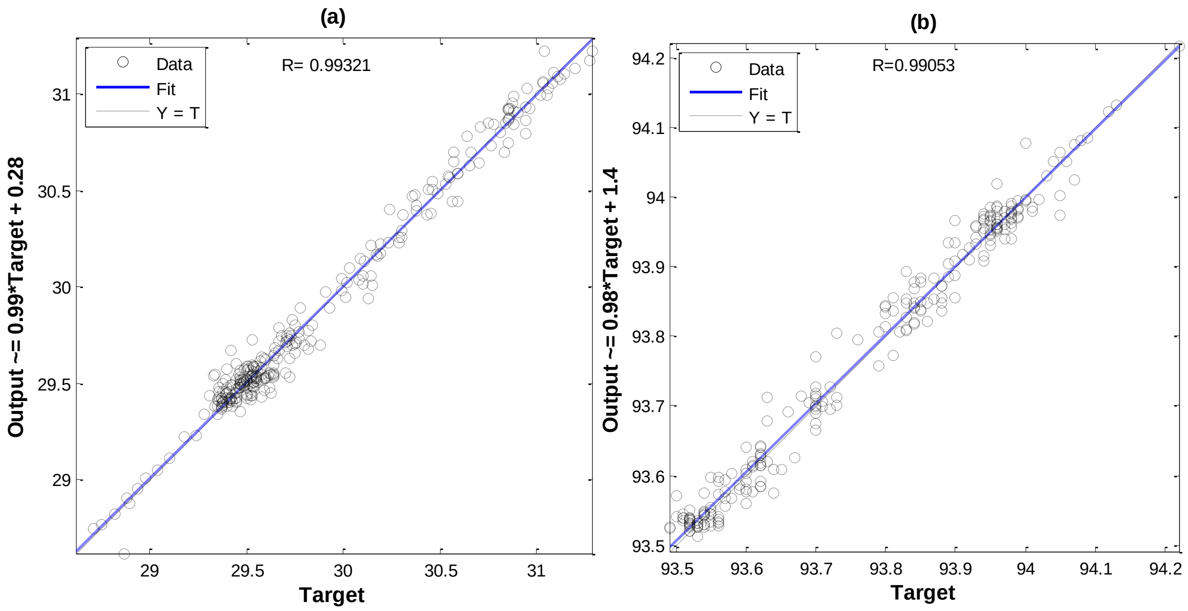


Figure 9. Plots indicate a linear regression between the network outputs and the corresponding targets a) temperature b) relative humidity.

Hygrothermal forecast of 90-steps-ahead is plotted in Figure 10. It can be observed that the forecasted temperature (90-steps-ahead) do not fit with the observed data fully. This is because of the used small training dataset. It is clearly seen that the last 90 time-steps has different trend compared with the other time steps which were used for training the model. The forecasting performance of the models was measured by mean square error. The mean square error for 90-steps-ahead forecast of temperature and relative humidity inside concrete were 0.0155 and 0.008, respectively. These findings revealed that the NARX model can forecast long-term hygrothermal condition inside concrete that have not been observed before with good accuracy.

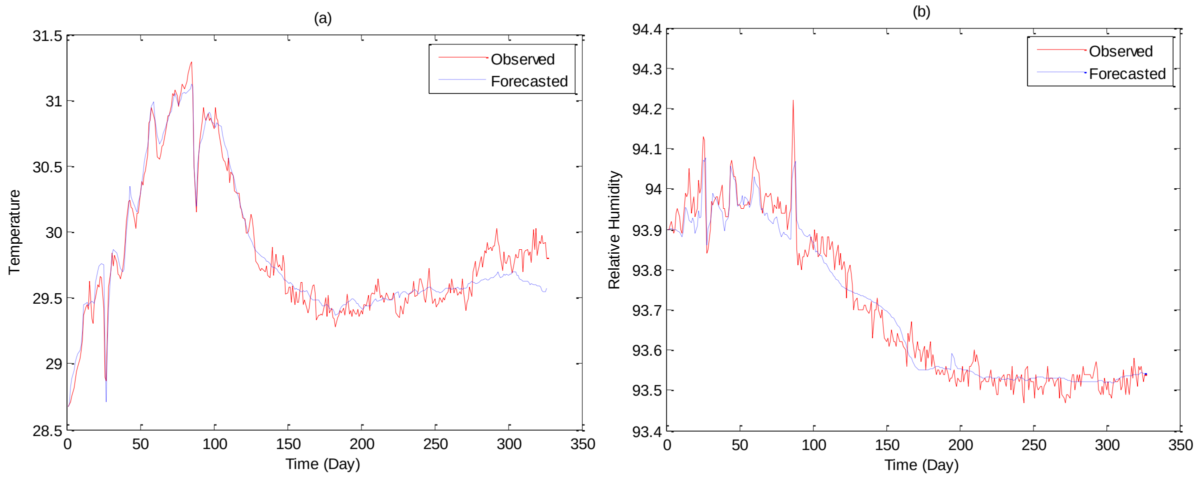


Figure 10. Plots of observed and forecasted data (90-steps-ahead) a) temperature b) relative humidity

A number of long-term forecasts with different time-steps-ahead were also performed using the NARX models and summarized in Table 2. It can be seen that the error range for the models is small, indicating that they all perform adequately. Table 2 also shows that when the forecasting horizon increases from 30-steps to 90-steps the mean square error is also increases, which in turn, deteriorates the forecasting ability. This is due to the compounding effects of the errors in the forecasted outputs at each time-step for n required time-steps. Though the forecasting ability decreases with increasing the time-steps, the developed NARX model reasonably forecast hygrothermal performance of 90-steps-ahead. This investigation confirmed that, even with small dataset, NARX model can forecast long-term hygrothermal behaviour inside concrete. The performance of long-term forecasting can be improved using large data since neural networks can learn very well from large data. Once trained, the model learns the aging effect on hygrothermal performance and can be used to make pragmatic decisions with regard to service-life extension of the structure.

Table 2. Mean square error of hygrothermal forecast of 30-steps, 60-steps and 90-steps-ahed

	30-steps-ahead	**60-steps-ahead**	**90-steps-ahead**
Temperature	mse=0.0151	mse= 0.0161	mse=0.0155
Relative humidity	mse=0.0022	mse=0.0064	mse=0.0080

5. Conclusions

Moisture and thermal interactions in concrete are the decisive factors influencing the durability of the concrete. Moisture content contributes a significant impact on several deterioration mechanisms, including corrosion of reinforcement steel, alkali-aggregate reactions, freezing and thawing, as well as sulphate attack. Thermal interaction inside concrete is also one of the dominant factors in accelerating deterioration processes caused by chemical and physical factors. The compressive strength, modulus of elasticity and volume deformation of concrete structures decrease remarkably upon elevated temperature.

Today, there are several concrete deterioration forecasting models caused by long-term hygrothermal interactions. However, the models contain assumptions and approximations about the hygrothermal performance inside concrete and other parameters. Assumptions and simplifications compounded with the dynamic behavior of hygrothermal interaction as well as complexity of thick-walled concrete structure the existing models are inadequate to use for service-life forecasting. Long-term, in-service hygrothermal performance monitoring of thick-walled concrete structures in regular interval using sensors is essential. It increases reliability of deterioration prediction models significantly.

Understanding of the long-term hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life. Two NARX (artificial neural network based long-term hygrothermal forecasting models) for temperature and relative humidity were developed. The models were trained to forecast the future hydrothermal behaviour inside concrete ranging from 30-steps to 90-steps-ahead. When the forecasting horizon increases the mean square error is also increases. It indicates that the larger samples have the advantage of reducing the total error. Even though the forecasting ability decreases with increasing the time-steps, the developed NARX model reasonably forecast for 90-steps-ahead. The mean square error for 90-steps-ahead forecast of temperature and relative humidity inside concrete were 0.0155 and 0.008, respectively. Thus, using long-term hygrothermal data, it is possible to capture the aging effect on hygrothermal performance and can be used to make realistic decisions with regard to service-life extension of the structure.

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Workshop on non-destructive evaluation of thick walled concrete structures

Prague, Czech Republic, 17-19 September 2013

Monitoring, evaluation and long-term forecasting of hygrothermal performance of thick-walled concrete structure

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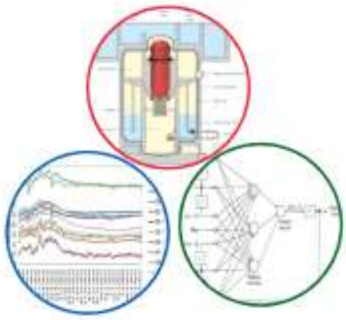
Outlines

- Objectives of the study
- Effect of moisture and temperature on the durability of thick-walled concrete structures
- Monitoring of the hygrothermal performance of containment structure
- Long-term forecasting of the hygrothermal performance
- Conclusions



Aalto University School of Engineering

MANAGE research project

Aging Management of Concrete Structures in Nuclear Power Plants – MANAGE

- Funded by SAFIR 2014 (The Finnish Research Programme on Nuclear. Power Plant Safety 2011 – 2014).
- Objectives:
  - Development of a computerized aging management system for concrete structures in nuclear power plants
  - Development of an inspection database for NPP concrete structures
  - **Development of a monitoring and simulation system which supports aging management and condition assessment of concrete structures**
  - Development of structural analyses supporting aging management

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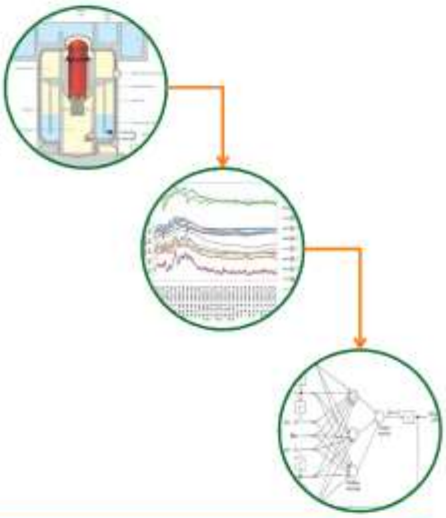
Objectives of the study

- Long-term and in-service hygrothermal **monitoring** of containment thick-walled concrete structure
- Analyzing of the **hygrotermal performance** of the monitored containment
- Forecasting Models for the hygrotermal performance of the monitored containment using **artificial neural network**.



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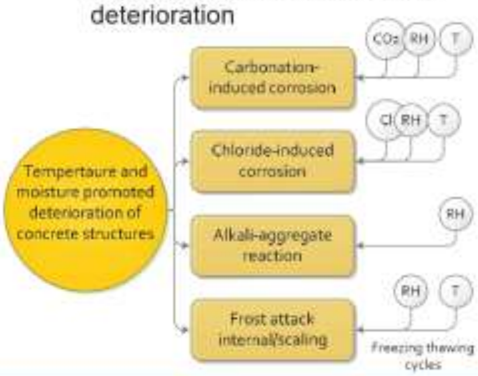
Effect of moisture and temperature on the durability of thick-walled concrete structures

- Thick-walled concrete structures face substantial temperature and humidity differences between the interior and exterior surfaces
- While the thick walls provide for low average temperature and/or moisture gradient, near surface gradients can be substantial due to exposure to rapid environmental condition changes.
- Temperature and moisture contribute a significant impact on several physical and chemical deterioration



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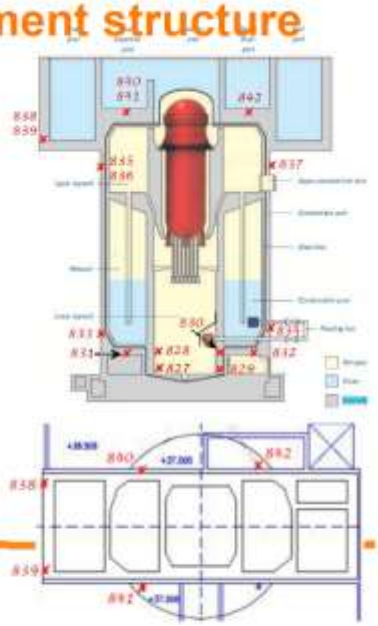
Monitoring of the hygrothermal performance of containment structure

- The ambient T & RH were collected inside containment at elevation of 1000mm.
- T & RH of concrete inside the containment in the depth of 400mm
- HMP44L sensors were used
- time intervals of 24 hours



Elevation (m)	Sensor label
36.6	840 841 842
31.8	838 839
30.0	835 836 837
6.0	833 834
2.5	831 828 830 832
1.0	827 829

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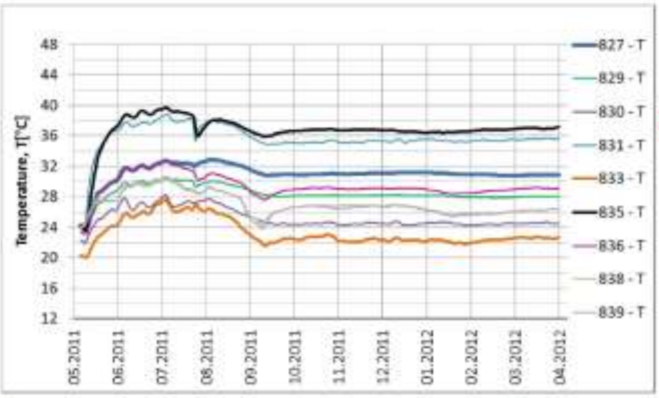
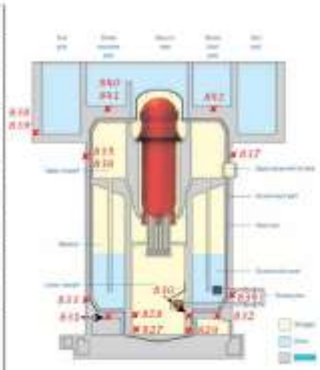
Monitoring of the hygrothermal performance of containment structure

Temperature inside concrete seems to have the same trend with the ambient temperature





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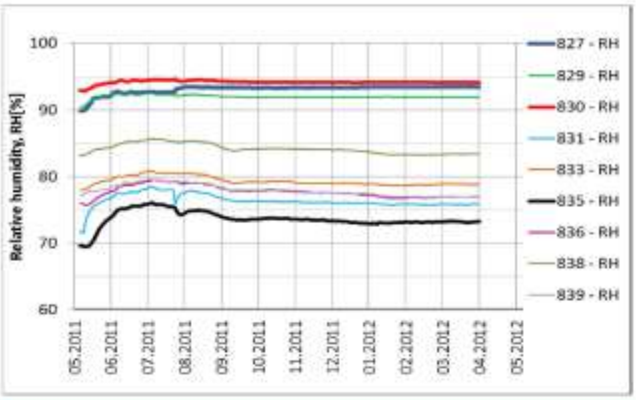
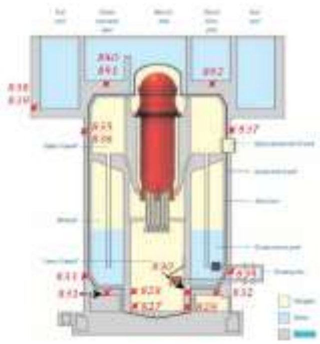
School of Engineering

Monitoring of the hygrothermal performance of containment structure

Relative humidity measurements inside concrete, in many cases, varied between 70% and 95% RH





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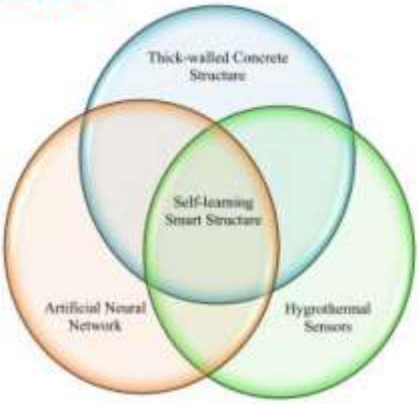
Long-term forecasting of the hygrothermal performance

- Real-time condition is monitored data by sensors
- The real-time data can be modeled using Artificial Neural Network , in turn makes self-learning smart structure which speaks the future hygrothermal performance for itself.
- Non-linear autoregressive with exogenous inputs (NARX) network with two layers was used to model the data



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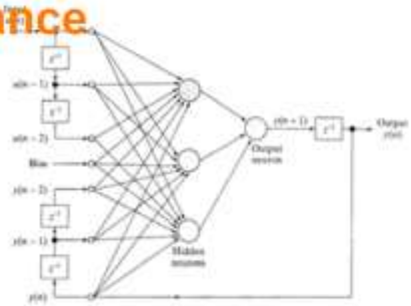
Long-term forecasting of the hygrothermal performance

- The NARX model has two inputs,
  - one is an external input (e.g monitored ambient temperature),
  - the other is a feedback connection from the model output.
- The feedback connection from the model output at future time-steps are forecasted hygrothermal data.
- The forecasting performance of the models was measured by Mean Square Error (MSE).



	30-steps-ahead	60-steps-ahead	90-steps-ahead
T	0.0151	0.0161	0.0155
RH	0.0022	0.0064	0.0080

Mean Square Error (MSE).

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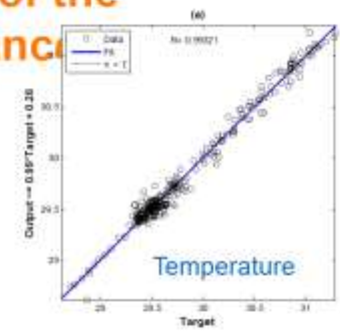
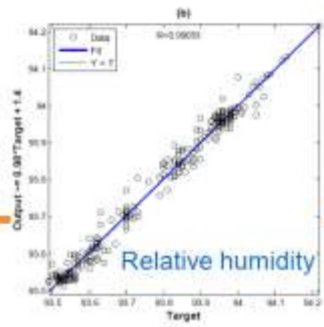
Long-term forecasting of the hygrothermal performance

- A linear regression between the network outputs and the corresponding targets were conducted
- R-value for temperature response was 0.99321
- R-value for relative humidity was 0.99053.
- In both cases the R-values are above 0.99 which indicates the model outputs tracks the targets (observed hygrothermal behaviour inside concrete) very well.





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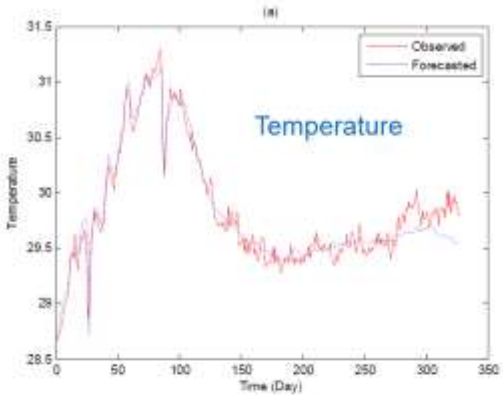
Long-term forecasting of the hygrothermal performance

Temperature

- It can be observed that the forecasted temperature (90-steps-ahead) do not fit with the observed data fully.
- This is because of the used small training dataset.
- MSE for 90-steps-ahead forecast of temperature inside concrete were 0.0155



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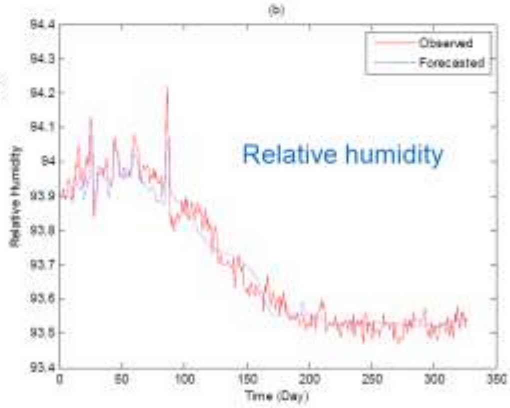
Long-term forecasting of the hygrothermal performance

Relative humidity

- MSE for 90-steps-ahead forecast of relative humidity inside concrete were 0.008



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Conclusions

- Understanding of the long-term hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life.
- Two NARX (artificial neural network based long-term hygrothermal forecasting models) for temperature and relative humidity were developed.
- The models were trained to forecast the future hydrothermal behaviour inside concrete ranging from 30-steps to 90-steps-ahead
- The mean square error for 90-steps-ahead forecast of temperature and relative humidity inside concrete were 0.0155 and 0.008, respectively.
- Thus, using long-term hygrothermal data, it is possible to capture the aging effect on hygrothermal performance and can be used to make realistic decisions with regard to service-life extension of the structure.

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Thank you for your attention

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The Effect of Irradiation on Thick Walled Concrete Structures in Nuclear Power Plants with Respect to Long Term Operation

September 17, 2013

Brian Hohmann, Thomas Esselman,
Paul Bruck (Lucius Pitkin, Inc.),
James J. Wall (EPRI)

Lucius Pitkin, Inc.
Consulting Engineers

1

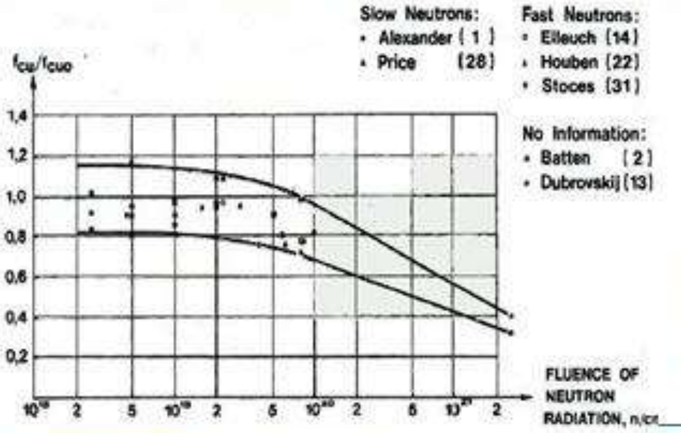
INTRODUCTION

- The literature on irradiation effects on concrete.
- Expected neutron fluence in the concrete at commercial nuclear plants.
- Temperature effects of gamma.
- Strategy to augment data.
- Conclusions.

2

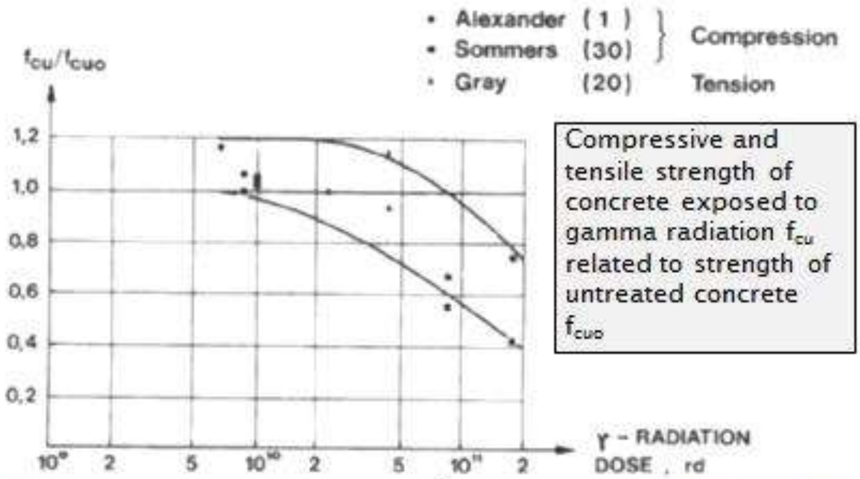
Literature Review

- H.K. Hilsdorf's 1978 paper described the effects of nuclear radiation on concrete properties.
- Hilsdorf compiled previously published data on the effect of nuclear radiation on concrete.



Source: Hilsdorf, H., J. Kropp, H. Koch. *The Effects of Nuclear Radiation on the Mechanical Properties of Concrete*. American Concrete Institute. Report SP-55-10. p. 223-251. 1978.

Hilsdorf Curve Gamma



Compressive and tensile strength of concrete exposed to gamma radiation f_{cu} related to strength of untreated concrete f_{cuo}

Source: Hilsdorf, H., J. Kropp, H. Koch. *The Effects of Nuclear Radiation on the Mechanical Properties of Concrete*. American Concrete Institute. Report SP-55-10. p. 223-251. 1978.

Hilsdorf cont.

- Hilsdorf concluded that neutron radiation with a fluence of greater than $1x10^{19}$ n/cm^2 and a gamma dose greater than 10^{10} rads could have a detrimental effect on concrete strength.
- This data is currently still being used as a reference threshold levels by many.

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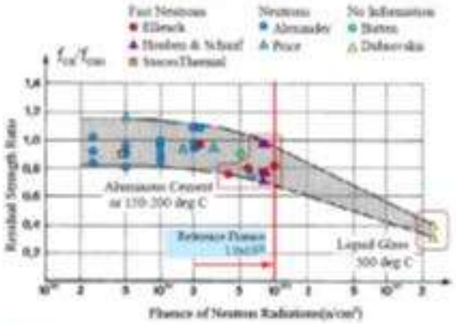
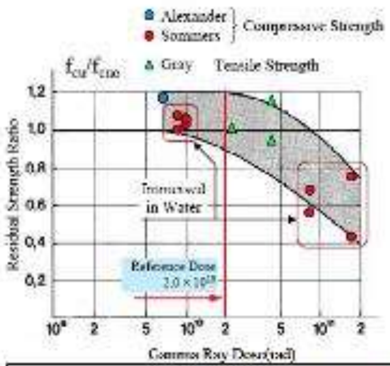
Kontani, et. al. – 2010

- Concluded that the test conditions from some of the experiments on which Hilsdorf based his conclusions were not representative of the typical operating history of a commercial nuclear reactor, and thus may not be applicable





Kontani, O. et al. *Irradiation Effects on Concrete Durability of Nuclear Power Plants.* ICAPP 2011 Conference (Paper 11561). Nice, France, May 2-5, 2011.

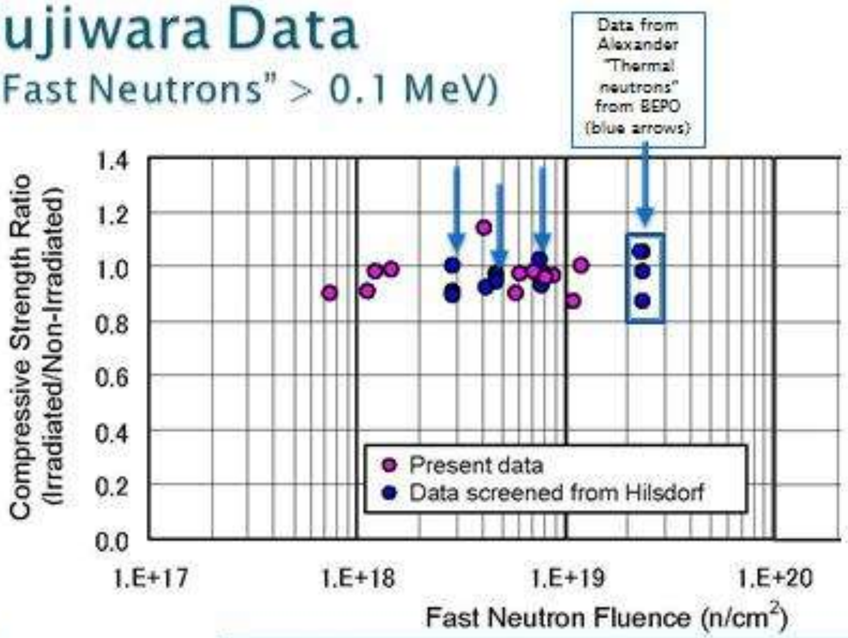
6

Fujiwara Neutron Data

- Test Results –No loss in compressive strength for specimens tested at fluence dose up to 1.2 E+19 n/cm² for E>0.1 MeV
- Test Reactor – JMTR
- Currently this is the most reliable and well documented research performed at E>0.1MeV.

7

Fujiwara Data
("Fast Neutrons" > 0.1 MeV)



Graph is from Fujiwara, et. al. *Experimental Study of Effect of Radiation Exposure to Concrete*, SMIRT, 2009

Alexander data are for E > 0.4 eV. When rescaled to E > 0.1 MeV, they are expected to move well to the left.

8

Radiation Exposure

- Determine the neutron and gamma exposure in the reactor cavity concrete for eighty years of operation (Note 1).
- For fluence consider energy at > 0.1 MeV (Note 2).
- Determine rate of attenuation of fluence into concrete.
- Define effect of gamma heating.

Note 1: A 92% capacity factor is considered, resulting in 80 yrs x 0.92 CF = 73.6 EFPY equivalent

Note 2: Energy >1 MeV has been used to assess damage to the steel of the RPV. A value of >0.1 MeV is commonly used for assessing concrete.

LPI

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Radiation Exposure

- Concrete fluence derived as the fluence at the OD of the RPV (i.e. thickness of the RPV – i.e. 1T).
- Fluence value at the RPV ID (i.e. "0T" value) derived from licensee reports to NRC for reported values of EFPY, scaled to 73.6 EFPY
- RPV fluence values reported are for > 1.0 MeV energy.

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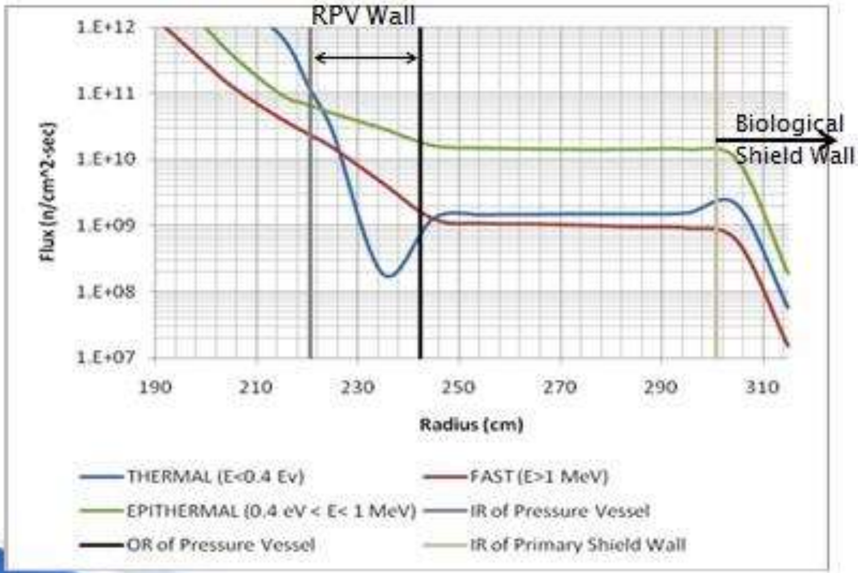
Typical Neutron Flux Curve

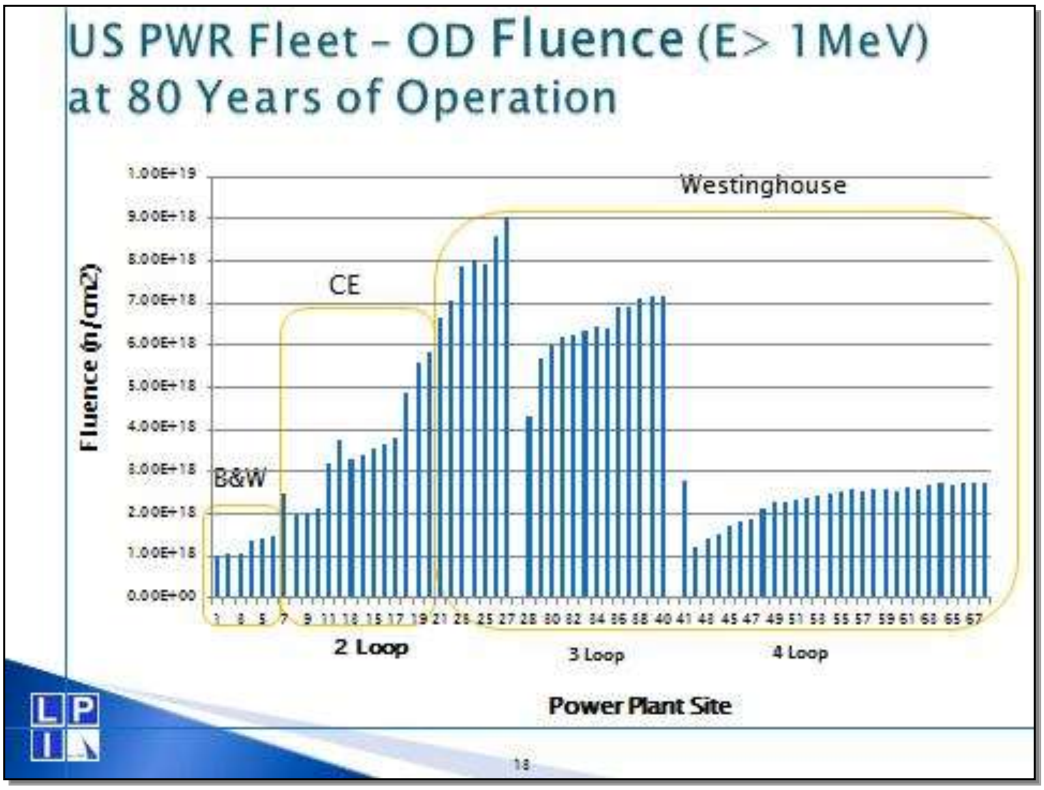


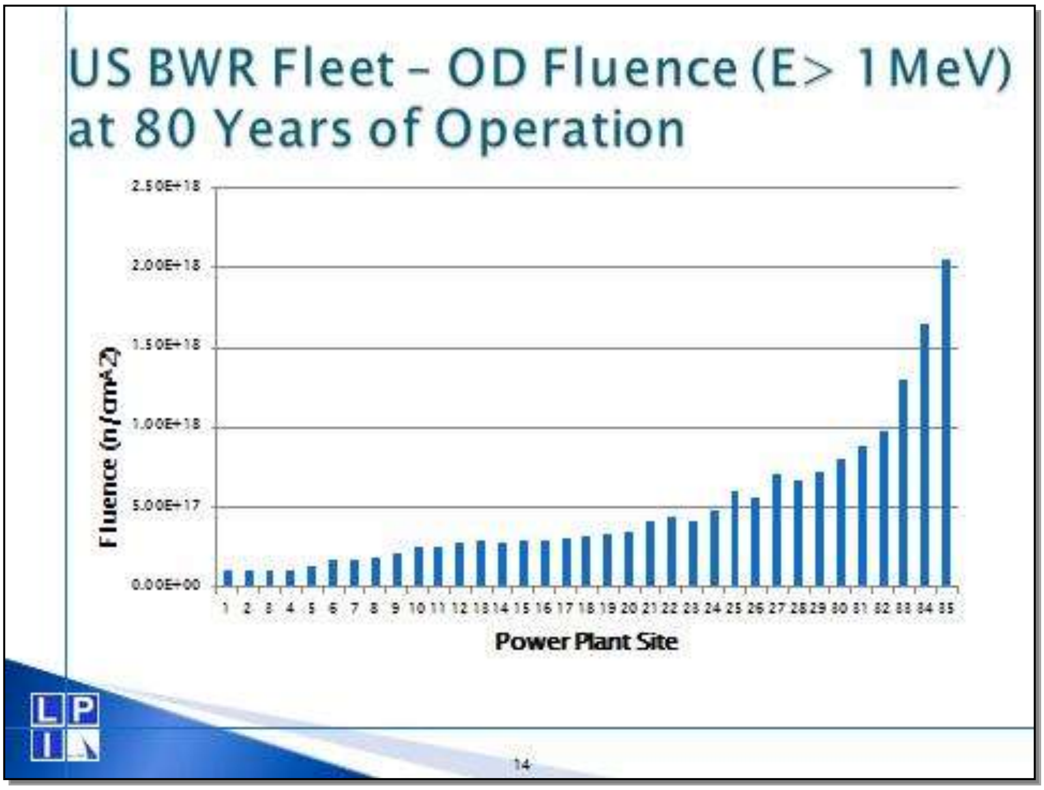
Attenuation

- Attenuation through RPV wall based on exponential fluence attenuation equations.
- US Nuclear Regulatory Commission Regulatory Guide 1.99 provides a basis for determining RPV OD fluence, but it is based on "dpa attenuation" to account for changes in vessel steel.
- Prior to the "dpa attenuation", the following relationship was used by the US NRC to determine neutron fluence (f_{OD}) at outside surface of the RPV (RPV thickness = t):

$$f_{OD} = f_{ID} \times e^{-0.33t}$$

12


US PWR Fleet – OD Fluence (E> 1MeV)
at 80 Years of Operation
Fluence (n/cm2)
Westinghouse
CE
B&W
2 Loop
3 Loop
4 Loop
Power Plant Site
13


US BWR Fleet – OD Fluence (E> 1MeV)
at 80 Years of Operation
Fluence (n/cm^2)
Power Plant Site
14

Neutron Fluence Summary

- A two loop plant has the highest 80 year RPV OD fluence of 9.0 E+18 at E > 1MeV.
- Fluence at > 0.1 MeV is higher than at > 1 MeV. The ratio depends on RPV wall thickness – two loop plant vessel wall thickness is 6.5 inches (16.7 cm).
- Fluence calculations provide a ">0.1 MeV to > 1 MeV ratio" of 8.5 for this vessel thickness.
- Fluence at RPV OD is then 7.6E+19 for E > 0.1 MeV.
- The fluence at the concrete ID is somewhat lower due to an increase in impacted surface area due to gap between vessel OD and concrete. Reduction will be approximately 10%.
- The fluence (E > 0.1 MeV) at the concrete ID will be 6.9 E+19 for 80 years of operation.

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Neutron Fluence Summary

- The highest three loop plant has an RPV OD fluence of 7.1E+18 at E > 1MeV.
- This plant has a RPV thickness of 7.75 inches (19.7 cm).
- Fluence calculations provided a ">0.1 MeV to > 1 MeV ratio" of approximately 9.5 for this vessel thickness.
- Fluence at RPV OD is then 6.7E+19 for E > 0.1 MeV.
- With the 10% reduction for the area difference, the fluence at the concrete ID will be 6.1 E+19 for 80 years of operation.
- A value of 7 E+19 n/cm^2 for 80 years appears to conservatively bound the US fleet for E > 0.1 MeV.

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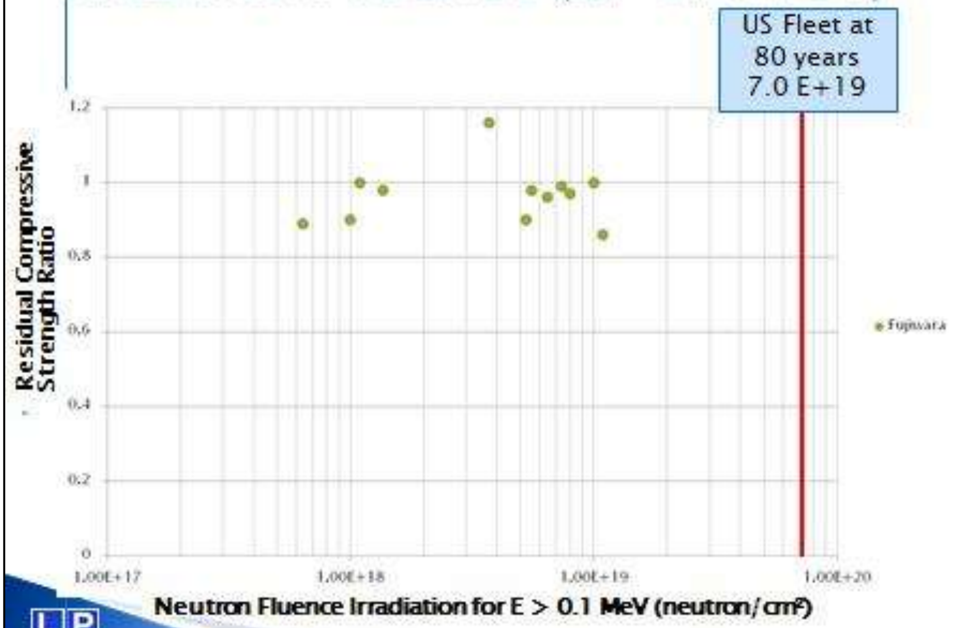
Neutron Fluence (E>0.1MeV)



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Shield Wall Requirements

- The biological shield wall concrete provides shielding, transfers load to the rebar, and reacts normal and accident loads from the RPV support.
- The fluence (E > 0.1 MeV) attenuates in the concrete.
  - In many plants, the major structural rebar is well below the surface of the concrete.
  - Reactor vessel supports are typically above the top of the core and out of the zone of maximum fluence.
  - The critical regions of the shield wall are not in the highest fluence regions of the concrete.
- Fluence at critical locations less than the maximum location.

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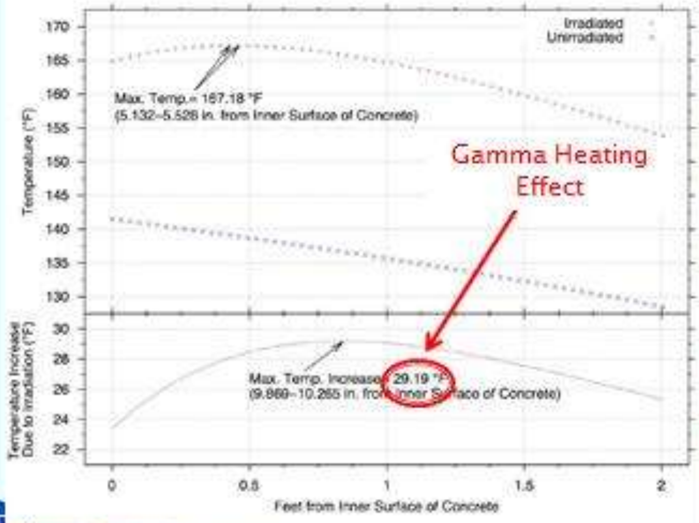
Gamma Heating Evaluation



If inner cavity wall assumed to be 150F (66C), the peak temperature in the concrete is 167F (75C) 5 inches (13 cm) below the surface.

Maximum temperature increase due to gamma heating approximately 30F (17C).

19

Temperature Effects

- Based on 150F (66C) cavity temperature (based on forced cooling of the cavity), the cavity concrete temperature is expected to be below 180F (82C).
- This is within American Concrete Institute code and US Plant FSAR requirements.

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Strategy to Augment Knowledge

- Improved knowledge of the performance of irradiated concrete would be helpful to support the long term operation of nuclear plants around the world.
- Testing is ongoing or is planned for radiation levels up to and exceeding 6 E+19 n/cm2 (E > 0.1 MeV).
- This testing will be useful to augment existing knowledge.

21

Conclusions

- There is no indication that concrete will not be adequate to 80 years of operation
- Additional data will be useful to augment existing data on the long term effects of radiation on concrete.

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SESSION THREE

The Use of Digital Image Correlations for Detection of Degradation in Concrete Structures
Paul Bruck, Sontra Yim, James Wall

Projects Dealing with Radiation Damage of Concrete at the LVR Research Reactor
Milan Marek et al.

Use of Fiber Optic Sensors for Monitoring Loads in Post-Tensioned Tendon
Sontra Yim, Thomas Esselman, James Wall

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

The Use of Digital Image Correlation (DIC) for Degradation Detection and Trending in Concrete Containment Structures

September 18, 2013

Sontra Yim, Tom Esselman,
Paul Bruck, Brian Hohmann (Lucius Pitkin, Inc.)
James Wall (Electric Power Research Institute)

Lucius Pitkin, Inc.
Consulting Engineers

1

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Introduction

- Motivation
- What is Digital Image Correlation (DIC)
- DIC technique
- Case study at Pilot Nuclear Plant
- Results
- Conclusions
- Questions

2

Motivation

- Nuclear Power Plant Extended Life Operation (Beyond 40 Years)
- Concrete Containment Structure Vital Part of Nuclear Power Plant
  - Withstand P&T of DBA w/o exceeding leak rate
  - Missile Shield and Fission Product Barrier
- Augment Existing Inspections and Testing
  - Effective Condition Assessment Requires Knowledge of Design and Expected Degradation
- Detect, Track and Trend Degradation
  - Obtain quantitative and repeatable data on the performance of the containment structure.
- Structural Integrity Test
  - Accurately measure behavior of the concrete surface during the SIT
  - Data can be taken again at the next SIT to confirm that the structural behavior of the containment has not changed.

3

What is DIC?

- Digital Image Correlation (DIC) is an optical method that employs pattern matching and image registration techniques for accurate two- and three-dimensional measurements
- System defines unique correlation areas, known as ***facets*** (typically 5-20 square pixels in size)
- Image correlation software tracks facets from successive images with **sub-pixel accuracy**

100	100	0	100	100
100	100	0	100	100
0	0	0	0	0
100	100	0	100	100
100	100	0	100	100

Time t

100	100	100	0	100
0	0	0	0	0
100	100	100	0	100
100	100	100	0	100
100	100	100	0	100

Time t'

4

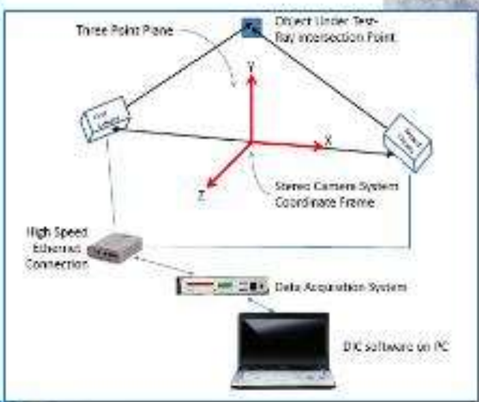
What is DIC?

- Sensitivity with 3D DIC is **1/30,000** the field of view
- Used to Measure
  - Changes in Shape
  - Deformation
  - Displacement
  - Strain
- Data can be taken for static or dynamic tests
- Common Example of DIC?
  - The Optical Mouse

5

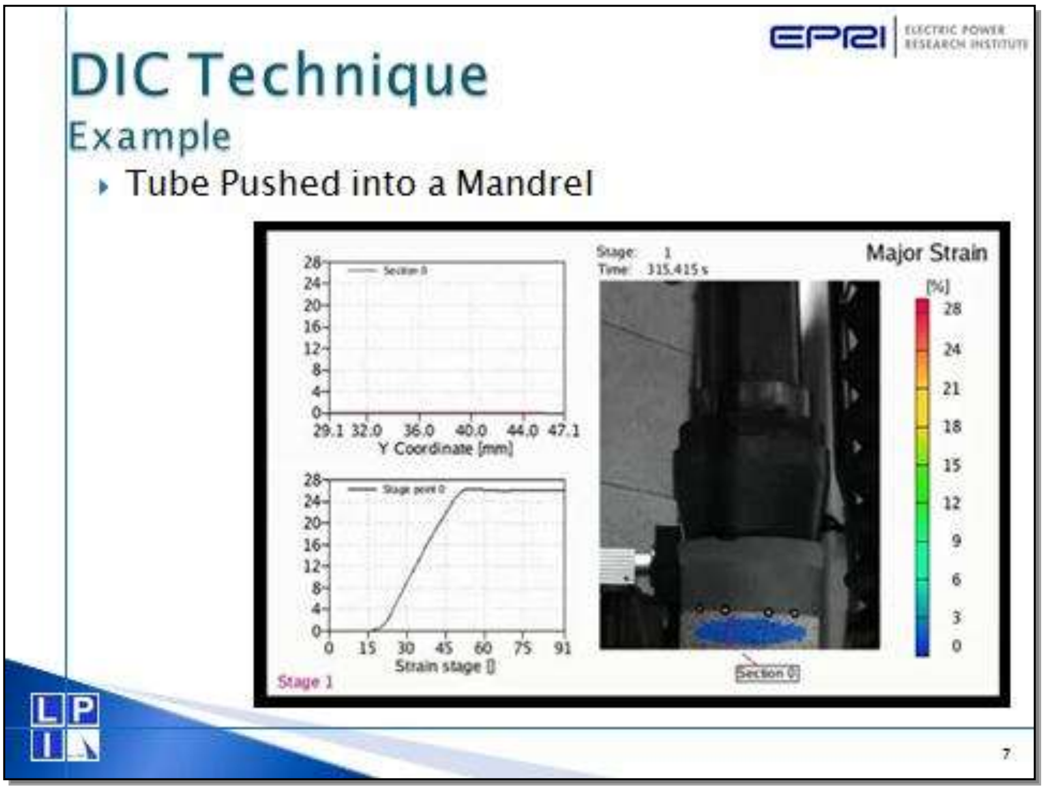
DIC Technique

3D Technique Overview



- Apply Non-repetitive Isotropic High-contrast pattern to object under test
- Set up 2 camera system – 3D vision
- Calibrate Camera System
- Data Acquisition system collects data
- DIC software interprets data

6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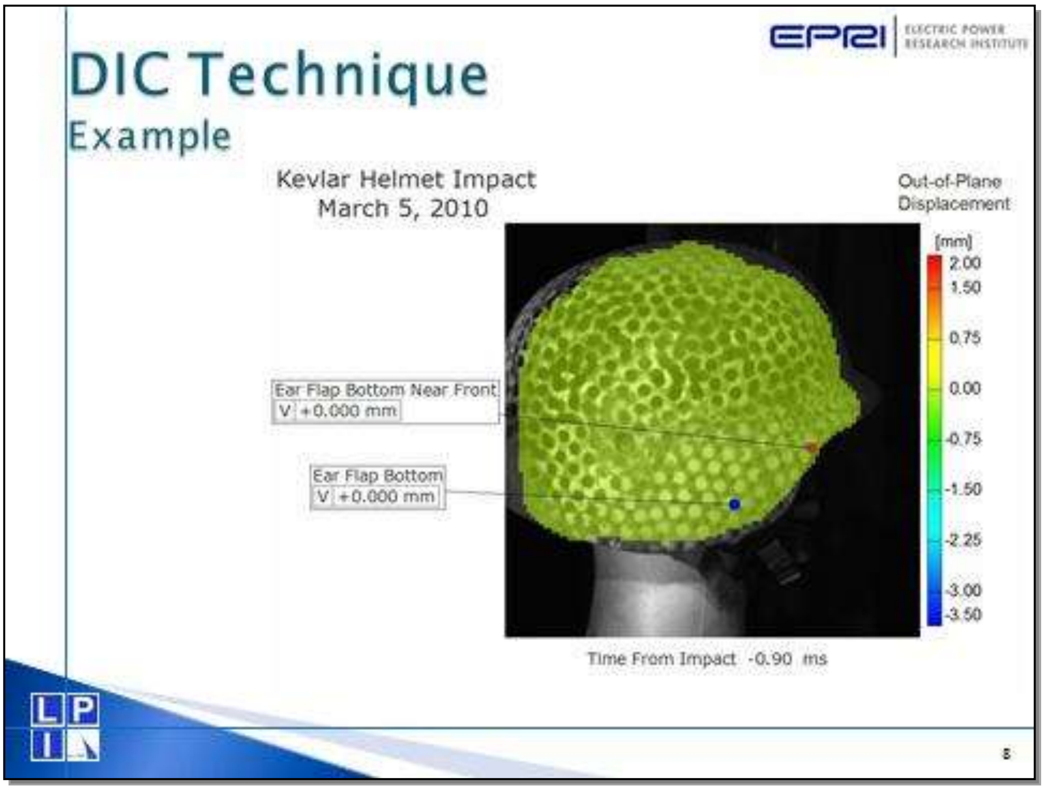
DIC Technique
Example
Tube Pushed into a Mandrel
Stage: 1
Time: 315.415 s
Major Strain
[%]
28
24
21
18
15
12
9
6
3
0
Y Coordinate [mm]
Strain stage []
Stage 1
Section 0
7


EPRI
ELECTRIC POWER RESEARCH INSTITUTE
DIC Technique
Example
Kevlar Helmet Impact
March 5, 2010
Out-of-Plane Displacement
[mm]
2.00
1.50
0.75
0.00
-0.75
-1.50
-2.25
-3.00
-3.50
Ear Flap Bottom Near Front
V +0.000 mm
Ear Flap Bottom
V +0.000 mm
Time From Impact -0.90 ms
8

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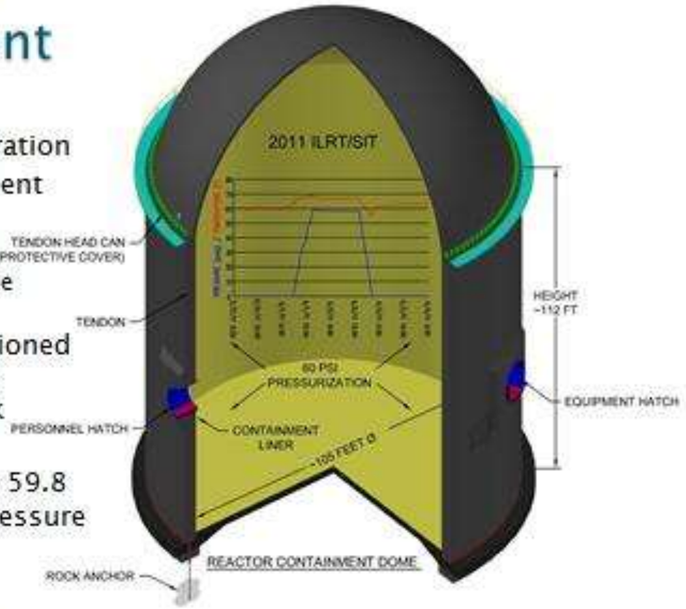
Pilot Plant Containment

- 2 Loop PWR
- >40 years of operation
- Vertical containment cylinder
  - 112ft (34m) high
  - 105 ft (32m) inside diameter
- Axially post-tensioned with 160 tendons connected to rock anchors
- SIT performed to 59.8 psi (0.41 MPa) pressure



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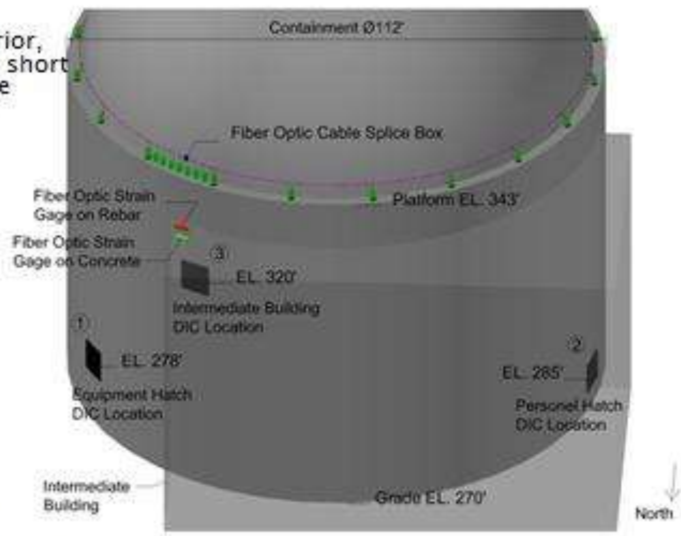
Pilot Plant

DIC Test Setup

- DIC at Three locations
  - Monitored just prior, during, and for a short time following the pressurization of containment
- Monuments affixed for future comparison



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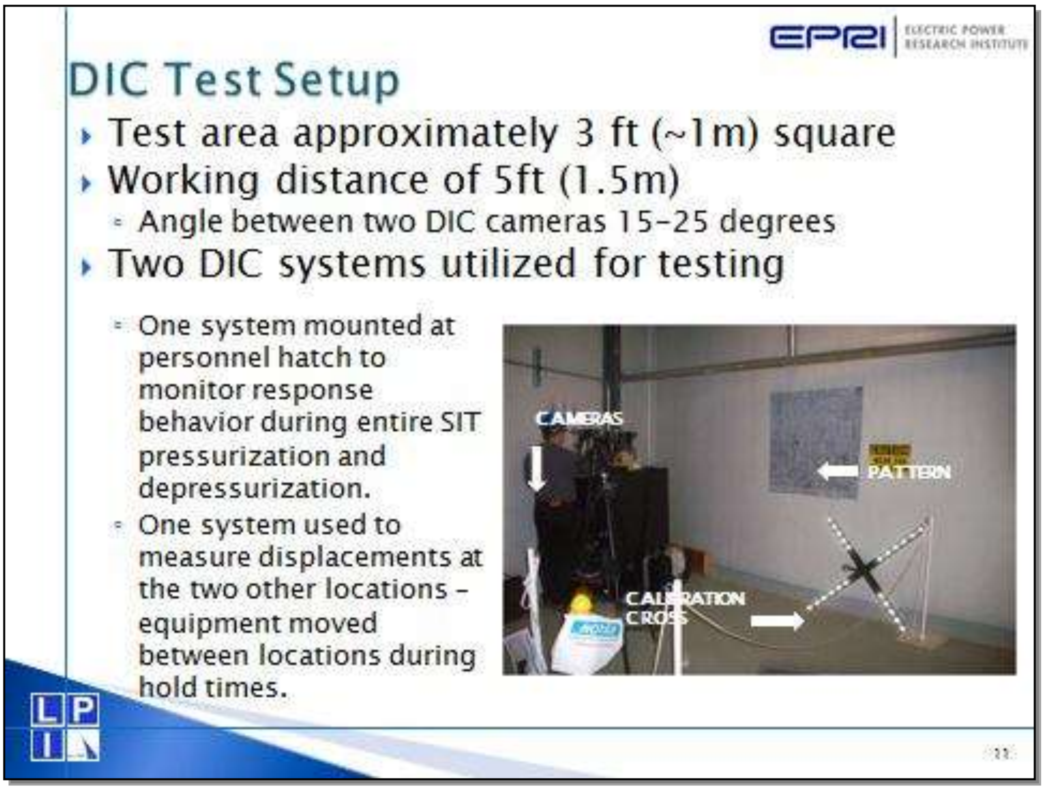
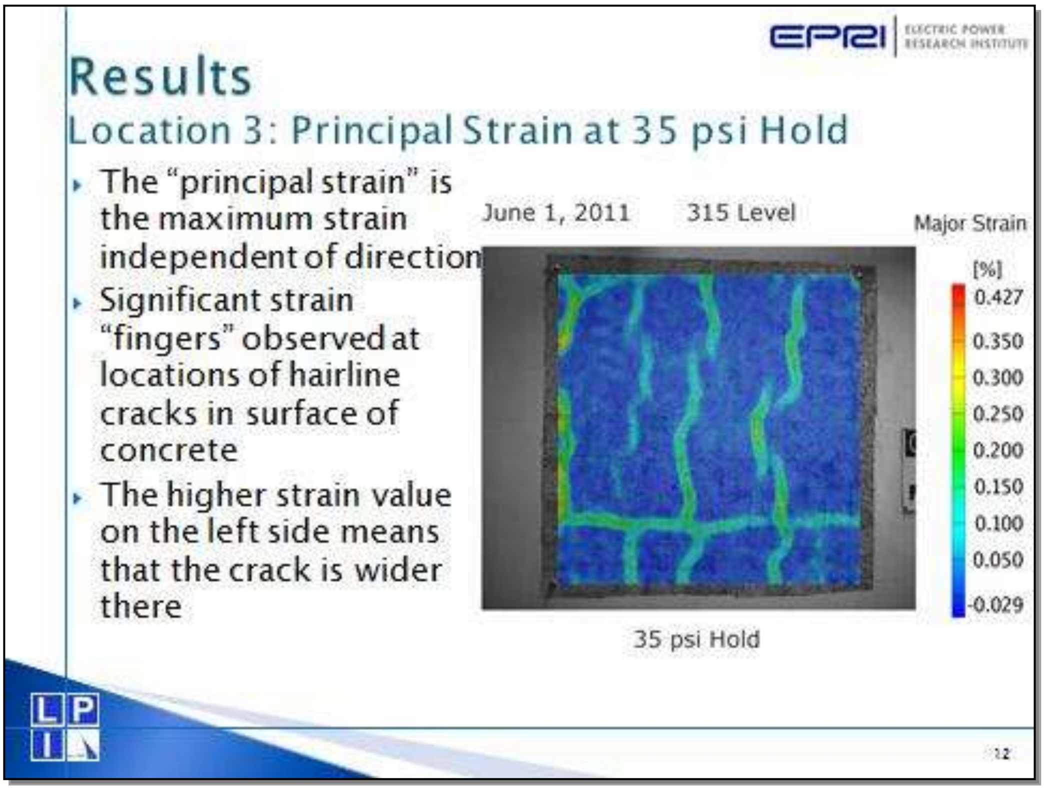
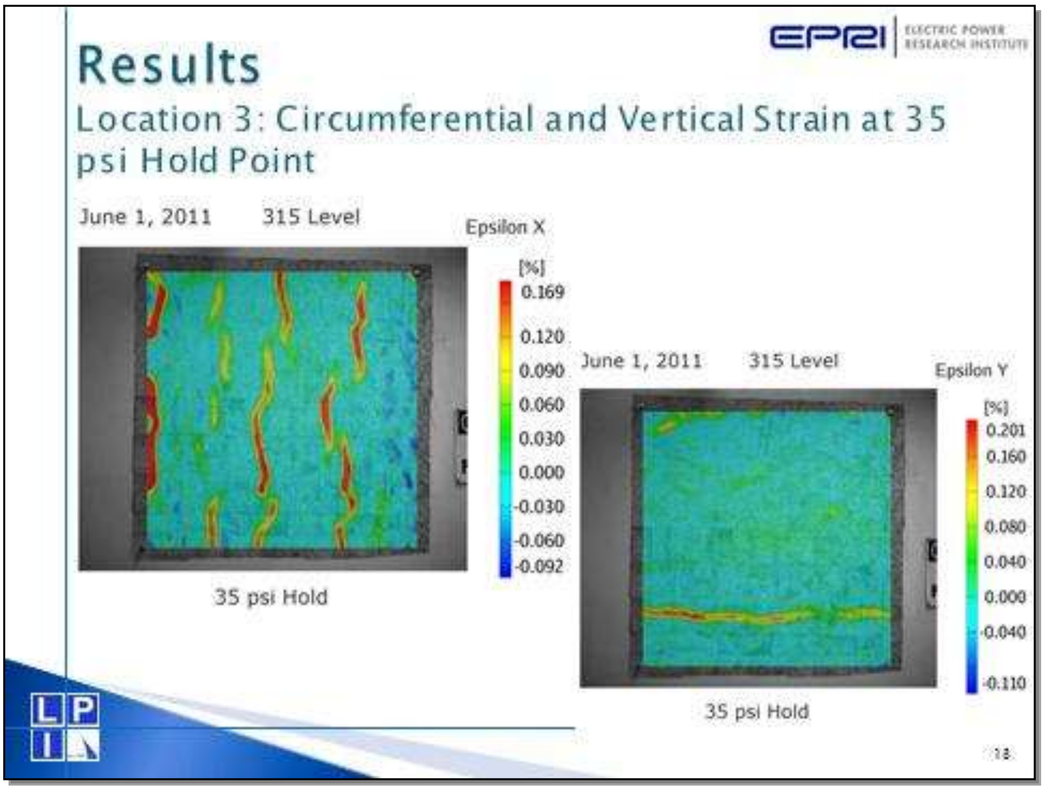
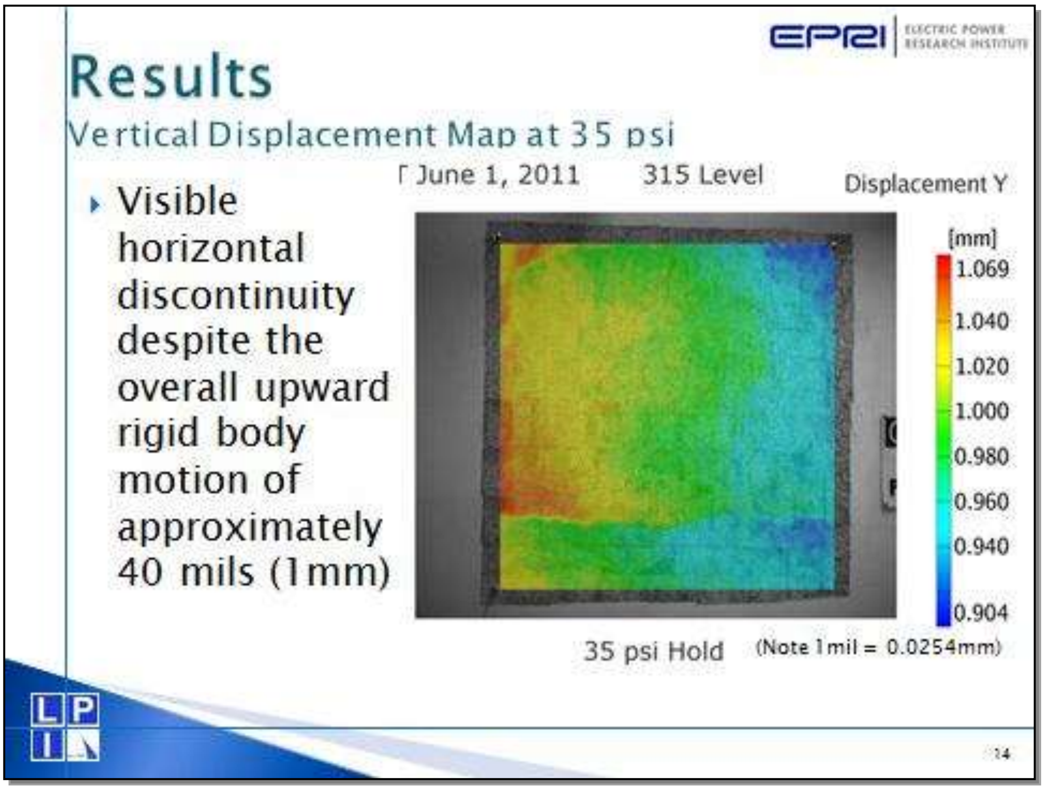

EPRI ELECTRIC POWER RESEARCH INSTITUTE
DIC Test Setup
Test area approximately 3 ft (~1m) square
Working distance of 5ft (1.5m)
Angle between two DIC cameras 15-25 degrees
Two DIC systems utilized for testing
One system mounted at personnel hatch to monitor response behavior during entire SIT pressurization and depressurization.
One system used to measure displacements at the two other locations – equipment moved between locations during hold times.
CAMERAS
PATTERN
11


EPRI ELECTRIC POWER RESEARCH INSTITUTE
Results
Location 3: Principal Strain at 35 psi Hold
The "principal strain" is the maximum strain independent of direction
Significant strain "fingers" observed at locations of hairline cracks in surface of concrete
The higher strain value on the left side means that the crack is wider there
June 1, 2011
315 Level
Major Strain
[%]
0.427
0.350
0.300
0.250
0.200
0.150
0.100
0.050
-0.029
35 psi Hold
12

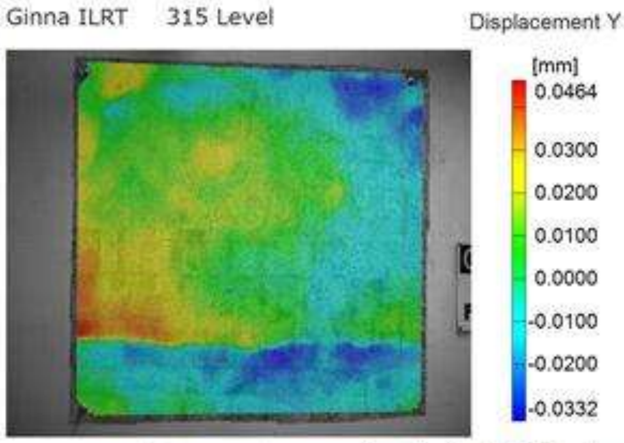

Results
Location 3: Circumferential and Vertical Strain at 35 psi Hold Point
June 1, 2011
315 Level
Epsilon X
[%]
0.169
0.120
0.090
0.060
0.030
0.000
-0.030
-0.060
-0.092
35 psi Hold
June 1, 2011
315 Level
Epsilon Y
[%]
0.201
0.160
0.120
0.080
0.040
0.000
-0.040
-0.110
35 psi Hold
13


Results
Vertical Displacement Map at 35 psi
Visible horizontal discontinuity despite the overall upward rigid body motion of approximately 40 mils (1mm)
June 1, 2011
315 Level
Displacement Y
[mm]
1.069
1.040
1.020
1.000
0.980
0.960
0.940
0.904
35 psi Hold
(Note 1mil = 0.0254mm)
14

Results

Vertical Displacement Map at 35 psi after Rigid Body Movement Correction

- Shows only the local relative displacements



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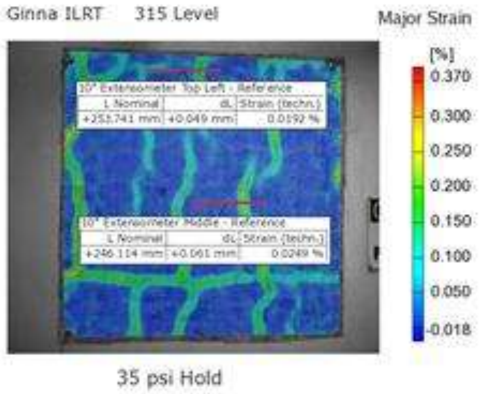
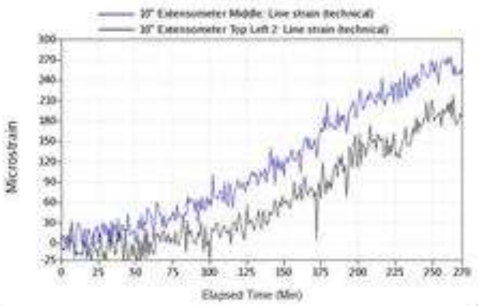
Results

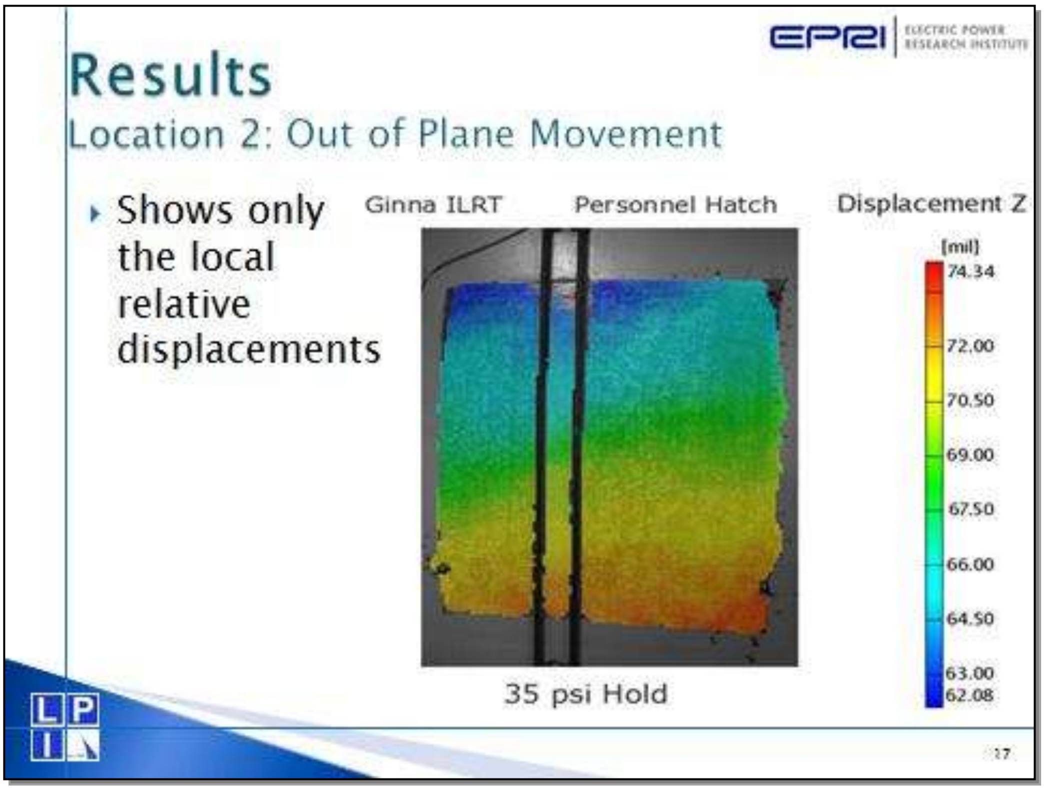
10" Long Extensometers

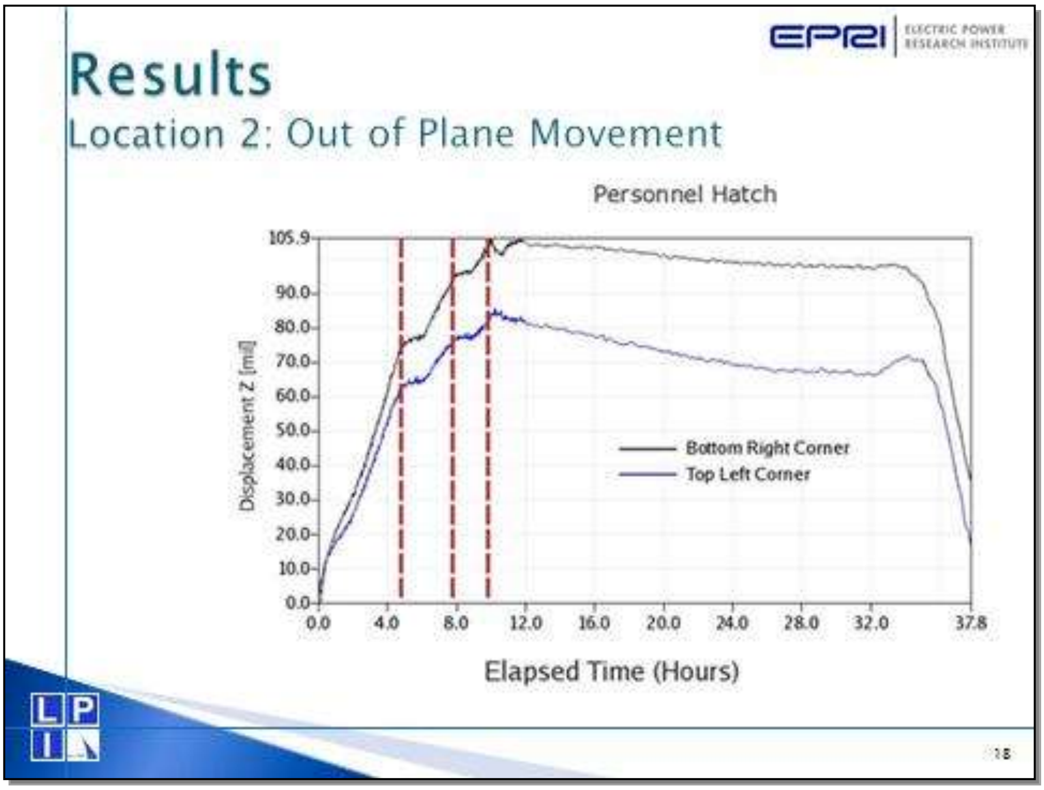
- Strain data calculated by DIC software
- "Virtual" strain gages set-up to compare with future DIC data.
- Compares well to Fiber Optic Strain Concrete Gage Near this Location ~ 190με

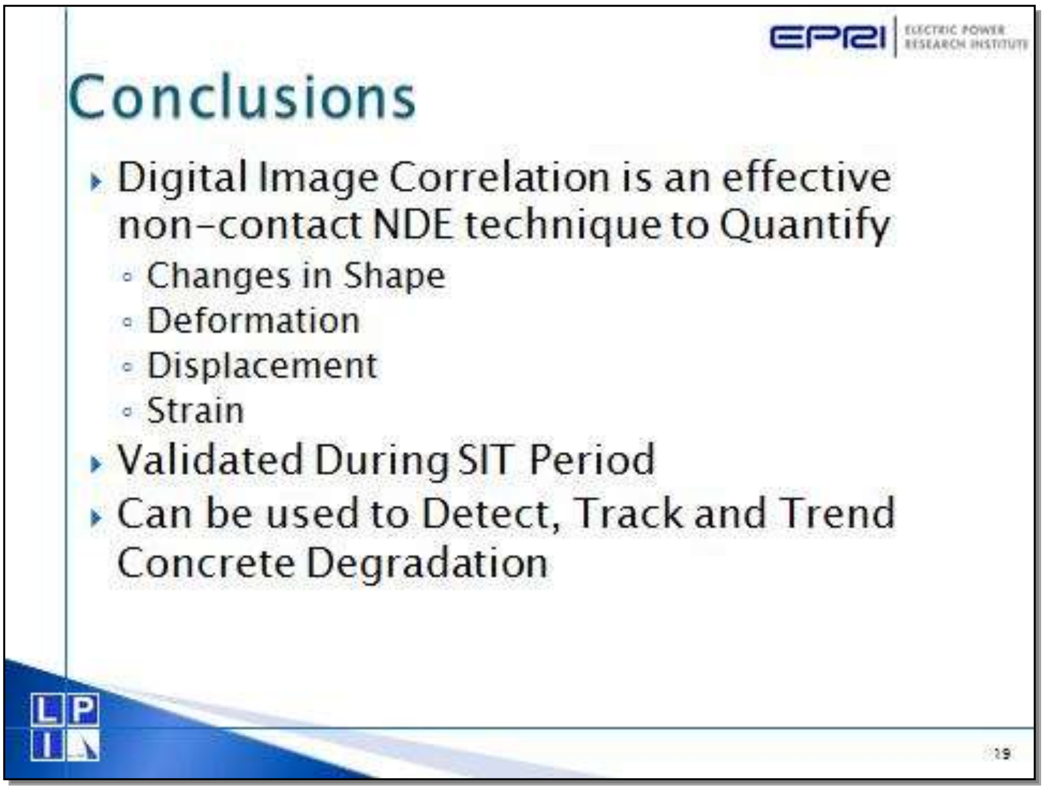




16


Results
Location 2: Out of Plane Movement
Shows only the local relative displacements
Ginna ILRT
Personnel Hatch
Displacement Z
[mil]
74.34
72.00
70.50
69.00
67.50
66.00
64.50
63.00
62.08
35 psi Hold
17


Results
Location 2: Out of Plane Movement
Personnel Hatch
Displacement Z [mil]
105.9
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
37.8
Elapsed Time (Hours)
Bottom Right Corner
Top Left Corner
18


Conclusions
Digital Image Correlation is an effective non-contact NDE technique to Quantify
Changes in Shape
Deformation
Displacement
Strain
Validated During SIT Period
Can be used to Detect, Track and Trend Concrete Degradation
19


Questions
20

Centrum výzkumu Řež s.r.o.

Project Dealing with Radiation Damage of Concrete at the LVR-15 Research Reactor

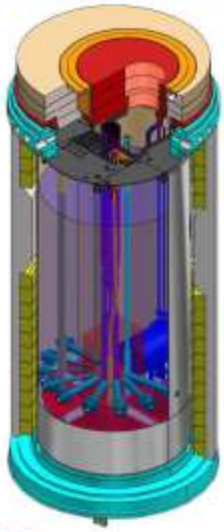
M. Marek, Z. Lahodová, M. Koleška, O. Frýbort, J. Vít,
P. Hájek Jr.,

OECD NEA Workshop „NDE of NPPs Concrete Structures", Prague, September 17-19

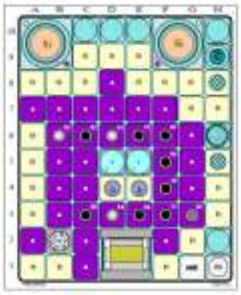
Outlines

- LVR-15 Research Reactor
- Preparation of Concrete Irradiation Project
- Mock-up
- Discussion

LVR-15 Research reactor at CV Rez



Reactor type	Tank
Pressure	Atmospheric
Average temperature	45 °C
LEU	IRT-4M 19.7% ^{235}U
Coolant	demineralized water
Reflector	beryllium
Nominal power	10 MW
Thermal flux	1.5 x 10^{18} n/m²s
Fast flux	2.5 x 10^{18} n/m²s



- **Material research**
  - Rigs - CHOUCA, Flat rigs, TW3
  - Loops - 2x BWR, 2x PWR
- **Isotope production**
  - Medical application - ^{99}Mo
  - Defektoskopy – ^{192}Ir
- **Si doping (NTD)**
  - 2 irradiation facilities- „DONA"
- **Horizontal channels – basic research**
  - BNCT Facility
  - Neutronography
  - 8 beams – neutron diffraction, scattering, neutron interactions

Material Irradiation at CV Rez

- Design of experimental facilities
  - Loops
  - Rigs – inert gas,
  - Autoclaves
- Irradiation in LVR-15 reactor
- Irradiation experiments oriented on research of material changes and influence of chemical parameters and radiation (VGB, Hitachi, MHI, TVEL,…)
- Irradiation in epithermal neutron beam - materials of storage casks - CASTOR/CONSTOR, concretes (GNB-GNS)

Material Irradiation at CV Rez

Loops
- PWR (RVS-3)
- BWR (BWR 1 and BWR 2)
- Zinc injection rig
- RVS-4 (Hydrogen / ammonia)

Special Loop Channels
- SSRT (slow strain rate testing) of PWR pre-irradiated samples
- IASCC – static / cyclic load
- 1 CT and 2 CT,
- Electrically heated fuel rods

Control of water chemistry
- system for gas dosing
- orb sphere – H2/O2 measurement
- Dionex ion - chromatograph

Irradiation Rigs
- Inert gas He, Ar
- Temperature control from 200℃ to 350℃, ±10 ℃
- CHOUCA rig - Charpy V, tensile, SSRT, 0,5 CT
- Flat Rigs – 1 CT, 2CT specimens (total irradiation volume 40x120x450mm)

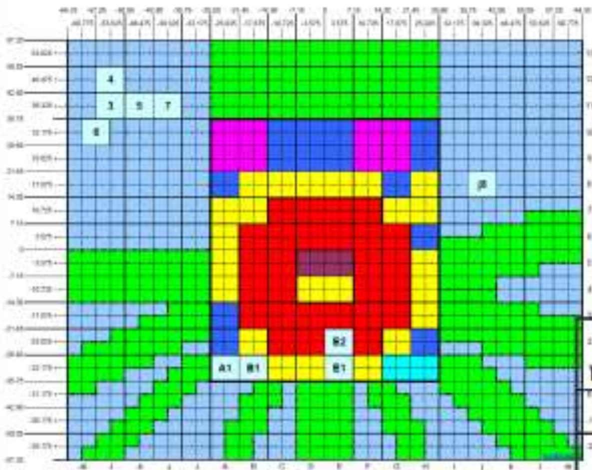
- ***Reactor dosimetry***
- Neutron monitors
- Calculations
- Mock - up experiments

Irradiation Conditions

- **We will use a 5cm diameter cylindrical sample, 10 cm long**
- **Concrete mix is still to be determined**
- **The sample will be housed in an He-filled, water cooled aluminum, casing**
- **Thermocouples will measure the sample core and surface temperatures**
- **The sample will be irradiated**
  - Neutron fluence1.5E+20 n/cm^2, E>0.1 MeV
  - The sample temperature will be bellow 90℃
- **The sample will be removed from the reactor for PIE and NDE**

- **J. Wall, Nuclear Power Council Advisory Meeting, 08/26/13 – 08/29/13**

Irradiation possibilities for concrete



Neutron spectrum in the LVR-15 reactor differs from the neutron spectrum in the concrete of PWR reactor especially the ratio of the neutron flux above 1 MeV to that above 0.1 MeV.

- Neutron fluence and gamma dose will be monitored during irradiation.
- 1.5E+20, E>0.1 MeV

Position	$\Phi_{E>0.1MeV}$ [$cm^{-2} s^{-1}$]	Irradiation time [days]	Heating [W/g]
A1	1.42E+13	122	1.6
B1	1.73E+13	100	2
E2	8.70E+13	20	3.1
E1	4.83E+13	36	2.8

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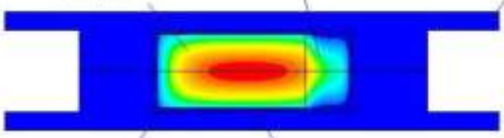
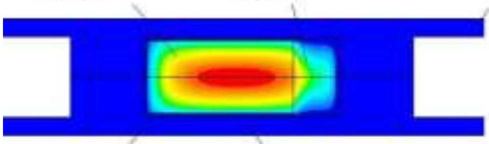
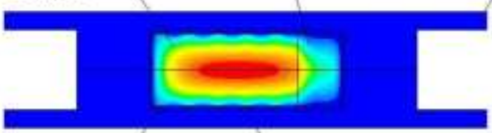
CFD Calculations for Concrete Sample Cooling

- **Models of cooling**
  - #1 – helium gap
  - #2 – full contact
  - #3 – partial contact
- **Four types of concrete –**
  - density 2.42 to 3.56 g/cm^3







7

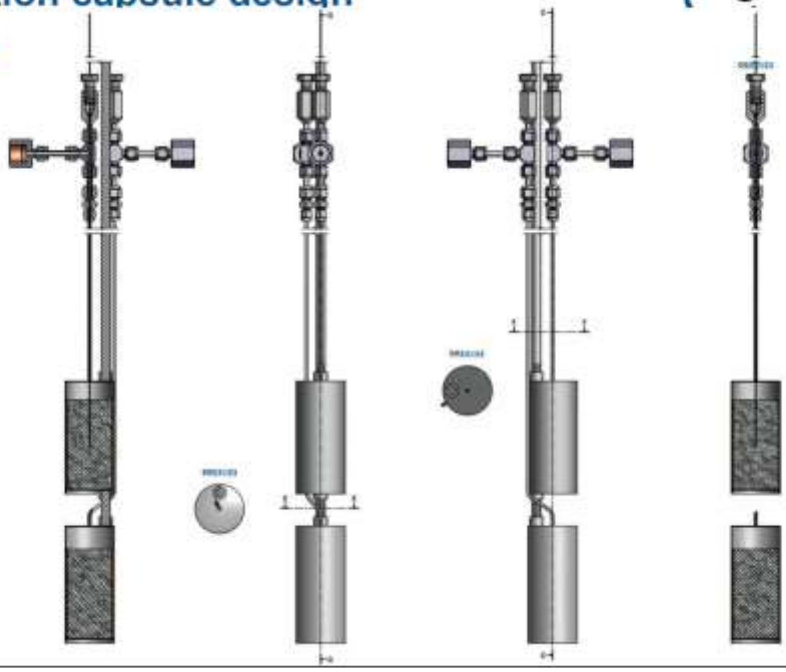
CFD Calculations for Concrete Sample Cooling

density [g/cm³]	Conductivity [W/mK] (Estimation)	Heat source [W/g]	Model #1 – helium gap	Model #2 – full contact	Model #3 – partial contact
			Max. Temperature [℃]		
3.56	1.7	0.1	91	78	80
	3.2	0.1	76	63	64
	3.2	0.2	-	-	84
2.46	1.7	0.1	76	68	69
	1.7	0.2	108	91	94
2.42	1.7	0.1	-	-	69
2.44	2.5	0.1	-	-	69
	2.5	0.2	-	-	79
	5.0	0.1	-	-	54
	5.0	0.5	-	-	89

Irradiation possibilities

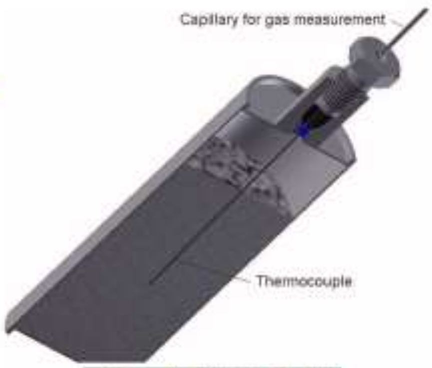
- **At present**
  - Based on contemporary knowledge of concrete parameters
    - Conductivity
  - Position out of core – in reflector area
- **Proposed action**
  - Mock-up test for irradiation - used to verify the thermal conductivity of the considered concrete and composition (impurities) of the material
  - Reactor availability
    - In 2014 – since Feb.
- **Modified irradiation arrangement**
  - Special irradiation cell with Bi shielding to decrease gamma heating in concrete
  - Irradiation time – ~100 days

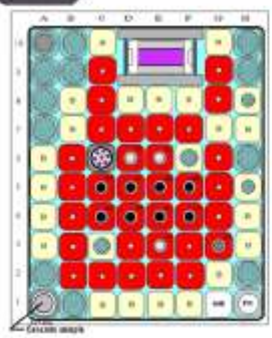
Irradiation capsule design



Mock-up experiment

- Aim:
  - Determination of thermal condition – reactor power
  - Test of gas measurement
  - Composition of the concrete – for the mock-up the Temelin type of concrete will be used.
  - Test of concrete release
- Design:
  - Simple case with thermocouple and capillary
  - Position in the core – A1
- Program
  - Temperature measurement
    - at different power levels – case in central position
    - at 10 MW – case moving up
  - Activity measurement
    - Released gas
    - Concrete sample





Discussion

- **Preparation of specimens and capsules**
  Design of the case - according to the mockup design
  Concrete will be cast in the metallic case with/without thermocouple
- **Irradiation**
  Evaluation of the mock-up and comparison of thermal conditions in the sample using gamma heating calculation
  Determination of the irradiation condition and time
  Additional gamma shielding in the irradiation channel is considered
- **Gas release**
  Gas pressure measured on-line using capillary
  Collection of gas after irradiation
- **Removal of concrete specimen from metallic case – has been tested**

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- **Thank you**

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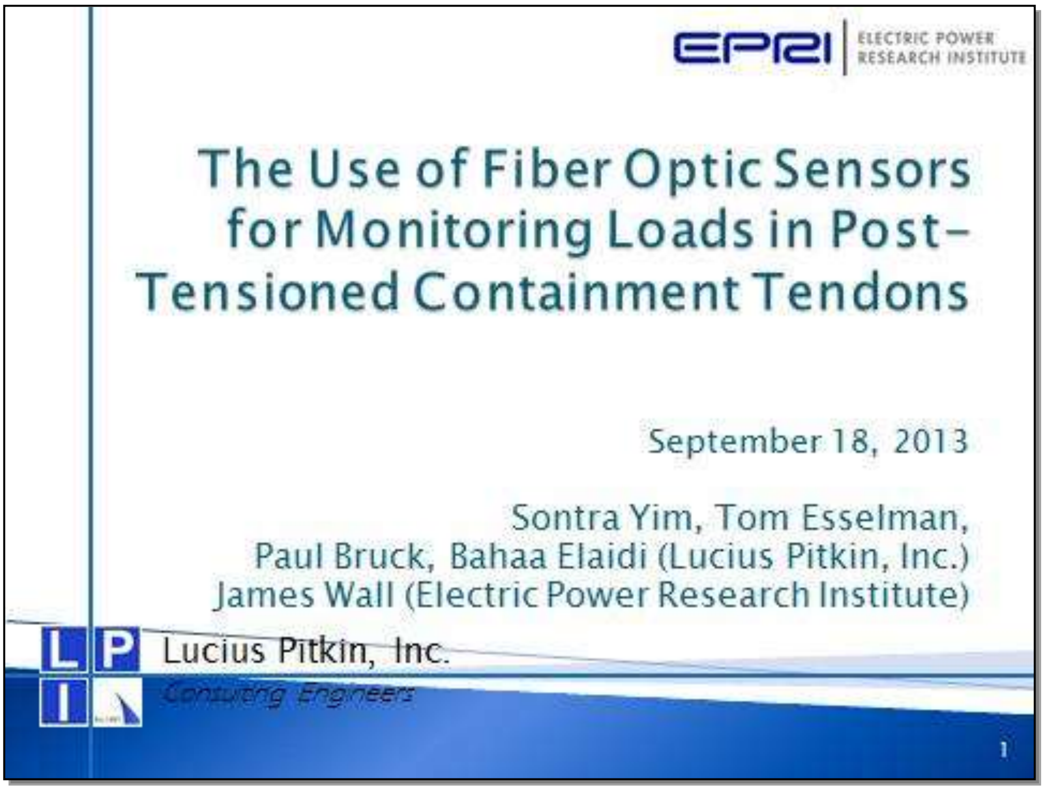
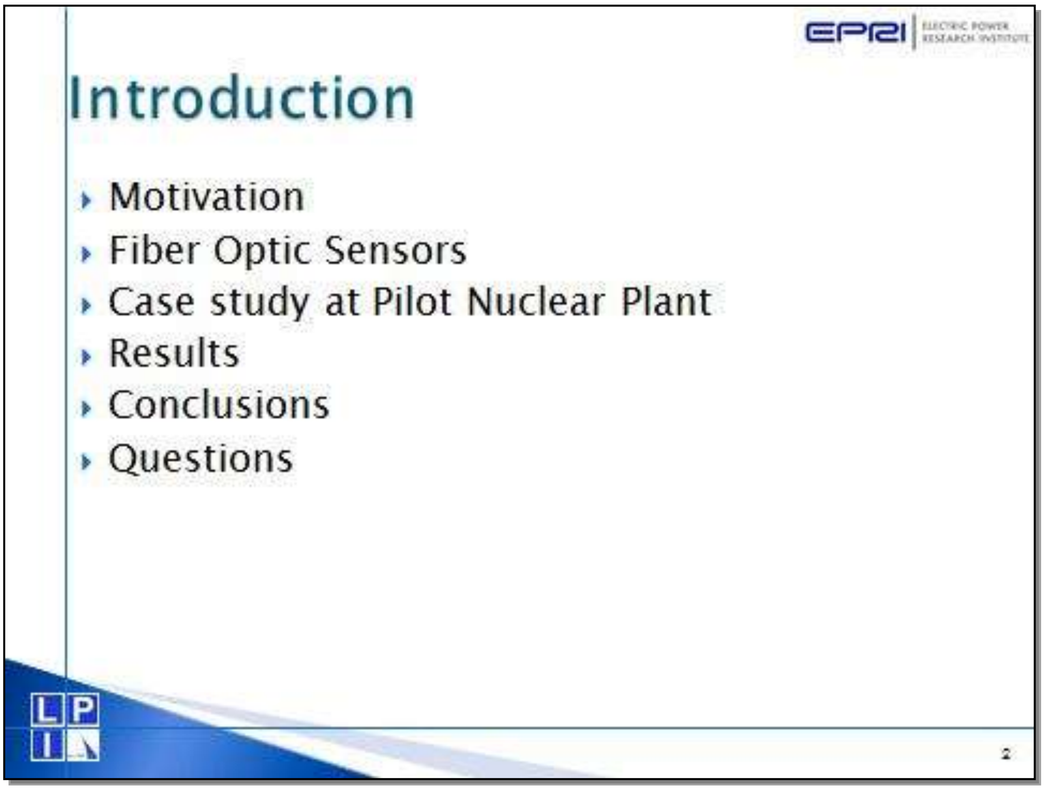
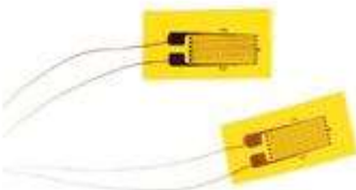

ELECTRIC POWER RESEARCH INSTITUTE
The Use of Fiber Optic Sensors for Monitoring Loads in Post-Tensioned Containment Tendons
September 18, 2013
Sontra Yim, Tom Esselman,
Paul Bruck, Bahaa Elaidi (Lucius Pitkin, Inc.)
James Wall (Electric Power Research Institute)
Lucius Pitkin, Inc.
Consulting Engineers
1


Introduction
Motivation
Fiber Optic Sensors
Case study at Pilot Nuclear Plant
Results
Conclusions
Questions
2

Motivation

- Nuclear Power Plant Extended Life Operation (Beyond 40 Years)
- Augment Existing Inspections and Testing
  - Effective Condition Assessment Requires Knowledge of Design and Expected Degradation
  - Concrete - Good in Compression; Poor in Tension
- Post-Tensioned Tendons Verified by Lift Off Testing
  - Costly, time and labor intensive, requires special equipment. Load 700,000 lb (~3,114kN)
- Potentially Alleviate Need to Perform Lift-Off Testing
- Robust Real-Time Monitoring
  - Via Foil Based Load Cells - Not Robust
  - Electrical sensors susceptible to transmission loss and EMI (noise)
- Detect, Track and Trend Degradation
  - Detect Wire Break, Relaxation, Loss of Anchor



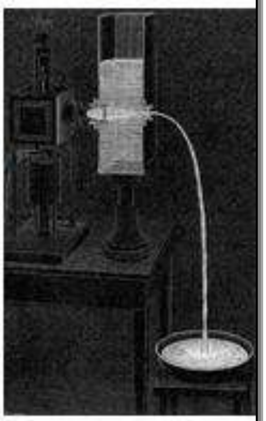
3

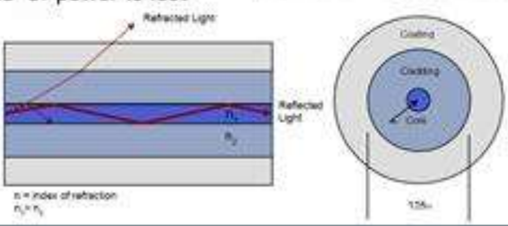
Fiber Optic Sensors

- Fiber Optics
  - Fairly simple, and relatively old technology
  - Principle that makes fiber optics possible, was first demonstrated by Daniel Colladon and Jacques Babinet in Paris in the early 1840s
  - Core - Transmits light; Cladding - reflects light; Coating - Protects

Why Fiber Optic Sensors?

- Immunity to EMI and not susceptible to cabling-induced noise
- Totally passive (no resistive heating) and requires no power at the sensor
- Long cable runs up to 31 miles (50km) are possible
- Resistant to corrosion, chemicals, lighting
- Ability to multiplex, Sensors measuring different physical parameters can be put on the same fiber
- No loss of calibration when disconnected or power is lost

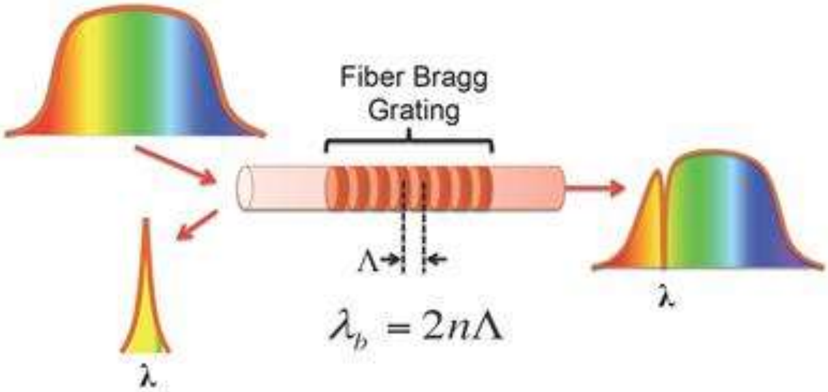




4

Fiber Optic Sensors

- Fiber Bragg Grating (FBG) Sensor
  - Most Widely Used
  - Input Spectrum, FBG Reflects Specific Wavelength
  - FBG Wavelength is Dependent on Grating Spacing

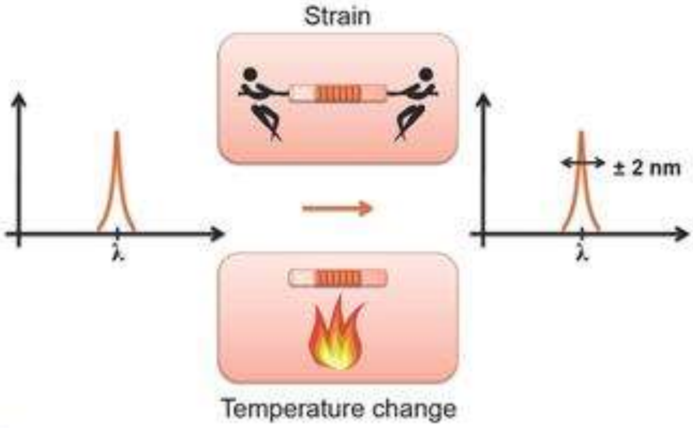


$$\lambda_b = 2n\Lambda$$

5

Fiber Optic Sensors

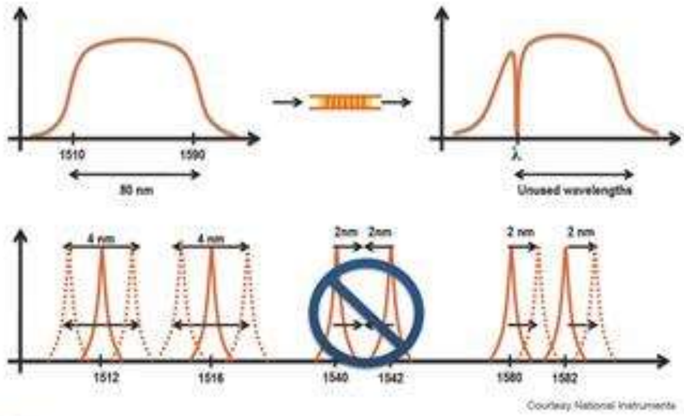
- Wavelength Shift with Physical Parameter
  - Perform a direct transformation of the sensed parameter to optical wavelength, independent of light levels, connector or fiber losses, or other FBGs at different wavelengths



6

Fiber Optic Sensors

- Wavelength Division and Multiplexing
  - Ability to daisy chain multiple sensors with different Bragg wavelengths along a single fiber over long distances
  - Allows ability to measure multiple parameters along a single fiber

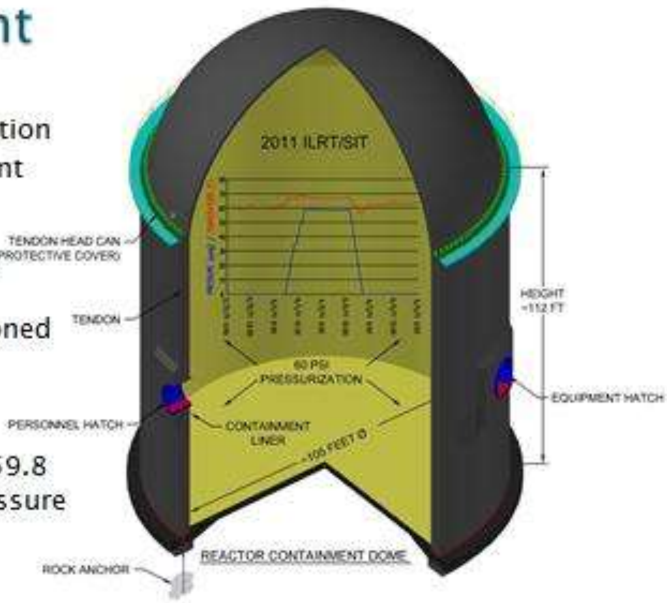


Courtesy National Instruments

7

Pilot Plant Containment

- 2 Loop PWR
- >40 years of operation
- Vertical containment cylinder
  - 112ft (34m) high
  - 105 ft (32m) inside diameter
- Axially post-tensioned with 160 tendons connected to rock anchors
- SIT performed to 59.8 psi (0.41 MPa) pressure

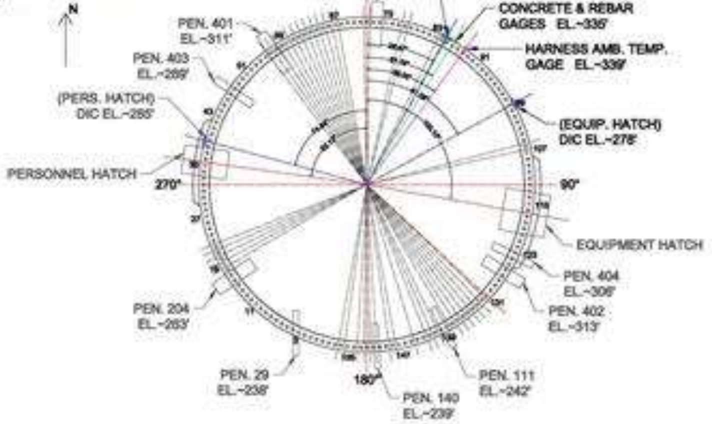


8

Pilot Plant

Monitored Tendons

- Selected 20 of 160 Tendons
  - Statistically sufficient confidence (98.5%) in the condition of all 160 tendons (as compared to the current inspection program of randomly testing 14 tendons every 5 years) is achieved.

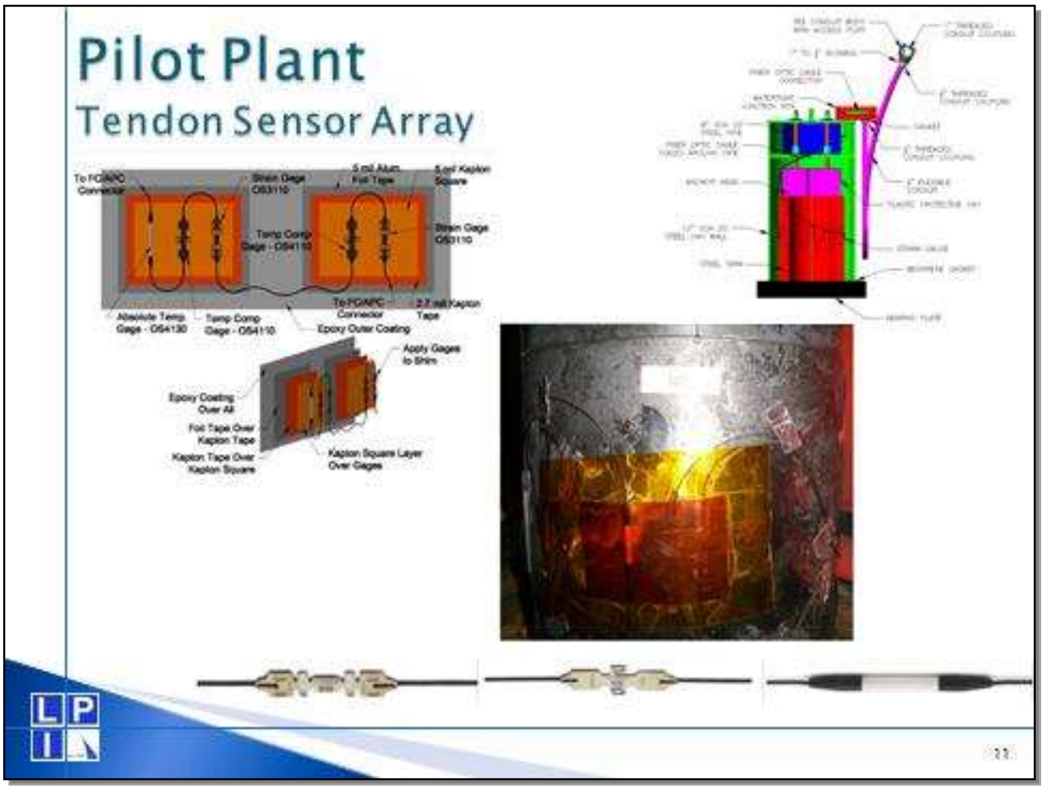


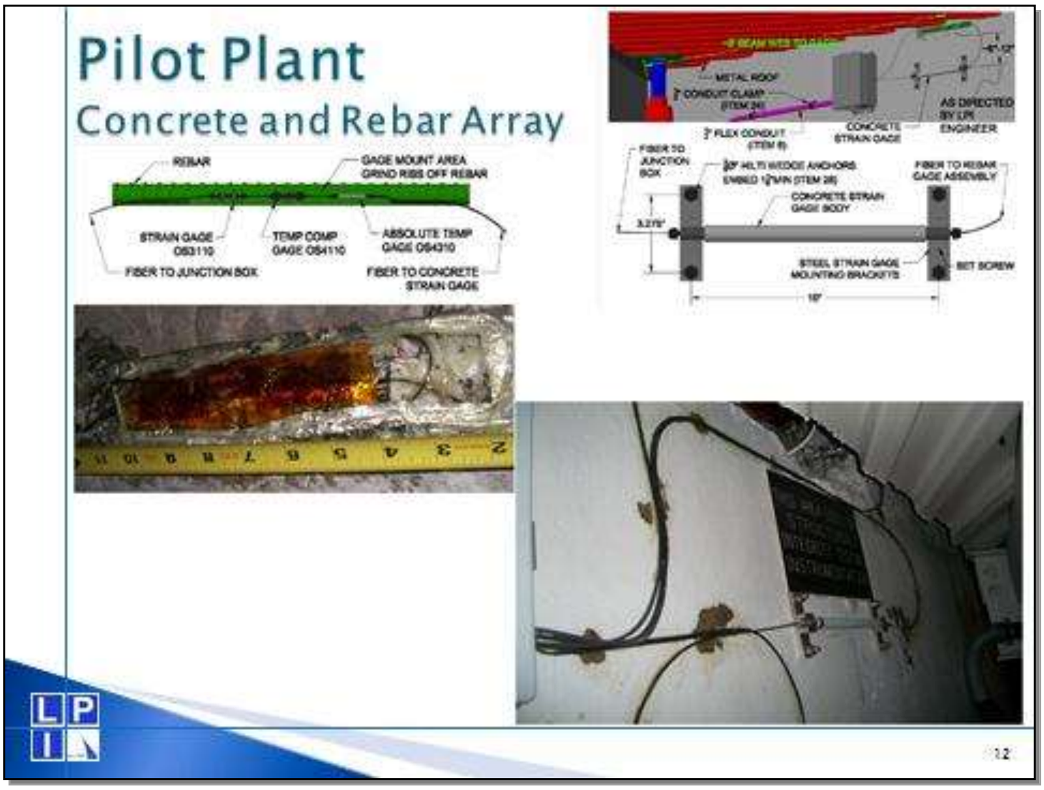
9

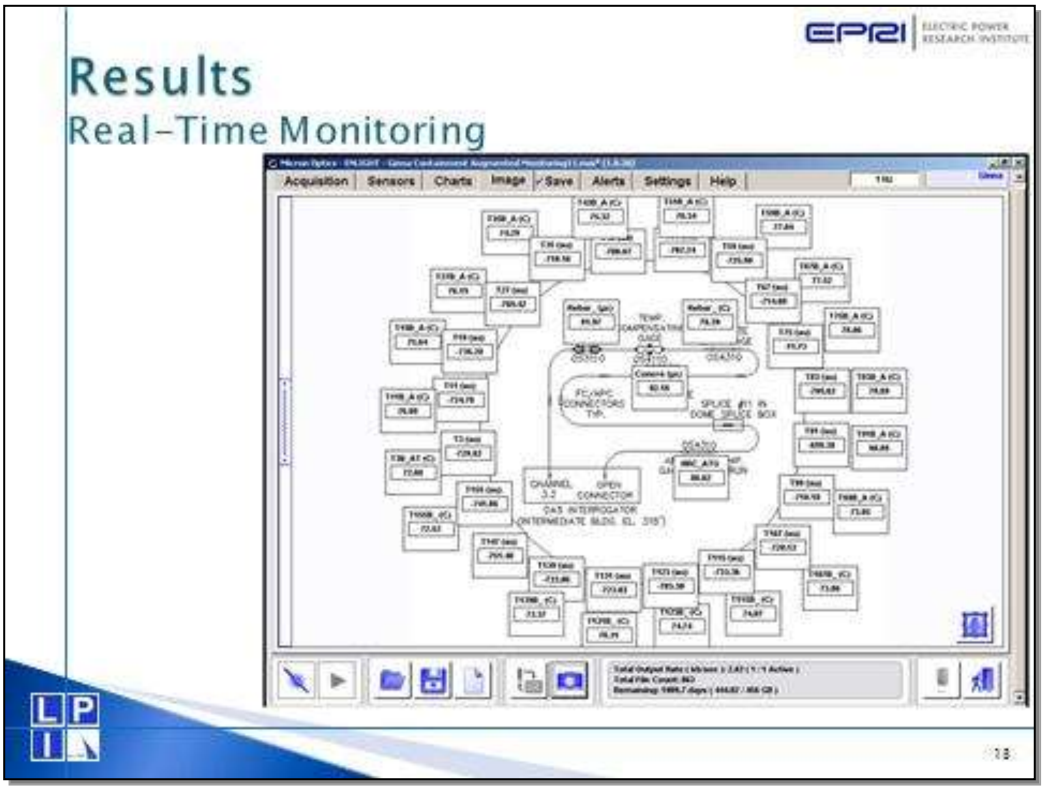
Pilot Plant

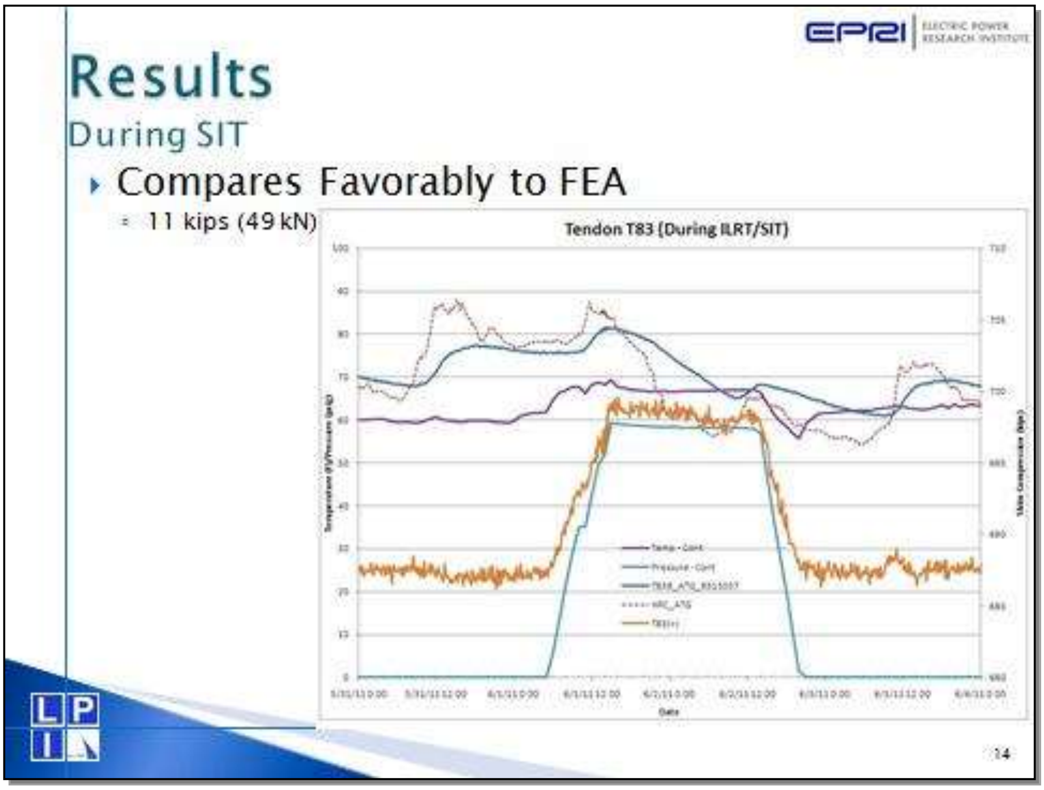
Tendon Anchor Head Design

10


Pilot Plant
Tendon Sensor Array
To FC/APC Connector
Strain Gage OS3110
5 mil Alum. Foil Tape
5 mil Kapton Square
Temp Comp Gage - OS4110
Strain Gage OS3110
Absolute Temp Gage - OS4130
Temp Comp Gage - OS4110
To FC/APC Connector
2.7 mil Kapton Tape
Epoxy Outer Coating
Apply Gages to Shim
Epoxy Coating Over All
Foil Tape Over Kapton Tape
Kapton Tape Over Kapton Square
Kapton Square Layer Over Gages
11


Pilot Plant
Concrete and Rebar Array
REBAR
GAGE MOUNT AREA GRIND RIBS OFF REBAR
STRAIN GAGE OS3110
TEMP COMP GAGE OS4110
ABSOLUTE TEMP GAGE OS4310
FIBER TO JUNCTION BOX
FIBER TO CONCRETE STRAIN GAGE
METAL ROOF
CONCRETE STRAIN GAGE
AS DIRECTED BY LPI ENGINEER
FIBER TO JUNCTION BOX
FIBER TO REBAR GAGE ASSEMBLY
CONCRETE STRAIN GAGE BODY
STEEL STRAIN GAGE MOUNTING BRACKETS
SET SCREW
12

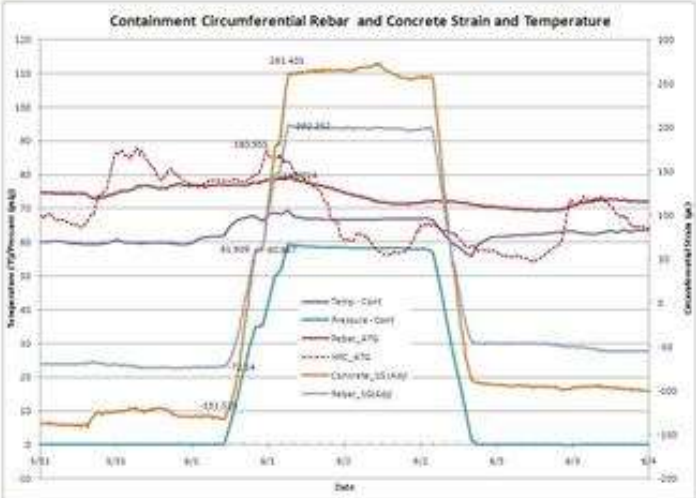

EPRI ELECTRIC POWER RESEARCH INSTITUTE
Results
Real-Time Monitoring
Acquisition
Sensors
Charts
Image
Save
Alerts
Settings
Help
LPI
13


EPRI ELECTRIC POWER RESEARCH INSTITUTE
Results
During SIT
Compares Favorably to FEA
11 kips (49 kN)
Tendon T83 (During ILRT/SIT)
Date
LPI
14

Results

During SIT

- Concrete and Rebar also Compares Favorably to FEA, DIC

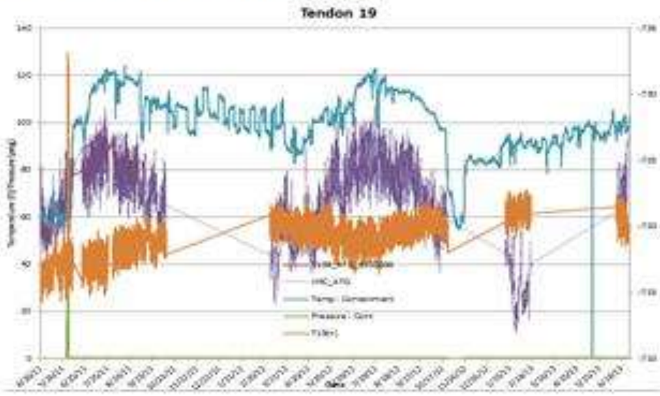


15

Results

Long Term Monitoring

- Greater Than 2 years
- 18 of 20 Perform as Predicted by FEA
- Other 2, Issues with Installation



16

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Conclusions

- Fiber Optic Sensing System Provides Real Time Tendon Monitoring
- Accurately Detected Load Change During SIT of 11,000 lb (49 kN)
- Should Detect Wire Break 7,777 lb (34.6 kN)
- Robust – Continues to Perform as Expected with More Than 2 Years of Service
- Holds Promise as Alternative to Lift-off Testing

LP
IA

17

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Questions

LP
IA

18

SESSION FOUR

Hydraulic Exciter of Vibrations
Josef Machac

Experimental Stand UVJ Rez for Probability of Detection Evaluation
Ladislav Pecinka

Hydraulic vibration exciter

Ing. Josef Machač

Dynamic measurement

- vibration exciter
- three dimensional velocity sensors
(or acceleration sensors, or displacement sensors)

- modal analysis (fourier transformation)
- natural frequencies, mode shapes

Equation of motion

$$K \cdot r(t) + C \cdot \dot{r}(t) + M \cdot \ddot{r}(t) = F(t)$$

stiffness
displacement

damping
velocity

mass
acceleration

loading
vibration exciter

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Hydraulic vibration exciter

- horizontal or vertical movement
- frame 0.8 x 2.0 m
- maximal force ± 10.0 kN
- weight of frame 750 kg, weight of moving mass up to 900 kg
- weight of attached engine 1200 kg

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Dynamic load test of bridges

Nuselsky Bridge in Prague
485 m long, 26.5 m wide
prestressed concrete

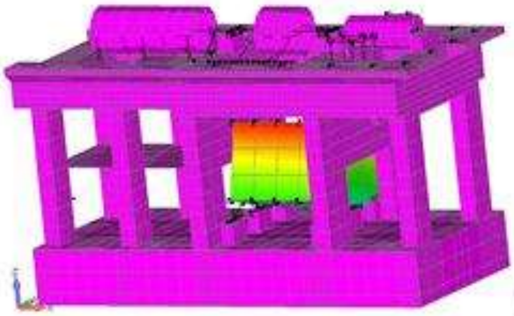
box girder bridge
subway and road traffic

Dynamic test of exhauster in Trbovlje

Power plant Trbovlje

360 m high exhauster
tube in tube construction

Dynamic test of turbine and generator foundations



Power plant Pocerady
270 MW

aprox. 37 m long, 15 m wide, 15 m high

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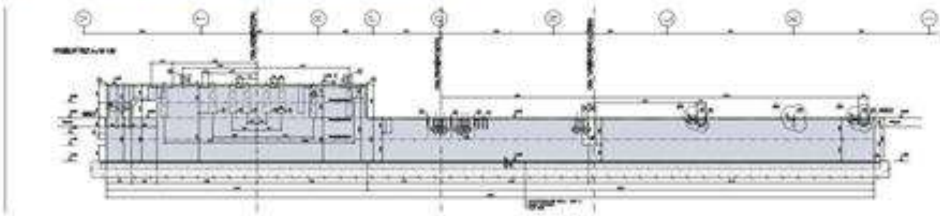
Dynamic test of gas turbine foundations

Power plant Pocerady
gas turbine 284 MW

42 m long, up to 8.6 m wide, 2.4 m high (4.3 m high)



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Comparison between experiment and simulation

- comparison of calculated natural frequencies and in-situ measured frequencies
- improving numerical model
  - realistic boundary conditions
  - overall structural stiffness (Young modulus)
  - prestress concrete simulation
  - damping coefficient

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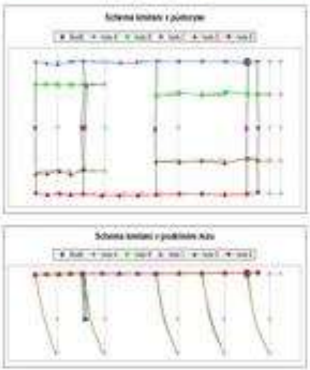
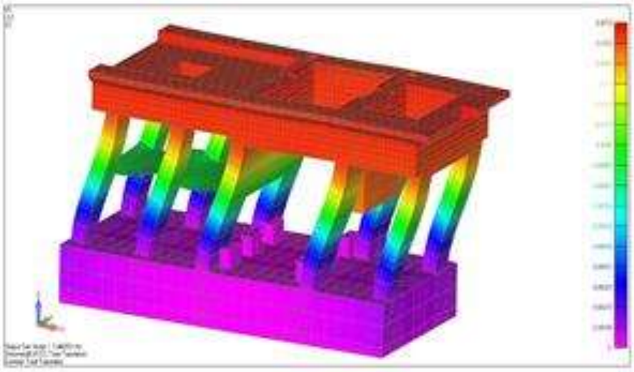
Comparison between experiment and simulation

First natural frekvency





- measured frequency 3.40 Hz
- calculated frequency 3.45 Hz
- variance 1.47%

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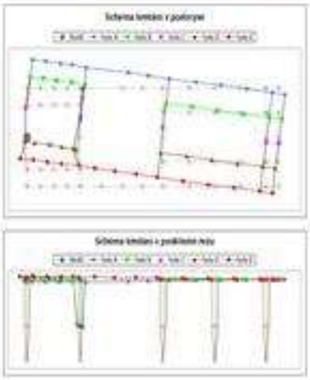
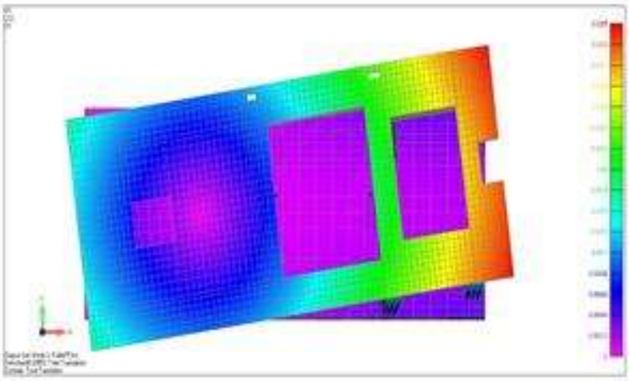
Comparison between experiment and simulation

Second natural frekvency





- measured frequency 5.70 Hz
- calculated frequency 5.44 Hz
- variance 4.68%

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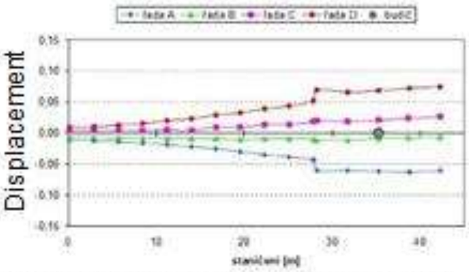
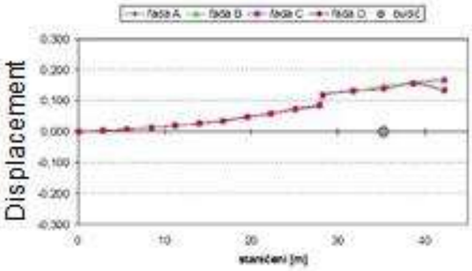
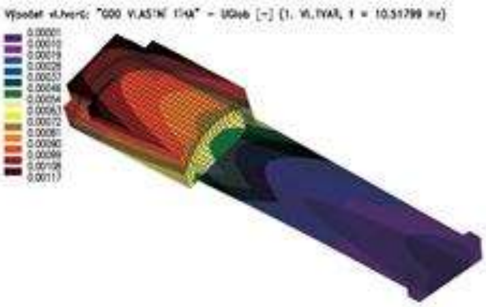
Comparison between experiment and simulation

Vertical direction



Horizontal direction





- measured frequency 10.9 Hz
- calculated frequency 10.5 Hz
- variance 3.8%

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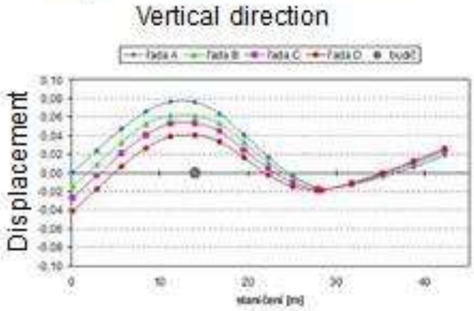
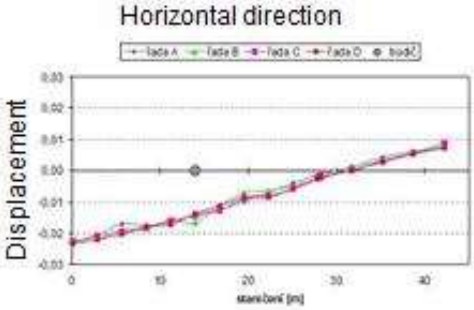
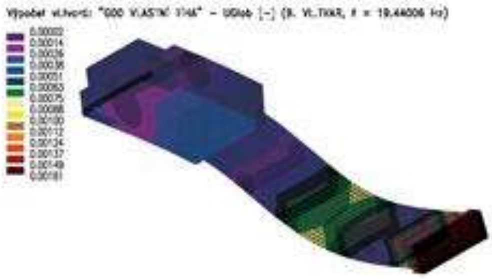
Comparison between experiment and simulation







- measured frequency 18.9 Hz
- calculated frequency 19.4 Hz
- variance 2.6%

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Experimental examination of damage structure

- degradation processes (chemical, mechanical degradation, cracks or corrosion) change stiffness of whole structure (or structural part)
- vibration characteristics of the structure change according to degradation processes and can be measured

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Experimental examination of damage structure

Article: Dynamic behaviour comparison of the damaged bridge before and after its reconstruction, prof. ing. Michal Polák, CSc., CTU in Prague

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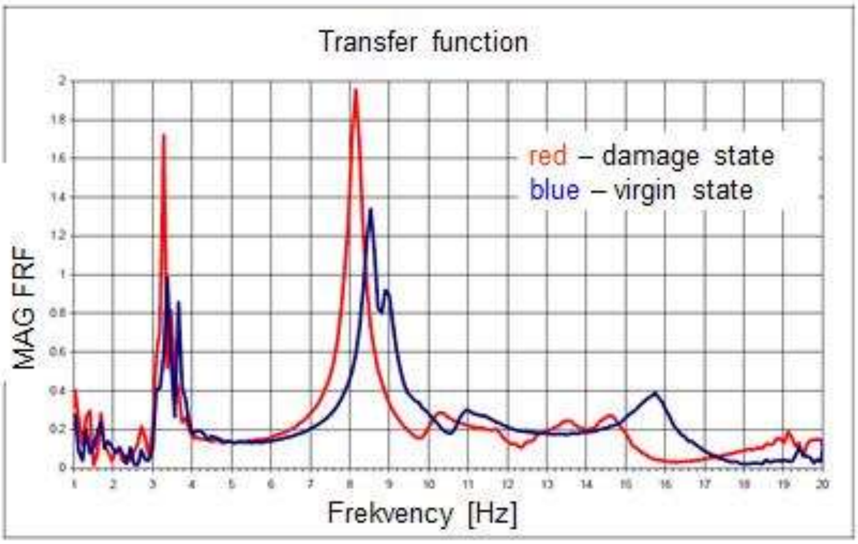

Article: Dynamic behaviour comparison of the damaged bridge before and after its reconstruction, prof. ing. Michal Polák, CSc., CTU in Prague

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Containment structure examination

- vibration exciter can be used for in-situ measuring structural natural-frequencies and modal shape
- experimentally measured values can be compared with the numerical modeling (mass and stiffness of a whole structure)
- repeated measurements (with time period 5 - 10 years) can be used for the monitoring of temporal changes and for the estimation of concrete degradation (overall loosing of stiffness)

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Thank you for your atention

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ÚJV Řež, a. s.

EXPERIMENTAL STEND UJV REZ FOR PROBABILITY OF DETECTION ASSESSMENT

Ladislav Pecinka

OECD-NEA WORKSHOP NDE OF NPPs CONCRETE STRUCTURES
PRAGUE, 17-19 SEPTEMBER 2013

GOAL OF PRESENTATION

- WHAT IS PROBABILITY OF DETECTION (POD)
- LESSONS LEARNT FROM NDE EXPERIMENTS IN UJV REZ

CONTENT

- BASIC IDEAS
- POD EXPECTED INDICATIONS
- UJV EXPERIMENTAL STEND
- SOME RESULTS OF NDE
- POD VERSUS NDE METHODS
- CONCLUSIONS

2

BASIC IDEAS

- POD DEMONSTRATION TEST AND ANALYSIS IS THE BEST AVAILABLE TECHNIQUE FOR QUANTIFYING THE DETECTION CAPABILITY OF A NDT SYSTEM
- DEPARTMENT OF DEFENSE MIL-HDBK-1823A: NON-DESTRUCTIVE EVALUATION SYSTEM REALIABLITY ASSESSMENT:

PROBABILITY OF DETECTION IS THE FRACTION OF TARGETS OF NOMINAL SIZE, A EXPECTED TO BE FOUND, GIVEN THEIR EXISTENCE

- IN GENERAL, POD IS EXPECTED TO INCREASE AS TARGET SIZE (THAT IS, INDICATION SIZE) INCREASES
- A POD DEMONSTRATION TEST IS TYPICALLY CONDUCTED USING A SET OF STANDARD SPECIMENS OF THE SAME GEOMETRY AND MATERIAL THAT HAVE A KNOWN NUMBER AND DISTRIBUTION OF INDICATION SIZES

3

BASIC IDEAS – cont. 1

- DATA GENERATED BY A POD TEST ARE EITHER BINARY OR MEASURABLE, DEPENDING ON THE RESPONSE PRODUCED BY THE NDT SYSTEM
- THEORETICAL BACKGROUND
  - STATISTICS IS THE FIELD IN WHICH THE THEORY IS DEVELOPED
  - NDT IS THE FIELD IN WHICH THE THEORY IS APPLIED
- THE SUCCES OF POD, AS WELL AS FUTURE ADVANCEMENTS, DEPENDS ON THE PARTNERSHIP FORMED AND COLLABORATION BETWEEN STATISTICS AND NDT
- FOR THE DETAIL INFORMATIONS SEE THE JOURNAL OF THE AMERICAN SOCIETY FOR NONDESTRUCTIVE TESTING „MATERIALS EVALUATION“, Vol.70, No. 4, pp 421-426, April 2012:

  Jennifer Brown: IT TAKES MORE THAN A STATISTICIAN TO DO PROBABILITY OF DETECTION

4

POD-EXPECTED INDICATIONS

- DEFECTS, i.e.
  - QUALITY OF CONCRETE (DENSIFICATION, MOISTURE etc)
  - CRACKS
  - DELAMINATION
  - VOIDS
  - DEBONDING BETWEEN LINER AND CONCRETE
  - CREEP
- SHRINKAGE
- INTERNAL STEEL COMPONENTS AS LINER etc.
- REBARS
- DUCTS OF PRESTRESS TENDONS
- TECHNOLOGICAL CHANELS

5

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND

6

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 1

SPECIMEN № 1

7

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 2

SPECIMEN № 2

8

EXPERIMENTAL STEND

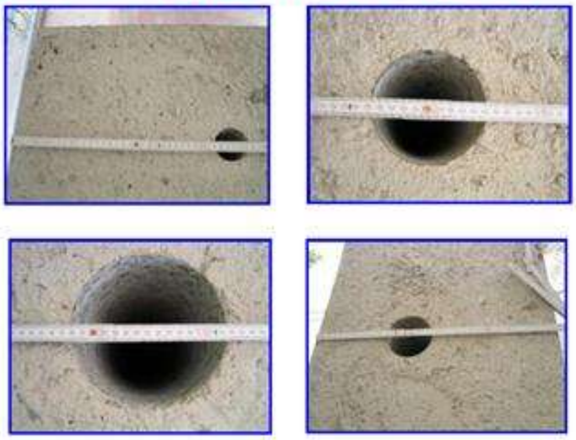
DESCRIPTION OF THE STAND – cont. 3

INTERNAL LINER WITH DEFECTS

9

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 4



SPECIMEN № 3

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 5

SPECIMEN № 4 WITH GRID OF REBARS

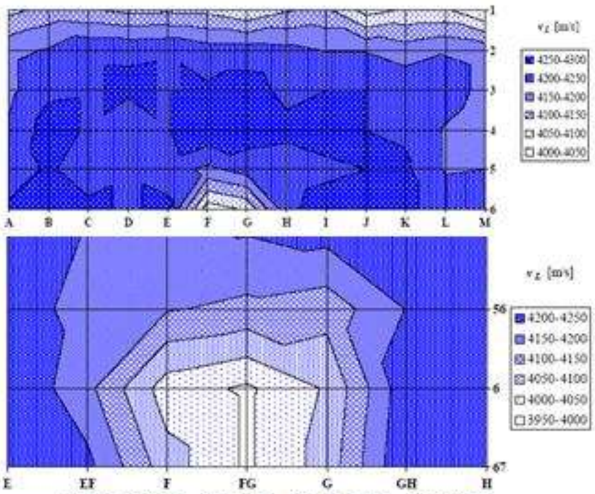
EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 6

SPECIMEN № 5: CONTAINMENT WALL WITH REBARS AND DUCTS

12

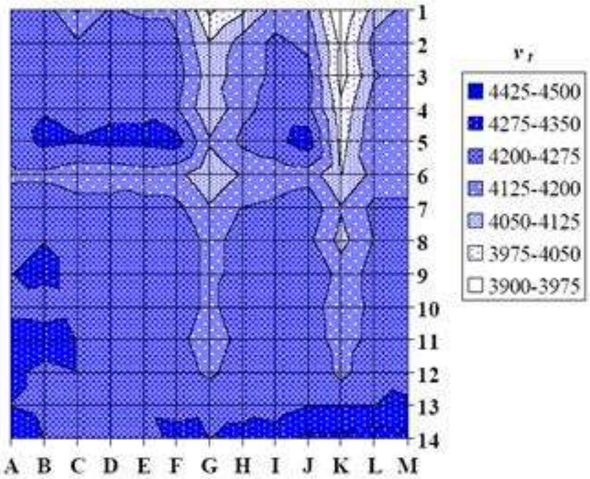
SOME RESULTS OF NDE



DETECTION OF THE ARTIFICIAL CAVITY

13

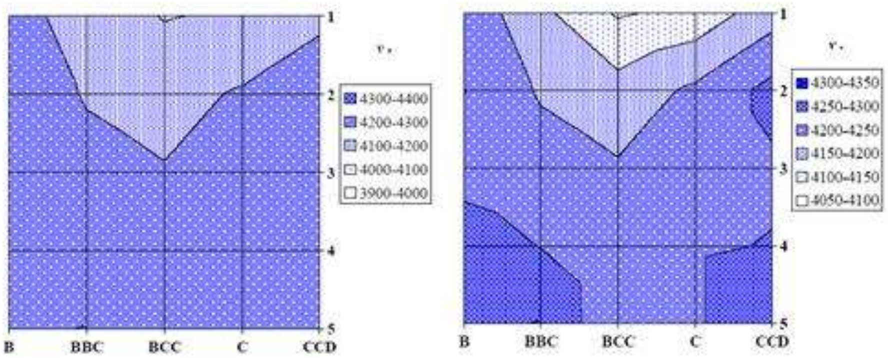
SOME RESULTS OF NDE – cont. 1



DETECTION OF HOLES ø 150 AND 100 mm

14

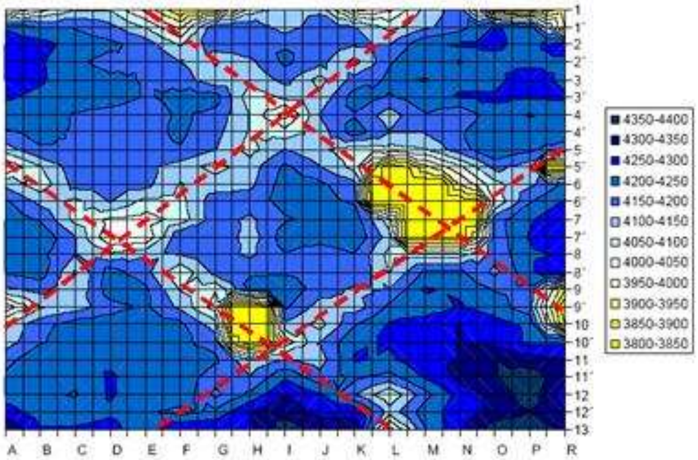
SOME RESULTS OF NDE – cont. 2



HOLE WITH ø 50 mm

15

SOME RESULTS OF NDE – cont. 3

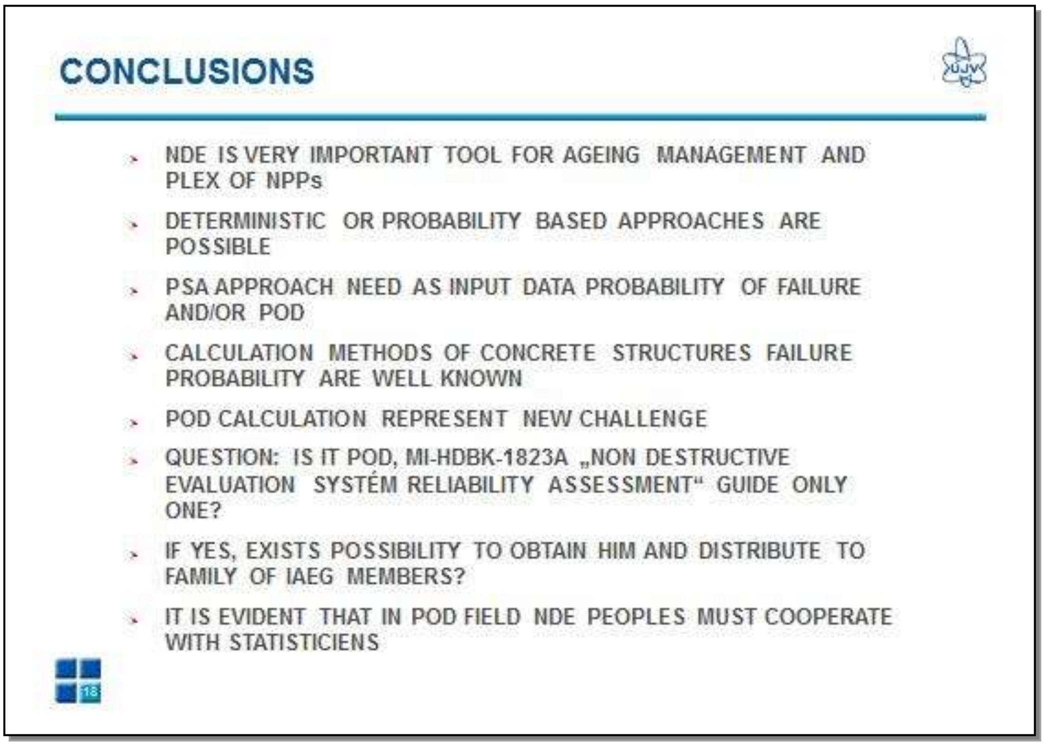


DETECTION OF THE DUCTS

POD VERSUS NDE METHODS

- IN OUR EXPERIMENTS THE FOLLOWING METHODS HAVE BEEN USED
  - ULTRASOUND
  - GROUND PENETRATION RADAR
  - IMPACT ECHO
- APPLICATIONS WITH HIGH VALUE OF POD

NDE METHOD	SUCCESFUL APPLICATION TO
UT, Impact Echo, Laser	Delamination
UT, Impact Echo	Cracks
GPR, Impact Echo, UT	Voids, Channels
GPR	Cover depth
GPR, Impact Echo	Reinforcement
UT	Concrete properties
GPR, Impact Echo	Internal Liner


CONCLUSIONS
NDE IS VERY IMPORTANT TOOL FOR AGEING MANAGEMENT AND PLEX OF NPPs
DETERMINISTIC OR PROBABILITY BASED APPROACHES ARE POSSIBLE
PSA APPROACH NEED AS INPUT DATA PROBABILITY OF FAILURE AND/OR POD
CALCULATION METHODS OF CONCRETE STRUCTURES FAILURE PROBABILITY ARE WELL KNOWN
POD CALCULATION REPRESENT NEW CHALLENGE
QUESTION: IS IT POD, MI-HDBK-1823A „NON DESTRUCTIVE EVALUATION SYSTÉM RELIABILITY ASSESSMENT“ GUIDE ONLY ONE?
IF YES, EXISTS POSSIBILITY TO OBTAIN HIM AND DISTRIBUTE TO FAMILY OF IAEG MEMBERS?
IT IS EVIDENT THAT IN POD FIELD NDE PEOPLES MUST COOPERATE WITH STATISTICIENS
18


THANK YOU
FOR YOUR
ATTENTION
19

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Unclassified **NEA/CSNI/R(2014)1**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **30-Jan-2015**

English text only

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

NEA/CSNI/R(2014)1
Unclassified

Cancels & replaces the same document of 15 October 2014

Proceedings of OECD/NEA WGIAGE Workshop on the Non-Destructive Evaluation of Thick-walled Concrete Structures

Prague, Czech Republic, 17-19 September 2013

JT03369895

Complete document available on OLIS in its original format

English text only

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Republic of Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

THE COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

"The Committee on the Safety of Nuclear Installations (CSNI) shall be responsible for the activities of the Agency that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations, with the aim of implementing the NEA Strategic Plan for 2011-2016 and the Joint CSNI/CNRA Strategic Plan and Mandates for 2011-2016 in its field of competence.

The Committee shall constitute a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It shall have regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee shall review the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensure that operating experience is appropriately accounted for in its activities. It shall initiate and conduct programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It shall promote the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings, and shall assist in the feedback of the results to participating organisations. The Committee shall ensure that valuable end-products of the technical reviews and analyses are produced and available to members in a timely manner.

The Committee shall focus primarily on the safety aspects of existing power reactors, other nuclear installations and the construction of new power reactors; it shall also consider the safety implications of scientific and technical developments of future reactor designs.

The Committee shall organise its own activities. Furthermore, it shall examine any other matters referred to it by the Steering Committee. It may sponsor specialist meetings and technical working groups to further its objectives. In implementing its programme the Committee shall establish co-operative mechanisms with the Committee on Nuclear Regulatory Activities in order to work with that Committee on matters of common interest, avoiding unnecessary duplications.

The Committee shall also co-operate with the Committee on Radiation Protection and Public Health, the Radioactive Waste Management Committee, the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle and the Nuclear Science Committee on matters of common interest."

FOREWORD

The Committee on the Safety of Nuclear Installations (CSNI) Working Group on Integrity and Ageing of Components and Structures (IAGE) has as a general mandate to advance the current understanding of those aspects relevant to ensuring the integrity of structures, systems and components, to provide for guidance in choosing the optimal ways of dealing with challenges to the integrity of operating as well as new nuclear power plants, and to make use of an integrated approach to design, safety and plant life management.

The Working Group has three subgroups dealing with (a) integrity and ageing of metal structures and components, (b) integrity and ageing of concrete structures, and (c) seismic behaviour of components and structures.

Over the last two decades, the IAGE Concrete Sub-group has convened a series of workshops and published reports on integrity and aging of thick-walled concrete structures, primarily aimed at containment structures. The last workshop was "Ageing Management of Thick Walled Concrete Structures, including ISI, Maintenance and Repair – Instrumentation Methods and Safety Assessment in view of Long Term Operation" held in Prague, Czech Republic, on 1-3 October 2008. One of the conclusions from that workshop was that further meetings or workshops should be held every few years to review progress on non-destructive examination (NDE) of concrete, and to provide a forum for information exchange.

With developments in NDE methodologies over the intervening 5 years, the IAGE working group considered it was timely to host a follow-on to the 2008 workshop in 2013, with the objective to present and discuss the state-of-the-art techniques for the integrity assessment of concrete structures, and to recommend areas where further research is needed. This report documents the proceedings for the 2013 workshop on "Non-Destructive Evaluation of Thick Walled Concrete Structures".

Overall, the workshop demonstrated there has been significant development in NDE methodologies for thick-walled concrete since 2008. There is still substantial work to be done before fully qualified techniques can be deployed on a regular basis to determine the overall health of a concrete structure. The workshop concluded with recommendations for areas that would benefit from further study, and from international cooperative programmes. These include: i) appropriately capturing the information on effects of irradiation in standards or guidance documents, ii) following up on the state-of-the-art report on concrete NDE methodologies, iii) undertaking development of standard specimens and using round-robins for intercomparisons, and iv) holding a subsequent meeting or workshop to review progress after a few more years.

ACKNOWLEDGMENTS

Gratitude is expressed to the Nuclear Research Institute Rez in the Czech Republic for hosting the Workshop, and in particular, to Dr. Ladislav Pecinka for his help, and excellent organisation of the meeting.

Thanks are also expressed to the Workshop Technical Committee, the Session Chairpersons and the workshop participants for their effort and cooperation.

Organizing Committee

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SUMMARY AND CONCLUSIONS

1. Introduction

This report documents the proceedings for the workshop on "Non-Destructive Evaluation of Thick Walled Concrete Structures", held in Prague, Czech Republic on 17-19 September 2013. A total of 34 specialists from 15 countries and international organisations attended. The Meeting was sponsored by the OECD Nuclear Energy Agency Committee on the Safety of Nuclear Installations and hosted by the Nuclear Research Institute Rez.

The objective of this workshop was to present and discuss the state of the art techniques for the integrity assessment of concrete structures, and to recommend areas where further research is needed. The workshop was structured in 4 technical sessions, with papers covering degradation mechanisms, application of NDE methodologies, and test rigs for determining NDE effectiveness.

2. Background of the Workshop

Concrete structures are essentially passive components under normal operating conditions, but play a key role in mitigating the impact of extreme or abnormal operating and environmental events. Structural components are somewhat plant specific, may be difficult to inspect and the limiting factor for plant life since they are mostly irreplaceable. Structures are subject to time-dependent changes that may impact their ability to perform safety functions. As NPPs age, assurance is needed that the capacity of concrete structures to mitigate extreme events has not deteriorated unacceptably.

Of particular importance to most nuclear facilities are concrete containment structures whose main purposes are to provide the final physical barrier to the release of fission products to the environment and to protect the reactor and other safety related structures, systems and components.

Although, it was thought that concrete was maintenance-free with a design life of hundreds of years, this has proved to be optimistic. Experience has demonstrated that concrete structures can exhibit the first signs of degradation after 20 years or even earlier. Concrete containments of the nuclear facilities are subjected to many types of environmental effects that can, over time, initiate a variety of degradation mechanisms.

The safety significance of containment combined with the current trend towards life extension and the regulatory authorities' demands for even higher levels of safety assurance, means that ageing degradation mechanisms must be effectively understood and monitored, and the recognised ageing mechanisms should be continuously controlled. An important element of this control is inspection and monitoring to assess and determine the condition of the concrete structures and associated components. Modern NDE methods and instrumentation are providing useful techniques for the detection and measurement of the extent of internal damage and providing information on the quality of construction. Nevertheless, further work is required to provide standardized and qualified inspection techniques.

3. Summaries for the Workshop Sessions

Session 1

Herbert Wiggenhauser summarized the "State-of-the-Art of non-destructive methods and technologies for application to nuclear power plant safety-related concrete structures". This state-of-the-art report provides a comprehensive assessment of the various available NDE techniques (e.g. ultrasonics, radiography, radar, etc.) and their strengths and limitations for various applications (thickness, cover depth, detection of rebar, detection of defects, etc.). Recommendations are for further research to develop:

- validation and reference specimens
- software for data analysis and modelling
- combined techniques and automation
- improvements to equipment and techniques.

Georgios Michaloudis presented "Applying numerical simulations for the non-destructive evaluation of concrete structural components subjected to high-dynamic loading". Numerical simulations were used to assess the damage induced in a concrete structure from a high-dynamic load (e.g. explosion). The complex energy propagation through air and then into a structure was modelled and compared well with actual results. The models can be used to determine the residual load capacity of the structure following an impact event.

Brian Hohmann presented "Inspection of Containment Liners and Shells Utilizing Advanced Nondestructive Examination Techniques". Some areas of containment liners and shells are not readily accessible for inspection, but can have installation defects and can degrade in-service. Ultrasonic techniques have been developed to detect flaws in a liner or shell, and applied to full-scale mock-ups. The techniques were able to detect flaws introduced in the mock-ups, but require further work to provide reliable defect sizing and characterization. It was noted that discontinuities in a liner or shell, such as a butt weld, can seriously attenuate the NDE signal.

Session 2

Jiri Zdarek presented "Temperature and Radiation Effects on the RPV Concrete Cavity: Project Description on Irradiation, Testing and NDE Development". Long term exposure to radiation and thermal loading can result in degradation of mechanical properties of concrete structures such as RPV cavities. An experiment is being conducted to determine the effects of high-radiation fields on concrete behaviour (described further in a presentation in Session 3). In addition, NDE techniques using Non-linear Elastic Wave Spectroscopy are being developed and applied to a sample of concrete from a biological shield from a mothballed VVER. One possible opportunity is to use the ionization penetrations in the VVER biological shield as access points for NDE probes in an operational VVER.

Fahim Al-Neshawy presented "Monitoring of hygrothermal performance of thick-walled concrete structures". Exposure of concrete structures to variations in temperature and humidity can lead to deterioration. Dr. Al-Neshawy described a technique for collecting data on the effects of temperature and humidty on concrete, and using neural networks to forecast hygrothermal performance.

Brian Hohmann provided a summary of “The Effect of Irradiation on Thick Walled Concrete Structures in Nuclear Power Plants with Respect to Long Term Operation”. Mr. Hohmann presented the available data on the effects of irradiation on concrete, and showed that the data of most relevance to reactor containment structures indicates there is not likely to be any deterioration for fast neutron fluences up to $\sim 10^{19}$n/cm^2. Thus there is no indication that containment concrete will deteriorate due to irradiation, but additional data (as is being sought in the experiment described in Sessions 2 and 3) will be useful to confirm the lack of effect at high fluences.

Session 3

Sontra Yim presented “The Use of Digital Image Correlations for Detection of Degradation in Concrete Structures”. The digital image correlation (DIC) - that combines photogrammetry and image correlation - is an effective non-contact non-destructive evaluation (NDE) technique to quantify changes in shape, deformation, displacement and strain. This method was successfully validated 2011 during a structural integrity test (SIT) period in the framework of pressurization, hold and depressurization on inner concrete surfaces ($\sim$1m^2) of a NPP containment. The quantitative data that was recorded will provide a basis for comparison to future tests (e.g. at 10 years interval). DIC can be used to detect, track and trend concrete degradation.

Milan Marek presented “Projects Dealing with Radiation Damage of Concrete at the LVR Research Reactor”. This contribution is a complement to the presentation “Temperature and Radiation Effects on the RPV Concrete Cavity: Project Description on Irradiation, Testing and NDE Development” of the 2nd session. An experiment to determine the effects of irradiation on concrete using the LVR-15 reactor was described. Concrete cylindrical samples (5 cm diameter, 10 cm height) will be irradiated with a neutron flux of 1.5E+20 n/cm^2 (E>0.1 MeV) below 90°C temperature. The samples will be investigated by means of post irradiation examination (PIE) and NDE. The data will be useful in assessing the safety of NPP concrete structures since they will provide information regarding degradation (material changes and influence of chemical parameters) of irradiated concrete.

Sontra Yim presented “Use of Fiber Optic Sensors for Monitoring Loads in Post-Tensioned Tendon”. Fiber optic sensors were selected due to their expected stable performance over long time periods, accuracy, immunity to electromagnetic interferences as well as electrical noise, and environmental stability. The resulting fiber optic sensing system (FOSS) was installed in a NPP with a post-tensioned tendon systems and provides real time tendon monitoring in order to detected tendon wire breaks, wire relaxation, local concrete failure under tendon anchorage or loss of rock anchor. FOSS holds promise to be an alternative to lift-off testing. It has worked robustly for over two years, and is anticipated to perform over a long-time period (e.g. more than 10 years).

Session 4

Josef Machac presented his work on a “Hydraulic Vibration Exciter.” In this study numerical simulation of the response of structures to a dynamic vibration load was performed and compared with the experimental measured values. Experimental case studies included dynamic load test of bridges, the Orlik dam, the tallest exhaust stack in Europe, and a power plant turbine and generator basemat. The technique shows promise for monitoring degradation through systematic repeated measurements over long time periods, e.g. 5-10 years.

Ladislav Pecinka presented the topic "Experimental Stend UJV Rez for Probability of Detection (POD) Assessment." He provided background on a methodology for quantifying the detection capability of a NDE technique. A POD demonstration test is typically conducted using a set of standard specimens of the same geometry and material that have a known number and distribution of indication sizes. An important consideration is that the size distribution should go beyond the NDE technique's detection capability to establish the POD. Dr. Pecinka also elaborated on a set of four specimens of dimension 2mx2mx1m, UJV has constructed with known defects and internal components (rebar, tendon ducts). UJV has examined the specimens with ultrasound, ground penetration radar and impact echo NDE methods and identified which method is suitable and successful to detect the particular types of defects. Although not a complete spectrum of indication sizes, the set of specimens should be valuable for comparison testing by other organizations.

4. Discussion

The workshop provided ample opportunity for discussion amongst participants on various aspects of degradation of concrete structures, and use of NDE to monitor concrete performance. Key areas of discussion are captured here.

Since the last workshop in 2008, there has been significant development of NDE methodologies for concrete. The application of various ultrasonic techniques continues to be expanded and refined. Digital Image Correlation is showing promise as a technique for monitoring deformation and tracking degradation. The use of fiber optics is enabling reliable NDE measurements over an extended time period, and could potentially avoid costly and dangerous direct measurement such as post-tensioning tendon lift-off. Hydraulic exciters can be used to look at the mechanical response of large structures, and monitor for changes over time.

Nevertheless, we are far from having a comprehensive set of qualified techniques that can be standardized and applied by certified contractors. We are still at the stage of much of the work being performed in research centres and universities, prior to standardization and commercialization. As techniques move from the laboratory into regular application, there will be a need for appropriate training to ensure the techniques are used properly and consistently. Given the complex and expansive nature of thick-walled concrete structures, it is anticipated that multiple techniques will be required to assess the full-range of potential indications, and to probe the entire volume of a structure.

A big challenge is posed by the lack of standardization in concrete. While there can be specifications for mix ratios, aggregate size distribution, rebar arrangement, etc., key aspects of concrete can change with location and time. For example, cement and aggregate composition can vary. The effects of these differences are not well understood nor well characterized, and could influence properties enough to make prediction of aging effects difficult.

In terms of aging, the work underway at UJV Rez should go a long way toward resolving the effects of irradiation. Nevertheless, the challenges to integrity posed by environmental exposures (temperature, moisture, contaminants, etc.) can stem from a wide range of phenomena, and continued investigation is required to ensure the phenomena of importance to nuclear structures are well understood and characterized.

Advances in computer technologies are helping to improve NDE methodologies. Post-processing software can be used to turn NDE measurements into 3-D representations of a structure, its internals, and any flaws or defects. Finite-element and mechanical modelling is being used to supplement NDE methodologies in determining the nature of discontinuities and defects, and in determining the consequences of detected anomalies on mechanical properties. Statistical analysis and reliability methodologies are likewise showing promise in extrapolating from NDE findings to the consequences for a structure.

5. Conclusions and Recommendations

1) There is a clear need for means of ensuring concrete structures meet their design criteria. During and immediately following construction, NDE can provide quality control and verification. After being subjected to aging degradation, NDE can be used to characterize material properties and ensure adequate performance. It is therefore recommended that there be a follow-on workshop or meeting in few years to allow for further exchange of information.
2) The state-of-the-art report [ORNL/BAM] provides a valuable assessment of the current applicability and limitations of available concrete NDE methodologies. The IAGE Concrete subgroup should review the recommendations in the report and identify areas that can benefit from international collaboration.
3) Methodologies for concrete NDE continue to evolve, and there are, as yet, no standardized and qualified techniques. As a result, international standard specimens should be developed to allow direct comparisons between various techniques, with consideration given to ensuring a broad range of defects to ensure the Probability of Detection (POD) for a method can be properly determined. Test rigs such as those developed at UJV Rez and LPI could provide a starting point for such inter-comparisons. In addition, samples should be removed from plants under decommissioning. A round-robin study could be valuable in comparing between NDE techniques, and in determining variability in the application of the same technique. The highest priority testing tasks should be determined to ensure that resources are appropriately focussed.
4) Once the experiments on the effects of irradiation are completed, it is recommended that the results be captured in standards and / or regulatory guides. This will likely require radiation effects to be included in constitutive models for concrete used in finite-element modelling and used in fracture mechanics assessments.

OECD/NEA WGIAGE Workshop on the Non-destructive Evaluation of Thick-walled Concrete Structures – Prague, Czech Republic 17-19 September 2013

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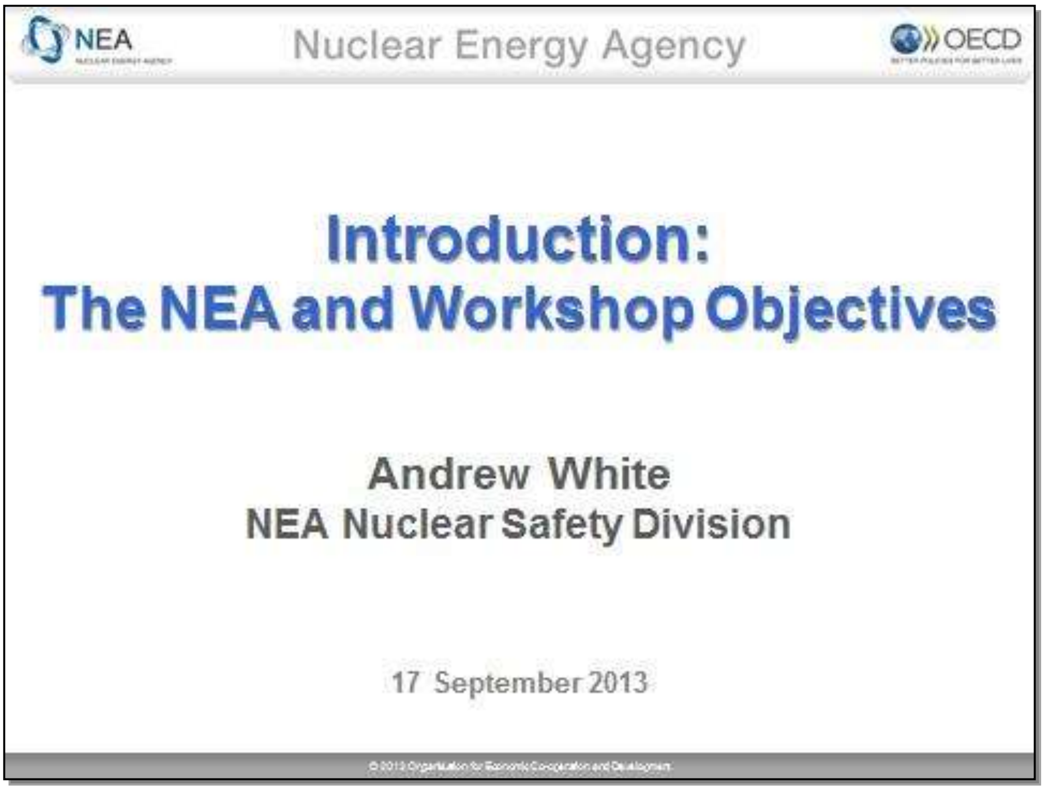
OPENING SESSION

Presentation on NEA and WGIAGE
Andrew White

Welcome and Overview of UJV Rez
Vladimir Stratil


NEA
Nuclear Energy Agency
OECD
Introduction:
The NEA and Workshop Objectives
Andrew White
NEA Nuclear Safety Division
17 September 2013
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NEA
Nuclear Energy Agency
OECD
The NEA Mission
• To assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes.
• To provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy, and to broader OECD policy analyses in areas such as energy and sustainable development.
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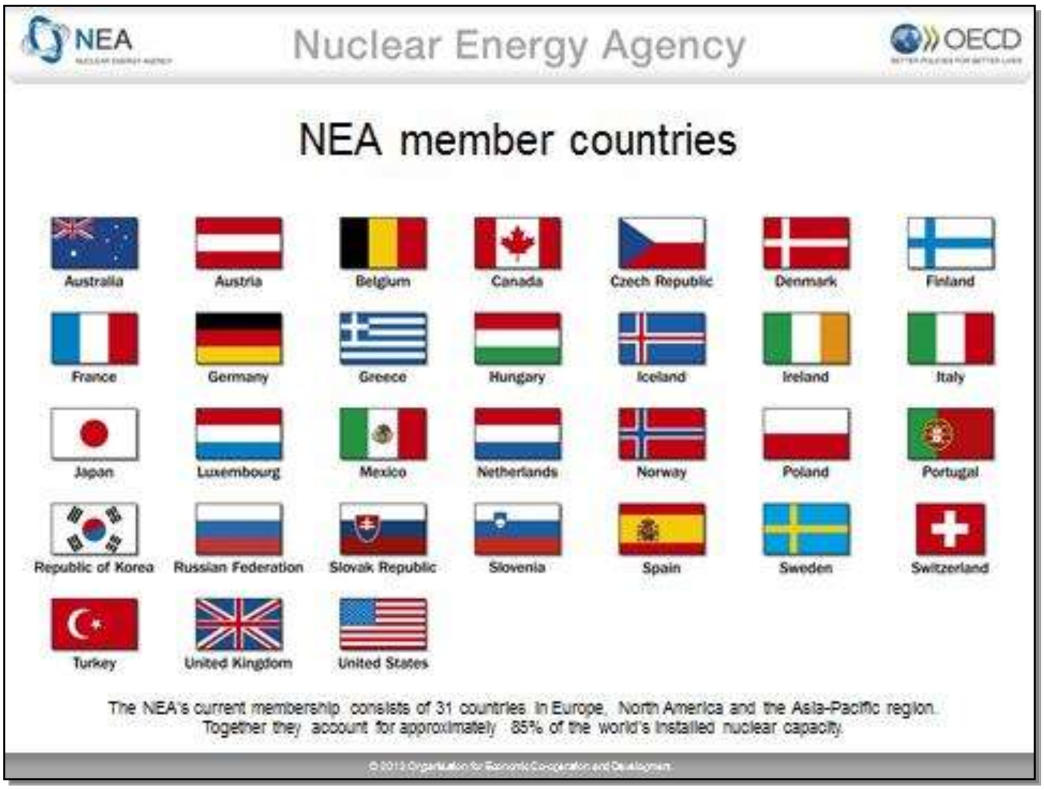
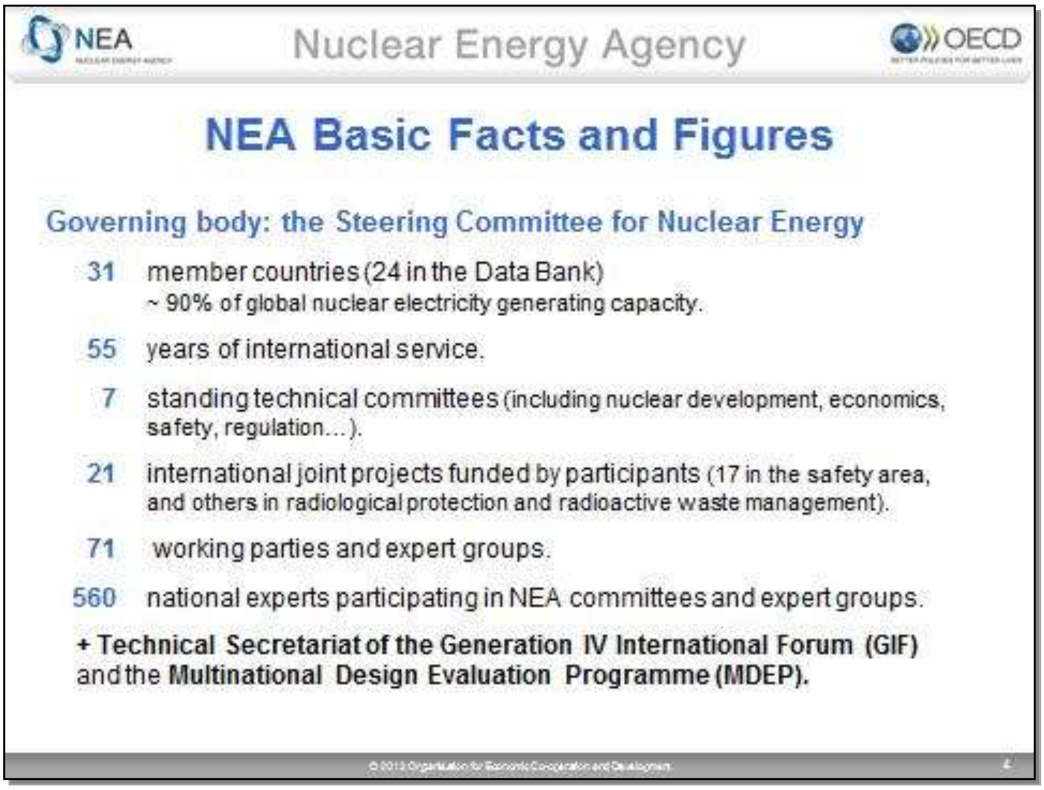
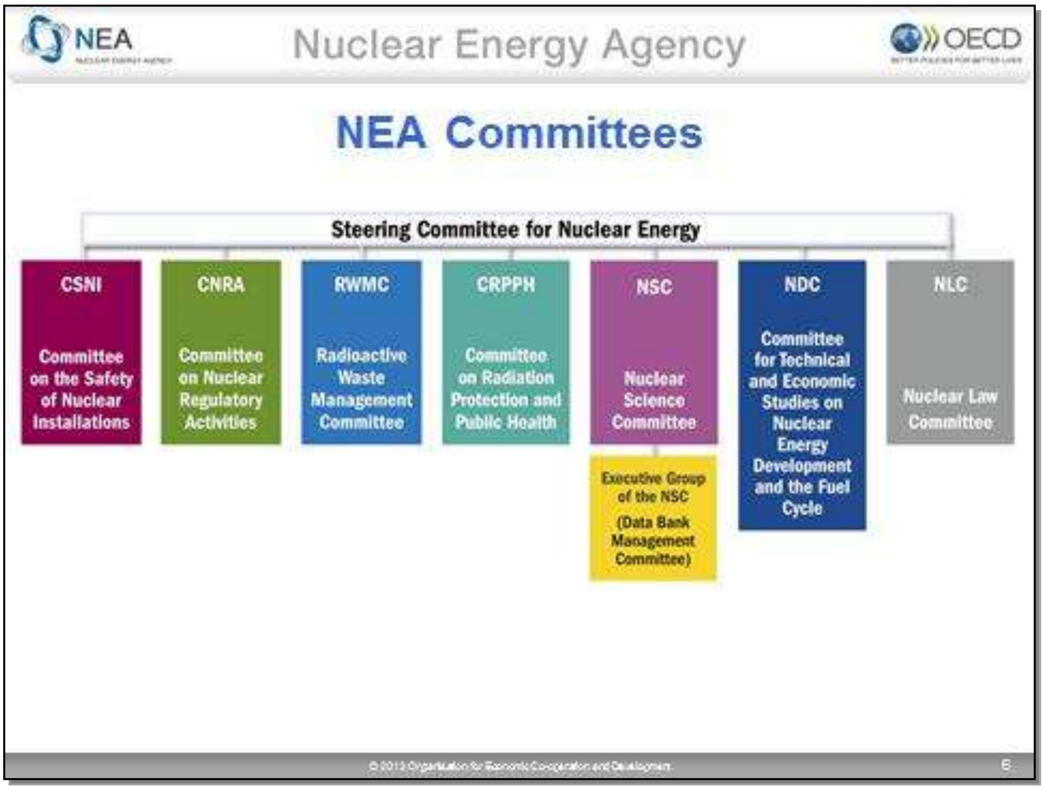
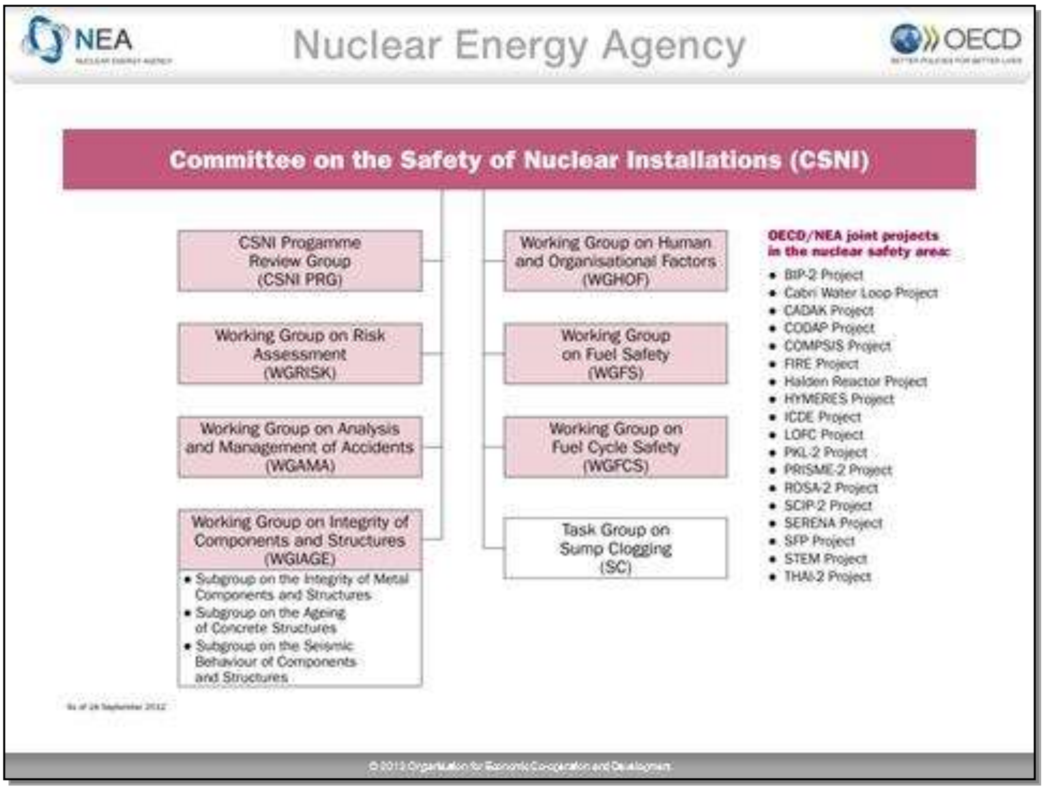

NEA
Nuclear Energy Agency
OECD
NEA member countries
Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Japan
Luxembourg
Mexico
Netherlands
Norway
Poland
Portugal
Republic of Korea
Russian Federation
Slovak Republic
Slovenia
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States
The NEA's current membership consists of 31 countries in Europe, North America and the Asia-Pacific region.
Together they account for approximately 85% of the world's installed nuclear capacity.


NEA
Nuclear Energy Agency
OECD
NEA Basic Facts and Figures
Governing body: the Steering Committee for Nuclear Energy
31 member countries (24 in the Data Bank)
~ 90% of global nuclear electricity generating capacity.
55 years of international service.
7 standing technical committees (including nuclear development, economics, safety, regulation…).
21 international joint projects funded by participants (17 in the safety area, and others in radiological protection and radioactive waste management).
71 working parties and expert groups.
560 national experts participating in NEA committees and expert groups.
+ Technical Secretariat of the Generation IV International Forum (GIF) and the Multinational Design Evaluation Programme (MDEP).


NEA
Nuclear Energy Agency
OECD
NEA Co-operation and Interactions
• International Energy Agency (IEA): OECD family,
• International Atomic Energy Agency (IAEA): agreement,
• European Commission (EC): full participant,
• China: Joint Declaration on Co-operation approved,
• India: expert invitations,
• Ad hoc observers (national governments),
• Industry input to selected studies.


NEA
Nuclear Energy Agency
OECD
NEA Committees
Steering Committee for Nuclear Energy
CSNI
Committee on the Safety of Nuclear Installations
CNRA
Committee on Nuclear Regulatory Activities
RWMC
Radioactive Waste Management Committee
CRPPH
Committee on Radiation Protection and Public Health
NSC
Nuclear Science Committee
Executive Group of the NSC
(Data Bank Management Committee)
NDC
Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NLC
Nuclear Law Committee


NEA
Nuclear Energy Agency
OECD
Committee on the Safety of Nuclear Installations (CSNI)
CSNI Progamme Review Group (CSNI PRG)
Working Group on Risk Assessment (WGRISK)
Working Group on Analysis and Management of Accidents (WGAMA)
Working Group on Integrity of Components and Structures (WGIAGE)
• Subgroup on the Integrity of Metal Components and Structures
• Subgroup on the Ageing of Concrete Structures
• Subgroup on the Seismic Behaviour of Components and Structures
Working Group on Human and Organisational Factors (WGHOF)
Working Group on Fuel Safety (WGFS)
Working Group on Fuel Cycle Safety (WGFCS)
Task Group on Sump Clogging (SC)
OECD/NEA joint projects in the nuclear safety area:
• BIP-2 Project
• Cabri Water Loop Project
• CADAK Project
• CODAP Project
• COMPSIS Project
• FIRE Project
• Halden Reactor Project
• HYMERES Project
• ICDE Project
• LOFC Project
• PKL-2 Project
• PRISME-2 Project
• ROSA-2 Project
• SCIP-2 Project
• SERENA Project
• SFP Project
• STEM Project
• THAI-2 Project
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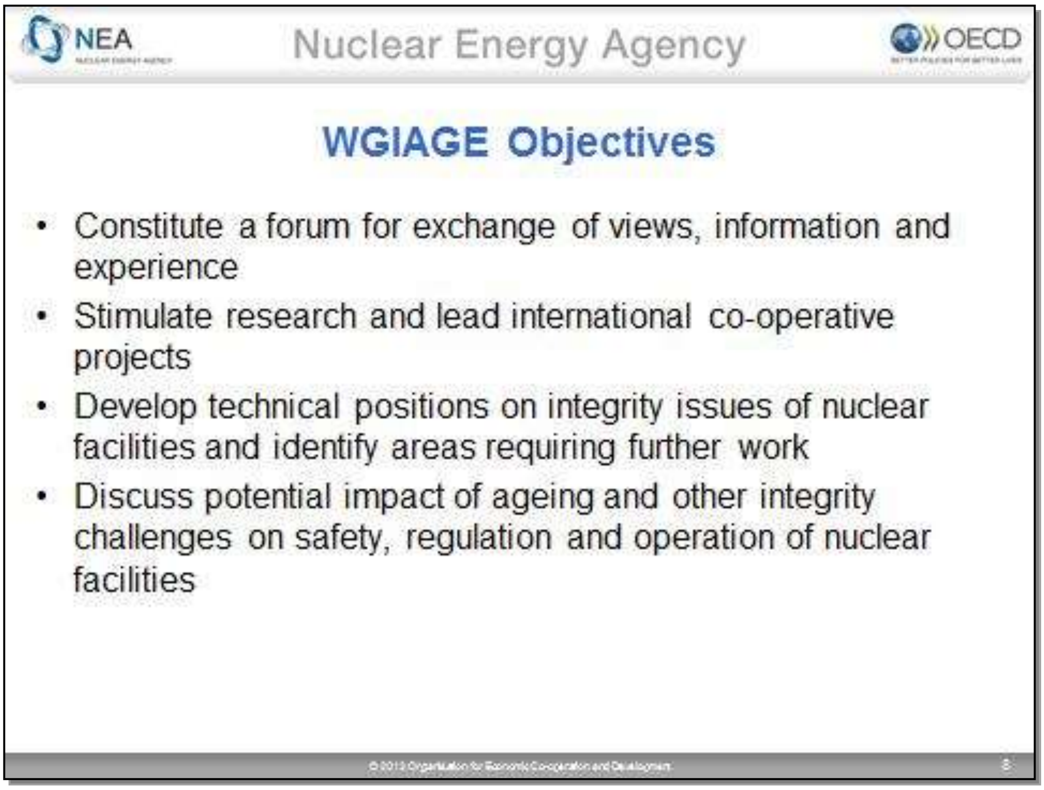
NEA
Nuclear Energy Agency
OECD
WGIAGE Objectives
• Constitute a forum for exchange of views, information and experience
• Stimulate research and lead international co-operative projects
• Develop technical positions on integrity issues of nuclear facilities and identify areas requiring further work
• Discuss potential impact of ageing and other integrity challenges on safety, regulation and operation of nuclear facilities
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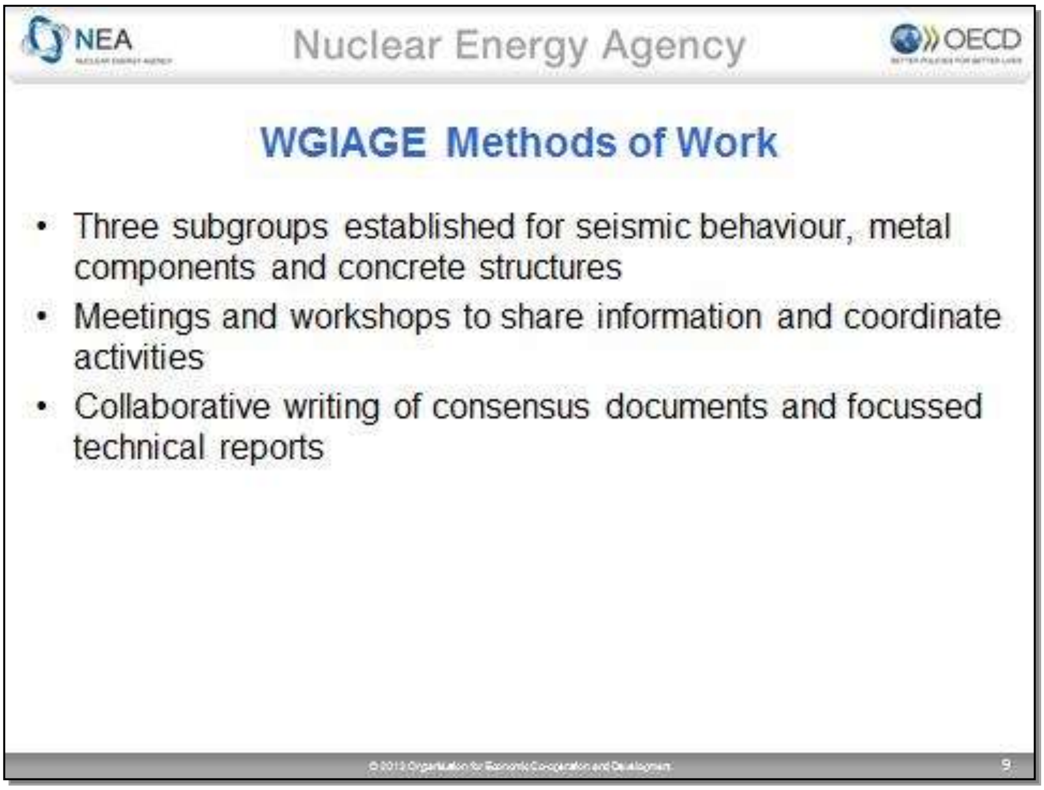
NEA
Nuclear Energy Agency
OECD
WGIAGE Methods of Work
• Three subgroups established for seismic behaviour, metal components and concrete structures
• Meetings and workshops to share information and coordinate activities
• Collaborative writing of consensus documents and focussed technical reports
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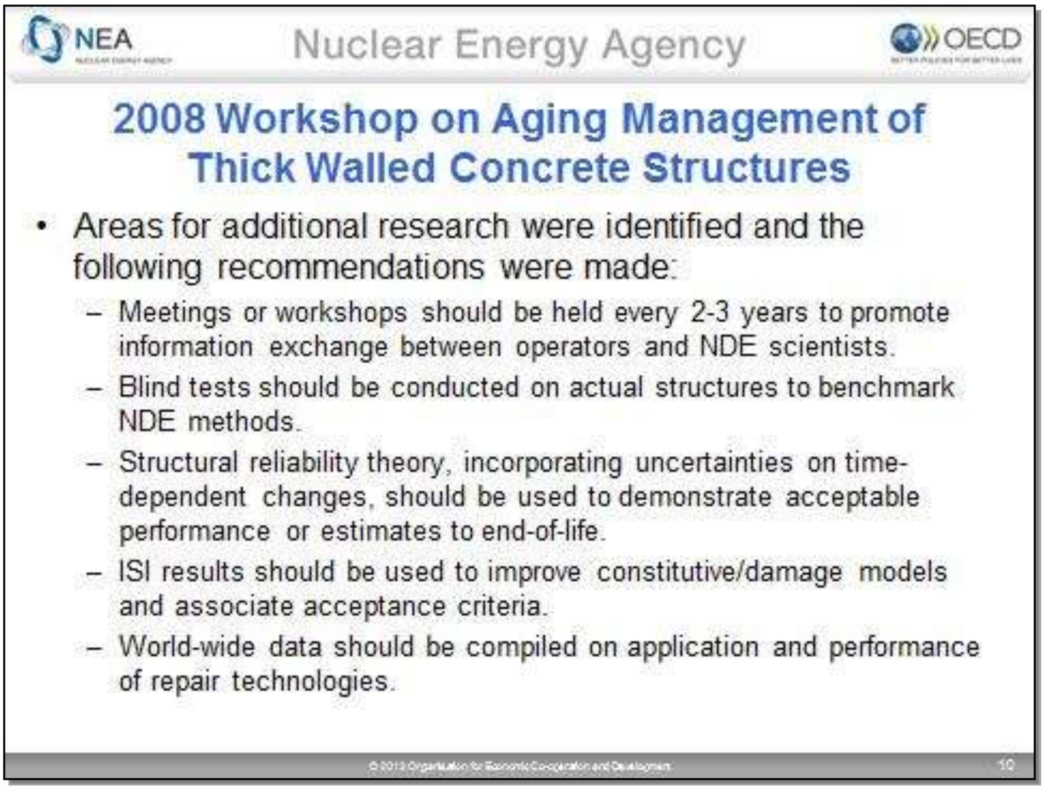
NEA
Nuclear Energy Agency
OECD
2008 Workshop on Aging Management of Thick Walled Concrete Structures
• Areas for additional research were identified and the following recommendations were made:
– Meetings or workshops should be held every 2-3 years to promote information exchange between operators and NDE scientists.
– Blind tests should be conducted on actual structures to benchmark NDE methods.
– Structural reliability theory, incorporating uncertainties on time-dependent changes, should be used to demonstrate acceptable performance or estimates to end-of-life.
– ISI results should be used to improve constitutive/damage models and associate acceptance criteria.
– World-wide data should be compiled on application and performance of repair technologies.
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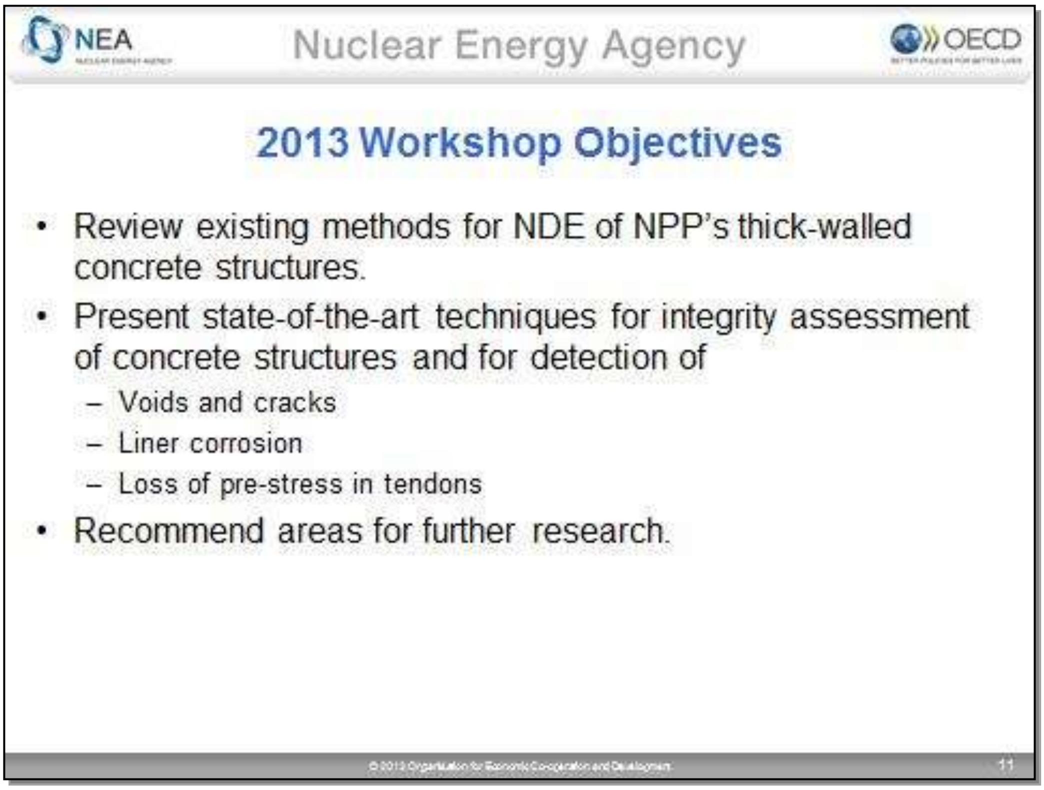
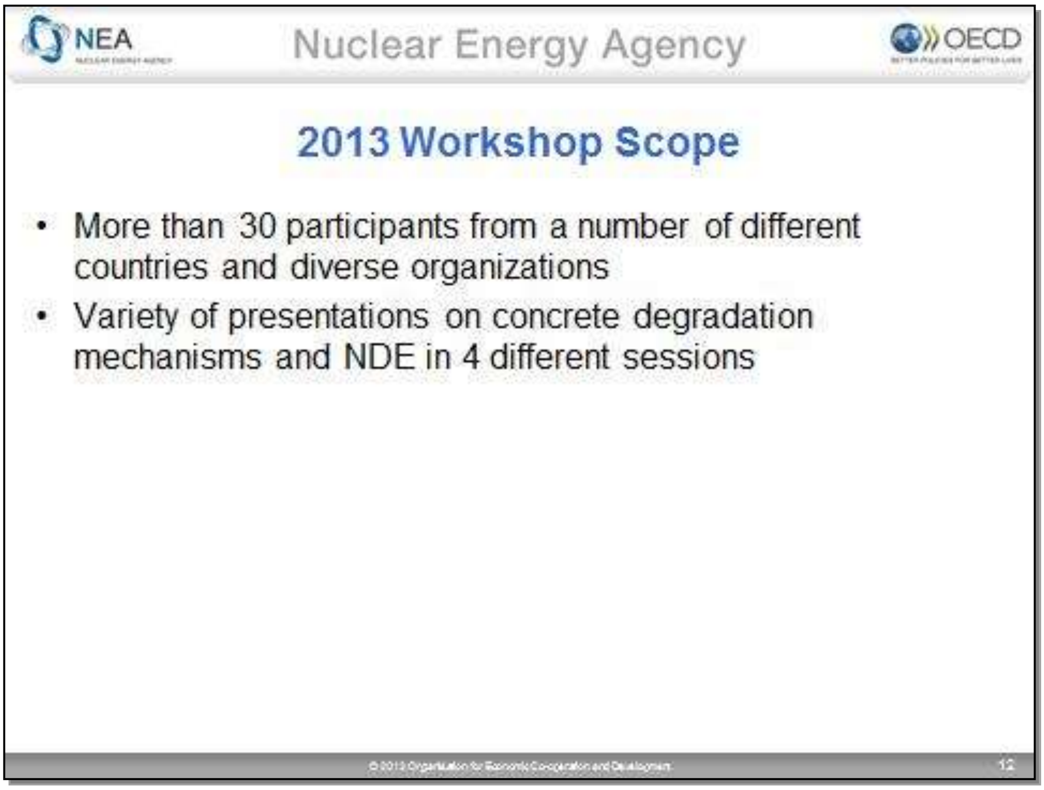
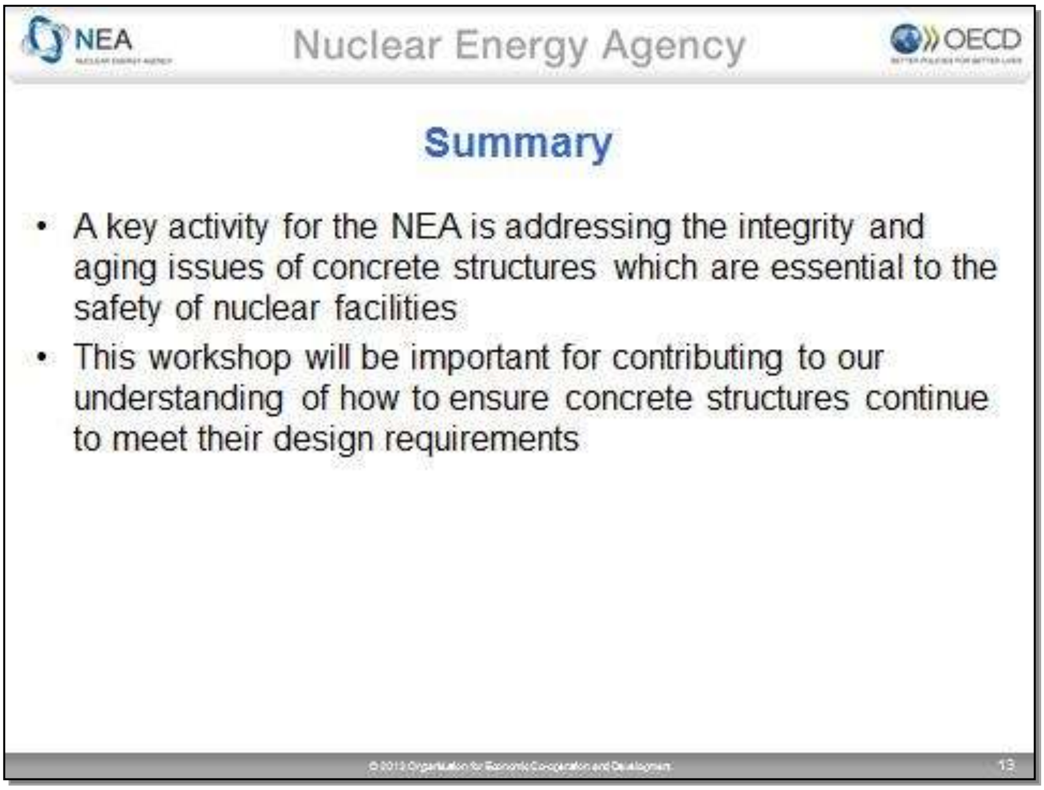

NEA
Nuclear Energy Agency
OECD
2013 Workshop Objectives
• Review existing methods for NDE of NPP's thick-walled concrete structures.
• Present state-of-the-art techniques for integrity assessment of concrete structures and for detection of
– Voids and cracks
– Liner corrosion
– Loss of pre-stress in tendons
• Recommend areas for further research.


NEA
Nuclear Energy Agency
OECD
2013 Workshop Scope
• More than 30 participants from a number of different countries and diverse organizations
• Variety of presentations on concrete degradation mechanisms and NDE in 4 different sessions


NEA
Nuclear Energy Agency
OECD
Summary
• A key activity for the NEA is addressing the integrity and aging issues of concrete structures which are essential to the safety of nuclear facilities
• This workshop will be important for contributing to our understanding of how to ensure concrete structures continue to meet their design requirements
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ÚJV Řež, a. s.
IAGE workshop
AMBASSADOR - Prague

Vladimir Stratil
September 18th, 2013

Who we are

- We are a company operating in the area of research and development on the top national and global level more than 58 years.
- More than 1,000 persons employed by the ÚJV Group represent the potential from scientific capacities through technology specialists, designers to experienced production workers.

2

Who we are

- Our divisions, departments and daughter companies employ 62% of university-educated specialists, 26% of secondary-educated specialists and 12% of technically skilled persons.
- We are in possession of unique research, production and process facilities in the Central and Eastern Europe.
- We belong among the recognized and respected members of many of international and national organizations and companies.

3

History and milestones

- 1955 Foundation of the Nuclear Physics Institute in Rez
- 1957 VVR-S research reactor start-up
- 1972 The original Institute was separated into the Nuclear Physics Institute and the Nuclear Research Institute
- 1993 The Nuclear Research Institute Rez was privatised to joint-stock company
- 2000 Scientific leadership of the commissioning of Temelin NPP
  - Purchase of Institute of Applied Mechanics Brno, Ltd. (IAM)
  - 2002 Research Centre Rez Ltd. (CVŘ)
  - Purchase of part of ENERGOPROJEKT PRAHA a.s. – formation of the Division ENERGOPROJEKT
- 2009 Acquisition of
  - Research and Testing Institute Plzen (VZÚ Plzeň)
  - EGP INVEST, spol. s r.o. (EGPI)
- 2011 Formation of UJV Group
  - ÚJV Řež + CVŘ Řež + VZÚ Plzeň + ÚAM Brno + EGPI Uhersky Brod

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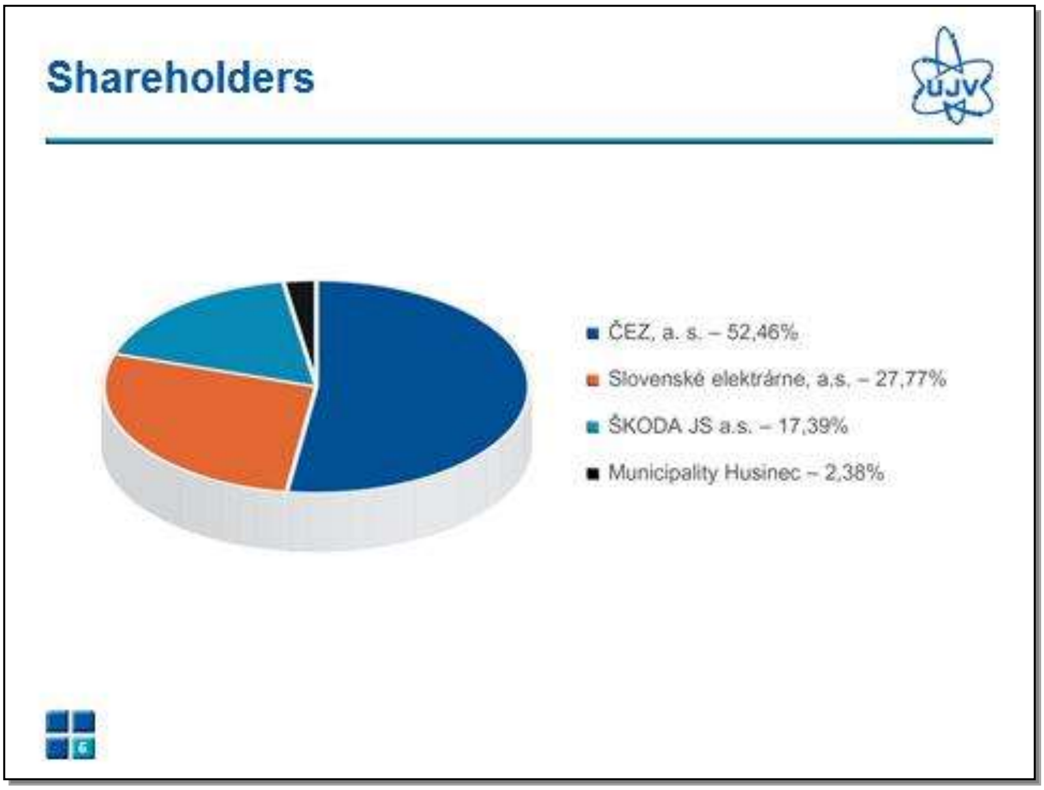
Shareholders
ČEZ, a. s. – 52,46%
Slovenské elektrárne, a.s. – 27,77%
ŠKODA JS a.s. – 17,39%
Municipality Husinec – 2,38%


Company strategy
To provide
Engineering, design, analytical and scientific support in operating and constructing new energy facilities including nuclear facilities.
Comprehensive and system R&D services, especially in the area of use of nuclear energy and ionizing radiation sources.
To be
Professional authority and promoter in the area of nuclear energy and utilization of ionizing radiation.
A transparent company with clear management, well-arranged finance and open information about implemented projects.
Good neighbor in all places where we implement our oobjectives and projects.

International cooperation I.

An inherent part of activities of the Institute from its foundation in 1955.

- **Multilateral cooperation**
  - International Atomic Energy Agency (IAEA), Vienna
  - Nuclear Energy Agency (NEA), Paris
  - Participation in framework programs of EURATOM, Brussels
  - Member of the European Nuclear Education Network (ENEN)
  - Member of the European Technical Safety Organizations Network (ETSON)
  - The Electric Power Research Institute (EPRI)
  - Key player in founding process of NUGENIA

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International cooperation II.

- **Bilateral cooperation**
  - Commission at Energy Atomic (CEA), France
  - Institute for Radiological Protection and Nuclear Safety (IRSN), France
  - Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany
  - Czech-Russian Work Group for Nuclear Energy, MPO/ROSATOM
  - State Scientific & Technical Centre for Nuclear and Radiation Safety (SSTC NRS), Ukraine
  - Cooperation with US institutes through agreements concluded between the regulatory bodies (USNRC–SÚJB) and ministries (USDOE–Ministry of Industry and Trade)
  - Bhabha Atomic Research Centre (BARC), India
  - Centrum of Nuclear Research (NCBJ),Poland

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Certificates
ÚJV
EN ISO 14001:2004, valid until: 2014-06-23
EN ISO 9001:2008, valid until: 2014-06-23
BS OHSAS 18001:2007, valid until: 2014-06-23
Certificate of Facility Security Clearance
TÜV NORD
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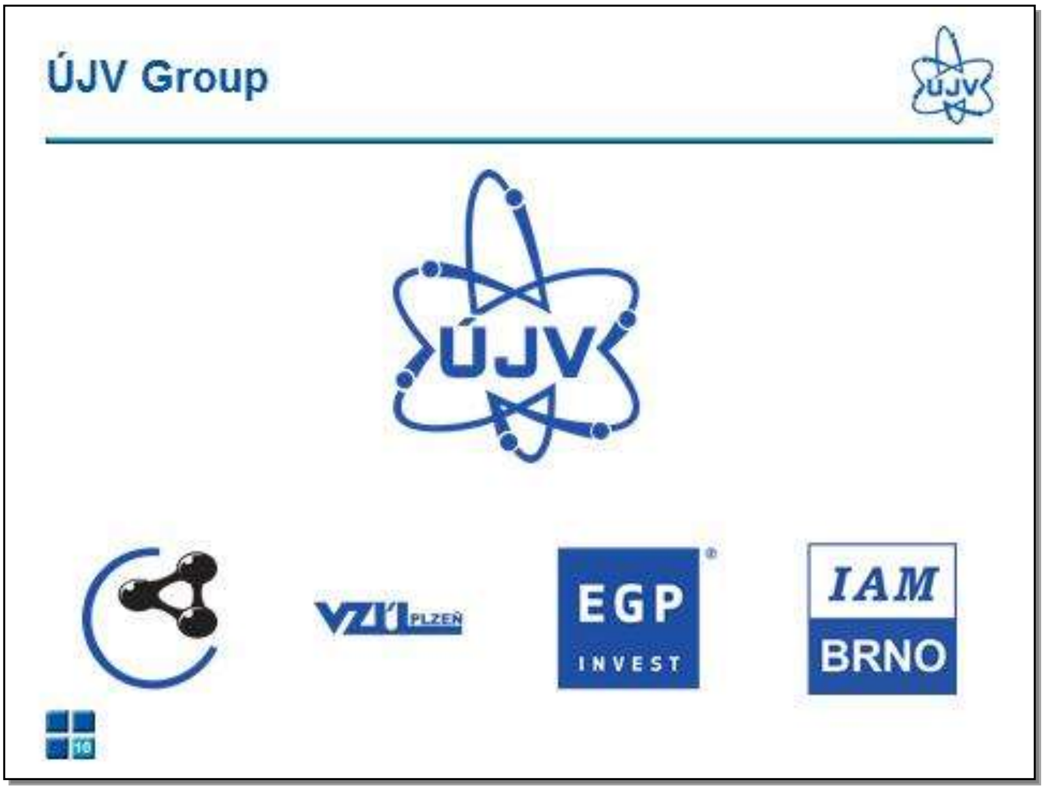
ÚJV Group
ÚJV
VZÚ PLZEŇ
EGP INVEST
IAM BRNO
10

Subsidiary companies

- **Research Centre Rez**
  - Founded in 2002; Director: Martin Ruščák
  - Research and development organisation focused on technologies in energy; Operator of research reactors LVR-15 and LR-0
- **Research and Testing Institute Plzen**
  - Founded in 1907, from 2006 owned by ÚJV Řež,a.s., Director: Václav Liška
  - Research, development and accredited testing; Research of materials and mechanical engineering; Computer modelling
- **EGP INVEST, spol. s r.o.**
  - Founded in 1991 in Uherský Brod, from 2009 owned by ÚJV Řež, a. s., Director: Petr Sláčala
  - Design activities, surveys; Engineering activity
- **Institute of Applied Mechanics Brno, Ltd.**
  - Founded in 1959, from 2004 owned by ÚJV Řež,a.s. Director: Lubomír Junek
  - Comprehensive analyses of strength, service life and seismic resistance of steel structures, pressure vessels; Advisory services in the area of mechanical engineering, metallurgy and energy

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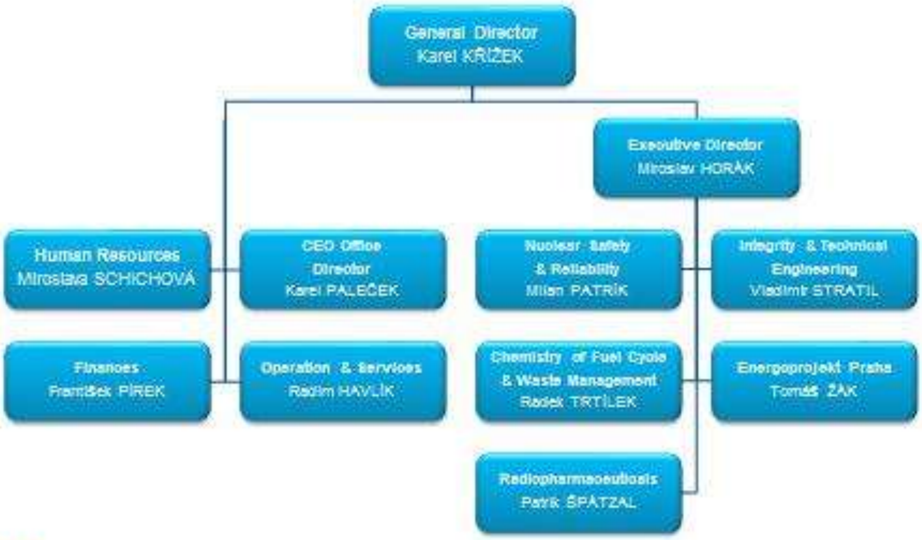
Divisions and their main services

Organization Chart



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Nuclear Safety and Reliability Division

- Reactor physics and fuel cycle
- Safety analyses, including
  - Severe accidents
  - Probabilistic safety assessment
  - Emergency preparedness
- Diagnostics and reliability of existing and new reactor technologies
- Non-nuclear activities
  - Hydrogen technologies in energy and transportation
  - Support to reliability and risk management of industrial technologies, gas transport, electric power transmission, aviation

14

Integrity and Technical Engineering Division

- Structural and life time assessment of sysetems, structures and components (RPV including surveillance programme, piping systems, valves, ...)
- PLIM/ LTO programmes including specific AM programmes
- Technical support and maintenance of NPP
- Tests and analyses of material properties
- Equipment qualification
- Non-destructive testing, in-service inspection (ISI) and ISI qualification
- Design and construction of experimental and customer-requested equipment

Chemistry of Fuel Cycle and Waste Management Division

- Radioactive waste management
  - Services and technologies of processing, treatment and conditioning of radioactive waste
  - Radiochemical analyses, characterization of radioactive waste, radiation monitoring
  - Transport of spent nuclear fuel
- Research and engineering support to the Deep Geological Disposal Project and for L&ILW Repositories
  - Barriers, safety assessment, WAC development, design, monitoring
- Decommissioning of nuclear facilities, fragmentation and decontamination

ENERGOPROJEKT PRAHA Division

- Design and engineering services
  - General designer or designer – all phases and areas of investment process mainly in energy sectors: electric power production and heating
- Data processing and associated services
- Database graphics
  - Preparation of technical documentation in the environment of graphic and relation databases
  - Development of applications to support designing and operation of energy and industrial projects – GAMED and GADUS application systems

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Radiopharmaceuticals Division

- Production of PET radiopharmaceuticals
  - „In the place of the application"
  - FDG (glucose marked ^{18}F)
- Production of SPECT radiopharmaceuticals and kits
- Research and development of radiopharmaceuticals
  - Mainly for diagnostic, but potentially also therapeutic use in the treatment of tumour diseases, neurodegenerative diseases
- Biological testing laboratory

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Significant
references


Area of nuclear safety and reliability
Development and applications of advanced algorithms for optimisation of fuel loading in NPPs
Significant participation in power uprating projects for Czech NPPs Dukovany and Temelin
Application of advanced knowledge of severe accident phenomenology during NPP safety enhancement
SCORPIO
Measurements in the core, including calculations (EDU, ETE)
Non-nuclear technologies
Development & Operation of hydrogen bus
Accumulation of energy in hydrogen
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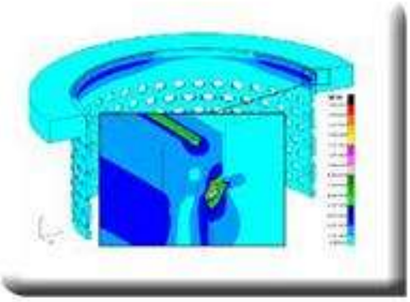
Area of integrity and technical engineering



- Development of the long-term operation and plant life management strategy for the Ukrainian nuclear power plants
  - European Commission project
  - Leading consortium member
    - ÚJV Řež, a. s.; NPP OSI Kiev; ENERGORISK Kiev; VÚJE, a.s. (SR)
- Evaluation of the technical conditions and lifetime extension of the reactor pressure vessel and internals for two units of Ukrainian NPPs
- Participation in EPRI (Electric Power Research Institute) activities
  - Successful and efficient transfer of "know-how" with unique safety and economic benefit
- Membership in NUGENIA association
  - ÚJV Řež,a.s. is one of 7 founders

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Area of chemistry of fuel cycle and waste management

- Global Threat Reduction Initiative(GTRI)
  - Transports of fresh and spent nuclear fuel from research reactors (projects RRRFR,RERT)
  - Executed transports: Czech Republic, Poland, Ukraine, Belarus, Serbia, Hungary, Bulgaria
- Decommissioning and radwaste treatment
  - Area „Velké zbytky", Řež,project of ecological solution of the past activities
- Deep Geological Repository Development
  - Provides technical support and analyses for RAWRA
- Radioactive Waste Regulatory Autority (RAWRA)
  - Barriers, safety assessment, WAC development, conceptual design

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Area of NPP Design

- Feasibility Studies
- All levels of Detail Design (studies, permit documentation, etc.)
- Safety reviews and analyses
- Author's supervision
- Participation in the commissioning and evaluation of defined success criteria fulfilment
- Customers:
  - Dukovany NPP (4x VVER 440 MWe)
  - Temelín NPP (2x VVER 1000 MWe)
  - Bohunice NPP (4x VVER 440 MWe)
  - Mochovce NPP (2x VVER 440 MWe)

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Area of radiopharmaceuticals

- PET Centres operation
  - Prague, Brno, Řež
- Supplier of PET radio-pharmaceuticals into six Czech hospitals
- PET Centre Řež constructed on the premises of the company (2010-2012)
  - with cyclotron for the production of positron emitters intended mainly for R&D PET radiopharmaceuticals
  - producing the new generation of radiopharmaceutical characterized by ultra-short lived radionuclides for diagnostics

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Contacts
ÚJV
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Phone: +420 266 170 000
E-mail: name.surname@ujv.cz
Web: www.ujv.cz
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SESSION ONE

State-of-the-Art of Nondestructive Testing Methods and Technologies for Application to NPPs Safety-Related Concrete Structures
Herbert Wiggenhauser

Applying Numerical Simulations for the Non-destructive Evaluation of Concrete Structural Components Subjected to High Dynamic Loading
Georgios Michaloudis

Inspection of Containment Liners and Shells Utilizing Advanced Non-destructiver Examination Testing
Brian P. Hohman

State-of-the-Art of Non-Destructive Testing Methods and Technologies for Nuclear Power Plant Safety-Related Concrete Structures.

Herbert Wiggenhauser

BAM Federal Institute for Materials Research and Testing, Berlin, Germany

Dan J. Naus

Oak Ridge National Laboratory, Oak Ridge, TN

Appearance of the typical RC- and PT-concrete containment in the US-American nuclear industry
Source: Strategic program Concrete (EPRI), http://mydocs.epri.com/docs/TI/frontPage_pdf/1023473_Concrete.pdf

Oak Ridge National Laboratory — CSNI Workshop 2013 — BAM

Non-destructive testing of NPP RC structures presents challenges different from conventional civil engineering structures

High Concentration of Steel Reinforcement

- Wall thickness can be in excess of one meter
- Structures often have increased steel reinforcement density with more complex detailing
- Can be a number of penetrations or cast-in-place items
- Accessibility may be limited due to presence of liners or other components, harsh environments, or structures may be located below ground
- A broad experience base on applications of NDE to NPP concrete structures does not exist

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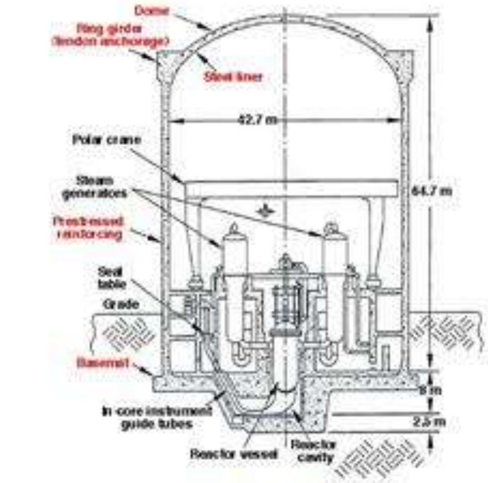
Several areas have been identified where improvements in NDT methods are desired



PWR Large Dry
Prestressed Concrete Containment

- Thick, heavily reinforced concrete sections
  - As-built or current structural features
  - Flaw detection and characterization
  - Honeycomb and embedded items
  - Voids adjacent to liner
- Basemats and other inaccessible areas
  - Based on indirect approach (i.e., environmental qualification)
- Liners –
  - Global inspection methods
  - Inaccessible areas
- Prestressing tendons
  - Real-time techniques to monitor post-tensioning systems for tendon wire failures and level of stressing

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General comments on application of NDT methods to thick, heavily-reinforced concrete structures

http://energy.gov/ne/downloads/light-water-reactor-sustainability-lwrs-program-rd-roadmap-non

Ultrasonic Shear-Wave Tomography

- Use of NDT techniques is required for compliance testing, collection of specific data or parameters, condition assessments, and damage assessments
- Quality of results is directly related to quality of concrete
- Combination of methods is often the most effective approach with first method used to detect and locate suspect areas followed by use of second method to provide high quality images to permit assessment of condition of area in question
- Acoustic (UPV, UPE, SASW, I-E, and AT), radar, and radiography appear to have greatest potential
- Inaccessible structures (i.e., foundations) are assessed through opportunistic inspections or indirectly through environmental qualification
- Development of standards to quantify capabilities of NDT for NPP safety-related concrete structures is desirable
- As NPP concrete structures age, NDT is likely to gain an increasingly important role in their aging management
- New designs should give consideration to providing improved accessibility for application of NDT techniques

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A SOA report summarizing available data and information on NDT methods and recommendations for research has been completed

- Recent operating experience has identified several areas of interest
  - Detection of cracking, voids, delamination, and honeycombing
  - Detection of inclusions of different materials or voids adjacent to concrete side of liner
  - Methods capable of identification of corrosion occurrence on the concrete side of the containment liner
  - Applicability of laser-induced breakdown spectroscopy to assess occurrence of concrete degradation in form of alkali-silica reactions, sulfate attack, irradiation, and elevated temperature
  - Locating steel reinforcement and identification of its cover depth
  - Locating tendon ducts and identification of the condition of grout materials

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Task (1) locating steel reinforcement and identification of its cover depth

Methods very well suited for the described task:

- inductive method with low frequency excitation (< 10 cm cover max 2 layers)
- inductive method with high frequency excitation (eddy-current) (< 10 cm cover max 2 layers)
- radar (< 30 cm cover diameter not measurable)

Methods well suited for the described task:

- Ultrasonic (> 5 cm cover)
- radiography (multi-angle technique) (< 60 cm two sided access)
- magnetic flux leakage (< 20 cm)

Methods partially suited for the described task:

- active thermography (< 10 cm cover; n/a for depth > 10 cm)

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Task (1) locating steel reinforcement and identification of its cover depth

The combination of radar and magnetic methods – mentioned already in the 1980ies – is still a very powerful tool for cover depth, rebar location and bar-sizing. Several devices exist; strategies how to apply both methods in combination and software for data assessment and imaging of both methods are of great interest for further development.

Research Needs

The inductive methods, both with high or low frequency excitation as well as the Radar method have to be validated to a large extent. Although commercial devices are available, the application is still not well established for the described tasks and particularly not in the needed thickness range. For radiography (e.g. Betatron) the time consumption is very high and and safety precautions have to be strictly followed.

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Task (2) locating tendon ducts + identification of the condition of the grout materials

Methods very well suited for the described task:

- ultrasound echo imaging (MIRA)
  locate (< 80 cm), cover (< 80 cm), grouting condition
- radar locate (< 50 cm) cover (< 50 cm)

Methods well suited for the described task:

- ultrasound echo (A-scan) locate (< 50 cm), cover (< 50 cm)
- radiography (x-ray, gamma, betatron, linear accelerator), locate: (< 60 cm), cover: (< 60 cm), grouting
- ultrasound transmission, locate (< 10 cm)

Methods partially suited for the described task:

- radiography (x-ray, gamma, betatron, linear accelerator) cover: + (< 60 cm),
- ultrasound echo (A-scan) for grouting condition

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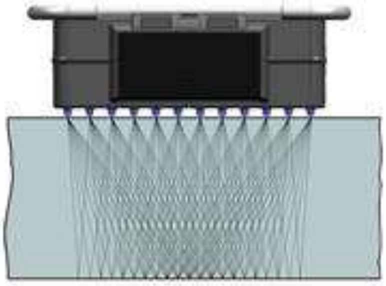
Task (2) locating tendon ducts + identification of the condition of the grout materials

Ultrasonic equipment and scanner system in BAM laboratory



Acsys MIRA A1040

Acsys A1220

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Task (2) locating tendon ducts + identification of the condition of the grout materials

Research Needs

Linear array (ACSYS MIRA A1040) should be tested in comprehensive experiments at new specimens.
Improvement of the ultrasonic echo imaging technique with SAFT including phase evaluation.

Special evaluation algorithms with back propagation and RTM (reverse time migration).

Hardware: development of transducers with adapted focusing range.
Size and area of synthetic aperture should be extended.

To improve the performance, the development of larger automated equipment to scan the surfaces should be done.

New vision: air coupled ultrasound application with new types of nano sensors.

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Task (3) **detection of cracking, voids, delamination and honeycombing in concrete structures**

Methods very well suited for the described task:

- none

Methods well suited for the described task:

- imaging ultrasonic echo (delaminations, cracks, voids) in a depth range < 100 cm
- impact echo (delaminations) in a depth range < 50 cm

Methods partially suited for the described task:

- imaging ultrasonic echo (honeycombs) in a depth range < 100 cm
- ultrasound, surface + lamb + diffracted waves (delaminations, cracks, voids) in a depth range < 50 cm
- impact echo (cracks, voids) in a depth range < 50 cm

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Task (3) **detection of cracking, voids, delamination and honeycombing in concrete structures**

Research Needs

It would be beneficial to do a comprehensive analysis of inspection records to collect information about the most typical defects in containments and related NPP-structures. Following this, the design of a mock-up for the typical NPP-containments with typical artificial defects (vertical cracks surface, near surface crack, irregular crack or deep delamination, honeycombing) can be made.

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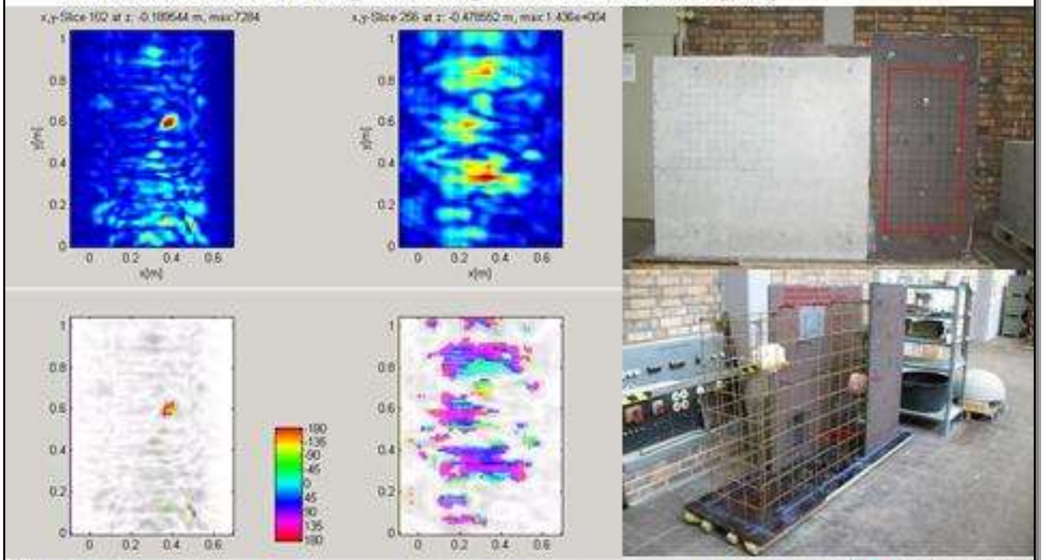
Task (3) detection of cracking, voids, delamination and honeycombing in concrete structures

Identification of voids and honeycombs using the ACSYS A1040 MIRA (BAM)



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Task (4) detection of inclusions of different materials or voids adjacent to the concrete side of the containment liner

Methods well or very well suited for the described task:

- none

Methods partially suited for the described task:

- imaging ultrasound with large aperture (location, material), depth range ~ 2 m

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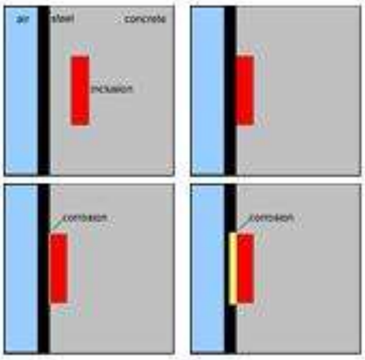
Task (4) detection of inclusions of different materials or voids adjacent to the concrete side of the containment liner

Four different scenarios may be of interest:

- Concrete layer between liner and inclusion
- Direct contact between inclusion and liner
- Early stage liner corrosion
- Significant liner thickness loss



Research Needs

To assess the ability of the techniques mentioned above to detect inclusions of anomalous material properties it is recommended to perform a series of test at full scale mockups, including all scenarios described above. In a first phase existing techniques should be assessed. Further research and development has to be discussed after evaluating the results.

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Task (5) methods capable of identification of corrosion occurrence on the concrete side of the containment liner

Methods well or very well suited for the described task:

- none

Methods partially suited for the described task:

- ultrasound echo large aperture (delamination),
- ultrasound echo high frequency (indirect measurement of corrosion by determination of liner thickness)
- acoustic emission (active corrosion)

Only indirect measurements can eventually point out that corrosion in one of the above described forms has happened. While ultrasound echo with large aperture might be able to identify delaminations (which might be an indication for corrosion and loss of contact near the liner), ultrasound echo high frequency can measure the remaining liner thickness (access to liner).

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Task (5) **methods capable of identification of corrosion occurrence on the concrete side of the containment liner**

Research Needs

This task needs fundamental research.
Detection of corrosion through the steel liner or through highly reinforced thick concrete.
Has any research in this area been tried?

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Conclusions (contd.)
Biggest impact on research into NPP related NDE

- The biggest impact on research into NPP related NDE of reinforced concrete structures may be found in improvement of the **research infrastructure** and support of synergy effects.

- **Combination** of methods is one of the key areas for finding solutions to the testing tasks
- **Automation** and scanning is vital for producing high quality data which is the basis for any subsequent data analysis.

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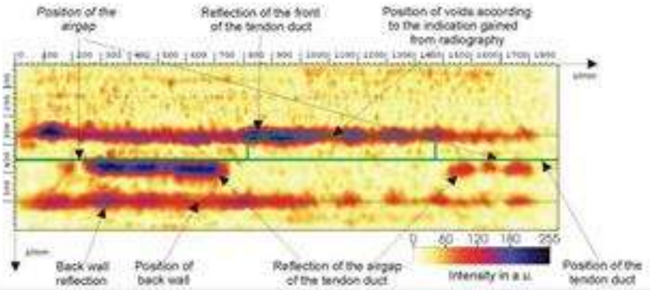
Conclusions (contd.)
Biggest impact on research into NPP related NDE

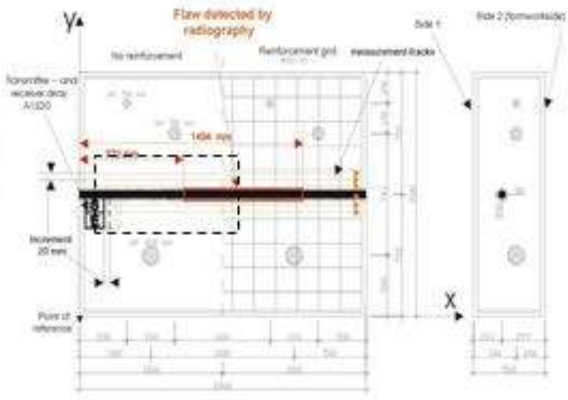
- A major role in any research is **software** for **modelling**, **simulation** and **data analysis**. It is necessary to be able to simulate a testing scenario as close as possible to reality to be able to choose the appropriate equipment and parameters for the test and the subsequent data analysis.
- A **common data format** would be a significant step towards more **collaboration** between research groups and comparability of results

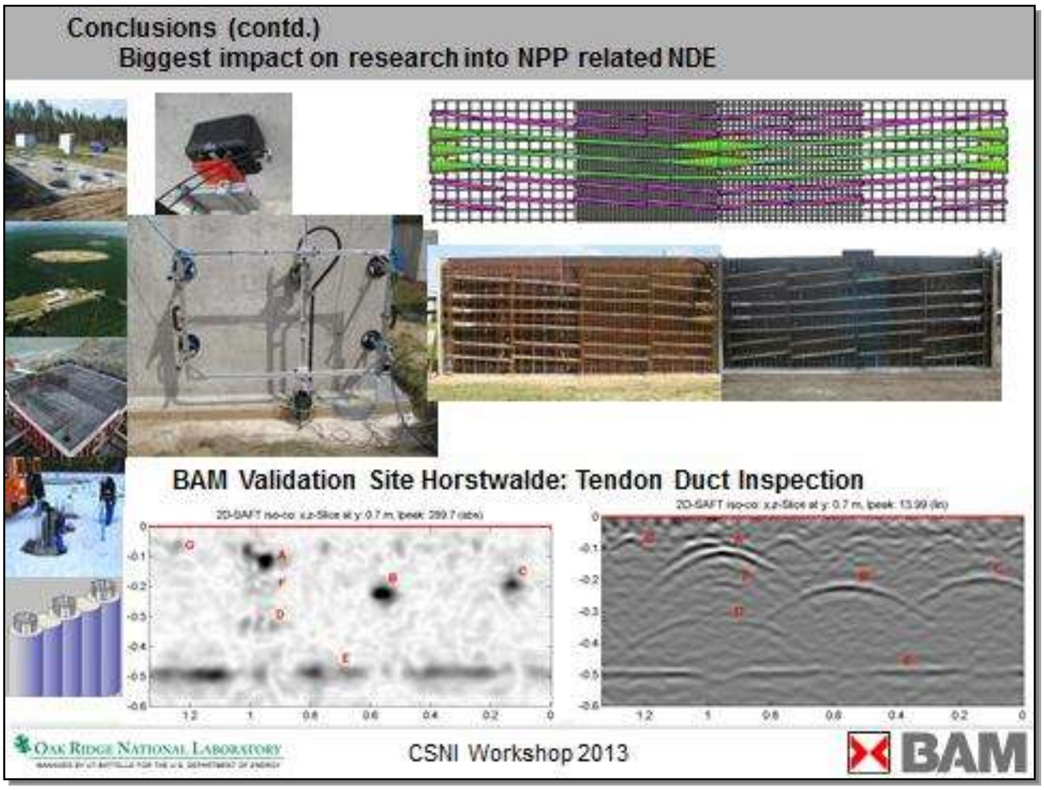
Result of imaging tendon duct in a specimen with shear waves: B-scan above the tendon duct from 3D-SAFT reconstruction.



Conclusions (contd.)
Biggest impact on research into NPP related NDE

- A **software pool** with dedicated numerical routines for data analysis, **visualization**, modeling, simulation and **validation** - as it is common in other areas of research, e.g. geophysics or medicine - would be very supportive for any NDE research and application.
- **Reference specimens** and **validation** are key elements for a streamlined research effort. Comparability of experiments and results should be assured.




Conclusions (contd.)
Biggest impact on research into NPP related NDE
BAM Validation Site Horstwalde: Tendon Duct Inspection
Oak Ridge National Laboratory
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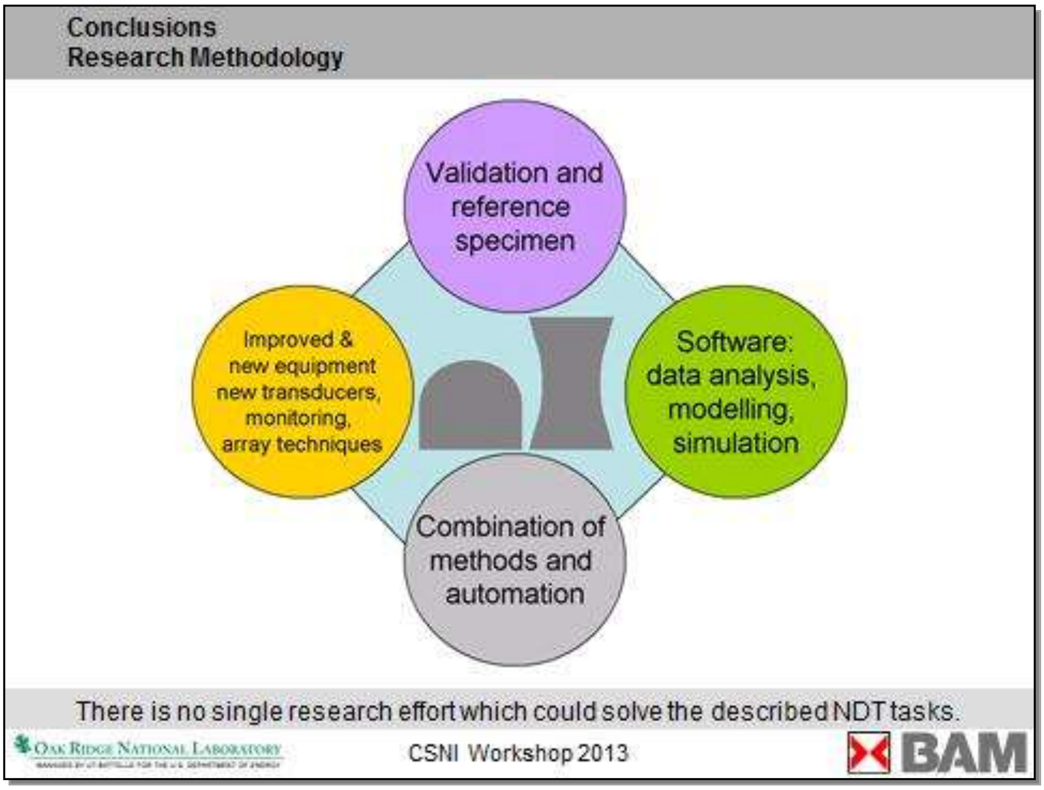
Conclusions
Research Methodology
Validation and reference specimen
Improved & new equipment new transducers, monitoring, array techniques
Software: data analysis, modelling, simulation
Combination of methods and automation
There is no single research effort which could solve the described NDT tasks.
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Thank you!

ORNL
E.M. Schilling

BAM
Dipl.-Ing. Rosemarie Helmerich
Dr. Martin Krause
Dr. Frank Mielentz
Dr. Ernst Niederleithinger
Dr. Alexander Taffe
Dipl.-Phys. Gerd Wilsch
Dipl.-Ing Christian Köpp

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NDT candidate methods for foundations/piles

- Candidate methods
  - Sonic echo
  - Impulse-response (mobility)
  - Impedance logging
  - Crosshole sonic logging
  - Parallel seismic
  - Gamma-gamma logging
- NPP basemats either partially or totally inaccessible
- Indirect methods related to environmental qualification often utilized

Item Measured	Candidate Methods or Reference
Air	
Acidity	ASTM D 1654, G 60, G 82
Carbon dioxide content	Sensors
Humidity	ASTM D 4230 and E 337
Temperature	Sensors
Soil	
Corrosivity/pH	ASTM G 51; BS 1377-3(9); BR 279
Sulfate ion concentration	ASTM D 4542; BS 1377-3(5); BR 279
Chloride ion concentration	ASTM D 4542; BS 1377(3); BR 279
Resistivity	ASTM G 57
Moisture content	ASTM D 2216, D 3017; DIN 18121-1, -2
Nitrate	BR 279
Permeability	ASTM D 2434; DIN 18130-1; prEN 1997-2; BS 8004, 5930
Groundwater	
Water table elevation/sampling	ASTM D 512, D 1293, D 4448; wells, piezometers
Corrosivity/pH	ASTM D 1067, D 1293, E 70; BR 279; BS 1377-3(9)
Hydrostatic pressure	Sensors
Dissolved oxygen content	ASTM D 888
Soluble sulfate	ASTM D 516, D 4327, D 4130, D 4327; BR 279, BS 1377-3; DIN 38406-5
Nitrate ion	ASTM 4327; BR 279
Chloride ion	ASTM D 4458, D 4327, D 512; BR 279; BS 1377-3(7)
Carbon dioxide content	EN 13577
Microorganisms/bacteria	ASTM D 4412

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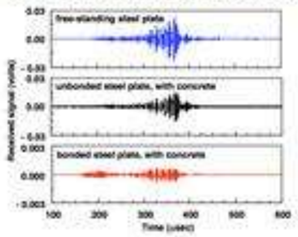
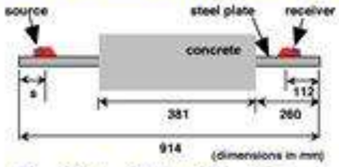
General comments on NDT techniques addressing containment metallic pressure boundaries

High-frequency acoustic imaging – effect of concrete and bond



Effect of Concrete and Bond on Signal



Steel Plates 914 x 203 x 25.4 mm³
w and w/o flaws Embedded in Concrete

- Inaccessible portions of containment metallic pressure boundary have experienced corrosion
- Available NDT techniques are time-consuming and costly because they generally examine only a small area at a time
- Concrete bonded to metallic pressure boundary can result in significant signal attenuation
- Techniques utilizing guided waves that interrogate specimen cross-section appear promising
- Additional activities are required to develop global inspection system as well as to characterize defects and assess flaw significance
- Lucius Pitkin/EPRI/DOE is looking at feasibility of tandem- synthetic aperture focusing technique and magnetostrictive sensors to detect corrosion in inaccessible areas

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Maintaining the post-tensioning system components in good working order is essential for prestressed concrete members

Example of multistrand tendon system

PT system examination

- Force determinations
- Mechanical tests
- Grease tests
- Anchorage inspections

- Current examination programs adequate for determining condition of PT tendon materials and evaluating effects of conventional degradation
- Conventional material degradation has not been a significant aging concern, but isolated incidences of wire failure due to corrosion have occurred
- Leakage of tendon sheathing filler (except for loss of corrosion protection) appears to be primarily an aesthetic problem
- Tendon forces at most plants are acceptable by a significant margin, but larger than anticipated loss of force has occurred in a few older plants
- What is the exact relationship between end-anchorage force measured by lift-off test and change in mean force along tendon length?
- Estimation of time-dependent loss of prestressing force is based on limited duration relaxation tests (e.g., 1000 h) and concrete creep results (e.g., 6 mo). What is validity of extrapolation of these results by time factors of ~ 500 and 120 (60 yr life)

Post-tensioning system degradation affects when concrete cracks and steel reinforcement yields

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General comments:

- Operating experience
  - Performance of concrete structures in NPPs has generally been good with majority of early problems primarily related to construction/design deficiencies or material selection problems that have been addressed
  - As the structures age and scope of inspection programs expands, increasing incidences of degradation are likely to occur, primarily due to environmental effects
  - Periodic inspection, maintenance, and repair are essential elements of an overall program to maintain an acceptable level of reliability for the structures
- Damage models and acceptance criteria for current and future condition assessments
  - Methods for conduct of condition assessments are fairly well established and generally start with a visual examination of the structure's exposed surfaces
  - Development and validation of improved damage models (including synergistic effects) and guidelines for their use are required for improved service life assessments and to predict failure probability, either at present or some future point in time
  - Collection of data and information from aged structures can be used to help provide an improved characterization of service environments, understanding of degradation mechanisms, and evaluate the impact of aging and environmental stressors on material properties and structural margins
  - Improved and more specific acceptance criteria for concrete degradation on both a deterministic and probabilistic basis (e.g., concrete cracking and ASR) is desired

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General comments (cont.):

- Several areas identified where improvements or development of NDT techniques is desirable
  - Techniques that can identify weld defects in stainless steel liners of spent fuel pools and reactor refueling cavities
  - Global inspection methods for metallic pressure boundary components including inaccessible areas and backside of liner
  - Non-intrusive techniques for inspection of thick-walled, heavily-reinforced concrete structures and basemats
  - Real-time techniques to monitor post-tensioning systems for tendon wire failures and level of stressing
  - Determination of grout continuity in grouted-tendon systems
- Repair of NPP concrete structures is an area requiring further investigation
  - Nuclear Energy Standards Coordinating Committee (NESCC) has drafted a report that identifies relevant repair standards and areas to be addressed in order to provide an improved basis for repair of NPP concrete structures
  - No repair code that specifically addresses nuclear structures
  - Guidelines are required on application of repair strategies to enhance structural reliability
  - Performance characteristics (e.g., effectiveness and durability) of candidate repair materials and techniques are required

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General comments (concl.):

- Extend application of time-dependent reliability-based approach
  - Evaluation of structures for continued service should provide quantitative evidence that their capacity is sufficient to withstand future demands within the proposed service period with a level of reliability sufficient to ensure public health and safety
    - Structural aging may cause the integrity of structures to evolve over time
    - Uncertainties that complicate the evaluation of aging effects arise from a number of sources and any evaluation of the reliability or safety margins of a structure during its service life must take these sources into account
    - Structural reliability analysis methods provide the framework for dealing with uncertainties
  - Assess the current and future performance of degraded structures
    - Hazard function [conditional probability of failure within the time interval (t,t+Dt) given that the component has survived up to t] is used to analyze structural failures due to aging
    - Fragility analysis (depicts the role of uncertainties in response of structures to specified challenges) provides a structured framework to:
      - Identify aging factors important to safety;
      - Identify areas where the potential for degradation to impact safety is important;
      - Focus in-service inspection, maintenance, and repair;
      - Guide acquisition of additional data; and
      - Make risk-informed service decisions regarding continued service
    - Develop risk-informed condition assessment guidelines for evaluating the performance of aging structures
    - Formulate in-service inspection/maintenance strategies aimed at ensuring that structures maintain a desired performance level

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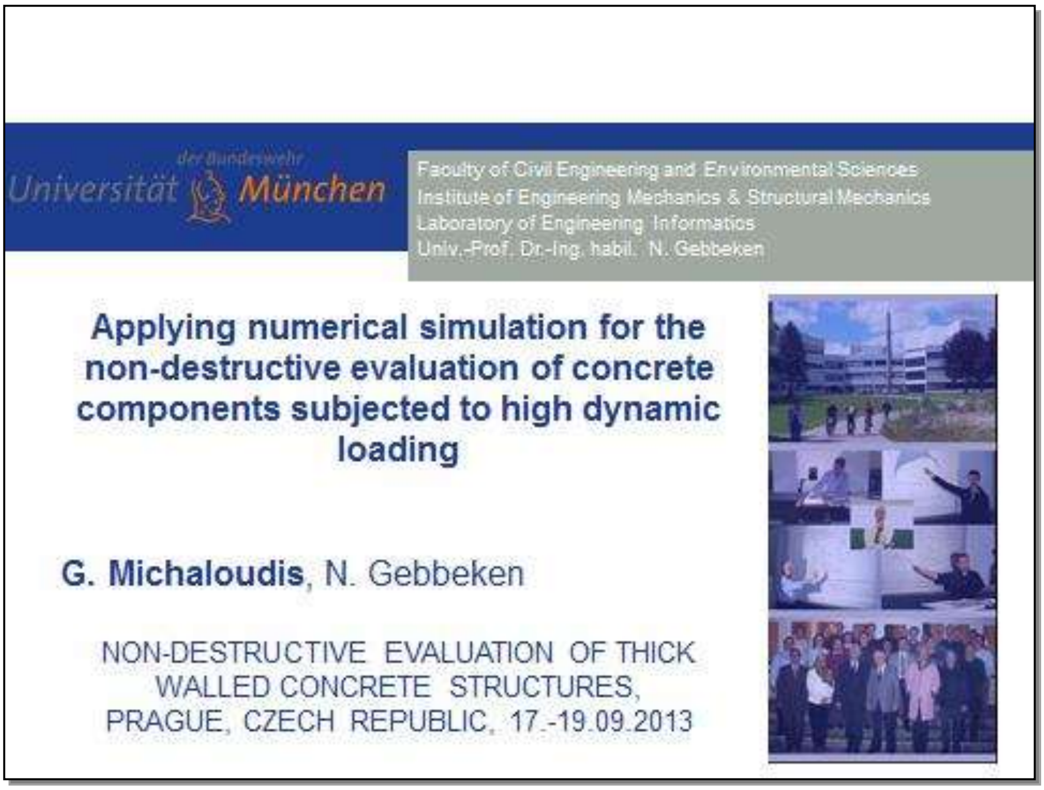
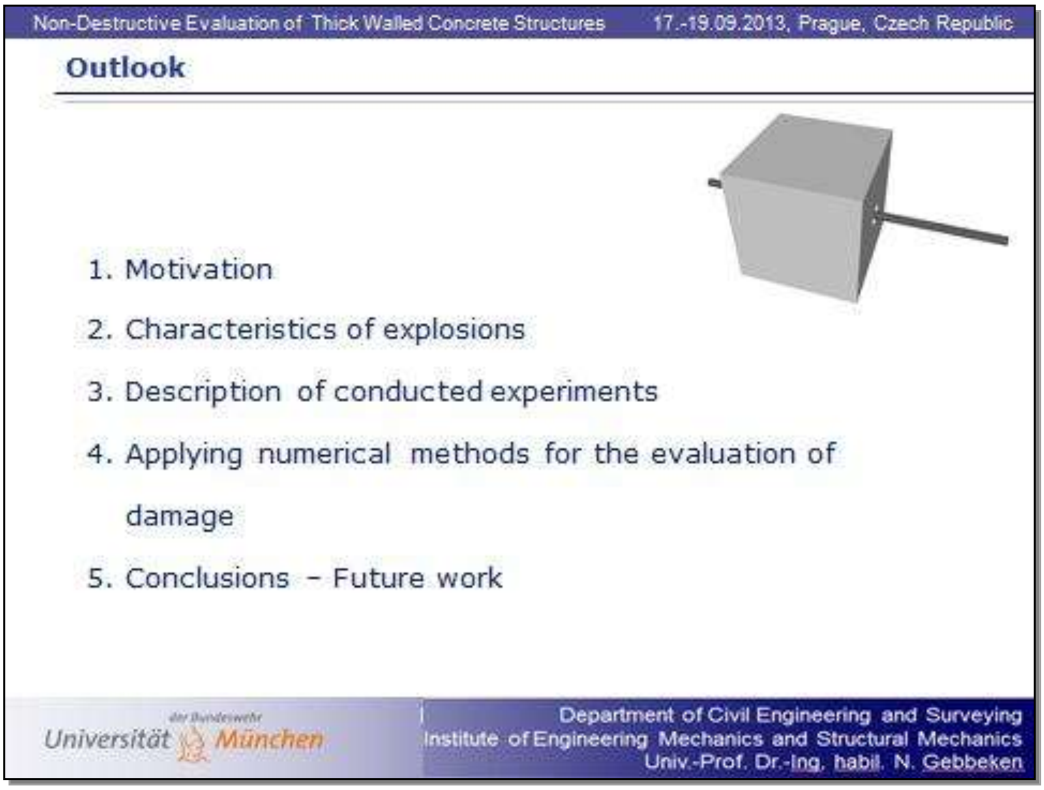

Universität der Bundeswehr München
Faculty of Civil Engineering and Environmental Sciences
Institute of Engineering Mechanics & Structural Mechanics
Laboratory of Engineering Informatics
Univ.-Prof. Dr.-Ing. habil. N. Gebbeken
Applying numerical simulation for the non-destructive evaluation of concrete components subjected to high dynamic loading
G. Michaloudis, N. Gebbeken
NON-DESTRUCTIVE EVALUATION OF THICK WALLED CONCRETE STRUCTURES, PRAGUE, CZECH REPUBLIC, 17.-19.09.2013


Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Outlook
1. Motivation
2. Characteristics of explosions
3. Description of conducted experiments
4. Applying numerical methods for the evaluation of damage
5. Conclusions – Future work
Universität der Bundeswehr München
Department of Civil Engineering and Surveying
Institute of Engineering Mechanics and Structural Mechanics
Univ.-Prof. Dr.-Ing. habil. N. Gebbeken


Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Motivation
Load carrying capacity tests of RC-plates
[WTD 52]
Universität der Bundeswehr München
Department of Civil Engineering and Surveying
Institute of Engineering Mechanics and Structural Mechanics
Univ.-Prof. Dr.-Ing. habil. N. Gebbeken


Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Motivation
Load carrying capacity tests of RC-plates
[Mangerig 2002]
Universität der Bundeswehr München
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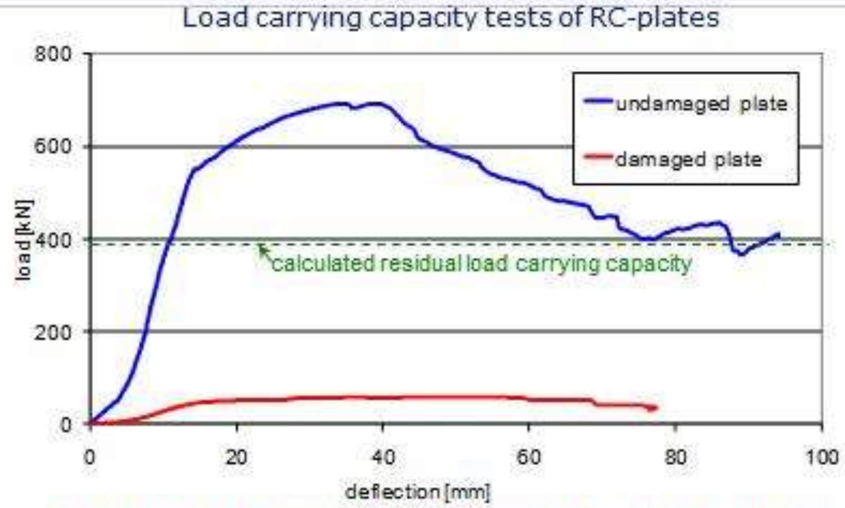
Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Motivation



Goal: Calculate the load carrying capacity of concrete structural members, partially damaged due to blast loading

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Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Characteristics of Explosions

Categorization of Explosions with respect to its:

a) Velocity of Propagation through the air

- Deflagration (subsonic propagation)
- Detonation (supersonic propagation)

b) Distance from the target (Scaled Distance $z = R/W^{1/3}$, R=distance, W=Mass of explosive material):

- Contact Explosion
- Close Range Explosion (z<0.5)
- Wide Range Explosion (z>0.5)

- Explosion → Propagation of large amounts of energy within microseconds
- Typical detonation velocities: 8000-10000 m/s
- Creation of a shock wave

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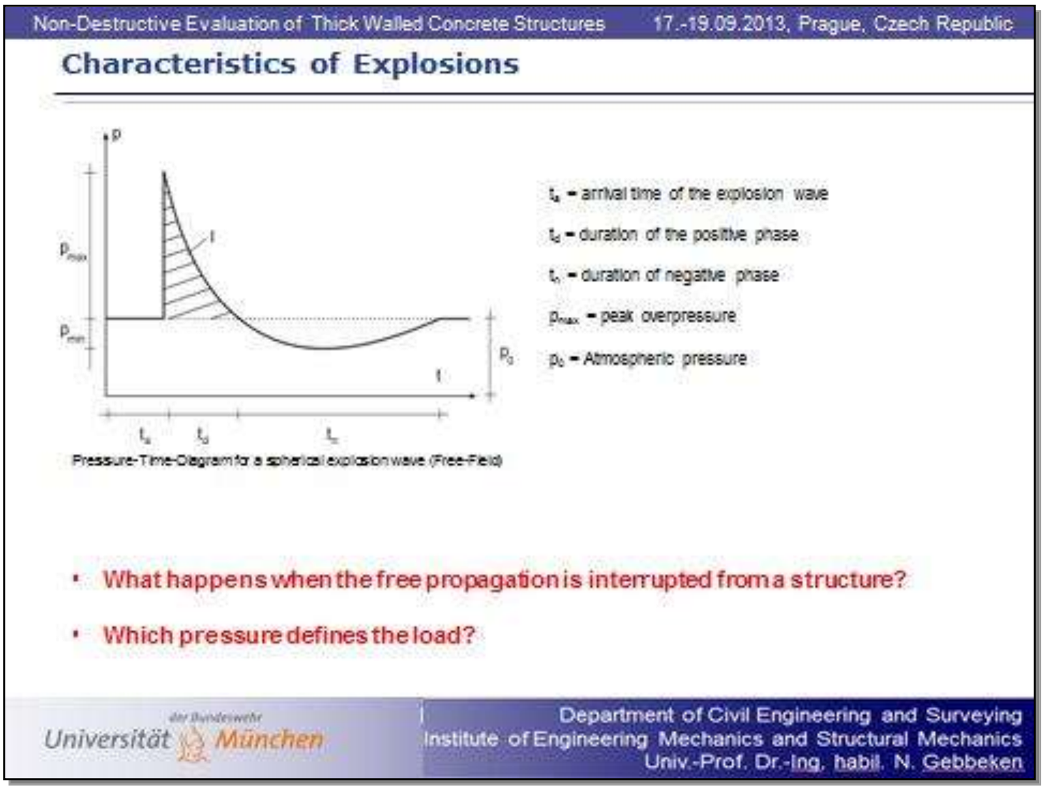
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Characteristics of Explosions
p
p_{max}
p_{min}
I
t
p_0
t_a
t_d
t_n
Pressure-Time-Diagram for a spherical explosion wave (Free-Field)
t_a = arrival time of the explosion wave
t_d = duration of the positive phase
t_n = duration of negative phase
p_{max} = peak overpressure
p_0 = Atmospheric pressure
• What happens when the free propagation is interrupted from a structure?
• Which pressure defines the load?
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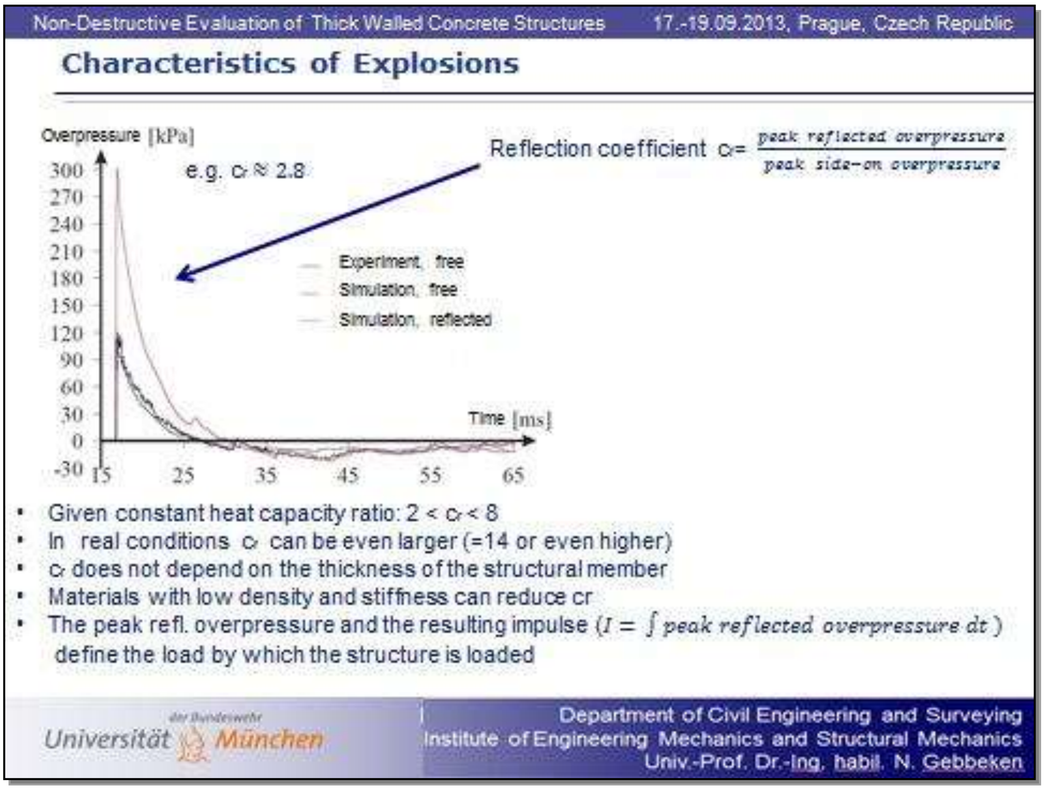
Univ.-Prof. Dr.-Ing. habil. N. Gebbeken


Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Characteristics of Explosions
Overpressure [kPa]
e.g. $c_r \approx 2.8$
Reflection coefficient $c_r = \frac{peak\ reflected\ overpressure}{peak\ side\text{-}on\ overpressure}$
Experiment, free
Simulation, free
Simulation, reflected
Time [ms]
300
270
240
210
180
150
120
90
60
30
0
-30
15
25
35
45
55
65
• Given constant heat capacity ratio: $2 < c_r < 8$
• In real conditions c_r can be even larger (=14 or even higher)
• c_r does not depend on the thickness of the structural member
• Materials with low density and stiffness can reduce cr
• The peak refl. overpressure and the resulting impulse ($I = \int peak\ reflected\ overpressure\ dt$) define the load by which the structure is loaded
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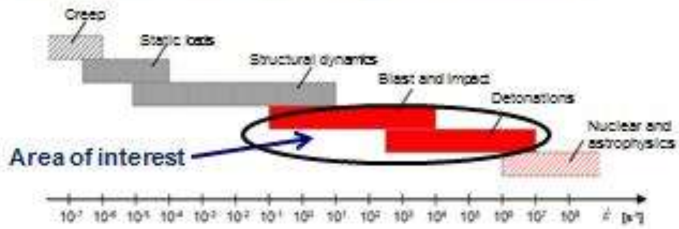
Department of Civil Engineering and Surveying
Institute of Engineering Mechanics and Structural Mechanics
Univ.-Prof. Dr.-Ing. habil. N. Gebbeken

Characteristics of Explosions

Equation of State for the air:

- Ideal Gas
- $pV = mRT$ *(ideal gas law)*
- $U = m\,c(v)\,T$ *(internal energy)*

Resulting strain rates of a material subjected to a blast load:



Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Description of conducted experiments

- Blast experiments on reinforced and unreinforced concrete structural members at WTD52
- Cubes (dimension of specimen: 150 x 150 x 150 mm), columns, plates
- Different masses of explosive material and distances to the specimen tested
- Several diameters of reinforcement and bond lengths tested

[WTD 52]

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Institute of Engineering Mechanics and Structural Mechanics
Univ.-Prof. Dr.-Ing. habil. N. Gebbeken

Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Description of conducted experiments

- Scenarios leading to

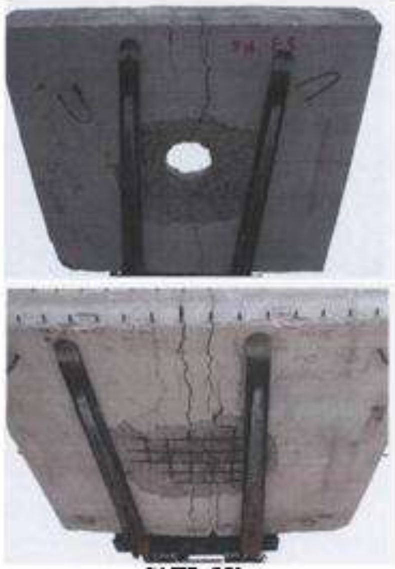
a) negligible damage

b) severe damage

c) total damage

are tested

- In a second phase the structural members are tested regarding their residual loading carrying capacity → Static tests



[WTD 52]

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Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Description of conducted experiments

[Institute of Structural Engineering, Universität der Bundeswehr München]

- Compression tests
- Pull-out tests
- Bending tests

} Evaluation of the residual load carrying capacity of the damaged structural members

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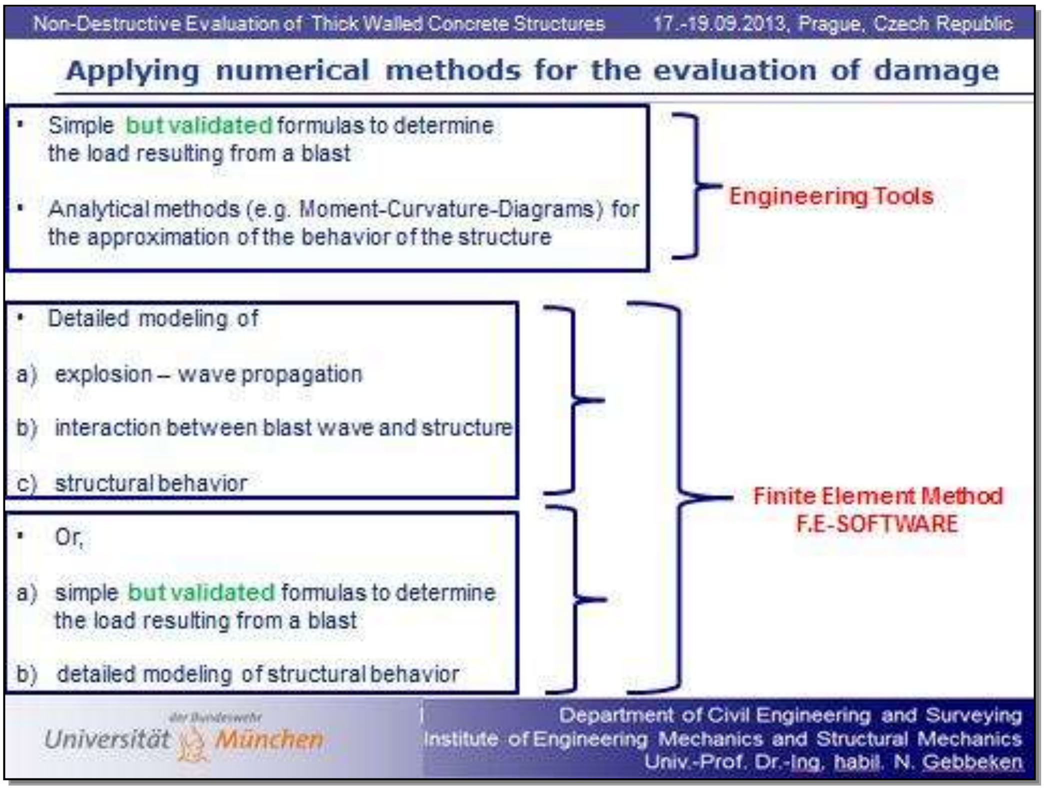
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Applying numerical methods for the evaluation of damage
• Simple but validated formulas to determine the load resulting from a blast
• Analytical methods (e.g. Moment-Curvature-Diagrams) for the approximation of the behavior of the structure
Engineering Tools
• Detailed modeling of
a) explosion – wave propagation
b) interaction between blast wave and structure
c) structural behavior
• Or,
a) simple but validated formulas to determine the load resulting from a blast
b) detailed modeling of structural behavior
Finite Element Method
F.E-SOFTWARE
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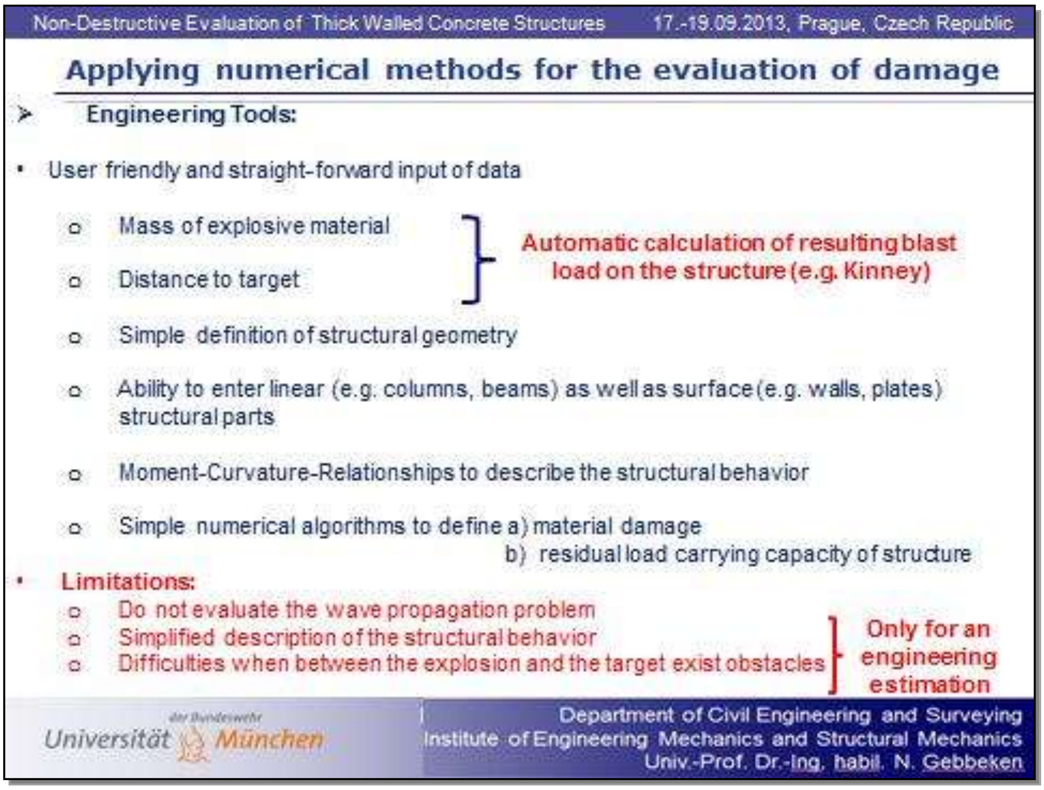
Non-Destructive Evaluation of Thick Walled Concrete Structures
17.-19.09.2013, Prague, Czech Republic
Applying numerical methods for the evaluation of damage
➢ Engineering Tools:
• User friendly and straight-forward input of data
○ Mass of explosive material
○ Distance to target
Automatic calculation of resulting blast load on the structure (e.g. Kinney)
○ Simple definition of structural geometry
○ Ability to enter linear (e.g. columns, beams) as well as surface (e.g. walls, plates) structural parts
○ Moment-Curvature-Relationships to describe the structural behavior
○ Simple numerical algorithms to define a) material damage
b) residual load carrying capacity of structure
• Limitations:
○ Do not evaluate the wave propagation problem
○ Simplified description of the structural behavior
○ Difficulties when between the explosion and the target exist obstacles
Only for an engineering estimation
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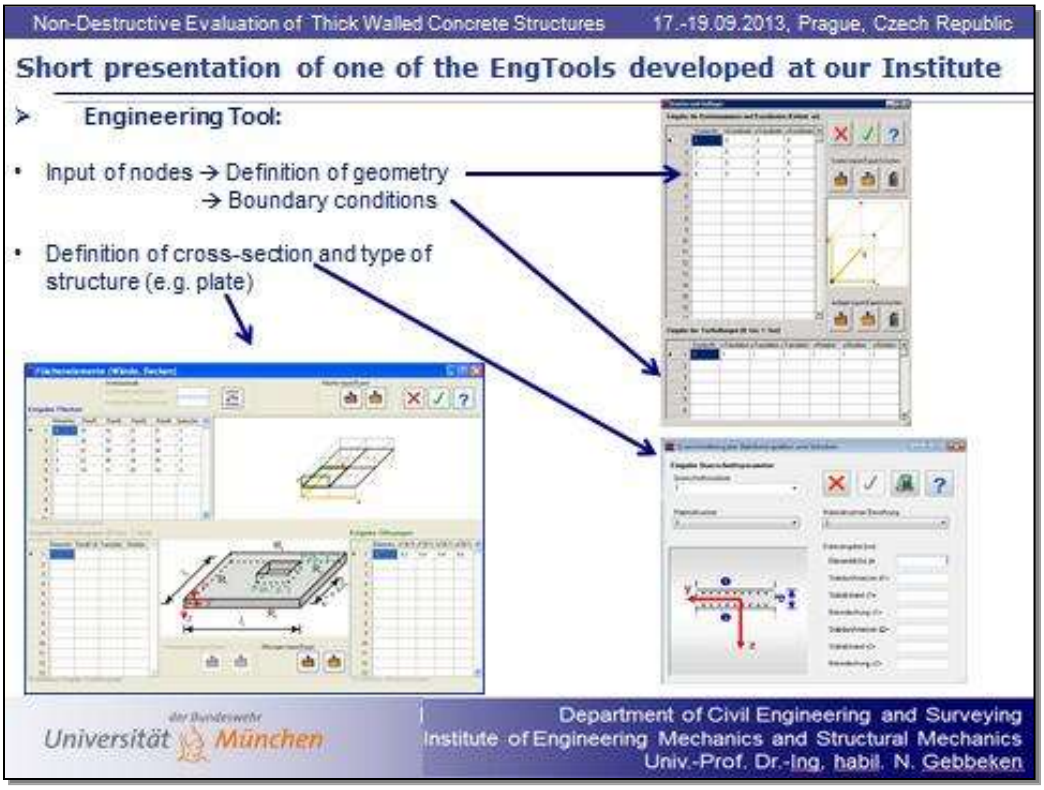
Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic
Short presentation of one of the EngTools developed at our Institute
Engineering Tool:
Input of nodes → Definition of geometry
→ Boundary conditions
Definition of cross-section and type of structure (e.g. plate)
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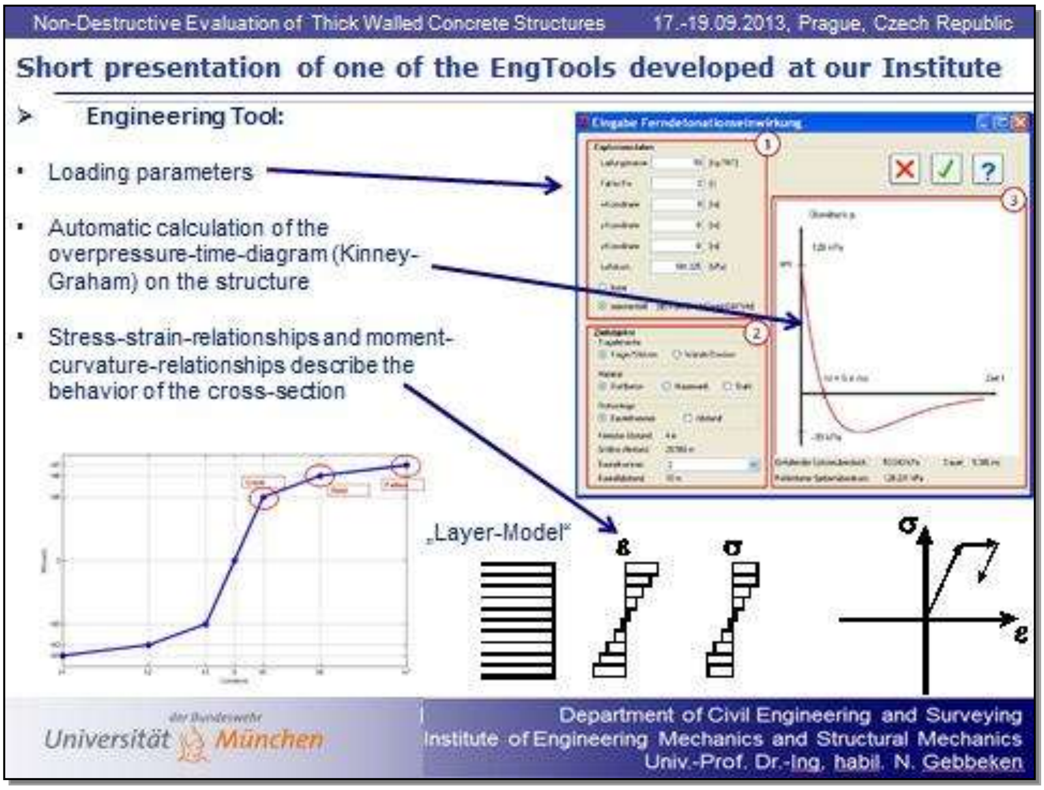
Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic
Short presentation of one of the EngTools developed at our Institute
Engineering Tool:
Loading parameters
Automatic calculation of the overpressure-time-diagram (Kinney-Graham) on the structure
Stress-strain-relationships and moment-curvature-relationships describe the behavior of the cross-section
Eingabe Ferndetonationseinwirkung
„Layer-Model"
ε
σ
σ
ε
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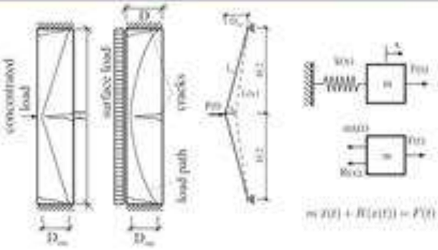
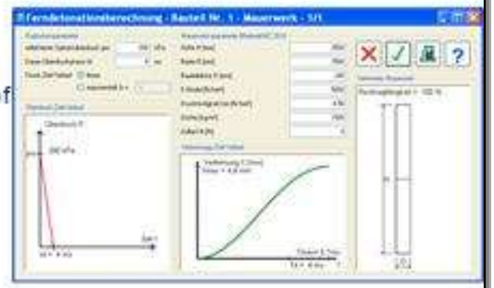


- **Engineering Tool:**
  - Simplified models, e.g. Single-degree-of-freedom system describe the behavior of the structural part
  - The EngTool calculates the deformation-time-diagram for the structural part and also the moment-time-diagram for the cross-sections
  - Delivers as final result the residual load carrying capacity of the part and also the strain condition of the different layers of the cross section. It categorizes them in 3 conditions:

a) Totally elastic
b) Plastic-partly damaged
c) Totally damaged



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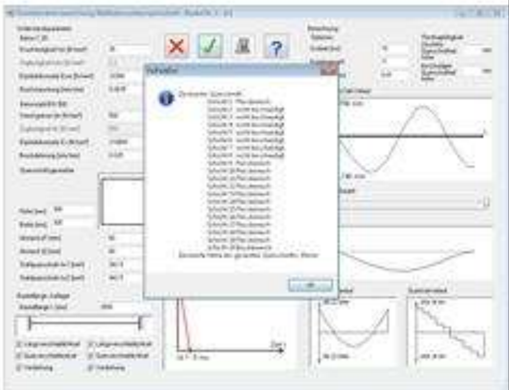

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Applying detailed FE-Models

Goal: Simulation of the entire experimental procedure – Describe all occurring phenomena

1. Simulation of the explosion
2. Capture the wave propagation phenomenon
3. Calculate the resulting strain and stresses of the structural part
4. Evaluate the damage of the material
5. Take into account the computed damage in order to evaluate the new condition of the structural part
6. Calculate its Residual Load Carrying Capacity (R.L.C.C.)

Up to now within this research project have been tested:

- Cubic specimens, with and without reinforcement
- Reinforced concrete plates

The numerical models are created and computed with:

- ANSYS-AUTODYN + SOFISTIK (one computational scheme), or/and
- LS-DYNA (second computational scheme)

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Applying detailed FE-Models

- **General aspects of the numerical simulation**

1. Create an appropriate Euler mesh for the wave propagation (convergence study – meshes in the of mm up to 2-3 cm in the areas of high pressures)
2. Choose the parameters of the explosive material (explosion velocity, internal energy etc.)
3. Describe the complicated interaction between the shock-wave and the structure (ALE algorithms)
4. Create an appropriate Lagrange mesh for the structure
5. Choose appropriate material models for the structure

- Modern F.E Codes provide adequate solutions to all these aspects
- Parallel computing allows the use of complicated algorithms and models with large numbers of degrees of freedom per model

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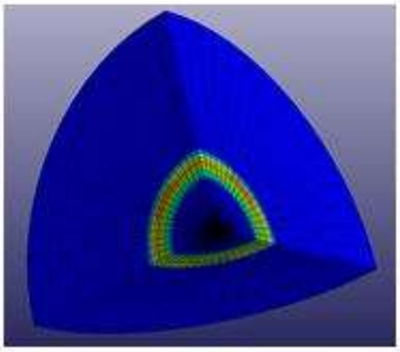
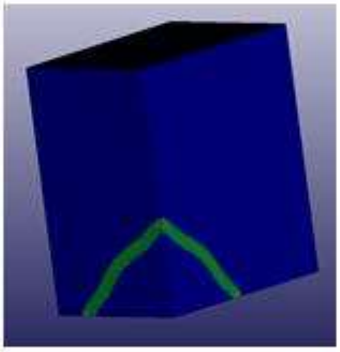
Applying detailed F.E Models

- **Case of explosion of a spherical shaped explosive with an expected spherical propagation: Does the geometry of the Euler mesh matter?**
- This symmetrical problem remains symmetrical only if it is described in spherical coordinates
- If Cartesian coordinates are used, the equations are no more symmetrical → artificial phenomena





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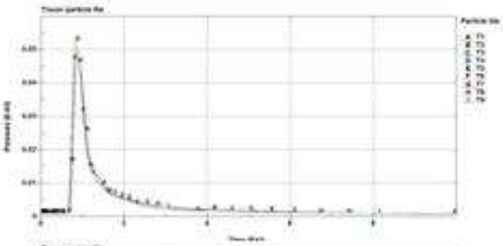
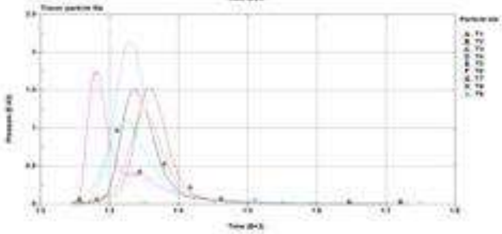
Applying detailed F.E Models

- Expected: Time of arrival and resulting pressure at equal radial distances from explosion to be equal → Symmetric problem
- Time of arrival and pressure are measured on radial distances of 1,5 m from the explosion



- Spherical coordinates



- Cartesian coordinates

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Applying detailed F.E Models

- Spherical coordinates: very similar pressure and identical times of arrival
- Cartesian coordinates: error imposed due to the cancelation of the symmetry condition

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Applying detailed F.E Models

- **Cubic specimens – Simple models to validate complicated numerical algorithms**
- General simulation strategy:

Goal: Simulation of the entire experimental procedure – Describe all occurring phenomena

1. Simulation of the explosion
2. Capture the wave propagation phenomenon
3. Calculate the damage of the material
4. Transfer the values of damage to the F.E-Model – Input for the material model
5. Calculate the Residual Load Carrying Capacity (R.L.C.C.) of the specimen

Steps 1-3:
Explicit dynamic computation → AUTODYN

Step 5:
Static F.E computation → SOFISTIK

Detailed models necessary – As consistent as possible

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Applying detailed F.E Models

AUTODYN: Explicit Hydrocode

- Appropriate for mixed-domain, multi-physics modeling
- Tool for simulating dynamic high velocity events:
  - High speed impacts
  - Mine explosions
  - Blasts in and around buildings
- Coupling of Lagrangian-Eulerian meshes possible
- Solvers for computational structural dynamics (computation of: deformations, stresses, damage etc.)

Powerful tool for solving numerical problems with large deformations on short time scales

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Applying detailed F.E Models

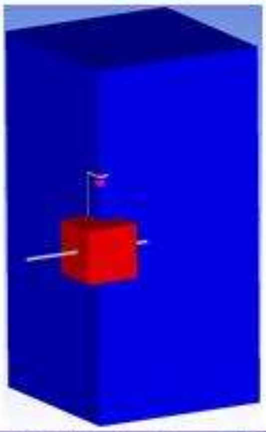
Euler-Mesh

- Air
- Explosion material
- Wooden box (Consideration of inertia phenomena)

Euler-Lagrange Interaction

Lagrange-Mesh

- Concrete specimen
- Steel



Material models in AUTODYN:

- Air: Ideal gas
- Explosion Material: AUTODYN PETN 1.5
- Wooden Box: Polynomial EOS
- Concrete: AUTODYN CONC -35MPA
- Reinforcement: Linear elastic behavior

Meshes created:

- Unreinforced specimen: 1.25 mm – 1.728.000 Elements
- Reinforced specimen : 1.875 mm ≈ 700.000, 1.25 mm ≈ 2.200.000 Elements

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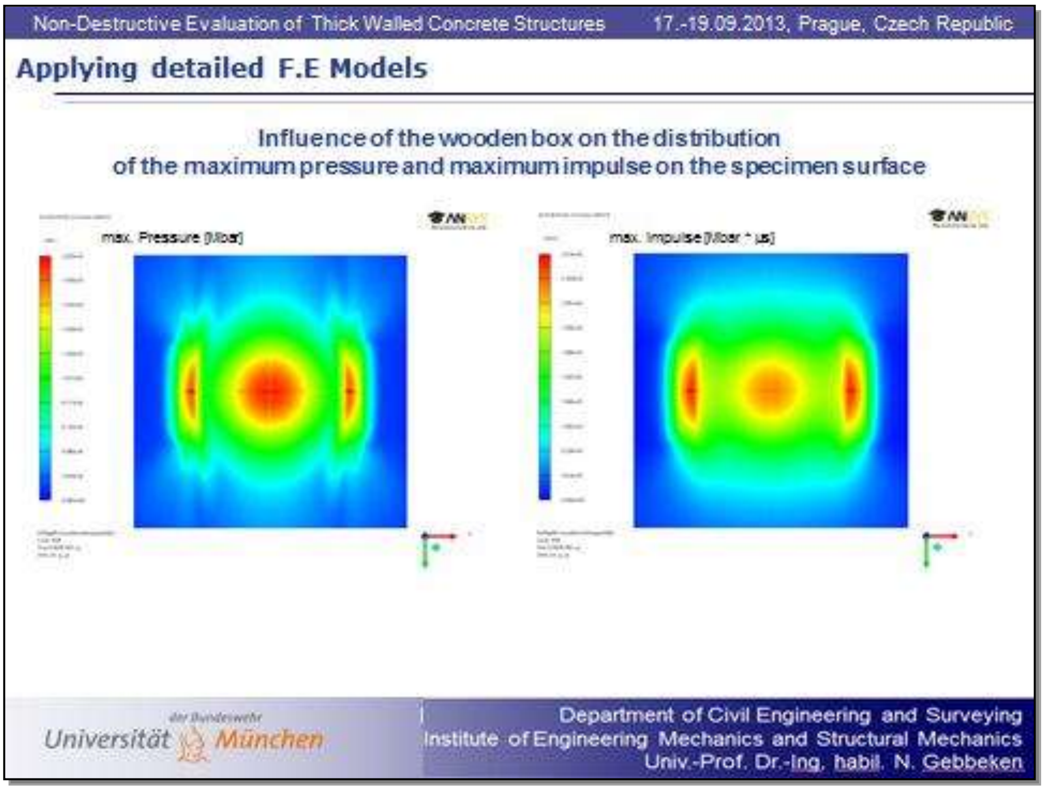
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17.-19.09.2013, Prague, Czech Republic
Applying detailed F.E Models
Influence of the wooden box on the distribution
of the maximum pressure and maximum impulse on the specimen surface
max. Pressure [Mbar]
max. Impulse [Mbar * µs]
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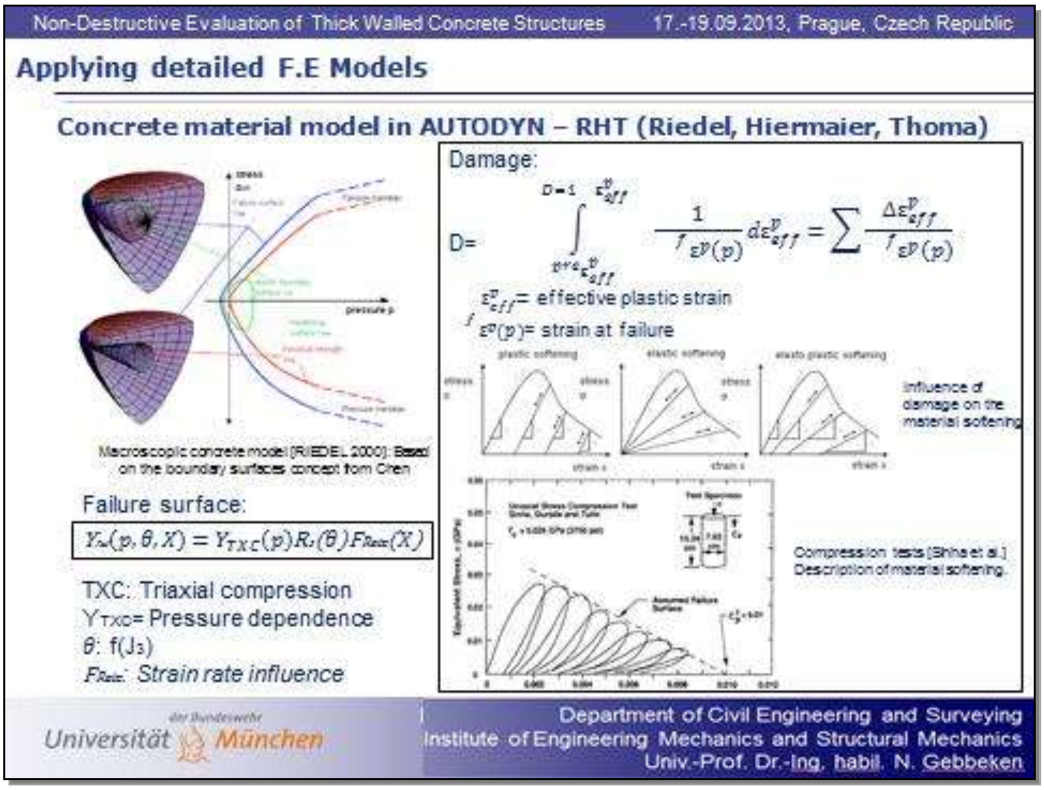
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Applying detailed F.E Models
Concrete material model in AUTODYN – RHT (Riedel, Hiermaier, Thoma)
Damage:
$D = \int_{pre\varepsilon^p_{eff}}^{D=1\ \varepsilon^p_{eff}} \frac{1}{^f\varepsilon^p(p)} d\varepsilon^p_{eff} = \sum \frac{\Delta\varepsilon^p_{eff}}{^f\varepsilon^p(p)}$
ε^p_{eff} = effective plastic strain
$^f\varepsilon^p(p)$ = strain at failure
plastic softening
elastic softening
elasto plastic softening
Influence of damage on the material softening
pressure p
Macroscopic concrete model [RIEDEL 2000]: Based on the boundary surfaces concept from Chen
Failure surface:
$Y_{fail}(p,\theta,\dot{X}) = Y_{TXC}(p)R_3(\theta)F_{Rate}(\dot{X})$
TXC: Triaxial compression
Y_{TXC}= Pressure dependence
θ: $f(J_3)$
F_{Rate}: Strain rate influence
Compression tests [Sinha et al.]
Description of material softening
Assumed Failure Surface
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Applying detailed F.E Models

Concrete material model in SOFISTIK – LADE

$$f = I_1^3 - \left(27 + p_1 \cdot \left(\frac{p_a}{I_1}\right)^m\right) \cdot I_3 = 0$$

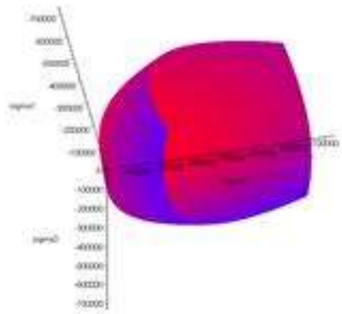
p_a – atmospheric pressure
m – shape factor

$$I_1 = -f_t - f_t - (f_t + f_c)$$

$$I_3 = (-f_t) \cdot (-f_t) \cdot (-f_t - f_c)$$

$$f_c(D) = f_{c,0} - D \cdot (f_{c,0} - f_{c,dam})$$

$$f_t(D) = f_{t,0} - D \cdot (f_{t,0} - f_{t,dam})$$



Lade, P.V., Failure Criterion for Frictional Materials, Mechanics of Engineering Materials, pp. 385–402 (1984)

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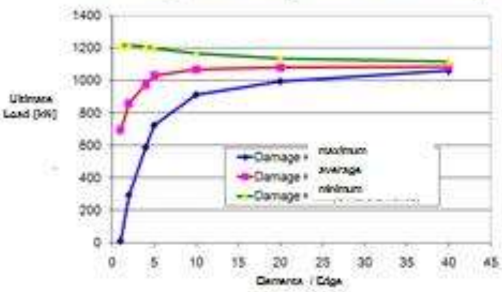
Applying detailed F.E Models

- Transfer the damage values from AUTODYN to SOFISTIK model → Input parameters for the material model
- Coarser mesh for the static analysis in SOFISTIK applicable
- Search algorithm: which AUTODYN elements belong to each SOFISTIK element
- Element wise calculation of damage in SOFISTIK
  → Average of damage values of corresponding AUTODYN elements



Bond:

- Rigid connection between concrete and steel elements on the interface
- Carrying capacity of bond = Carrying capacity of concrete
- Excess of the carrying capacity of concrete → Failure of the bond

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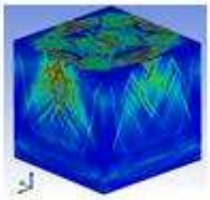
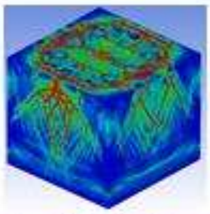
Applying detailed F.E Models

AUTODYN – Unreinforced specimens – Mesh size: 1.25mm

Explosion Material [g PETN]	Distance [cm]	Damage picture
30	8	
40	10	

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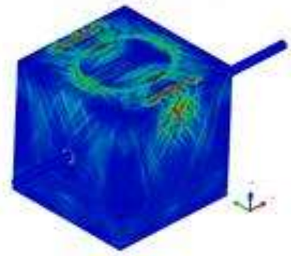
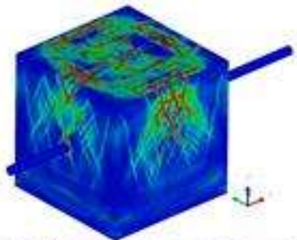
Applying detailed F.E Models

AUTODYN – Reinforced specimens – Mesh size: 1.25mm

Reinforcement diameter d_s Bond length l_b	Explosion material [g PETN]	Distance [cm]	Damage picture
d_s = 10 mm l_b = 100 mm	20	6	
	30	8	

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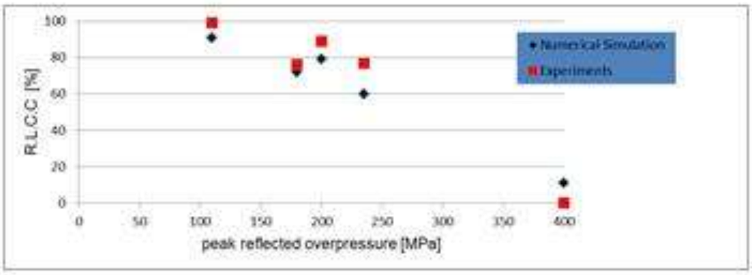
Applying detailed F.E Models

SOFISTIK– Unreinforced specimens

	Numerical results	Experiments
	R.L.C.C [%]	R.L.C.C [%]
undamaged	100	100
15g - 6cm	91	96
20g - 6cm	72	76
30g - 8cm	79	89
40g - 10cm	60	77



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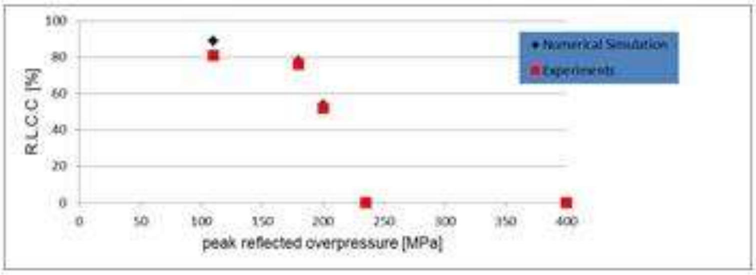
Applying detailed F.E Models

SOFISTIK– Reinforced specimens

d_s=10mm	Numerical results	Experiments
l_s=100mm	R.L.C.C [%]	R.L.C.C [%]
undamaged	100	100
15g - 6cm	89	81
20g - 6cm	88	73

d_s=10mm	Numerical results	Experiments
l_s=50mm	R.L.C.C [%]	R.L.C.C [%]
undamaged	100	100
20g - 6cm	78	77
30g - 8cm	54.5	54
40g - 10cm		



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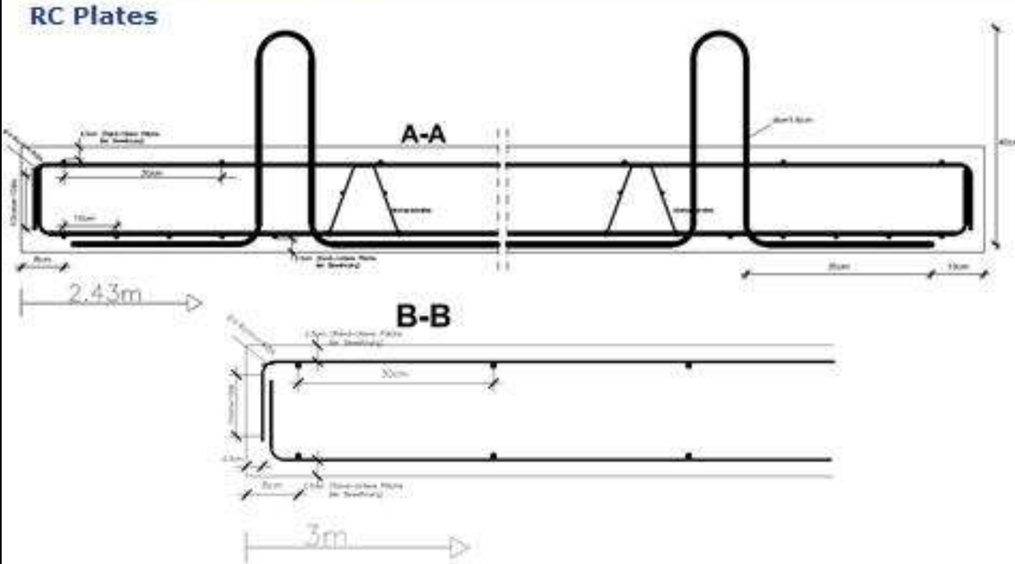
Applying detailed F.E Models

RC Plates



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Applying detailed F.E Models

Goal: Use the algorithms which have been validated with the smaller models

1. The RHT model describes the behavior of the concrete
2. Linear, hexahedral, reduced integrated with appropriate Hourglass stabilization finite elements to model the plate
3. Beam elements with elastic material assumption for the reinforcement
4. The model consists of three independent meshes: a) Lagrange for the plate, b) Lagrange for the reinforcement and c) Euler for the air
5. ALE algorithms for the interaction between air and plate
6. Special coupling between the plate and the reinforcement in order to describe the influence of the reinforcement on the behavior of the concrete
7. A large number of appropriate material models for concrete are nowadays implemented and available in commercial SOFTWARE (e.g. LS-DYNA)

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Applying detailed F.E Models

- LS-DYNA–> very efficient parallel computing algorithms: Wall times reduces from days to hours → Possible to create and compute very detailed models
- The entire experimental procedure (Explosion + Static test) can be modeled and computed within LS-DYNA → No additional SOFTWARE required → Consistent simulations

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Applying detailed F.E Models

Alternative strategy within LS-DYNA:

1. Avoid the simulation of air
2. Explosion is not modeled directly
3. Validated empirical formulas calculate the blasting load
4. Reduces strongly the number of finite elements used → Wall times reduced to minutes
5. Tests show that tends to underestimate the resulting pressures
6. Very attractive alternative due to reduced wall times
7. Adequate for cases of large distances between explosion and target

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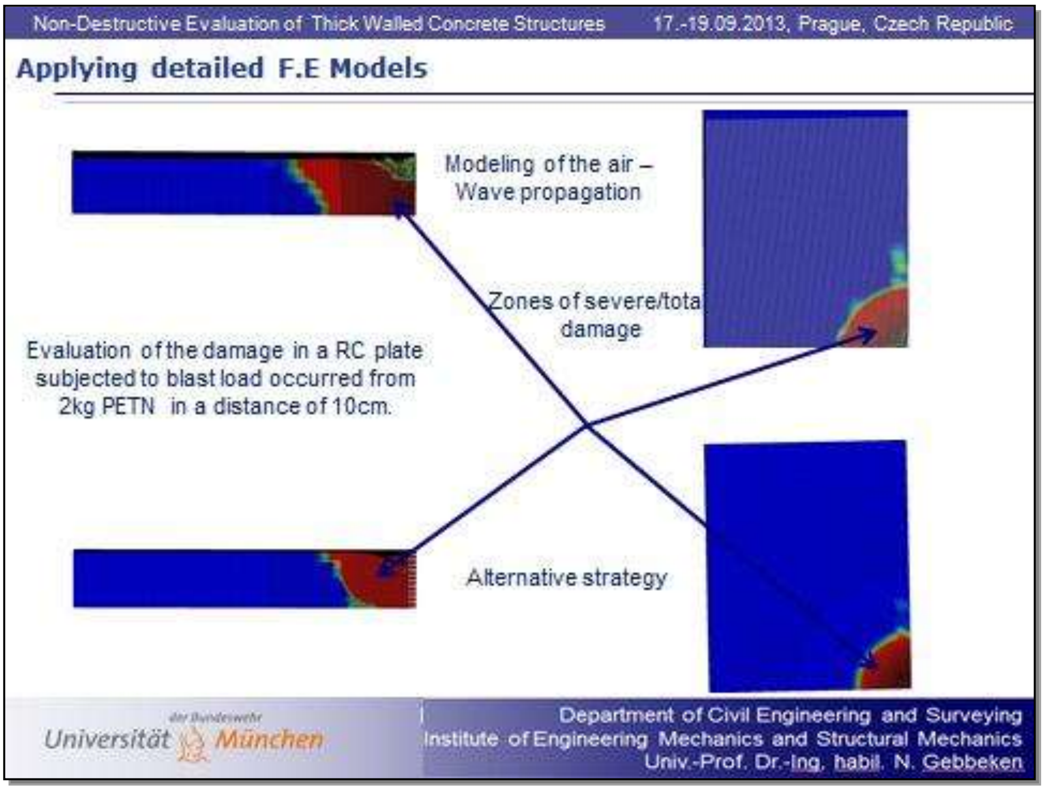

Non-Destructive Evaluation of Thick Walled Concrete Structures 17.-19.09.2013, Prague, Czech Republic

Conclusions – Future work

- EngTools: User friendly SOFTWARE – Combines simplified assumptions of structural behavior and validated formulas for the determination of the load resulting from an explosion.
- Within minutes the user can define and calculate the problem.
- Provide a good engineering solution which has limitations.
- With the Finite-Element-Method one can create detailed numerical models which describe all the aspects of the dynamic problem: explosion, wave propagation, structural response.
- A number of issues must be taken into account: reasonable meshes, appropriate material parameters, good description of interactions.
- Detailed finite element models can reach several millions degrees-of-freedom → Parallel computing is essential
- The numerical results deliver information about the **total stress-strain condition of the structural part, the developed damage, the post-damage behavior of the part → Numerical methods are a powerful modern tool for the evaluation of local and global structural response**

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Conclusions – Future work

Future work:

- Testing more material models which are available in the material libraries of modern SOFTWARE
- Implement in LS-DYNA the material model HPG which was developed at our Institute and is appropriate for describing the behavior of concrete subjected to blast loads
- Assumption of rigid connection of the bond: too coarse → refinement of the contact descriptions: Segment-based penalty formulation on the interface with an embedded failure criterion
- Development of a "bond finite element" for the modeling of the bond

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Acknowledgement

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ELECTRIC POWER RESEARCH INSTITUTE

Inspection of Containment Liners and Shells Utilizing Advanced Nondestructive Examination Techniques

September 17, 2013

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INTRODUCTION

- Discussion of Operational Experience.
- Design and Construction of the Mockups.
- Flaw Map and Inspection Procedure.
- Advanced NDE techniques.
  - Magnetostrictive Sensor (MsS) Guided Wave
  - SAFT UT
- Results of inspections and Discussion of Data.
- Conclusions.

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Operational Experience – Containment Liners and Shells

- Susceptible to ID and OD corrosion.
- Through-wall at Brunswick 2 (1999) North Anna 2 (1999), DC Cook 2 (2001), Beaver Valley 1 (2009).
- Some OD corrosion noted during concrete removal for SG replacement at Beaver Valley 1.
- Liner corrosion from the ID was noted at twenty three PWRs – all caused by coating failures or moisture barrier degradation.
- Shell corrosion noted at Oyster Creek and other BWR drywells.

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Degradation Mechanisms

- Pitting
- Uniform Corrosion
- Other forms of corrosion may contribute

D. Dunn, A Pulvirenti, and M. Hiser, "Containment Liner Corrosion Operating Experience summary, Technical Letter Report, Revision 1", US Nuclear Regulatory Commission, Office of Nuclear regulation Research, August 2, 2011.

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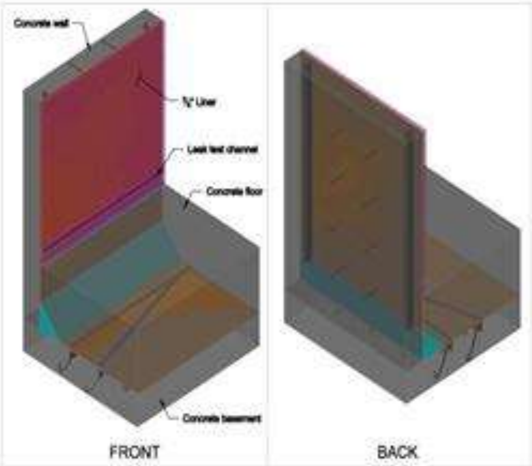
PWR Containment Liner Mock-Up

- The liner is ⅜" (9.5mm) thick with the liner thickness decreasing to ¼" (6.3mm) at weld location below the basemat region. Mock-up was full size.
- The liner had butt welds and channels welded over the welds. Studs were on the concrete side.
- Concrete is poured on the outside of the shell to represent the containment and on the the inside to represent a floor.



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PWR Containment Liner Mock-Up

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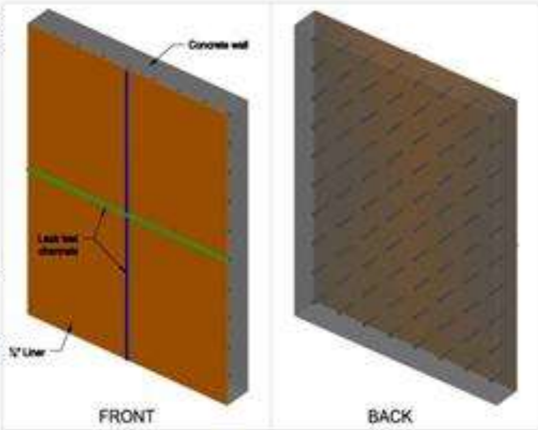
PWR Containment Flat Wall Liner Mock-Up

- The mock-up simulates a large area of flat accessible liner wall. Liner is ¼" (6.3mm) thick.
- The liner has butt welds, studs on the concrete side, and channels covering the butt welds.
- Concrete is poured on one side of the liner to a thickness of 12 inches (30.5 cm).



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PWR Containment Flat Wall Liner Mock-Up

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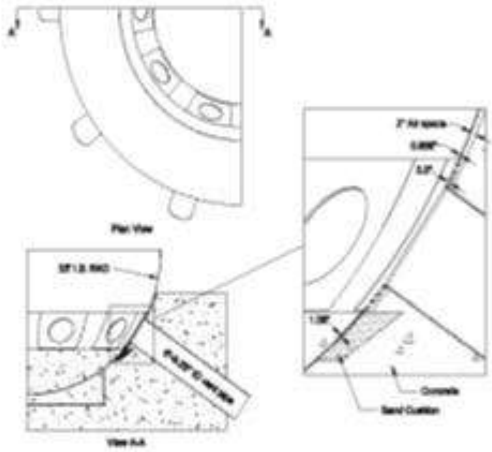
BWR Drywell Shell Mock-Up

- The drywell shell is approximately 1⅛" (28.6 mm) thick. Mock-up was full size.
- The shell section selected has no welds or studs.
- Concrete is poured on the outside of the shell near the location of the sand cushion and on the inside to represent a floor.



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BWR Drywell Shell Mock-Up

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Construction of Mockups–PWR Liner
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Fully constructed mockups
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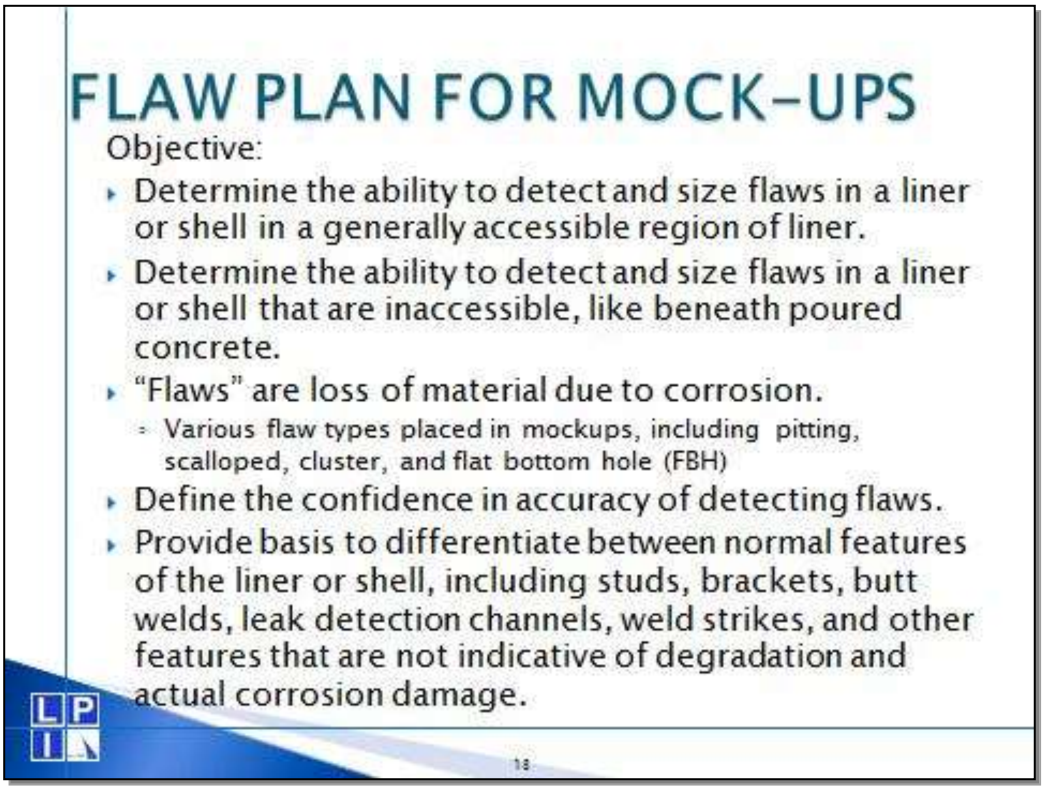
FLAW PLAN FOR MOCK-UPS
Objective:
Determine the ability to detect and size flaws in a liner or shell in a generally accessible region of liner.
Determine the ability to detect and size flaws in a liner or shell that are inaccessible, like beneath poured concrete.
"Flaws" are loss of material due to corrosion.
Various flaw types placed in mockups, including pitting, scalloped, cluster, and flat bottom hole (FBH)
Define the confidence in accuracy of detecting flaws.
Provide basis to differentiate between normal features of the liner or shell, including studs, brackets, butt welds, leak detection channels, weld strikes, and other features that are not indicative of degradation and actual corrosion damage.
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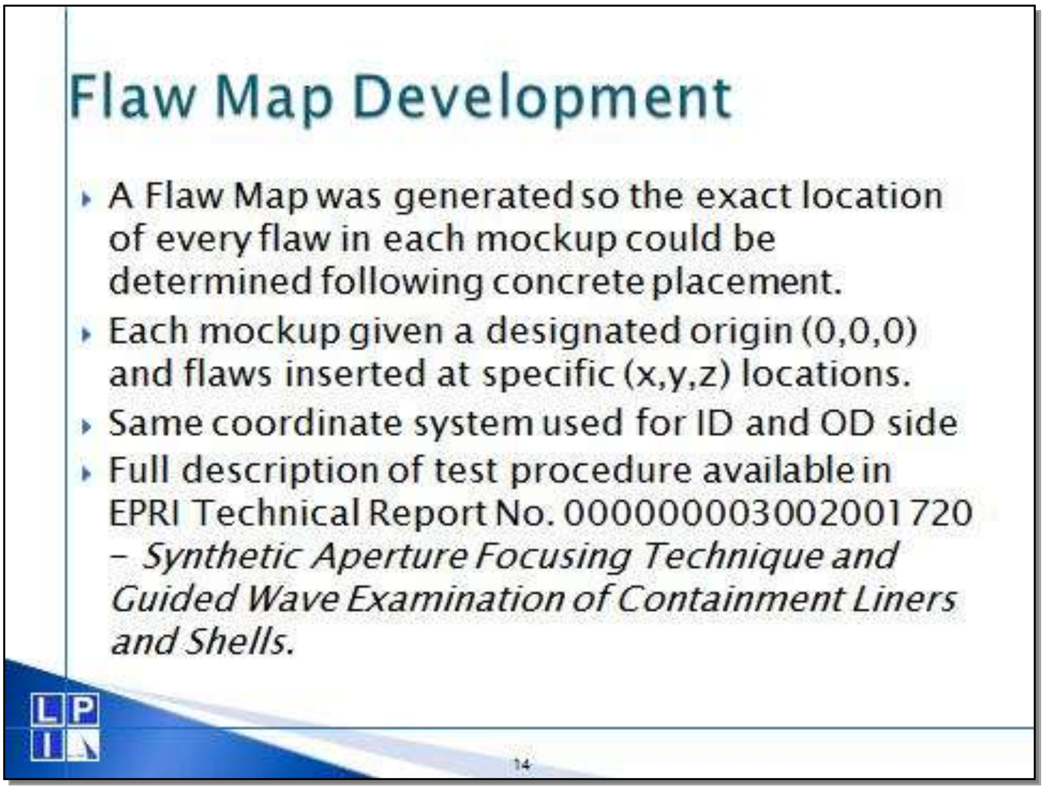
Flaw Map Development
A Flaw Map was generated so the exact location of every flaw in each mockup could be determined following concrete placement.
Each mockup given a designated origin (0,0,0) and flaws inserted at specific (x,y,z) locations.
Same coordinate system used for ID and OD side
Full description of test procedure available in EPRI Technical Report No. 000000003002001720 – Synthetic Aperture Focusing Technique and Guided Wave Examination of Containment Liners and Shells.
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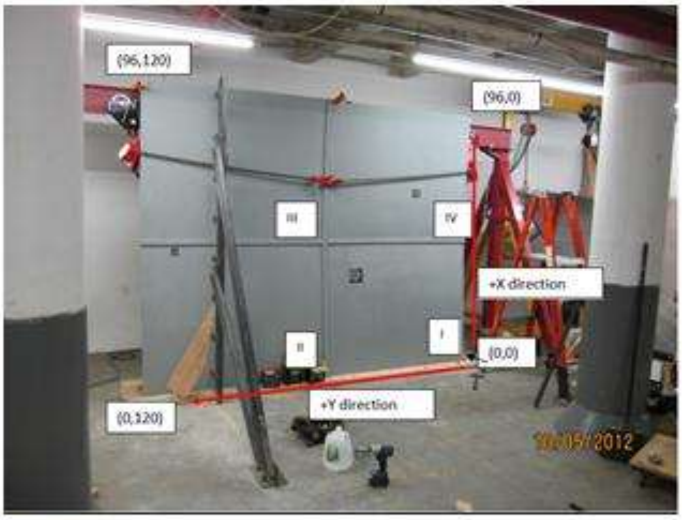
Coordinate system for flaws – PWR Flaw Wall Liner



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Inspection Procedure

- Assemble mock-ups without concrete and without flaws
  - Generate a baseline for evaluation of NDE signal attenuation due to flaws and concrete
- Perform Guided Wave and SAFT-UT
- Install flaws
  - Replication samples taken on all flaws to quantify flaw depth more accurately and keep for future testing
- Perform Guided Wave and SAFT-UT
- Material was placed in flaw to maintain space between steel and concrete to simulate wall loss that has occurred in-service
- Pour concrete and let it cure for 30 days
- Perform Guided Wave and SAFT-UT
- Evaluate flaw detection, flaw sizing, and signal attenuation of complete dataset

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Advanced NDE

- Guided Wave
  - Based on Magnetostrictive Sensor
- SAFT-UT
  - Synthetic Aperture Focused Transducer
  - System previously used to inspect knuckle region of double wall tanks at National Laboratory in US

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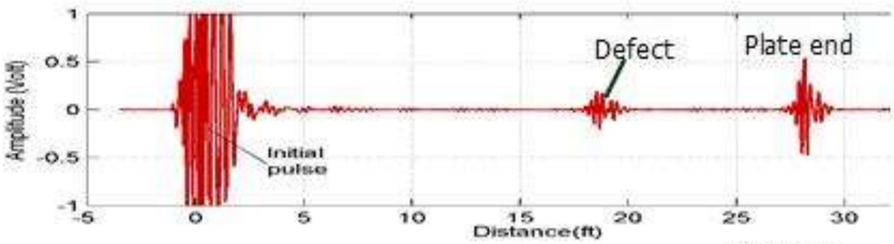
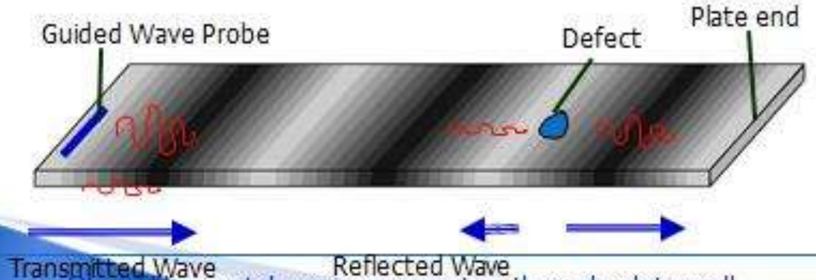
What is Guided Wave?

- Guided waves are ultrasonic waves that propagate along the length of a structure, guided by and confined in the geometric boundaries of the structure





Shear horizontal wave propagates through plate wall

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MERITS OF GUIDED WAVE INSPECTION

- Rapidly provides comprehensive condition information on large areas of structure
- Requires minimal preparation
  - Insulation removal, scaffolding, excavation, coating removal, etc.
- Inspects inaccessible areas remotely
- Pinpoints where to use quantitative follow-up
  - **Reduces inspection cost and enhances overall inspection efficiency**
  - **100 % of volume is inspected**

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MsS Guided Wave Testing System for Generating Shear Horizontal Wave

MsSR3030R

FeCo Strip

MsS plate probes

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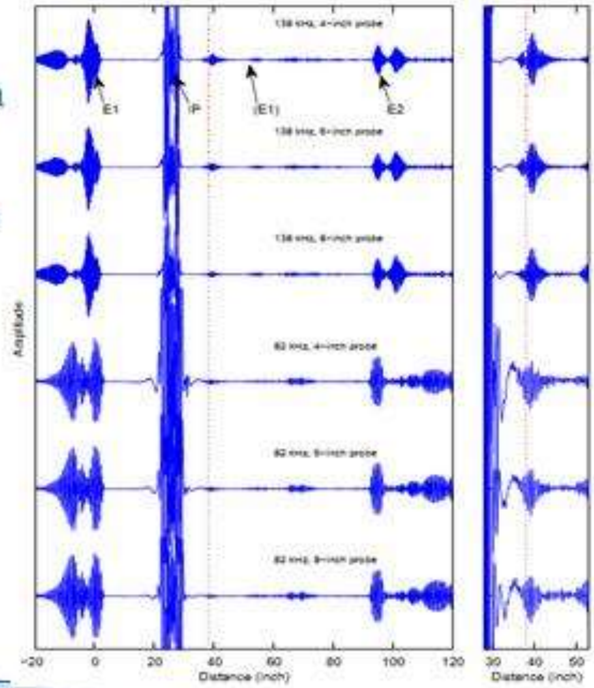
Inspection Data of BWR-ID-1 at (-38, 18.8) with MsS Probe at (-26, 19)



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SAFT/TSAFT Technology

- "Synthetic aperture focusing" refers to a process in which the focal properties of a large-aperture focused transducer are synthetically generated from data collected over a large area using a small transducer with a divergent sound field.
  - For more information the see: Busse et al. 1984 or Hall et al. 1988
- The processing required to focus this collection of data has been called beam-forming, coherent summation, or synthetic aperture processing.

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Status of TSAFT Technology

- The Current TSAFT system was configured to detect and size flaws in the double shelled tanks at Hanford
- The current system is used in two modes
  - Detection of Vertical Through-wall cracks
  - Through-wall sizing of Cracks
- SAFT/TSAFT was originally used to improve the detection and sizing of vertical defects
- SAFT/TSAFT was not designed to detect corrosion in Containments of BWRs and PWRs – it has been adapted for this purpose

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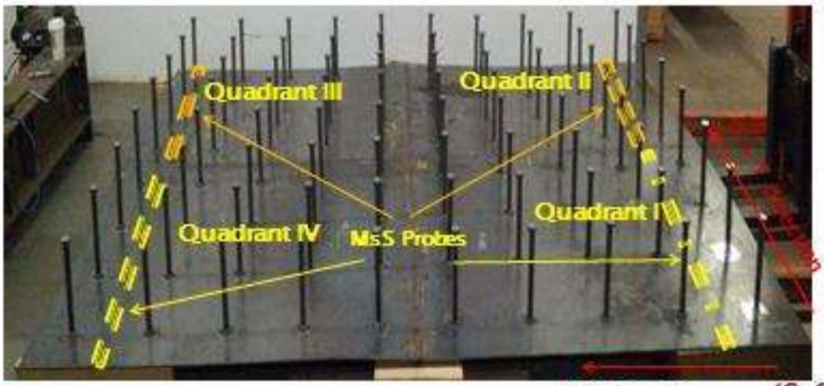
PWR Flaw Wall Liner Mockup MsS Probe placement

(96, 120) (0, 120)



(96, 0) + X direction (0, 0)

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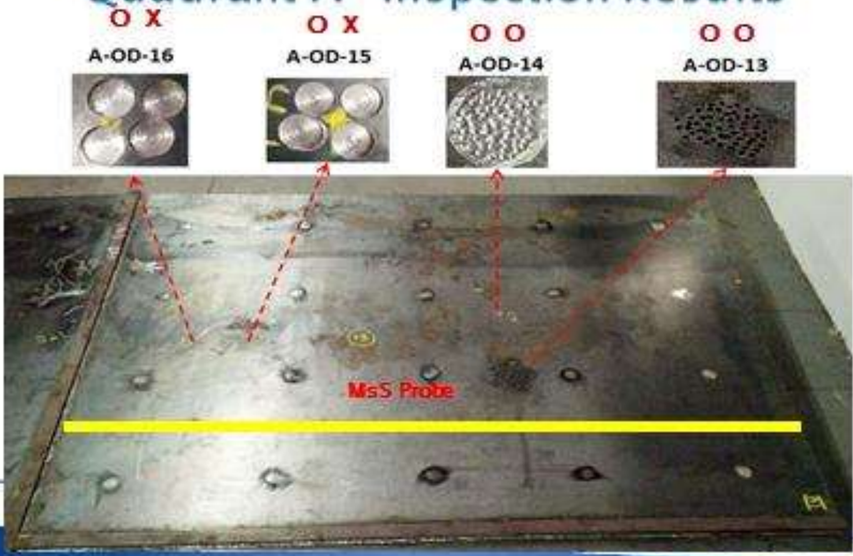
PWR Flat Wall Liner Mockup Quadrant IV–Inspection Results



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PWR Flat Wall Liner Mockup Quadrant IV – Defect Description

FLAW No.	LOCATION* (in.)	DESCRIPTION
A-OD-13	(66, 23.5)	"Pitting" flaw; approx. 3in. diameter with 1/4 in. through-wall depth pits
A-OD-14	(74.5, 23.5)	"Pitting" flaw; approx. 3in. diameter and 1/8 in. depth
A-OD-15	(72.5, 45)	"Cluster" flaw; four 0.5 in, diameter FBHs of 1/32 in. depth
A-OD-16	(72.5, 51)	"Cluster" flaw; four 0.5 in, diameter FBHs of 1/16 in. depth

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Results from MsS Inspections

- MsS system and plate probe works well for finding defects
- BWR Drywall Shell Mockup
  - 11 defects tested (9 defects detected, 2 defects were not detected)
  - Reduce inspection range for minimizing dispersion of SH1 mode
- PWR Containment Wall Liner Mockup
  - 13 defects tested (8 defects detected, 5 defects were not detected)
  - Install MsS probe in the tested plate instead of sending wave through U-shaped channel
- PWR Flat Wall Liner Mockup
  - 19 defects tested (17 defects detected, 2 defects were not detected)
  - Geometric features (stud, U-shaped channel) make difficult to detect defects. Recommend 1) to perform monitoring, 2) to use high frequency and one cycle for increasing spatial resolution, and 3) to compare the acquired data with data acquired at similar condition (geometric feature)

LPI

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Inspection results for BWR shell mock-up ID side

Flaw ID #	Location ID/OD Coordinates Y, X, Z	Flaw Type and Through Wall Depth	Guided Wave Pre-Concrete Detected (Yes/No)	Guided Wave After Concrete Detected (Yes/No)	T-SAFT System Pre-Concrete Detected (Yes/No)	T-SAFT System After Concrete Detected (Yes/No)
BWR-ID-1	(-36, 16.75)	"Pitting" flaw; approx. 2in. diameter and 1/4 in. depth	Yes	Yes	Yes	No
BWR-ID-2	(-45.75, 11.5)	"Corrosion" type flaw; Scalloped flaw appearance 1.5 in. diameter and 1/4 in. depth	Yes	No	Yes	Yes
BWR-ID-3	(-31.5, 6.25)	"Pitting" flaw; approx. 2in. diameter and 1/8 in. depth	Yes	Yes	Yes	Yes
BWR-ID-4	(-49.25, 37)	"Cluster" flaw; four 0.5 in. diameter FBHs of 1/4 in. depth	Yes	Yes	No	No
BWR-ID-5	(-76.75, 58.5)	FBH; 1in. diameter and 1/4 in. depth	Yes	Yes	No	No
BWR-ID-6	(-65, 19.75)	"Cluster" flaw; four 0.5 in. diameter FBHs of 1/4 in. depth	Yes	Yes	No	No

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Status of TSAFT Technology

- Detection of Corrosion in the PWR Containment Mockup

Flaws 1, 2 and 4 that were fabricated in the PWR Containment mockup

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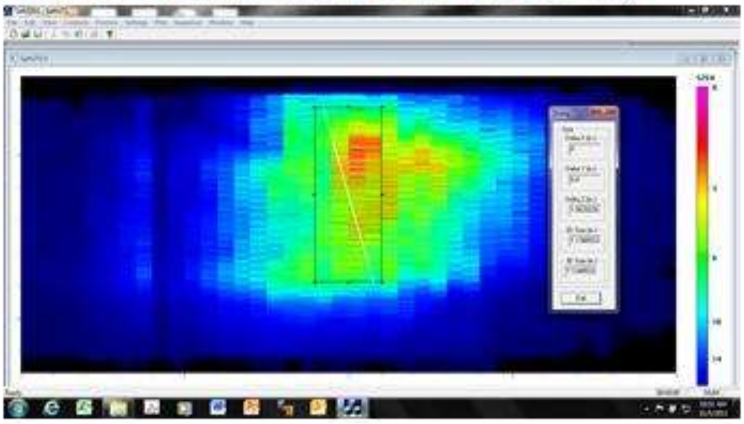
Process of Sizing a Flaw in BWR Mockup (25% Thru-Wall Flat Bottom Hole)



- The SAFT-UT estimate is 0.39 inches (9.9 mm) in Depth
- The Actual Depth is 0.28 inches (7.1 mm) based upon 25% wall loss of 1.125 inches (28.6 mm) total thickness

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Conclusions

- It is possible to detect defects such as corrosion in visually inaccessible areas of containment liners and shells.
- Guided Wave detected most flaws under each set of conditions.
- No ID versus OD differentiation provided.
- Geometric features, such as channels over butt welds, affected sensitivity.
- SAFT-UT detected most implanted flaws for conditions prior to concrete installation.
- SAFT-UT lost some sensitivity after concrete pour
- The SAFT system performed better on thicker components such as the drywell.
- The SAFT system was originally configured to detect cracks in welds and not round corrosion-like defects. Optimization would improve SAFT results.
- Neither system was sufficiently accurate at sizing defects.
- Additional development required regarding flaw characterization and acceptance criteria.

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SESSION TWO

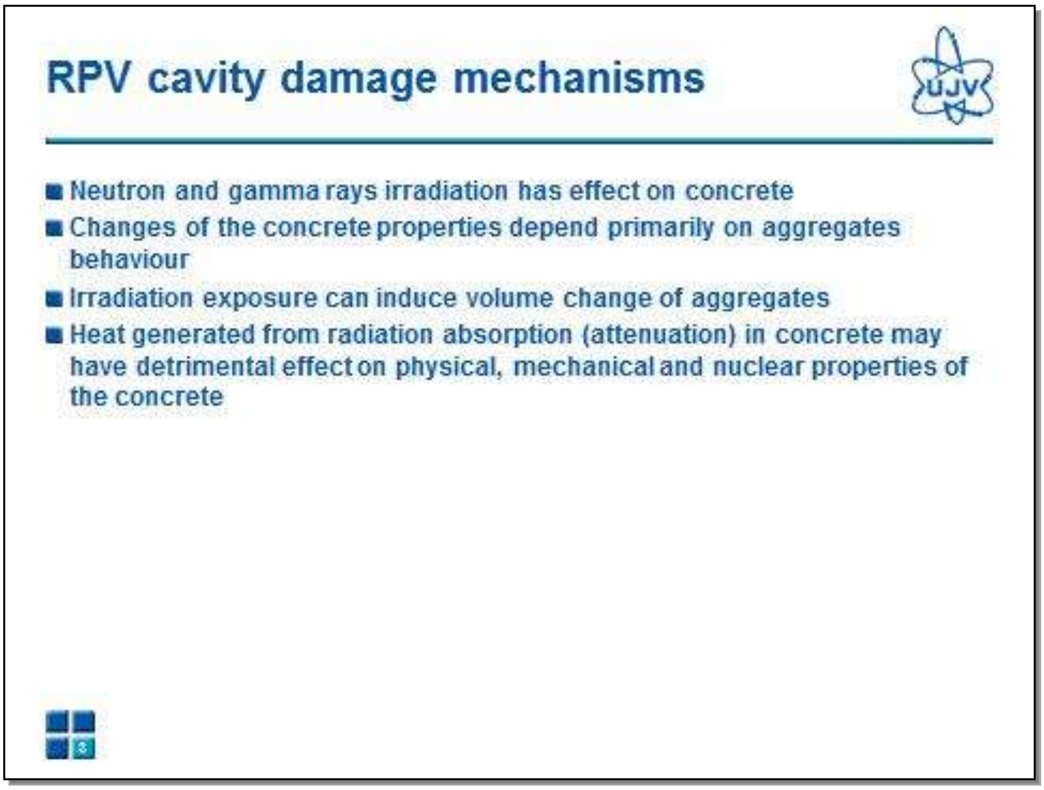
Temperature and radiation effect on the RPV concrete cavity. Project description on irradiation, testing and NDE development

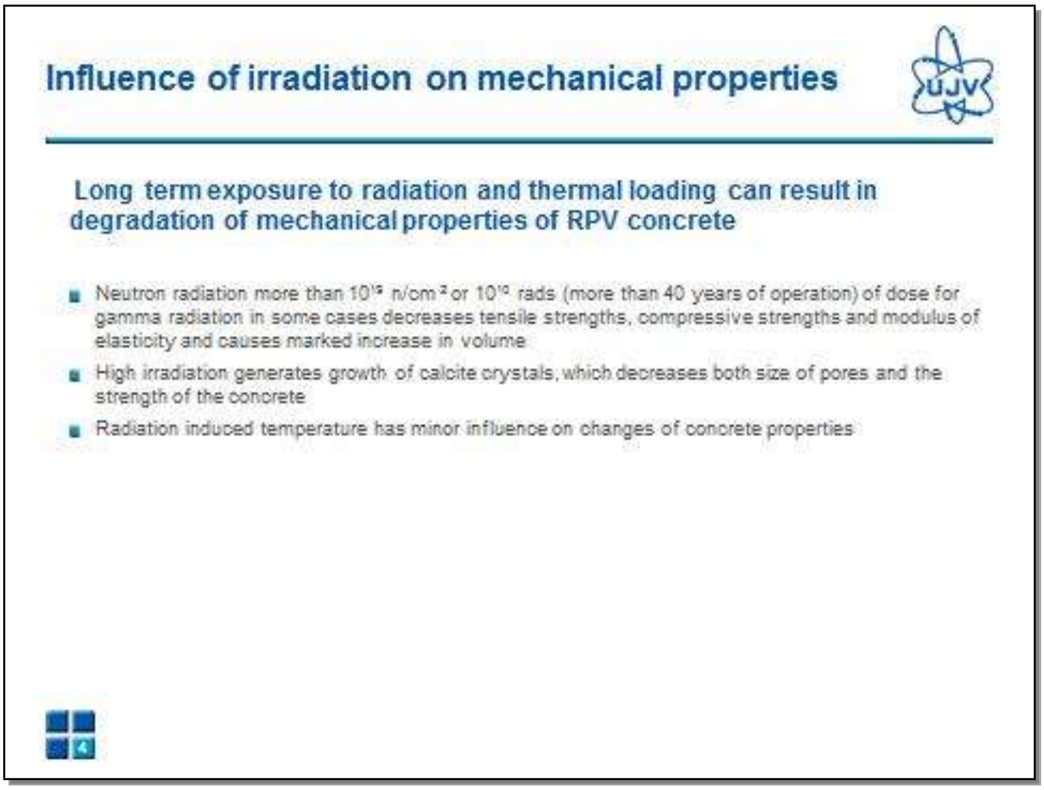
ÚJV Řež, a. s.
J. Žďárek, L. Horáček, P. Brabec
17. 09. 2013

NPP containment ageing

- More than 10 concrete degradation mechanism with influence on containment building
- RPV concrete cavity exposed to temperature and radiation loading as most critical damage mechanism
- No effective validated inspection procedure proposed for RPV cavity until now!

2


RPV cavity damage mechanisms
UJV
Neutron and gamma rays irradiation has effect on concrete
Changes of the concrete properties depend primarily on aggregates behaviour
Irradiation exposure can induce volume change of aggregates
Heat generated from radiation absorption (attenuation) in concrete may have detrimental effect on physical, mechanical and nuclear properties of the concrete
3


Influence of irradiation on mechanical properties
UJV
Long term exposure to radiation and thermal loading can result in degradation of mechanical properties of RPV concrete
Neutron radiation more than 10^{19} n/cm^2 or 10^{10} rads (more than 40 years of operation) of dose for gamma radiation in some cases decreases tensile strengths, compressive strengths and modulus of elasticity and causes marked increase in volume
High irradiation generates growth of calcite crystals, which decreases both size of pores and the strength of the concrete
Radiation induced temperature has minor influence on changes of concrete properties
4

Damage mechanisms in NPPs

- Following table shows ranking of importance for specified concrete damage mechanisms
- Identification of research gaps in three principle areas:
  - Materials
  - Inspection
  - Prediction

Issue	Ranking	Research Gap Analysis		
		Materials	Inspection	Prediction

Ranking and gap analysis of damage mechanisms

Issue	Ranking	Research Gap Analysis		
		Mate-rials	Inspe-ction	Predi-ction
Chloride diffusion into concrete	High		X	X
Boric acid effects on concrete	High	X	O	X
Corrosion of reinforcing steel embedded in concrete	High		X	X
Radiation damage of reactor cavity concrete	High	X	?	?
Containment liner corrosion-accessible and inaccessible areas	High		X	
Post-tensioning tendon relaxation	High		X	
Leaching of the containment liner	High			X
Bulging of the containment liner	High			X
Freeze-thaw damage	High	X	X	X
Spent fuel pool liner stress corrosion cracking (welds)	High		X	X
Pre- and post-tensioning tendon corrosion/stress corrosion cracking	High		X	X
Concrete carbonation and effects on steel reinforcement	Medium		X	
Swelling due to alkali-aggregate reaction or delayed ettringite formation	Medium	X	X	X
Concrete creep, microcracking	Medium	X	X	X
Concrete dissolution effects on spent fuel pool liners	Medium		X	X
Boric acid attack of steel reinforcement	Medium	X	?	?
Water treatment chemical attack of concrete	Medium	X	?	?
Aggressive groundwater/External sulfate attack	Low		X	X
Thermal cycling/cooling towers (operational temperatures)	Low			X
Containment pressurization/depressurization (integrated leak rate test)	Low		X	X
Hydrogen embrittlement of post-tensioning tendons	Low		O	X
Thermal fatigue at penetrations	Low	X		X
Differential settlement of structures	Low			X
Spent fuel pool channel corrosion	Low		X	

Ranking and gap analysis of damage mechanisms
- radiation damage of reactor cavity concrete -

Issue	Ranking	Research Gap Analysis		
		Mate-rials	Inspe-ction	Predi-ction
Chloride diffusion into concrete	High		X	X
Boric acid effects on concrete	High	X	O	X
Corrosion of reinforcing steel embedded in concrete	High		X	X
Radiation damage of reactor cavity concrete	High	X	?	?
Containment liner corrosion-accessible and inaccessible areas	High		X	
Post-tensioning	High		X	

- High ranking of damage mechanism
- Inspection and Prediction identified with question marks!

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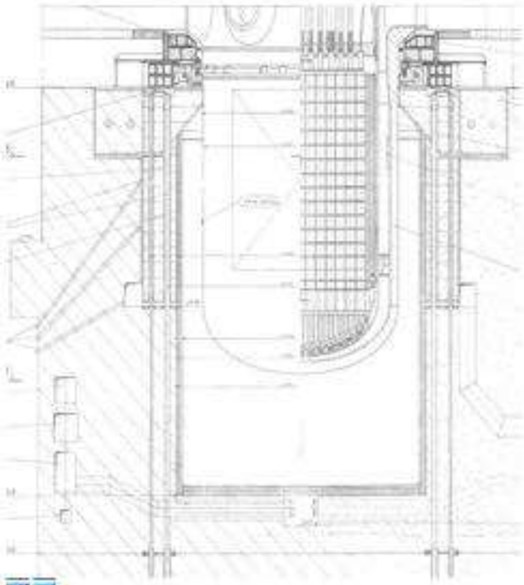
Design of VVER 1000/320 RPV cavity



- steel frame embedded in heavy concrete construction transfers weight of RPV to the cavity
- serpentine concrete segments, opposite to active core, serve as a biological shield
- ferrite steel cladding (11 mm thickness) on outer surface of biological shield
- structural concrete in the lower part of cavity
- ionization channels around cavity circumference formed by embedded steel pipes

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Experimental project mock-up

- Irradiation damage simulation of RPV cavity concrete after long term operation of NPPs
- Cylindrical samples (50 x 100 mm) of NPP Temelín type RPV cavity concrete – ferro-serpentine concrete
- Irradiation of samples above neutron fluence 10^{19} n/cm^2
- Post irradiation examination of samples focused on changes of mechanical and microstructural properties
- NDE inspection technique testing on model segment of outer part of reactor cavity with ionization channels

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Irradiation experiment

ÚJV

in cooperation with:

Centrum výzkumu Řež s.r.o.
Research Centre Rez
Člen skupiny ÚJV

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Irradiation experiment description

- Irradiation of concrete specimens in vertical channels of light water research reactor LVR-15
- Specimens in special aluminium capsules
- Thermocouples controlled temperature, temperature maintenance by passive systems
- Neutron monitors for neutron flux and fluence determination
- Monitoring of gas released from concrete sample during irradiation experiment

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Post irradiation examinations

ÚJV

in cooperation with:

team: **P. Štemberk et al.**

CTU Prague

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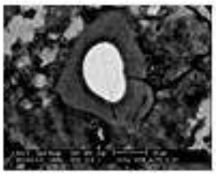
Post irradiation testing

- Optical Polarization Microscopy
- Scanning Electron Microscopy and Microanalysis
- Nano Hardness Testing – Micromechanics
- Thermogravimetry and Differential Thermal Analysis



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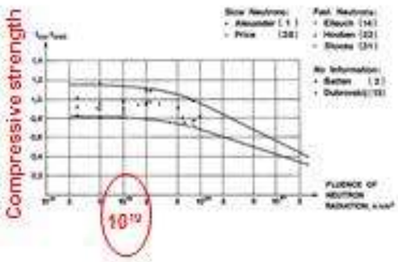
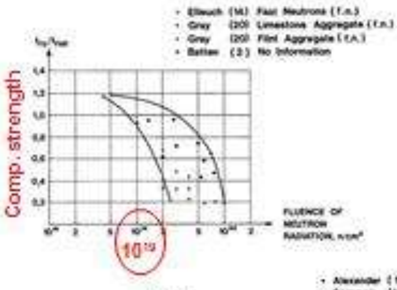
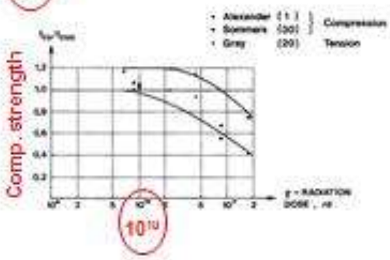
Reasons for post irradiation testing

- Decisive mechanical parameters (strength and stiffness) of concrete decrease under exposure to neutron and gamma radiation.





- Only collection of incompatible experimental data is available. (by Hilsdorf)
- Systematic data for real structural materials is needed. (e.g. on cylindrical 50x100 mm specimens)



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Optical polarization microscopy

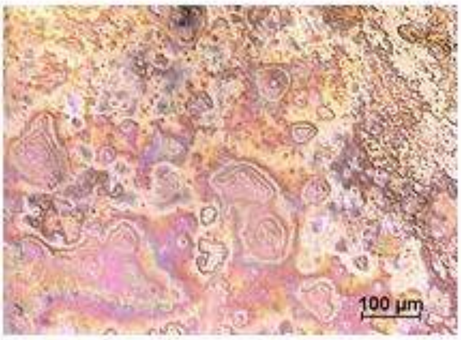
ZEISS Axio Imager

Optical polarization microscopy

- Detection of alteration processes in primary C-S-G gels (loss of bound water). Interpretation of alteration processes in concrete on micro-level
- Changes in structures on micro-level; i.e. occurrence of newly-formed shrinkage in consequence of mineral transformations and flux heat
- Occurrence of newly-formed mineral phases as a products of alteration processes

Optical polarization microscopy

Cross polished section of Portland cement



Partly hydrated Portland cement powder

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Scanning electron microscopy and microanalysis

- EDX – elementary microanalysis & simultaneous element mapping
- WDS microprobe for precise elementary analysis
- BSED – phase and chemical contrast
- EBSD / OIM – electron diffraction & preferential orientation analyses of mineral aggregates
- Resolution 0.8 nm @ 15 kV
- Probe current 10 pA – 300 nA: both for sensitive materials & analysis

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Scanning electron microscopy and microanalysis

- Detection of changes in microstructure from initial stages
- Decomposition of C-S-H gels on sub-micro level
- Phase mineral alterations in all spectra of intensities
- Indication of newly-formed phases in consequence of exposure to radiation energy and heat flux
- Interpretation of changes of mechanical properties on micro-level
- Textural arrangement of crystalline structures – statistical evaluation of prevailed lattice orientation

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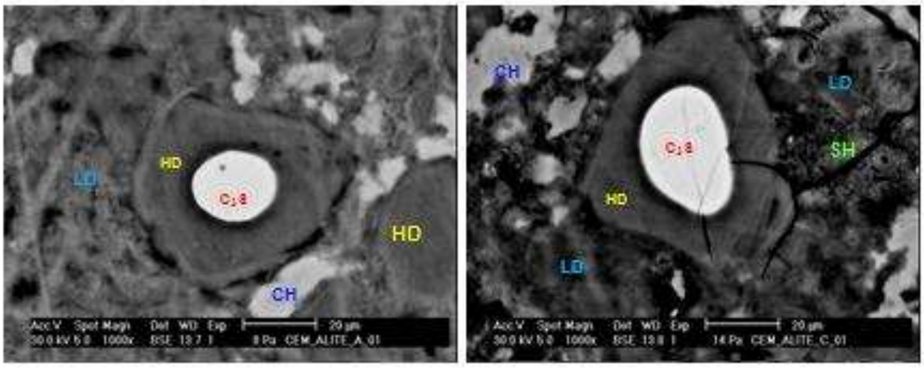
Scanning electron microscopy and microanalysis



C-S-H gel: high density gel (HD), low density gel (LD), portlandite (CH) and ettringite (SH)

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Nano hardness testing - micromechanics

NANOINDENTER – Nano Test, Micro Materials Ltd., UK

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Nano hardness testing - micromechanics

- Detection of changes in microstructure from initial stages
- Decomposition of C-S-H gels on sub-micro level in elementar clusters
- Phase mineral alterations in all spectra of intensities
- Indication of newly-formed phases in consequence of exposure to radiation energy and heat flux
- Detection and measurement of changes in mechanical properties of exposed material on micro-level
- Interpretation of changes of mechanical properties on micro-level

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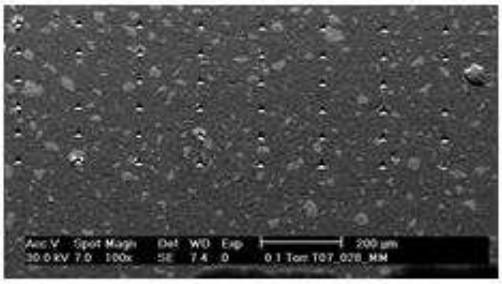
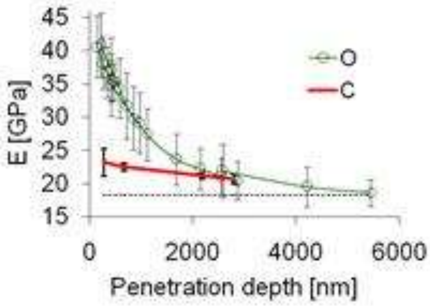
Nano hardness testing - micromechanics


Matrix of nanoindents



Modulus of elasticity

Thermogravimetry and differential thermal analysis


Quantitative detection of phase transitions during constant heat flux

Thermogravimetry and differential thermal analysis

- Identification and quantification of changes of phases in dependence on continual heat flux into the sample.
- The technique is based on the fact that when substance is heated, it undergoes reactions and phase changes that involve absorption or emission of heat. In DTA, the temperature of the test material is measured relative to that of an adjacent inert material.
- DTA can clearly identify the phase changes of material in original (intact) state, that is phase transformation in concrete due to irradiation.

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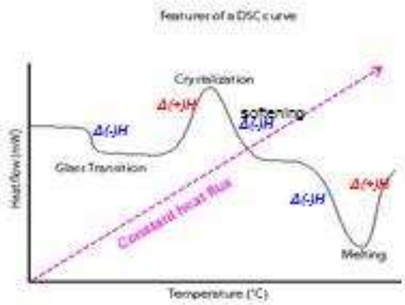
Thermogravimetry and differential thermal analysis



Heat flux vs. temperature of the system as a demonstration of phase and chemical changes in material

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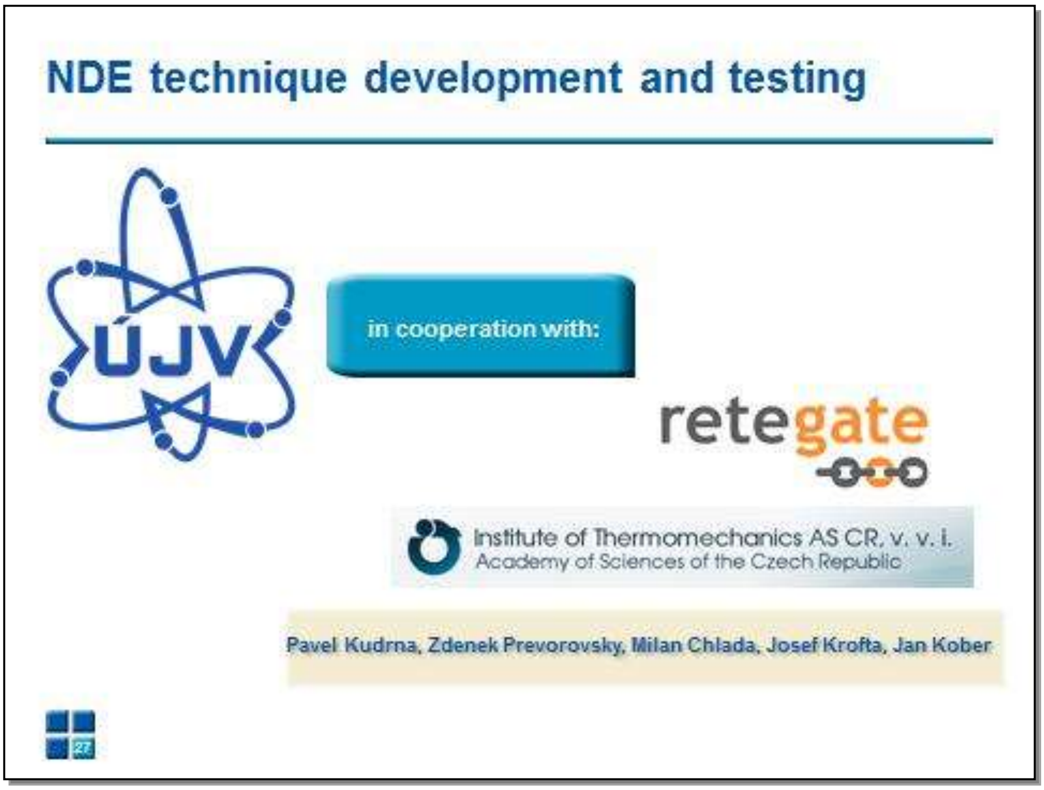
NDE technique development and testing
ÚJV
in cooperation with:
retegate
Institute of Thermomechanics AS CR, v. v. i.
Academy of Sciences of the Czech Republic
Pavel Kudrna, Zdenek Prevorovsky, Milan Chlada, Josef Krofta, Jan Kober
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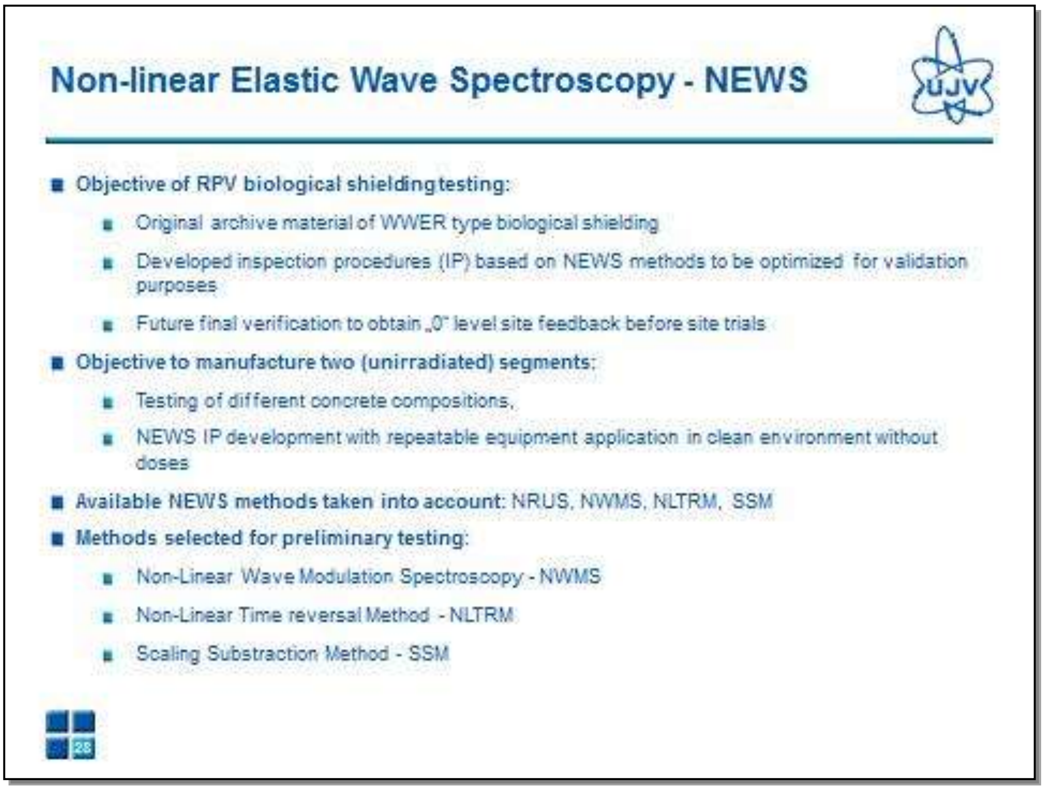
Non-linear Elastic Wave Spectroscopy - NEWS
ÚJV
Objective of RPV biological shielding testing:
Original archive material of WWER type biological shielding
Developed inspection procedures (IP) based on NEWS methods to be optimized for validation purposes
Future final verification to obtain „0" level site feedback before site trials
Objective to manufacture two (unirradiated) segments:
Testing of different concrete compositions,
NEWS IP development with repeatable equipment application in clean environment without doses
Available NEWS methods taken into account: NRUS, NWMS, NLTRM, SSM
Methods selected for preliminary testing:
Non-Linear Wave Modulation Spectroscopy - NWMS
Non-Linear Time reversal Method - NLTRM
Scaling Substraction Method - SSM
28

Original Biological Shielding Specimen and Specific Concrete Model Blocks

Two new manufactured model test blocks for NEWS methods testing – concrete composition

Ferro-serpentine concrete	kg/m3
Cement I 42,5	435
Drink water	241
Crushed aggregate (Bernatice quarry)	
0-2 mm	361
2-5 mm	136
4-8 mm	127
8-11 mm	42
11-16 mm	118
Glassfrit	280
Cast-iron L22	2118
Plasticizing admixture Stacheplast	2,26

Serpentine concrete	kg/m3
Cement I 42,5	499
Drink water	190
Crushed aggregate (Bernatice quarry)	
0-4 mm	690
8-16 mm	459
16-22 mm	527
Plasticizing admixture Stacheplast	4,1

Structural concrete	kg/m3
Cement I 42,5	499
Drink water	190
Crushed aggregate (Dobkovičky quarry)	
0-4 mm	800
8-16 mm	100
16-22 mm	776
Plasticizing admixture Stacheplast	4,1

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Non-linear Elastic Wave Spectroscopy – NEWS Method overview

- NRAS / NRUS (Nonlinear Resonant Acoustic / Ultrasonic Spectroscopy)
- SIMONRUS (Single-Mode NRUS)
- ❑ NWMS **(Non-linear Wave Modulation Spectroscopy)**
- SD (Slow Dynamics)
- NDIS (Nonlinear DISsipation / attenuation)
- Travelling Waves (Nonlinear ultrasonic wave transmission)
- ❑ NLTRA **(Nonlinear Time Reversal Acoustics)**
- ❑ SSM **(Scale Subtraction Method)**

S1

Non-linear Elastic Wave Spectroscopy - NEWS

Three main classes of phenomena associated to the non-linear elastic elements in the test-blocks are:

- Amplitude dependence of the elastic constants and, consequently, of the wave speed which causes changes in the phases of the recorded signal
- Non-linear attenuation mechanisms, which influence the amplitude of the recorded signal
- Non-linear coupling in the wave equation, which allows the generation of higher-order harmonics, sidebands, or sub-harmonics

- **Follow some examples of the preliminary result trends:**
  - NWMS (Non-linear Wave Modulation Spectroscopy)
    - Expected trend value can be provided by amplitude growth of the sideband (f_1+2f_0) vs. driving frequency (f_0) amplitude, higher value trend than:
    - Amplitude growth of the 3[rd] harmonic vs. f_0 driving frequency amplitude, will be compared with:
    - Amplitude growth of the ratio 3[rd]/2[nd] harmonic vs. f_0 driving frequency amplitude
  - SSM (Scaling Subtraction Method)
    - tested for ferro-serpentine concrete, serpentine concrete
    - nonlinear energy vs. driving amplitude seems to provide reasonable results

S2

Advantages & Limitations of NEWS techniques:

- Versatile tools for SHM
- High sensitive detection of defects and damaged zones
- Up to 1000x more sensitive than linear ultrasonic methods
- Detection of defects smaller than wavelength
- Distinguishing defects from pseudo-defects (e.g. structural notches)
- NDT/NDE at hidden places in complex structures
- Remote defect sensing relatively far from installed ultrasonic probes
- Material penetration depth (~ 0,01 - 1) m
- Low-amplitude interrogation of tested parts (e @ 10-9 - 10-4)

- Procedures are mostly global, and mostly reflect only presence
- of defects without their precise location ⊐ solution is e.g. multiplexing of transmitting / receiving channels using dependency of nonlinearity on the wave paths ("pseudo-tomography")
- Size of defects cannot be easily determined

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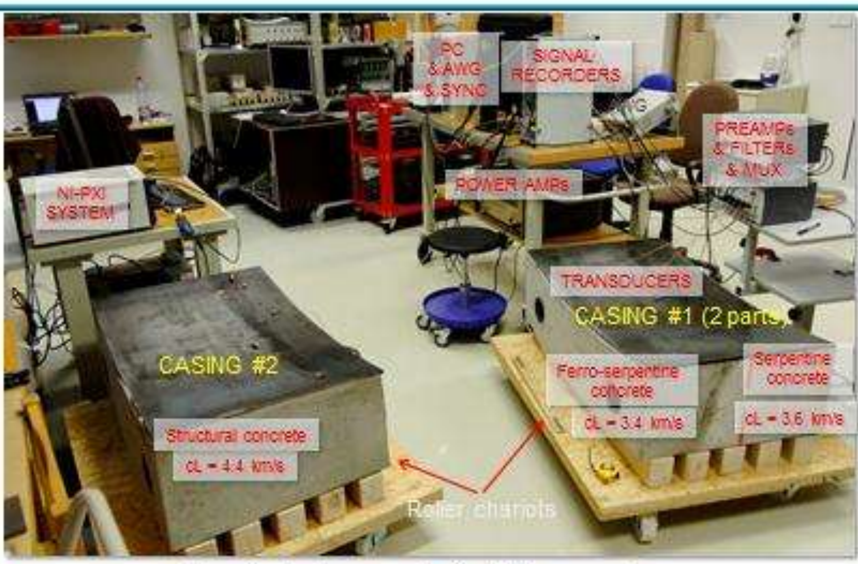
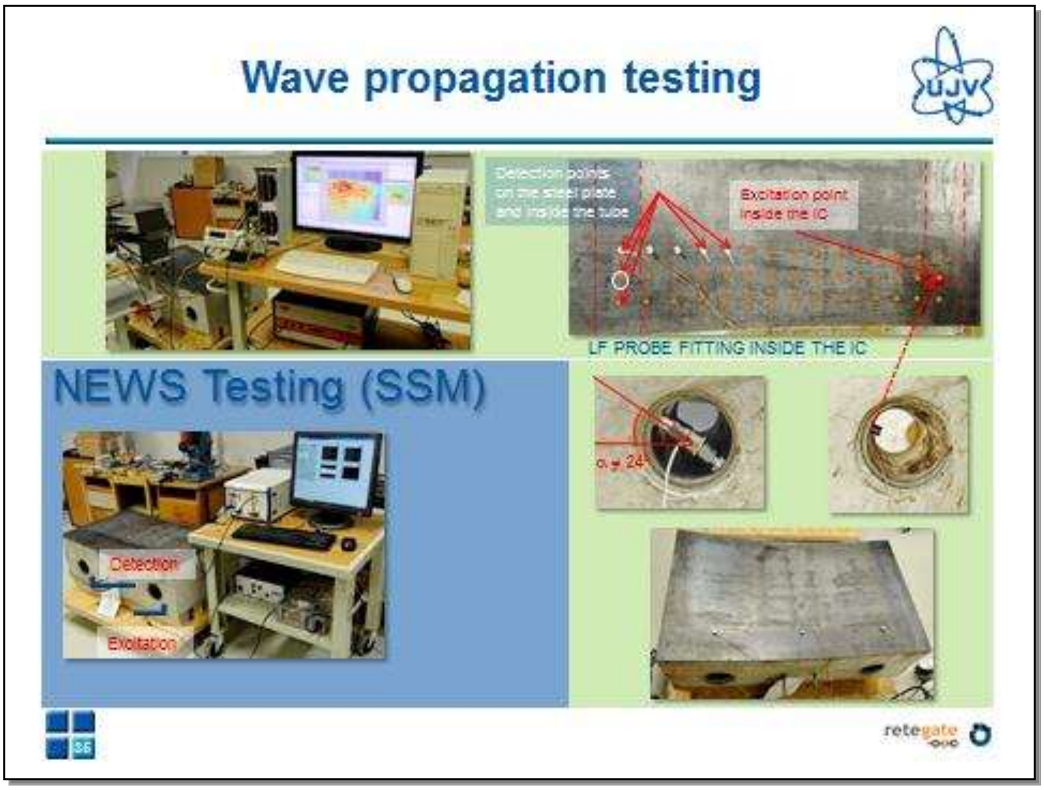
NEWS Equipment

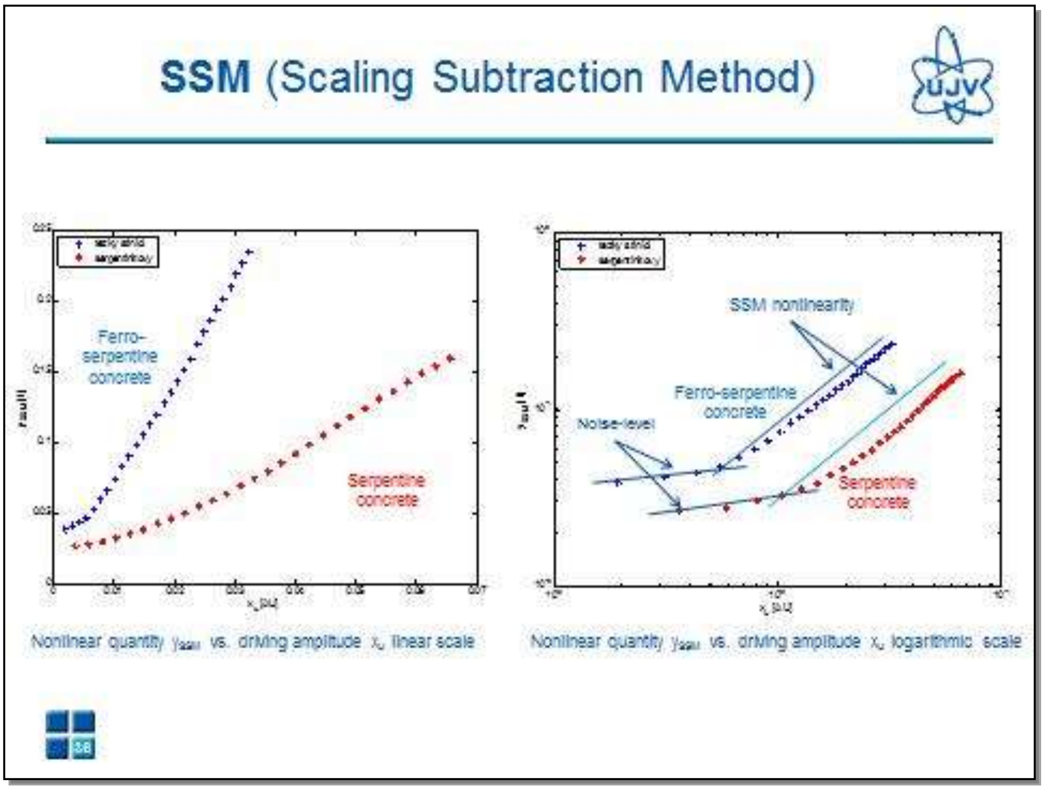


c_L ... measured longitudinal wave celerity in the concrete

34 retegate

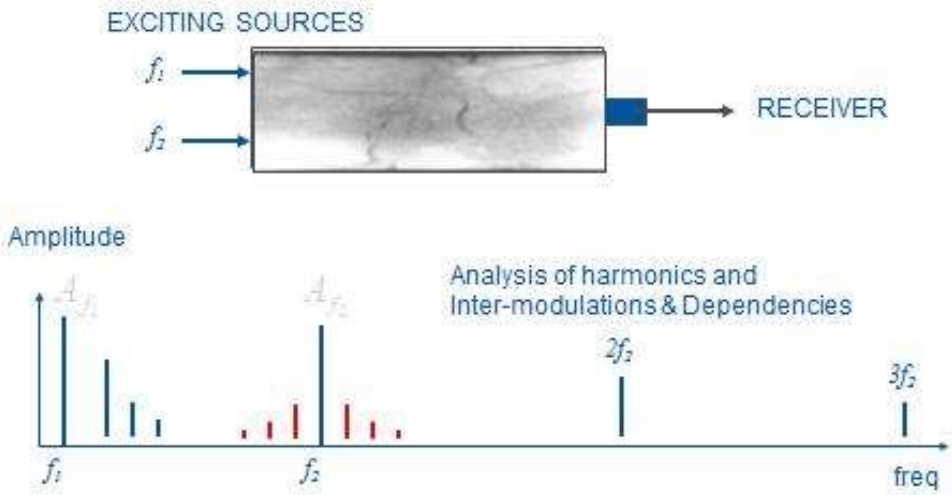


Wave propagation testing
Detection points on the steel plate and inside the tube
Excitation point inside the IC
LF PROBE FITTING INSIDE THE IC
NEWS Testing (SSM)
Detection
Excitation



SSM (Scaling Subtraction Method)
Ferro-serpentine concrete
Serpentine concrete
SSM nonlinearity
Noise-level
Nonlinear quantity y_{SSM} vs. driving amplitude x_0 linear scale
Nonlinear quantity y_{SSM} vs. driving amplitude x_0 logarithmic scale

Nonlinear Wave Modulation Spectroscopy (NWMS)



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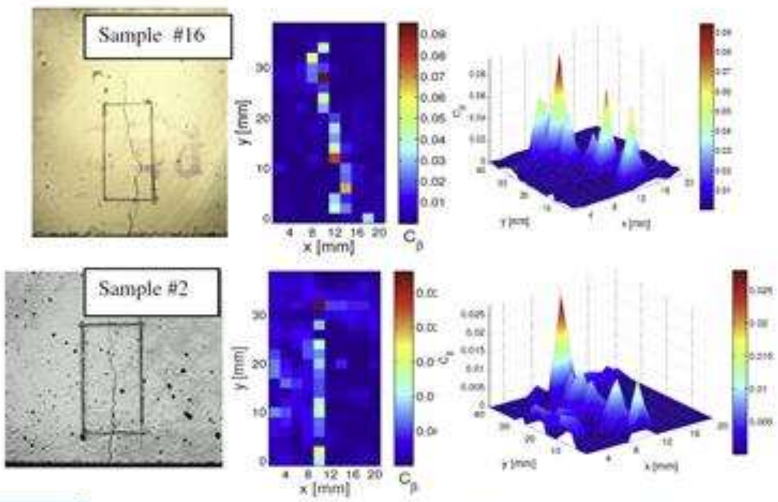
NEWS C-SCAN
(previous concrete structure research)



Cracks initiated during 4-point bending tests of slab samples #2 and #16. Crack photos (left) and their NWMS surface images

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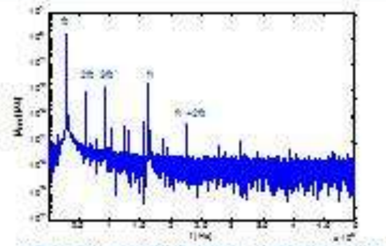
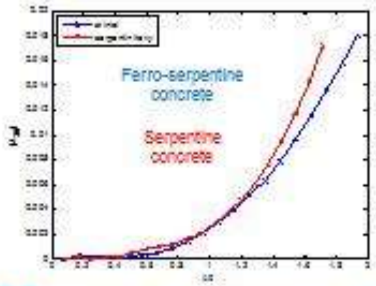
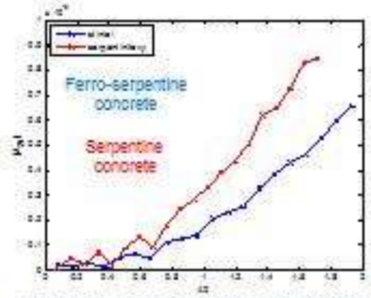
NWMS Specimen #1 (two kind of concrete)



Casing #1 concrete frequency spectrum (f_0 = 31 kHz, f_1 = 164 kHz)

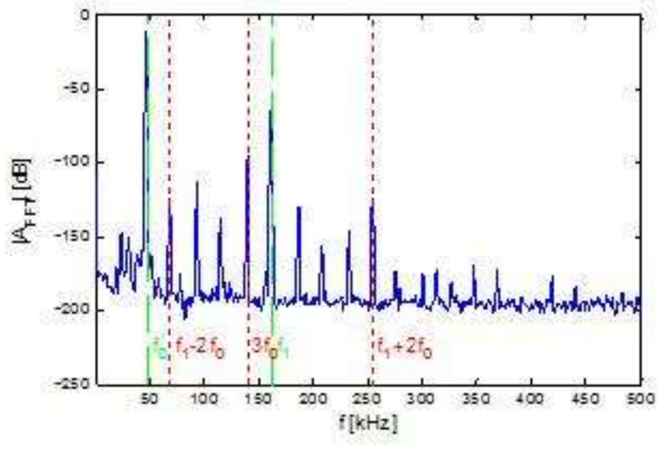


Amplitude growth of the 3rd harmonic (A30) vs. f_0 driving frequency (A0)

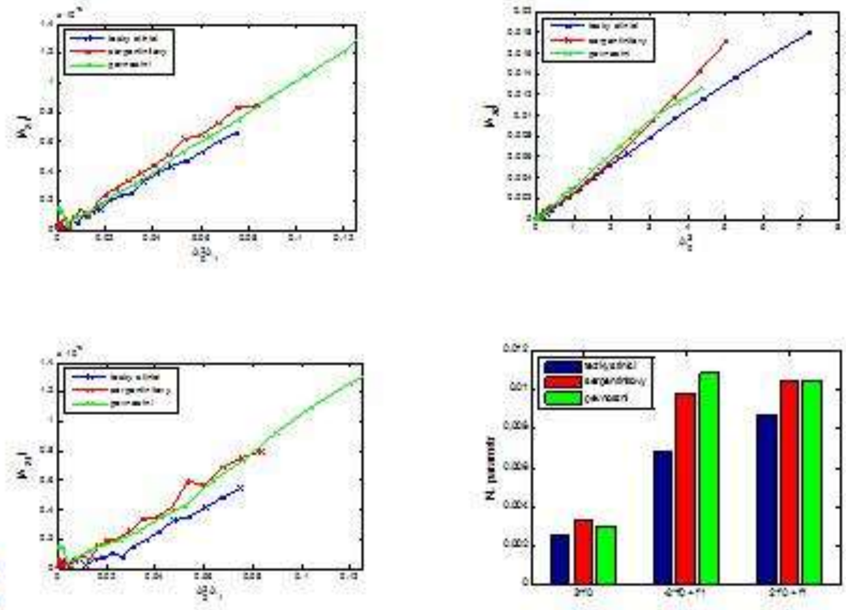


Amplitude growth of the sideband f_1+2f_0 (A21) vs. f_0 driving frequency (A0)

NWMS Specimen #1 (single concrete)



NWMS – Non-linear parameter (results)
Nonlinearities charakter/dependencies clearance



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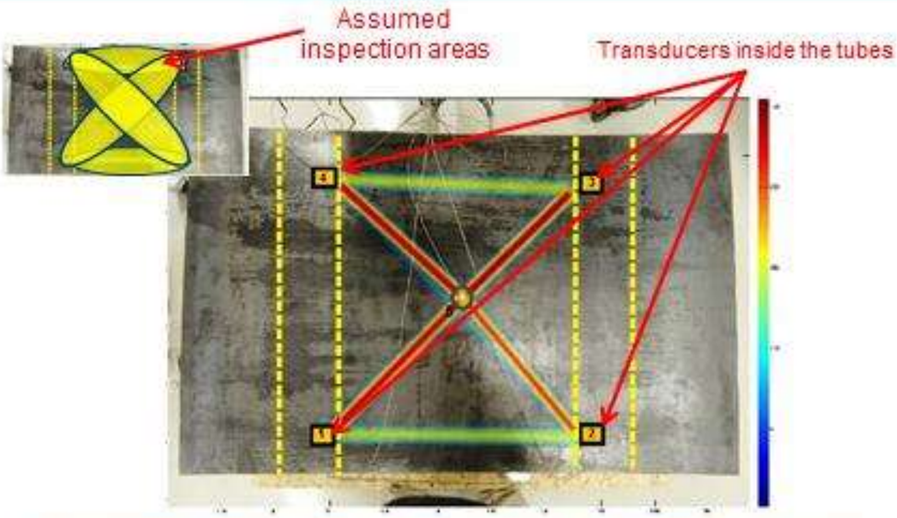
NLTRM (Non-Linear Time Reversal Method)



Heavy concrete (Nonlinearity index N_2 between 5 transducers is represented by color scaling)

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Future comparative works on unique segment of biological shielding from decommissioned NPP

- NPP Greifswald Unit 5 (Germany) – trial run stopped in 1990
- WWER 440 type reactor – PWR of Russian construction
- UJV Rez in 2012 purchased a block of biological shielding as a surveillance material for complex testing
- Segment of steel lined serpentine concrete
- Documentation available – plant operation history, recipe of concrete mix, drawings,...

- Segment 1 of RPV biological shielding
  - Represents full construction height (2,78 m) and thickness (0,7 m)
  - In width (1,62 m) separated by parallel cuts from original ring of biological shielding
  - Segment comprise two original neutron flux measuring channels
  - Original construction and composition reference material !

Segment No.	mass [kg]	max. dose rate 0.1 m distance [mSv/h]	max. dose rate 1 m distance [mSv/h]	contamination α [Bq/cm²]	contamination β/γ [Bq/cm²]	mass specific activity [Bq/g]
1	7290	8.500E-01	1.200E-01	<4.000E-02	7.000E-01	1.720E+03

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Movie – Wave propagation

44


Thank you for your attention
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Monitoring, evaluation and long-term forecasting of hygrothermal performance of thick-walled concrete structure

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Abstract

A thick-walled concrete structure may be considered as a massive, often heavily-reinforced concrete structure with thickness greater than one meter. The main reinforcement consists of steel bars located on the both sides of the concrete wall. Thick-walled concrete structures are extensively used for infrastructures and industrial installations such as nuclear containments, dams, and waste water treatment plants. They are among the biggest structures in civil engineering which demand high level of safety and huge amount of construction budgets.

Thermal and moisture interactions inside thick-walled concrete structures are one of the decisive factors influencing its durability. Hence, long-term, in-service monitoring of thick-walled concrete structures in regular interval is very essential especially those require high level of safety. In addition, long-term hygrothermal interactions in thick-walled concrete structure can result in changes in mechanical properties and may cause serious service failures. Accordingly, knowledge of the long-term hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life.

Several concrete deterioration forecasting models are caused by long-term hygrothermal interactions. However, these models are not based on real-time monitored data and contain assumptions and approximations. Assumptions and simplifications compounded with the dynamic behavior of hygrothermal interaction as well as complexity of thick-walled concrete structure the existing models may inadequate to use for service-life forecasting especially those structures require high level of safety .

In this paper, long-term and in-service hygrothermal monitoring in nuclear containment is discussed. The monitored hygrotermal performance was also analyzed statistically before processing with artificial neural network. Non-linear autoregressive with exogenous inputs (NARX) network was used to model the observed time-series hygrothermal data and to perform long-term hygrothermal performance forecast. The forecasting performance evaluations revealed that the model forecast long-term hygrothermal behaviour inside concrete with good accuracy.

1. Introduction

Thick-walled concrete structures are extensively used for infrastructures and industrial installations such as nuclear containments, dams, and waste water treatment plants. They are among the biggest structures in civil engineering which demand high level of safety and huge amount of construction budgets. Thick-walled concrete structures are often heavily-reinforced, with thickness greater than one meter. Thermal and moisture interactions inside thick-walled concrete structures are one of the decisive factors influencing its durability. Understanding of the foremost deterioration mechanisms caused by hygrothermal interaction inside concrete is vital to extend service-life and insure safety of the structures.

1.1 Moisture effect on durability of concrete structures

The presences of moisture filled pores in the concrete will remarkable influence on the kinetics of transport processes of aggressive substances. High moisture content in concrete hinders those processes that take place easily in the gaseous phase, such as oxygen and carbon dioxide diffusion. On the other hand, it facilitates those processes that occur in aqueous solution, like the diffusion of chlorides, or ions in general [1] and [2]. Consequently, it contributes a significant impact on several physical and chemical deterioration of reinforced concrete structures, including corrosion of reinforcement steel, alkali-aggregate reaction, freezing and thawing, as well as sulphate attack [3], [4], [5], [6], [7], [8] and [9].

Moisture content in the concrete strongly influences on the formation of corrosion products and the rate of corrosion of reinforcement steel [10] and [11]. The amount of moisture content close to saturation makes the departure of corrosion products easier, but it decreases the oxygen diffusivity and makes the supply of oxygen more difficult [12] and [13]. The optimum relative humidity range is between 70% and 80% that allows enough oxygen to diffuse into the concrete and initiate corrosion of reinforcement steel [10].

Moisture content in the concrete can chemically react with harmful substances (e.g. alkali and sulphate ions) penetrated in the concrete. The reactions can form products that are deleterious to concrete because of the volume expansion of the reaction products. The volume expansion is increasing with rising of the moisture content in the concrete. If the relative humidity inside the concrete is above 98%, the damage caused by such reactions is high [14] The amount of moisture content in the concrete also controls damage risk associated with frost. Concrete with high internal relative humidity (85-95%) and saturated (>98%) the damage risk related with frost attack is medium and high, respectively [14].

1.2 Thermal effect on durability of concrete structures

Thermal effects cause expansion or contraction of the concrete structures. There are three types of thermal effects on concrete structures: (i) bulk temperature change, where the entire structural components or segments of the component are subject to a uniform temperature change; (ii) thermal gradient, which is caused by different thermal conditions on two faces of a structure, such as two sides of a wall or the top and bottom of a beam; and (iii) local thermal exposure, which is elevated temperature at a local surface that is caused by an external source such as operating equipment or piping or an abnormal event such as a fire [14].

Thermal interaction inside concrete is also one of the dominant factors in accelerating deterioration processes caused by chemical and physical factors. To mention few, an increment of temperature by 10℃ increases the corrosion rate of reinforcement steel in concrete by two fold. When temperature of pore solution drops below freezing temperature, corrosion of reinforcement steel stops completely since ions cannot move in the pore solution. In carbonated concrete, the corrosion rate is increased logarithmically with temperature in the range between -20℃ and around 30℃. In chloride contaminated concrete, the concentration of chloride in pore solution is increased for temperature above 55℃ while the concentration of hydroxide decreases, in turn it may accelerate chloride associated deteriorations [12].

1.3 Combined effect of moisture and temperature on durability of concrete structures

Based on moisture content changes as well as progressive deterioration of concrete constituent's, the mechanical properties of structure may vary considerably. As temperature increases, water is partly evaporated and generates a pressure in the pore structure. If the stresses applied internally by the induced vapor pressures exceed the tensile strength of the concrete, spalling of concrete or even catastrophic service failures may be caused [15], [16] and [17]. Generally, significant deterioration of concrete strength occurs when the exposure temperature goes above 400℃ at which decomposition of calcium hydroxide occurs. The decomposition process can lead to the increase of porosity and degrade the mechanical properties of concrete. The compressive strength, modulus of elasticity and volume deformation, decrease remarkably upon heating, in turn, jeopardize the structural integrity and load bearing capacity of the structure [15], [16], [18], [19], [20] and [21]. Not only elevated temperature, but also long-term hygrothermal interactions in reinforced concrete structure can result in changes in mechanical properties and may cause catastrophic service failures.

2. Monitoring of hygrothermal performance

Currently, there are several concrete deterioration forecasting models caused by long-term hygrothermal interactions. Nonetheless, the models are not based on real-time monitored data and contain assumptions and approximations. Assumptions and simplifications compounded with the dynamic behavior of hygrothermal interaction as well as complexity of thick-walled concrete structure the existing models may not adequate to use for service-life forecasting especially those structures require high level of safety. Without systematic hygrothermal monitoring and modelling, it is impossible to maintain significant level of reliability over service-life of thick-walled concrete structures. Hence, long-term, in-service monitoring of thick-walled concrete structures in regular interval is very essential Precise knowledge of hygrothermal performance of concrete is also required at the time of performing various non-destructive testing such as ground penetrating radar, ultrasonic pulse velocity and impact-echo because they are very sensitive to hygrothermal conditions [22], [23], [24], [25] and [26].

In this paper, long-term real-time hygrothermal performance monitoring and evaluation in a thick-walled concrete structure is discussed. The case thick-walled concrete structure is containment in power plant situated in Northern Europe. The containment wall consists of an outer and an inner cylindrical wall with thicknesses of 850 mm and 250 mm, respectively, and of a 5 mm thick steel liner between them as shown in Figure 1.

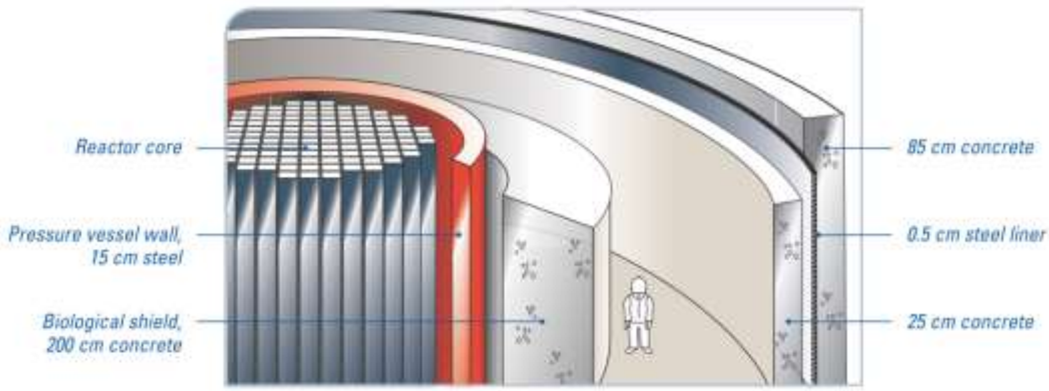
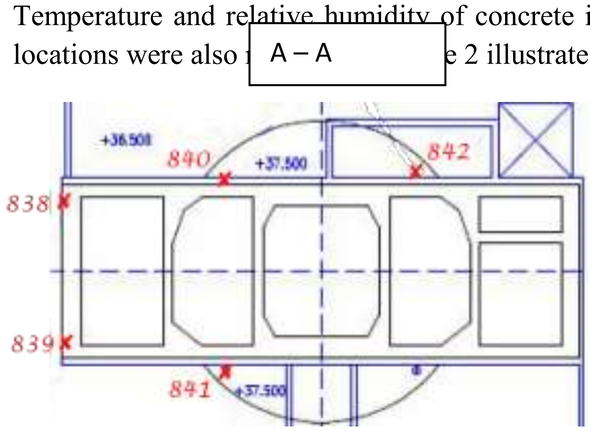


Figure 1. Cross-sections of the containment wall and pressure vessel wall made of concrete and steel.

The containment structure is heavily-reinforced, with a number of liners or cast-in-place items. The hygrothermal interaction among various elements in thick-walled concrete is complex. This makes mathematical analysis of hygrothermal performance in specific positions inside thick-walled concrete structure is challenging. The hygrothermal performance in the nuclear containment was monitored using HMP44L sensors. The sensors were produced by Vaisala Oy (Ltd.), Finland.

The ambient temperature and relative humidity were collected inside containment at elevation of 1000mm. Temperature and relative humidity of concrete inside the containment in the depth of 400mm at various locations were also [illegible] e 2 illustrates the sensors location in the case containment structure.



Elevation (m)	Sensor label
36.6	840 841 842
31.8	838 839
30.0	835 836 837
6.0	833 834
2.5	831 828 830 832
1.0	827 829

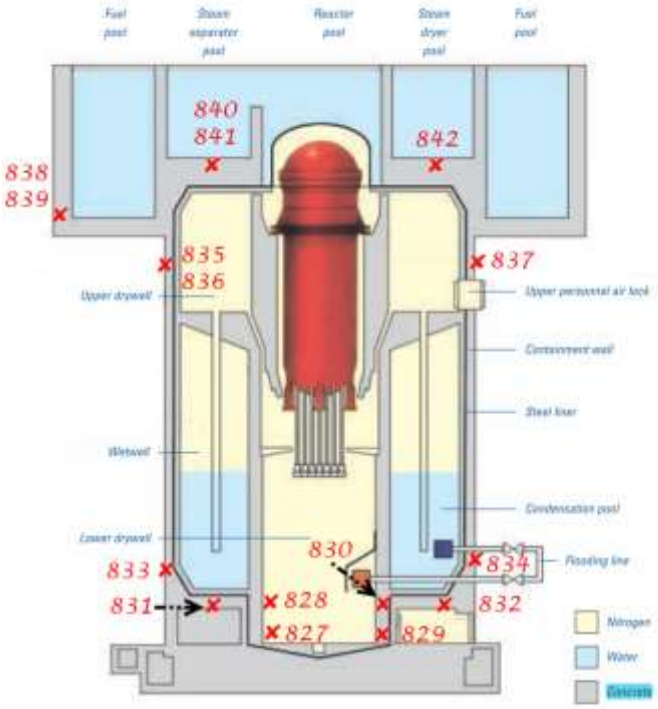


Figure 2. **Locations of temperature and relative humidity sensors within the containment structure.**

The monitored hygrothermal performance is corresponded to about a year period from 4 June 2011 to 24 April 2012 and illustrated in Figure 3 and Figure 4. Measurements were made at regular time intervals of 24 hours. Temperature inside concrete seems to have the same trend with the ambient temperature. In case of relative humidity, the ambient relative humidity measurements do not have the same trend with relative humidity inside concrete. Strong association can be observed among the relative humidity measurements inside concrete. Relative humidity measurements inside concrete, in many cases, are above 80%.

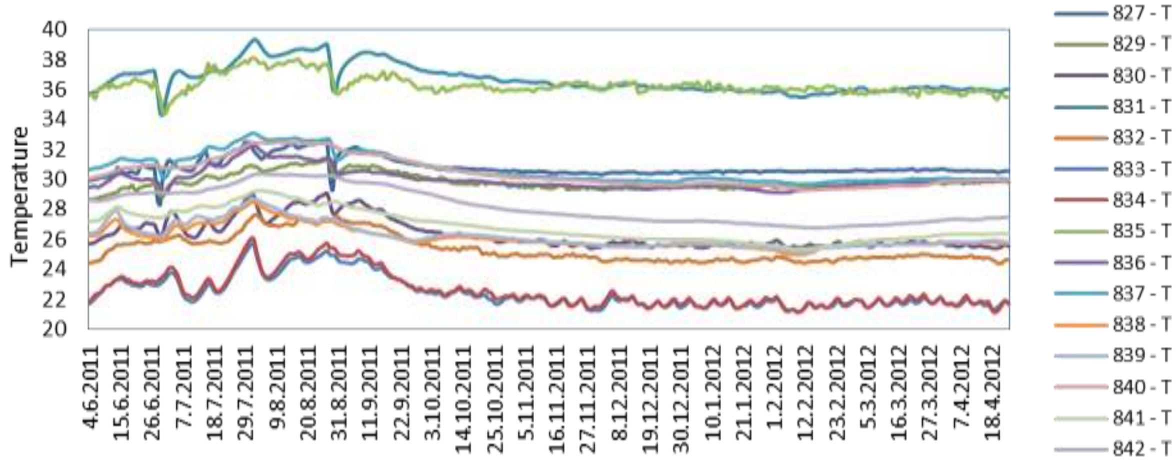


Figure 3.Time-series plot of temperature measurements in nuclear containment.

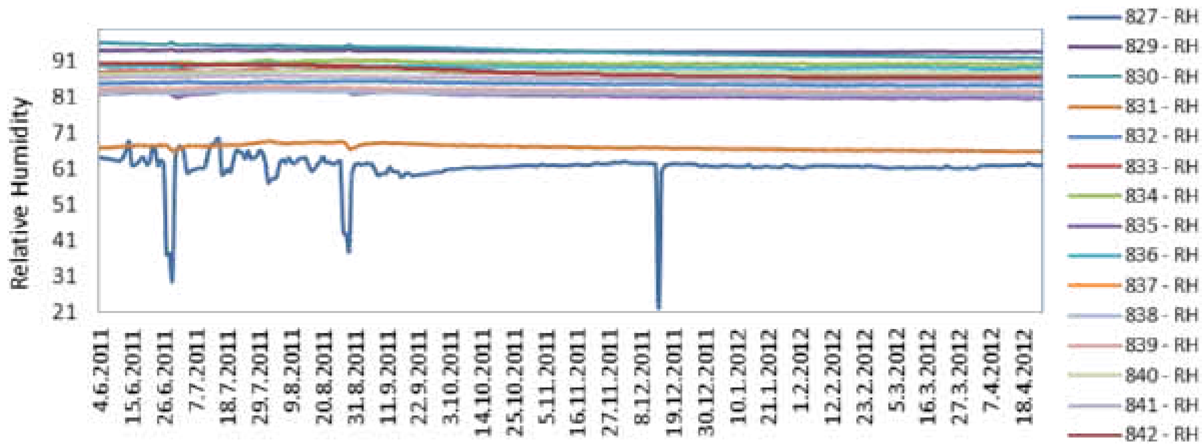


Figure 4.Time-series plot of relative humidity measurements in nuclear containment.

The correlation coefficients between hygrothermal performances at different locations were statistically analyzed and presented in Table 1. Hygrothermal dataset within the same elevation in the containment structure are presented in respective cells. Correlation coefficients of relative humidity and temperature are presented in bottom left triangle - and upper right triangle, respectively. The correlations between ambient temperature and temperature inside concrete at all locations are generally strong and positive. This implies that, when the ambient temperature increases or decreases the temperature inside the concrete increases or decreases accordingly. The temperature correlation coefficients are in the range between 0.66 and 0.88. The ambient temperature is found to be more strongly correlated with temperature inside concrete at a location labelled 829 with correlation coefficient of 0.88. This location is found in lower drywall with the same elevation as that of the ambient temperature monitoring location, labelled 827. This is one of the most probable reasons why location labelled 827 obtained a strong positive relation with the ambient temperature compared with the other locations.

Table 1. Correlation coefficients between temperature and relative humidity measurements in nuclear containment structure.

	827	829	830	831	832	833	834	835	836	837	838	839	840	841	842	T
827		***0.88***	***0.84***	***0.85***	***0.80***	***0.78***	***0.78***	***0.72***	***0.81***	***0.79***	***0.70***	***0.66***	***0.79***	***0.70***	***0.72***	**827**
829	***-0.11***		0.83	0.85	0.84	0.78	0.78	0.70	0.83	0.78	0.64	0.59	0.81	0.68	0.72	**829**
830	***-0.03***	0.93		0.90	0.96	0.98	0.98	0.69	0.84	0.91	0.81	0.78	0.93	0.87	0.91	**830**
831	***0.00***	0.80	0.82		**0.89**	0.86	0.85	0.81	0.88	0.91	0.80	0.77	0.91	0.85	0.88	**831**
832	***-0.09***	0.90	0.90	**0.92**		0.95	0.95	0.68	0.86	0.93	0.83	0.81	0.96	0.91	0.94	**832**
833	***-0.07***	0.93	0.91	0.90	0.98		**1.00**	0.68	0.84	0.90	0.82	0.80	0.92	0.87	0.90	**833**
834	***-0.16***	0.60	0.51	0.78	0.81	**0.80**		0.67	0.83	0.89	0.82	0.80	0.92	0.87	0.90	**834**
835	***-0.02***	0.89	0.85	0.95	0.91	0.93	0.75		**0.83**	**0.81**	0.72	0.68	0.75	0.67	0.67	**835**
836	***0.04***	0.87	0.82	0.82	0.79	0.84	0.57	**0.89**		**0.94**	0.93	0.90	0.91	0.89	0.84	**836**
837	***-0.04***	0.93	0.91	0.95	0.97	0.97	0.77	**0.98**	**0.88**		0.93	0.92	0.97	0.96	0.95	**837**
838	***0.01***	0.92	0.90	0.92	0.95	0.95	0.73	0.95	0.91	0.98		**0.99**	0.89	0.95	0.88	**838**
839	***0.01***	0.93	0.94	0.91	0.95	0.96	0.68	0.95	0.90	0.98	**0.99**		0.87	0.95	0.88	**839**
840	***-0.09***	0.55	0.48	0.81	0.79	0.70	0.88	0.73	0.55	0.75	0.73	0.68		**0.96**	**0.98**	**840**
841	***-0.02***	0.94	0.93	0.90	0.96	0.97	0.71	0.93	0.89	0.98	0.99	0.99	**0.71**		**0.98**	**841**
842	***-0.01***	0.97	0.98	0.82	0.91	0.94	0.56	0.88	0.86	0.93	0.93	0.95	**0.51**	**0.95**		**842**
RH	**827**	**829**	**830**	**831**	**832**	**833**	**834**	**835**	**836**	**837**	**838**	**839**	**840**	**841**	**842**	

It can be also observed that the correlation coefficients between temperature inside concrete (categorized in the same location or elevation) are generally strong and positive. Even there is a perfect positive correlation between sensors labelled 833 and 834. The correlation analysis between relative humidity of ambient and inside concrete showed that the ambient relative humidity do not have any linear correlation, even with the closest location labelled 829. Similar to temperature, positive linear correlation between relative humidity inside concrete within the same group is noticed.

3. Artificial neural network for long-term forecasting of hygrothermal performance

Knowledge of the future hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life. Developing a model to forecast hygrothermal performance in thick-walled concrete structure is a major problem because of its dynamic, complex and nonlinear characteristics. Such a problem requires systems approach where the most essential features of a complex problem with multiple interactions are modelled so that the system behaviour can be forecasted reliably. Thus, the best solution is to learn system behaviour through observations. Artificial neural network (ANN) has been found useful in solving complex time-series problems in different applications as they are modelled after the brain.

ANN is a computational network which attempt to simulate the networks of nerve cell (neurons) of the biological central nervous system [27], [28] and [29]. Artificial neurons form massively parallel networks, whose function is determined by the network structure, the connection strengths between neurons, and the processing performed at neurons [28].

The model of a neuron, which forms the basis for designing artificial neural networks are shown in Figure 5. It basically consists of:

- A set of synapses or connecting links, each of which is characterized by a weight or strength of its own. Specifically, a single x_j at the input of synapse j connected to network k is multiplied by synaptic weight w_{kj}.
- An adder for summing the input signals, weighted by the respective synapses of the neuron;
- An activation function for limiting the amplitude of the output of a neuron.

A neuron k, can be mathematically described by the following equations:

$$u_k = \sum_{j=1}^{m} w_{kj}\, x_j \qquad (1)$$

$$y_k = \varphi(u_k + b_k) \qquad (2)$$

Where:

$x_1, x_2, \ldots, x_m$ are the input signals;
$w_{k1}, w_{k2}, \ldots; w_{km}$ are the synaptic weights of neuron k;
u_k is the linear combiner output due to the input signals;
b_k is the bias;
$\varphi(.)$ is the activation function; and ;
y_k is the output signal of the neuron.

The externally applied bias b_k has the effect of increasing or lowering the net input of the activation function, depending on whether it is positive or negative, respectively.

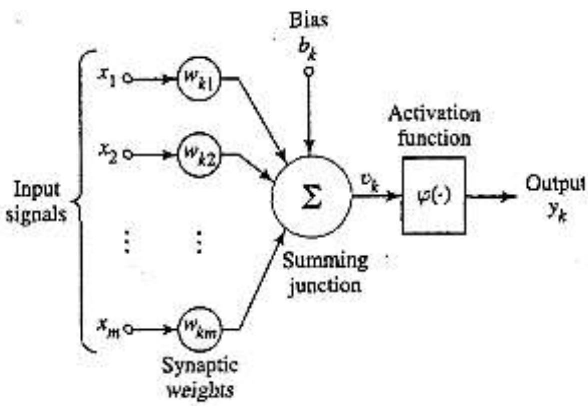


Figure 5. A simplified model of artificial neuron [29].

ANNs are flexible, adaptive learning systems that follow the observed data freely to find patterns in the data and develop nonlinear system models to make reliable forecast of the future [28]. By the help of hygrothermal sensors real-time data can be monitored. The real-time data can be modelled using ANN, in turn makes self-learning smart structure which speaks the future hygrothermal performance for itself. Figure 6, Venn diagram indicates self-learning smart structure by confluence of thick-walled concrete structure, hygrothermal sensors and artificial neural networks.

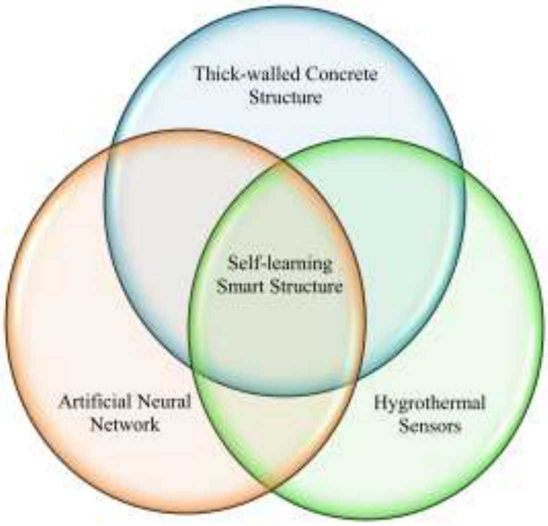


Figure 6. Venn diagram indicates self-learning smart structure by confluence of thick-walled concrete structure, hygrothermal sensors and artificial neural networks.

3.1 Neural Network Architecture

The pattern of connections between the neurons is called the architecture of the neural network [30]. Depending on their architecture neural networks may be classified in a number of different ways which is intimately linked with the learning algorithm used to train the network. Different neural network architectures are widely described in the literature. However, there are three fundamentally different classes of network architectures: Single-layer feedforward networks, multilayer feedforward networks and recurrent networks [29].

Recurrent neural network model have been successfully used for various time-series forecasting tasks. It attempts to incrementally build the autocorrelation structure of a series into the model internally, using feedback connections relying solely on the current values of the input(s) provided externally. The network learn the dynamics of the series over time from the present state of the series, which is continuously fed into it, and then the network uses this memory when forecasting [28] and [29]. The architectural layout of recurrent network takes many different forms. In this study, non-linear autoregressive with exogenous inputs (NARX) model was selected.

3.2 Non-linear autoregressive with exogenous inputs (NARX)

NARX model is recurrent dynamic network and in this model external inputs are presented to the network in addition to those fed back from the output [28]. This model may have input that is applied to a tapped-delay-line memory of q units. The output is also fed back to the input via another tapped-delay-line memory of q units. The contents of these two tapped-delay-line memories are used to feed the input layer of the multilayer perceptron. The present value of the model input is denoted by $u(n)$, and the corresponding value of model output is denoted $y(n+1)$; that is, the output is ahead of the input by one time unit. Thus, the signal vector applied to the input layer of the multilayer perceptron consists of a data window made up as follows:

- Present and past values of the input, namely $u(n)$, $u(n-1)$,..., $u(n-q+1)$, which represent exogenous inputs originating from outside the network,
- Delayed values of the output, namely, $y(n)$, $y(n-1)$,..., $y(n-q+1)$, on which the model output $y(n+1)$is regressed.

The dynamic behaviour of the NARX model is described by Equation 3.

$$y(n+1) = F\big(y(n), \dots, y(n-q+1), u(n), \dots, u(n-q+1)\big) \qquad (27)$$
(3)

where F is a non-linear function of its arguments.

4. Modelling of artificial neural network

4.1 Network structure

Two long-term hygrothermal forecasting models: one is for temperature and the other is for relative humidity was developed. MATLAB® neural network toolbox [31] was used for modelling the data. The models use ambient hygrothermal data as inputs to forecast the hygrothermal performance inside nuclear containment structure. The dependency of the hygrothermal behaviour inside the containment with the ambient hygrothermal performance is somewhat identical in all locations of the structure as proofed by the correlation analysis. Accordingly, in this paper, forecasting performance of hygrothermal behaviour in nuclear containment structure only for the location labelled 829 is presented.

Non-linear autoregressive with exogenous inputs (NARX) network with two layers was used to model the data. The fundamental architecture of the network is the same as shown in Figure 7. The model has two inputs, one is an external input (e.g monitored ambient temperature), and the other is a feedback connection from the model output. The feedback connection from the model output at future time-steps (which are then used as inputs) are forecasted hygrothermal data. The model must recursively make forecasts for the n required time-steps of $(t+1)$, $(t+2)$,..., $(t+n)$ using only the inputs at time t. As a consequence, long-term forecasting performance depends on its own prediction in a single-step to recursively predict the outcome for the next step.

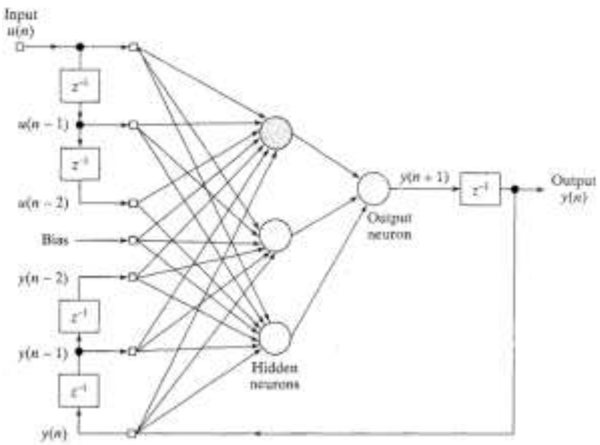


Figure 7. NARX model with three hidden neurons [29].

The time-steps of the inputs were equals to the whole hygrothermal time-steps minus n size of required future time-steps. The subtracted n size of required time-steps is monitored hygrothermal data which are used to evaluate the model forecasting performance since they were not used for network training. A tapped-delay-line memory of two units was assigned for both input and feedback. The network obtained five hidden neurons and one output neuron. The optimal number of neurons in the hidden layer and a tapped-delay-line memory was based on the generalization error and found after several trainings. The activation functions selected for the layers were hyperbolic tangent transfer function in the hidden layer and linear transfer function in the output layer. The input and target outputs were randomly divided to 70% for training, 20% for validation and 10% for testing. The training hygrothermal dataset was used to train the network. Training begins with the third data point since a tapped-delay-line memory of two units was assigned. Validation dataset was used to measure the network generalization, and to halt training when the generalization stops improving. Test dataset used to measure network performance during and after training. The applied training algorithm was the Levenberg-Marquardt. This algorithm is an iterative technique that locates the minimum of a multivariate function that is expressed as the sum of squares of non-linear real-valued functions and is the fastest method for training.

4.2 Result analyses

Training performance of the NARX model for long-term (90-steps-ahead) forecasting of hygrothermal behaviour inside containment structure is shown in Figure 8. It illustrates training, validation and testing performance functions versus the iteration number. The error on the validation set is monitored during training, and the training is stopped when the validation error stop decreasing further. As indicated by the dashed line in the performance plot, the best model generalization for temperature was obtained at epoch 23 where minimum mean square error of validation is dropped to 6.82e-03. In case of relative humidity, best validation performance was occurred at epoch 54 with minimum mean square error of 9.1e-04. The error in case of temperature is a bit higher compared to relative humidity.

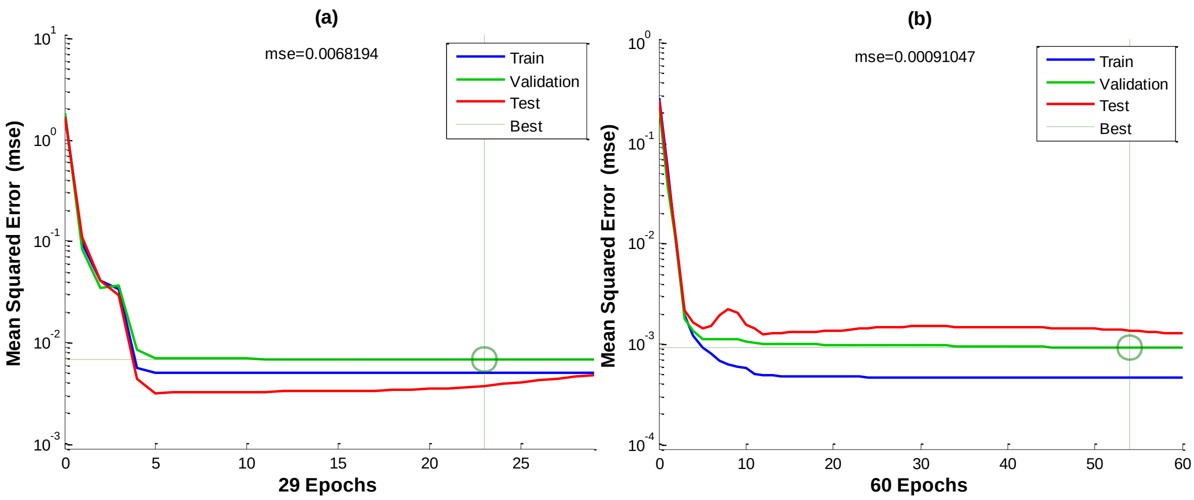


Figure 8. Plot of training of the NARX model for long-term forecasting of hygrothermal performance inside containment concrete a) temperature b) relative humidity.

A linear regression between the network outputs and the corresponding targets were conducted and shown in Figure 9. The R-value for temperature response was 0.99321 and for relative humidity was 0.99053. In both cases the R-values are above 0.99 which indicates the model outputs tracks the targets (observed hygrothermal behaviour inside concrete) very well.

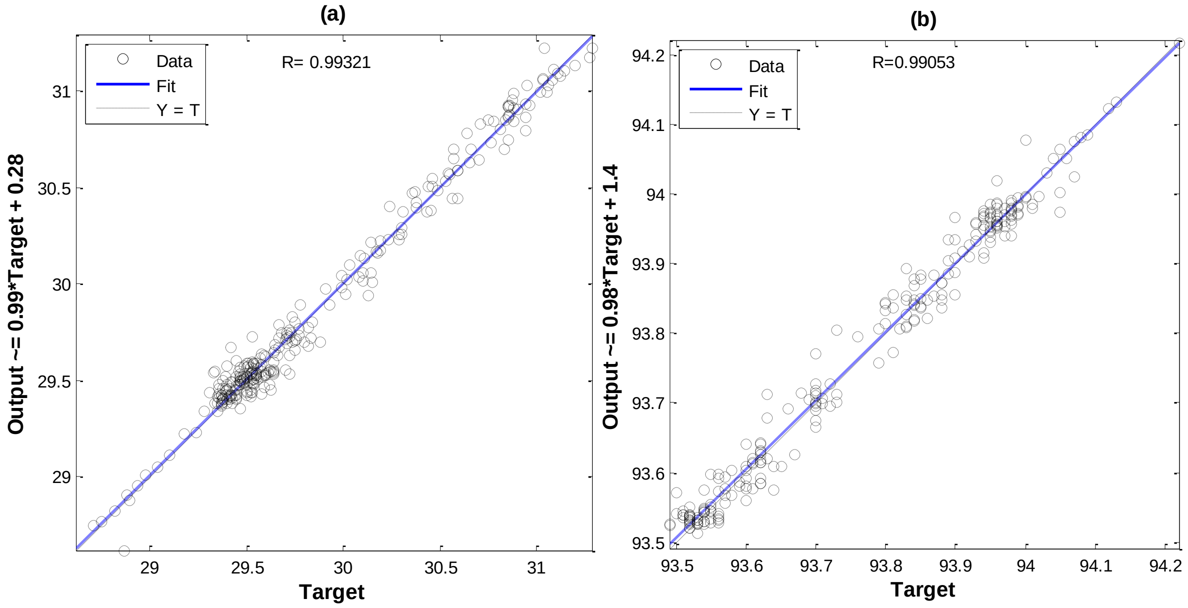


Figure 9. Plots indicate a linear regression between the network outputs and the corresponding targets a) temperature b) relative humidity.

Hygrothermal forecast of 90-steps-ahead is plotted in Figure 10. It can be observed that the forecasted temperature (90-steps-ahead) do not fit with the observed data fully. This is because of the used small training dataset. It is clearly seen that the last 90 time-steps has different trend compared with the other time steps which were used for training the model. The forecasting performance of the models was measured by mean square error. The mean square error for 90-steps-ahead forecast of temperature and relative humidity inside concrete were 0.0155 and 0.008, respectively. These findings revealed that the NARX model can forecast long-term hygrothermal condition inside concrete that have not been observed before with good accuracy.

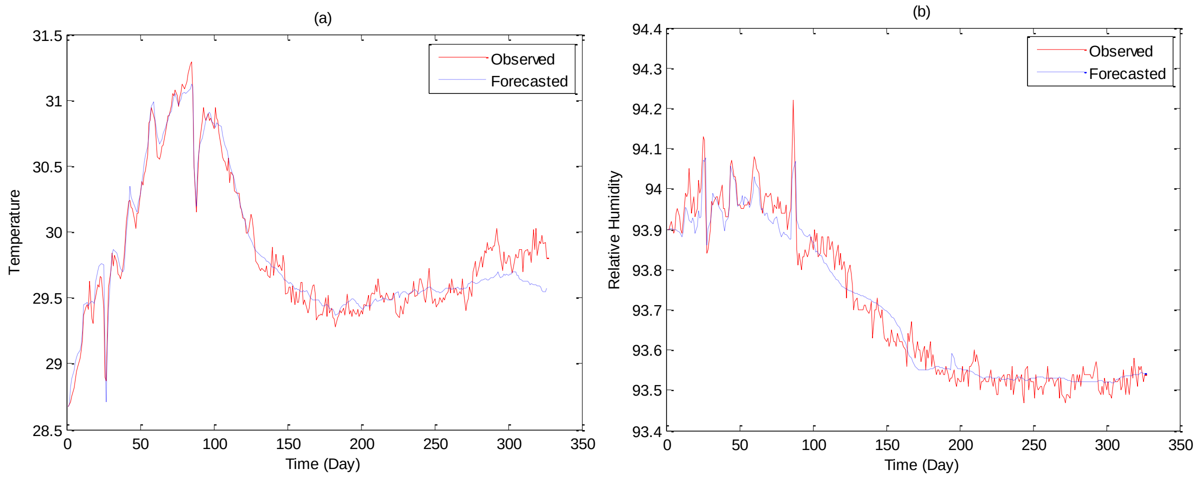


Figure 10. Plots of observed and forecasted data (90-steps-ahead) a) temperature b) relative humidity

A number of long-term forecasts with different time-steps-ahead were also performed using the NARX models and summarized in Table 2. It can be seen that the error range for the models is small, indicating that they all perform adequately. Table 2 also shows that when the forecasting horizon increases from 30-steps to 90-steps the mean square error is also increases, which in turn, deteriorates the forecasting ability. This is due to the compounding effects of the errors in the forecasted outputs at each time-step for n required time-steps. Though the forecasting ability decreases with increasing the time-steps, the developed NARX model reasonably forecast hygrothermal performance of 90-steps-ahead. This investigation confirmed that, even with small dataset, NARX model can forecast long-term hygrothermal behaviour inside concrete. The performance of long-term forecasting can be improved using large data since neural networks can learn very well from large data. Once trained, the model learns the aging effect on hygrothermal performance and can be used to make pragmatic decisions with regard to service-life extension of the structure.

Table 2. Mean square error of hygrothermal forecast of 30-steps, 60-steps and 90-steps-ahed

	30-steps-ahead	60-steps-ahead	90-steps-ahead
Temperature	mse=0.0151	mse= 0.0161	mse=0.0155
Relative humidity	mse=0.0022	mse=0.0064	mse=0.0080

5. Conclusions

Moisture and thermal interactions in concrete are the decisive factors influencing the durability of the concrete. Moisture content contributes a significant impact on several deterioration mechanisms, including corrosion of reinforcement steel, alkali-aggregate reactions, freezing and thawing, as well as sulphate attack. Thermal interaction inside concrete is also one of the dominant factors in accelerating deterioration processes caused by chemical and physical factors. The compressive strength, modulus of elasticity and volume deformation of concrete structures decrease remarkably upon elevated temperature.

Today, there are several concrete deterioration forecasting models caused by long-term hygrothermal interactions. However, the models contain assumptions and approximations about the hygrothermal performance inside concrete and other parameters. Assumptions and simplifications compounded with the dynamic behavior of hygrothermal interaction as well as complexity of thick-walled concrete structure the existing models are inadequate to use for service-life forecasting. Long-term, in-service hygrothermal performance monitoring of thick-walled concrete structures in regular interval using sensors is essential. It increases reliability of deterioration prediction models significantly.

Understanding of the long-term hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life. Two NARX (artificial neural network based long-term hygrothermal forecasting models) for temperature and relative humidity were developed. The models were trained to forecast the future hydrothermal behaviour inside concrete ranging from 30-steps to 90-steps-ahead. When the forecasting horizon increases the mean square error is also increases. It indicates that the larger samples have the advantage of reducing the total error. Even though the forecasting ability decreases with increasing the time-steps, the developed NARX model reasonably forecast for 90-steps-ahead. The mean square error for 90-steps-ahead forecast of temperature and relative humidity inside concrete were 0.0155 and 0.008, respectively. Thus, using long-term hygrothermal data, it is possible to capture the aging effect on hygrothermal performance and can be used to make realistic decisions with regard to service-life extension of the structure.

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Workshop on non-destructive evaluation of thick walled concrete structures

Prague, Czech Republic, 17-19 September 2013

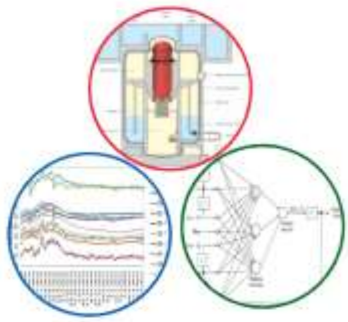
Monitoring, evaluation and long-term forecasting of hygrothermal performance of thick-walled concrete structure

Woubishet Zewdu Taffese, Fahim Al-Neshawy Jukka Piironen, Esko Sistonen and Jari Puttonen

Aalto University School of Engineering, Department of Civil and Structural Engineering, Espoo, Finland

Outlines

- Objectives of the study
- Effect of moisture and temperature on the durability of thick-walled concrete structures
- Monitoring of the hygrothermal performance of containment structure
- Long-term forecasting of the hygrothermal performance
- Conclusions



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MANAGE research project

Aging Management of Concrete Structures in Nuclear Power Plants – MANAGE

- Funded by SAFIR 2014 (The Finnish Research Programme on Nuclear. Power Plant Safety 2011 – 2014).
- Objectives:
  - Development of a computerized aging management system for concrete structures in nuclear power plants
  - Development of an inspection database for NPP concrete structures
  - **Development of a monitoring and simulation system which supports aging management and condition assessment of concrete structures**
  - Development of structural analyses supporting aging management

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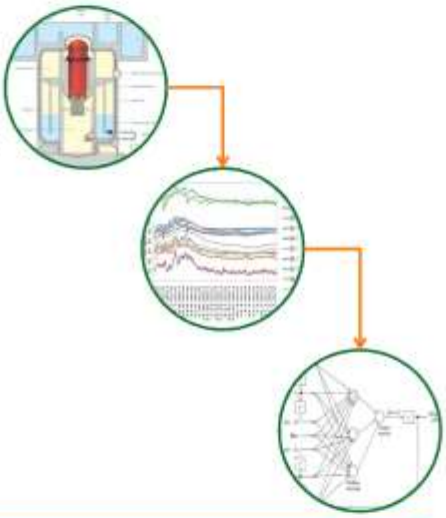
Objectives of the study

- Long-term and in-service hygrothermal **monitoring** of containment thick-walled concrete structure
- Analyzing of the **hygrotermal performance** of the monitored containment
- Forecasting Models for the hygrotermal performance of the monitored containment using **artificial neural network**.



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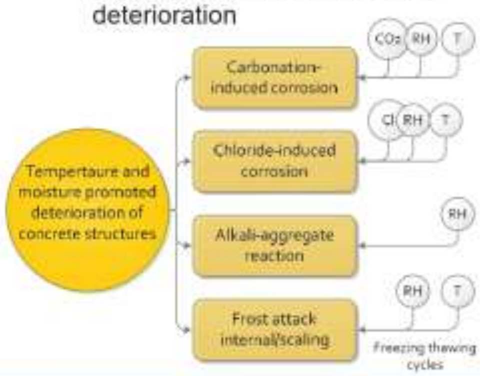
Effect of moisture and temperature on the durability of thick-walled concrete structures

- Thick-walled concrete structures face substantial temperature and humidity differences between the interior and exterior surfaces
- While the thick walls provide for low average temperature and/or moisture gradient, near surface gradients can be substantial due to exposure to rapid environmental condition changes.

- Temperature and moisture contribute a significant impact on several physical and chemical deterioration



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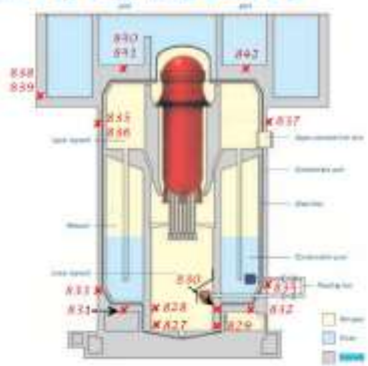
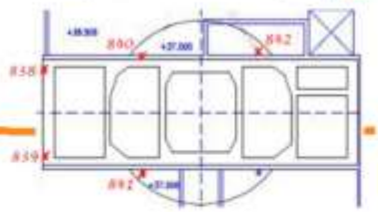
Monitoring of the hygrothermal performance of containment structure

- The ambient T & RH were collected inside containment at elevation of 1000mm.
- T & RH of concrete inside the containment in the depth of 400mm
- HMP44L sensors were used
- time intervals of 24 hours



Elevation (m)	Sensor label
36.6	840 841 842
31.8	838 839
30.0	835 836 837
6.0	833 834
2.5	831 828 830 832
1.0	827 829



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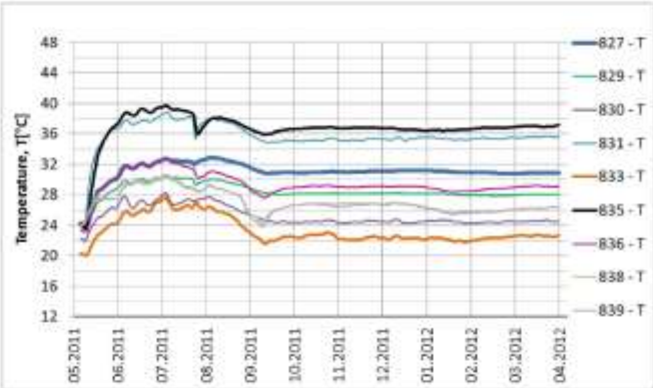
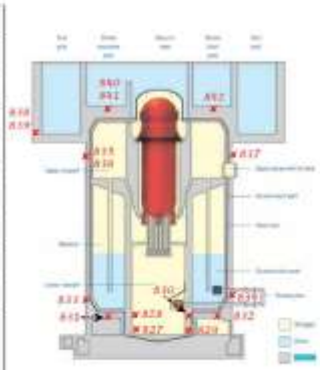
Monitoring of the hygrothermal performance of containment structure

Temperature inside concrete seems to have the same trend with the ambient temperature





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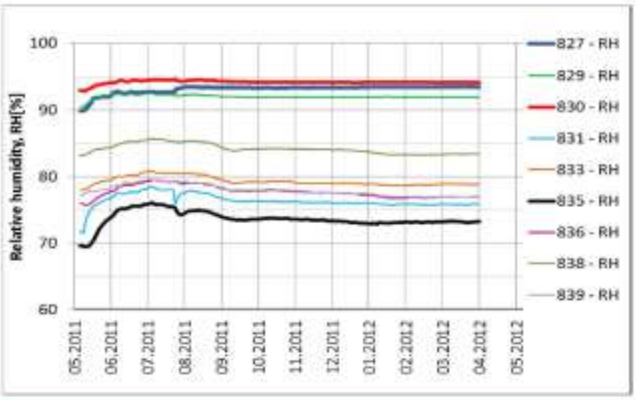
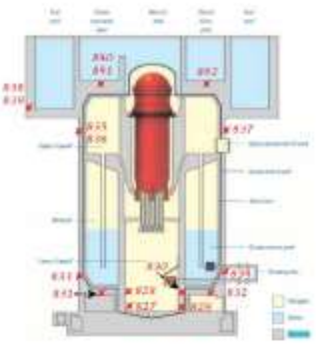
Monitoring of the hygrothermal performance of containment structure

Relative humidity measurements inside concrete, in many cases, varied between 70% and 95% RH





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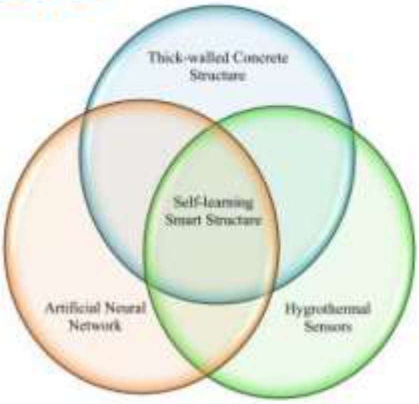
Long-term forecasting of the hygrothermal performance

- Real-time condition is monitored data by sensors
- The real-time data can be modeled using Artificial Neural Network , in turn makes self-learning smart structure which speaks the future hygrothermal performance for itself.
- Non-linear autoregressive with exogenous inputs (NARX) network with two layers was used to model the data



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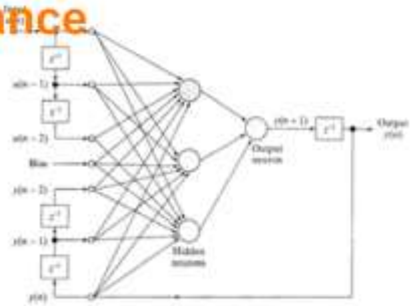
Long-term forecasting of the hygrothermal performance

- The NARX model has two inputs,
  - one is an external input (e.g monitored ambient temperature),
  - the other is a feedback connection from the model output.
- The feedback connection from the model output at future time-steps are forecasted hygrothermal data.
- The forecasting performance of the models was measured by Mean Square Error (MSE).



	30-steps-ahead	60-steps-ahead	90-steps-ahead
T	0.0151	0.0161	0.0155
RH	0.0022	0.0064	0.0080

Mean Square Error (MSE).

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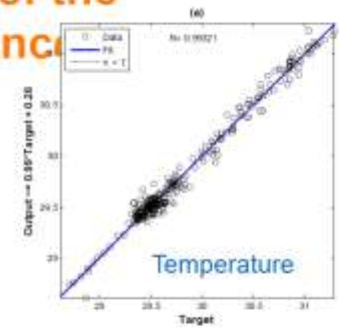
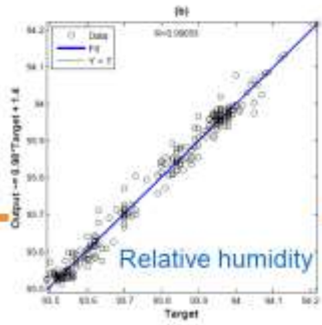
Long-term forecasting of the hygrothermal performance

- A linear regression between the network outputs and the corresponding targets were conducted
- R-value for temperature response was 0.99321
- R-value for relative humidity was 0.99053.
- In both cases the R-values are above 0.99 which indicates the model outputs tracks the targets (observed hygrothermal behaviour inside concrete) very well.





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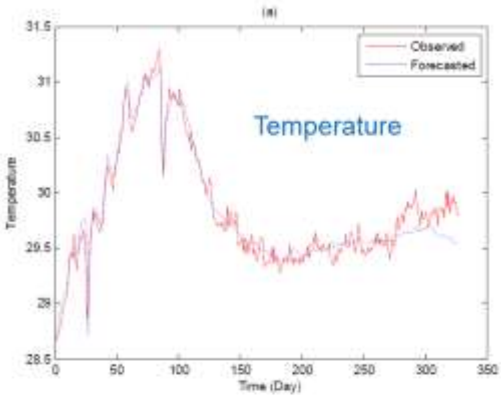
Long-term forecasting of the hygrothermal performance

Temperature

- It can be observed that the forecasted temperature (90-steps-ahead) do not fit with the observed data fully.
- This is because of the used small training dataset.
- MSE for 90-steps-ahead forecast of temperature inside concrete were 0.0155



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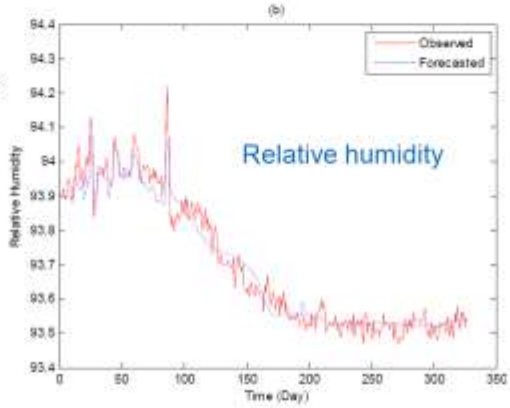
Long-term forecasting of the hygrothermal performance

Relative humidity

- MSE for 90-steps-ahead forecast of relative humidity inside concrete were 0.008



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Conclusions

- Understanding of the long-term hygrothermal performance in thick-walled concrete structures is of great interest when considering extension of its service-life.
- Two NARX (artificial neural network based long-term hygrothermal forecasting models) for temperature and relative humidity were developed.
- The models were trained to forecast the future hydrothermal behaviour inside concrete ranging from 30-steps to 90-steps-ahead
- The mean square error for 90-steps-ahead forecast of temperature and relative humidity inside concrete were 0.0155 and 0.008, respectively.
- Thus, using long-term hygrothermal data, it is possible to capture the aging effect on hygrothermal performance and can be used to make realistic decisions with regard to service-life extension of the structure.

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Thank you for your attention

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EPRI | ELECTRIC POWER RESEARCH INSTITUTE

The Effect of Irradiation on Thick Walled Concrete Structures in Nuclear Power Plants with Respect to Long Term Operation

September 17, 2013
Brian Hohmann, Thomas Esselman,
Paul Bruck (Lucius Pitkin, Inc.),
James J. Wall (EPRI)

Lucius Pitkin, Inc.
Consulting Engineers

1

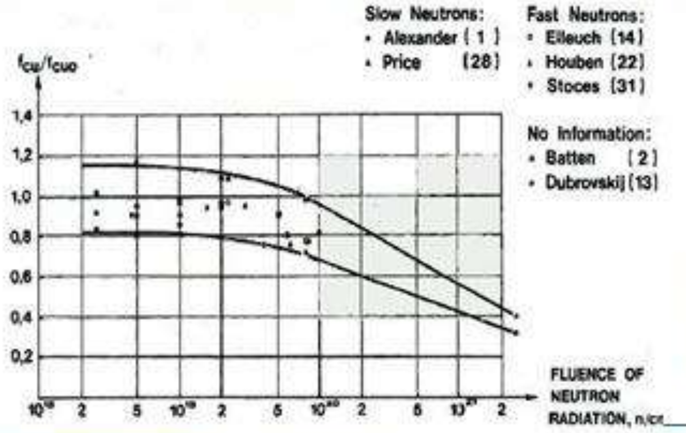
INTRODUCTION

- The literature on irradiation effects on concrete.
- Expected neutron fluence in the concrete at commercial nuclear plants.
- Temperature effects of gamma.
- Strategy to augment data.
- Conclusions.

2

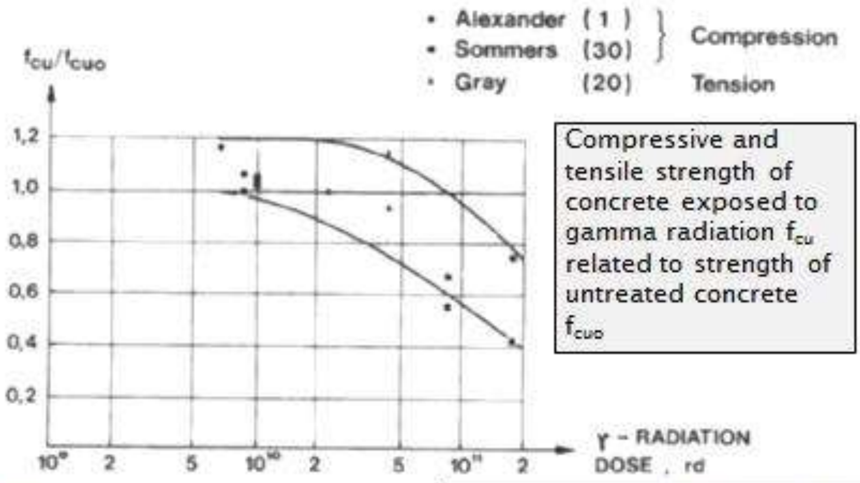
Literature Review

- H.K. Hilsdorf's 1978 paper described the effects of nuclear radiation on concrete properties.
- Hilsdorf compiled previously published data on the effect of nuclear radiation on concrete.



Source: Hilsdorf, H., J. Kropp, H. Koch. *The Effects of Nuclear Radiation on the Mechanical Properties of Concrete.* American Concrete Institute. Report SP-55-10. p. 223-251. 1978.

Hilsdorf Curve Gamma



Source: Hilsdorf, H., J. Kropp, H. Koch. *The Effects of Nuclear Radiation on the Mechanical Properties of Concrete.* American Concrete Institute. Report SP-55-10. p. 223-251. 1978.

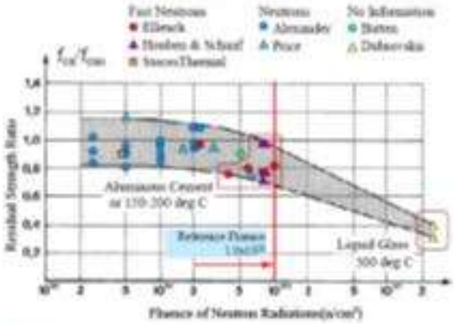
Hilsdorf cont.

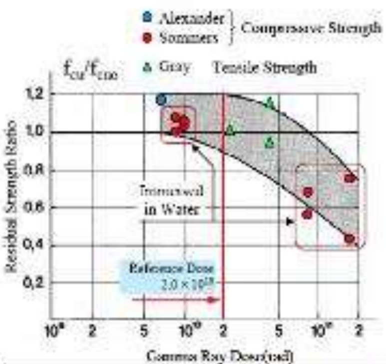
- Hilsdorf concluded that neutron radiation with a fluence of greater than 1×10^{19} n/cm^2 and a gamma dose greater than 10^{10} rads could have a detrimental effect on concrete strength.
- This data is currently still being used as a reference threshold levels by many.

5

Kontani, et. al. – 2010

- Concluded that the test conditions from some of the experiments on which Hilsdorf based his conclusions were not representative of the typical operating history of a commercial nuclear reactor, and thus may not be applicable





Kontani, O. et al. *Irradiation Effects on Concrete Durability of Nuclear Power Plants.* ICAPP 2011 Conference (Paper 11361). Nice, France, May 2-5, 2011.

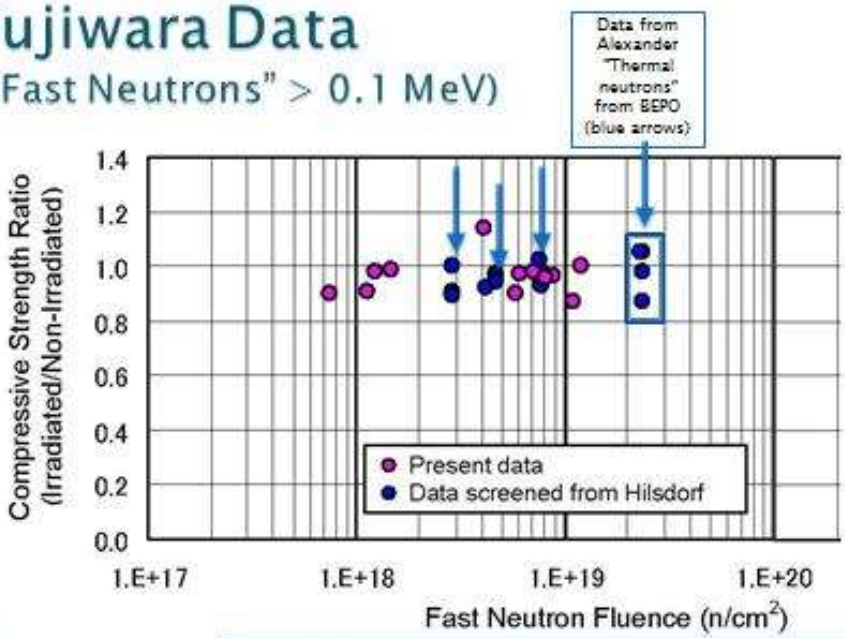
6

Fujiwara Neutron Data

- Test Results –No loss in compressive strength for specimens tested at fluence dose up to 1.2 E+19 n/cm² for E>0.1 MeV
- Test Reactor – JMTR
- Currently this is the most reliable and well documented research performed at E>0.1MeV.

7

Fujiwara Data
("Fast Neutrons" > 0.1 MeV)



Graph is from Fujiwara, et. al. *Experimental Study of Effect of Radiation Exposure to Concrete*, SMIRT, 2009

Alexander data are for E > 0.4 eV. When rescaled to E > 0.1 MeV, they are expected to move well to the left.

8

Radiation Exposure

- Determine the neutron and gamma exposure in the reactor cavity concrete for eighty years of operation (Note 1).
- For fluence consider energy at > 0.1 MeV (Note 2).
- Determine rate of attenuation of fluence into concrete.
- Define effect of gamma heating.

Note 1: A 92% capacity factor is considered, resulting in 80 yrs x 0.92 CF = 73.6 EFPY equivalent

Note 2: Energy >1 MeV has been used to assess damage to the steel of the RPV. A value of >0.1 MeV is commonly used for assessing concrete.

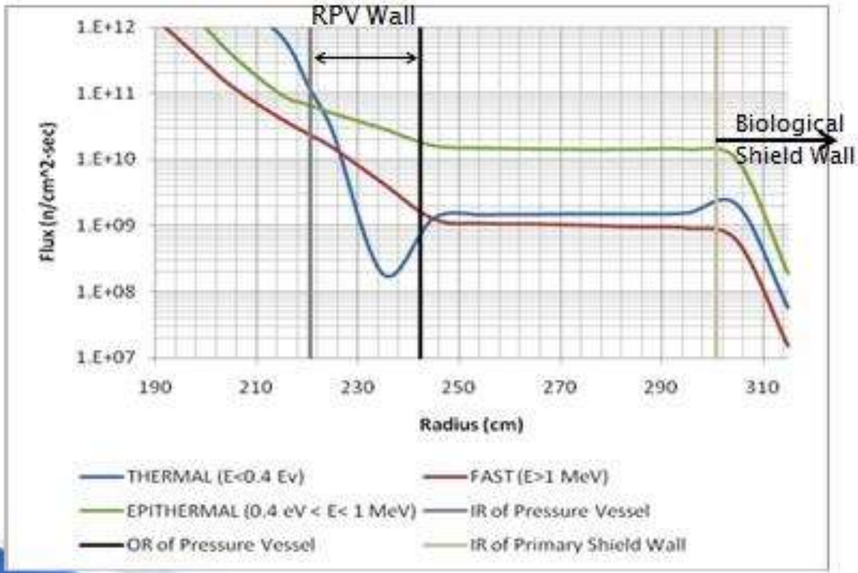
9

Radiation Exposure

- Concrete fluence derived as the fluence at the OD of the RPV (i.e. thickness of the RPV – i.e. 1T).
- Fluence value at the RPV ID (i.e. “0T” value) derived from licensee reports to NRC for reported values of EFPY, scaled to 73.6 EFPY
- RPV fluence values reported are for > 1.0 MeV energy.

10

Typical Neutron Flux Curve

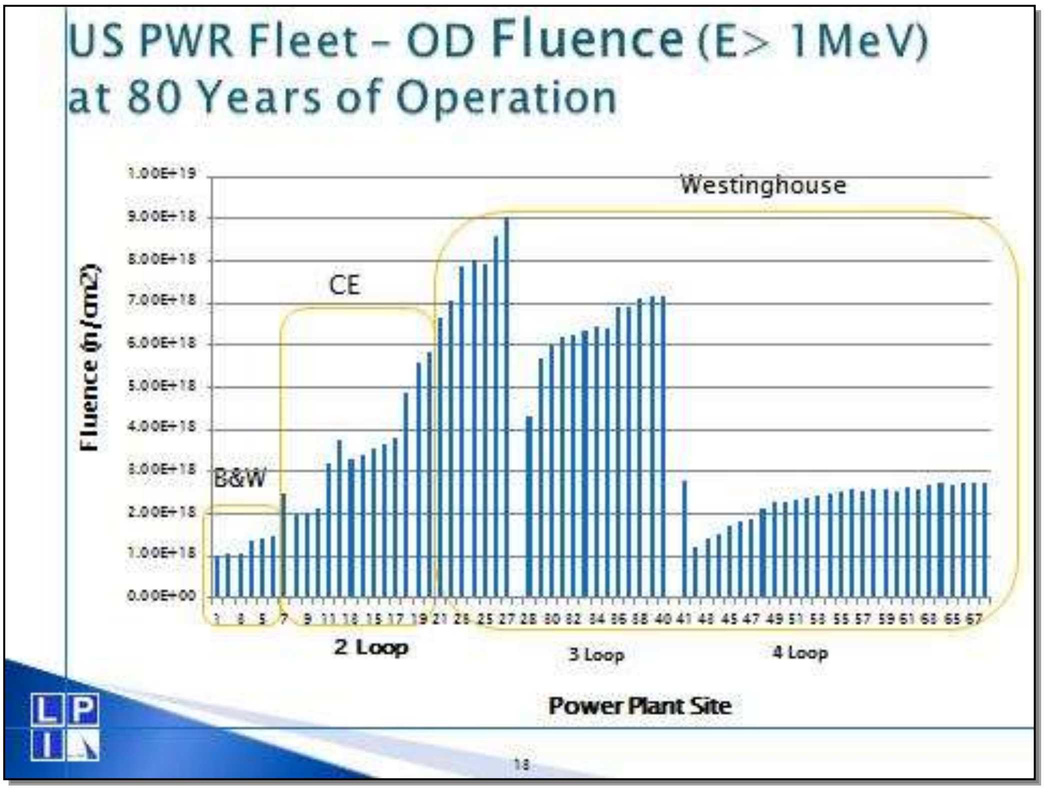


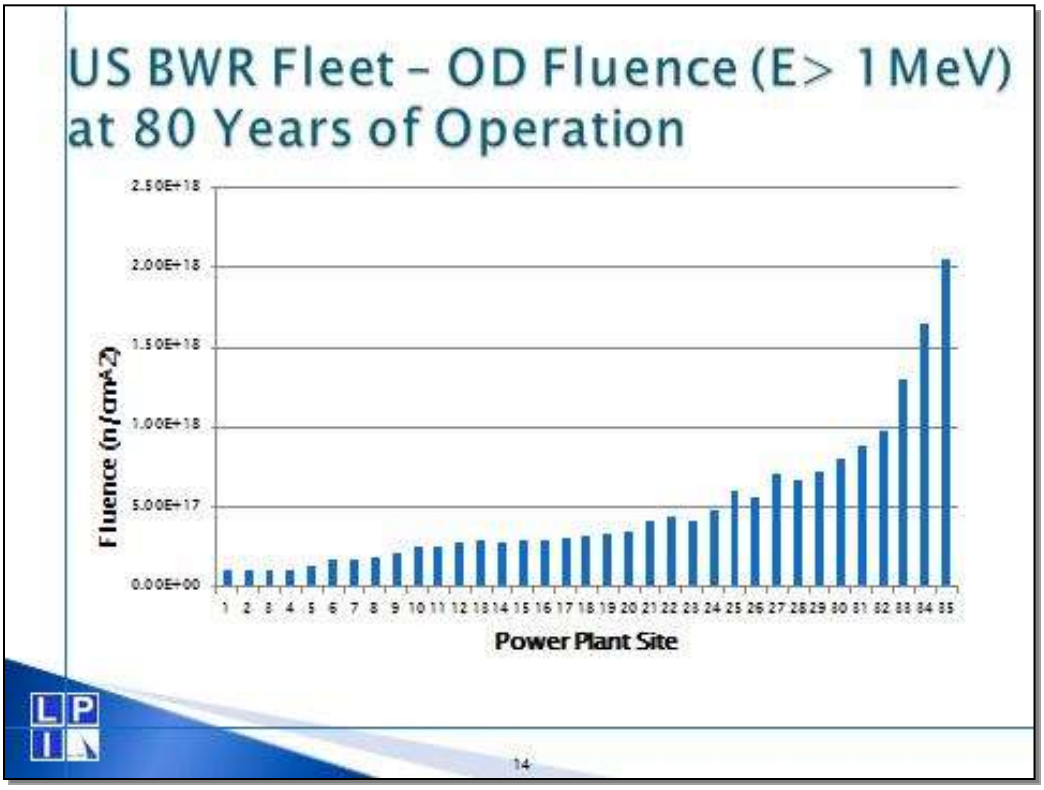
Attenuation

- Attenuation through RPV wall based on exponential fluence attenuation equations.
- US Nuclear Regulatory Commission Regulatory Guide 1.99 provides a basis for determining RPV OD fluence, but it is based on "dpa attenuation" to account for changes in vessel steel.
- Prior to the "dpa attenuation", the following relationship was used by the US NRC to determine neutron fluence (f_{OD}) at outside surface of the RPV (RPV thickness = t):

$$f_{OD} = f_{ID} \times e^{-0.33t}$$

12


US PWR Fleet – OD Fluence (E> 1MeV)
at 80 Years of Operation
Fluence (n/cm2)
Westinghouse
CE
B&W
2 Loop
3 Loop
4 Loop
Power Plant Site
13


US BWR Fleet – OD Fluence (E> 1MeV)
at 80 Years of Operation
Fluence (n/cm^2)
Power Plant Site
14

Neutron Fluence Summary

- A two loop plant has the highest 80 year RPV OD fluence of 9.0 E+18 at E > 1MeV.
- Fluence at > 0.1 MeV is higher than at > 1 MeV. The ratio depends on RPV wall thickness – two loop plant vessel wall thickness is 6.5 inches (16.7 cm).
- Fluence calculations provide a ">0.1 MeV to > 1 MeV ratio" of 8.5 for this vessel thickness.
- Fluence at RPV OD is then 7.6E+19 for E > 0.1 MeV.
- The fluence at the concrete ID is somewhat lower due to an increase in impacted surface area due to gap between vessel OD and concrete. Reduction will be approximately 10%.
- The fluence (E > 0.1 MeV) at the concrete ID will be 6.9 E+19 for 80 years of operation.

15

Neutron Fluence Summary

- The highest three loop plant has an RPV OD fluence of 7.1E+18 at E > 1MeV.
- This plant has a RPV thickness of 7.75 inches (19.7 cm).
- Fluence calculations provided a ">0.1 MeV to > 1 MeV ratio" of approximately 9.5 for this vessel thickness.
- Fluence at RPV OD is then 6.7E+19 for E > 0.1 MeV.
- With the 10% reduction for the area difference, the fluence at the concrete ID will be 6.1 E+19 for 80 years of operation.
- A value of 7 E+19 n/cm^2 for 80 years appears to conservatively bound the US fleet for E > 0.1 MeV.

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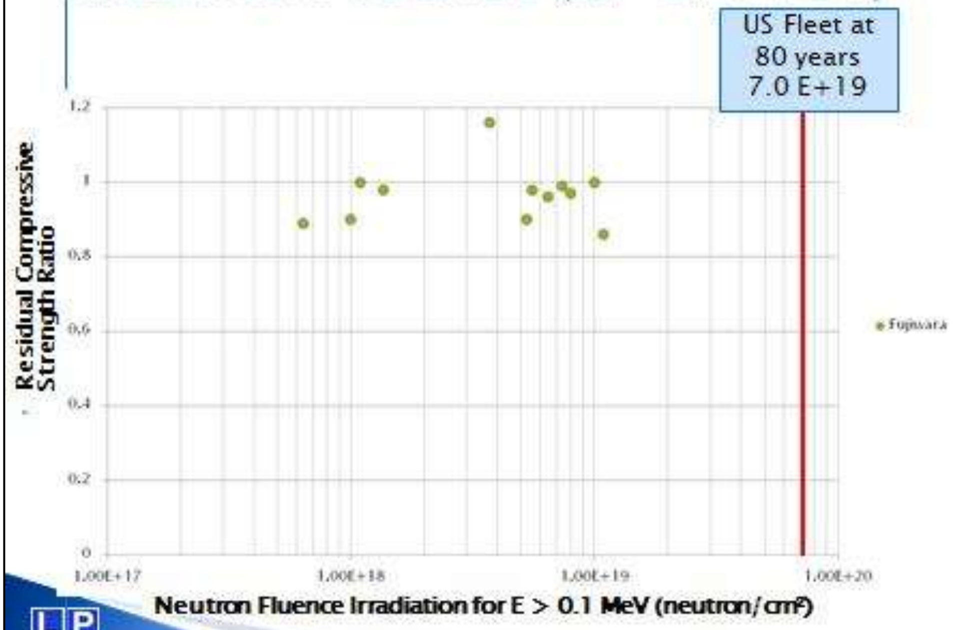
Neutron Fluence (E>0.1MeV)



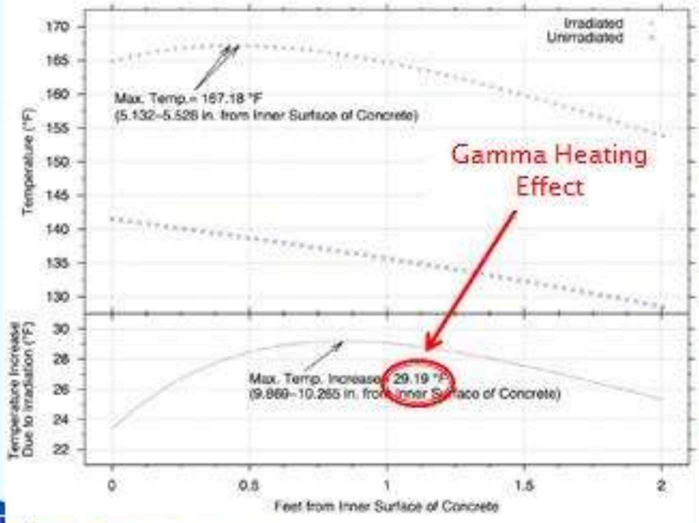
17

Shield Wall Requirements

- The biological shield wall concrete provides shielding, transfers load to the rebar, and reacts normal and accident loads from the RPV support.
- The fluence (E > 0.1 MeV) attenuates in the concrete.
  - In many plants, the major structural rebar is well below the surface of the concrete.
  - Reactor vessel supports are typically above the top of the core and out of the zone of maximum fluence.
  - The critical regions of the shield wall are not in the highest fluence regions of the concrete.
- Fluence at critical locations less than the maximum location.

18

Gamma Heating Evaluation



If inner cavity wall assumed to be 150F (66C), the peak temperature in the concrete is 167F (75C) 5 inches (13 cm) below the surface.

Maximum temperature increase due to gamma heating approximately 30F (17C).

19

Temperature Effects

- Based on 150F (66C) cavity temperature (based on forced cooling of the cavity), the cavity concrete temperature is expected to be below 180F (82C).
- This is within American Concrete Institute code and US Plant FSAR requirements.

20

Strategy to Augment Knowledge

- Improved knowledge of the performance of irradiated concrete would be helpful to support the long term operation of nuclear plants around the world.
- Testing is ongoing or is planned for radiation levels up to and exceeding 6 E+19 n/cm2 (E > 0.1 MeV).
- This testing will be useful to augment existing knowledge.

21

Conclusions

- There is no indication that concrete will not be adequate to 80 years of operation
- Additional data will be useful to augment existing data on the long term effects of radiation on concrete.

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SESSION THREE

The Use of Digital Image Correlations for Detection of Degradation in Concrete Structures
Paul Bruck, Sontra Yim, James Wall

Projects Dealing with Radiation Damage of Concrete at the LVR Research Reactor
Milan Marek et al.

Use of Fiber Optic Sensors for Monitoring Loads in Post-Tensioned Tendon
Sontra Yim, Thomas Esselman, James Wall

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

The Use of Digital Image Correlation (DIC) for Degradation Detection and Trending in Concrete Containment Structures

September 18, 2013

Sontra Yim, Tom Esselman,
Paul Bruck, Brian Hohmann (Lucius Pitkin, Inc.)
James Wall (Electric Power Research Institute)

Lucius Pitkin, Inc.
Consulting Engineers

1

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Introduction

- Motivation
- What is Digital Image Correlation (DIC)
- DIC technique
- Case study at Pilot Nuclear Plant
- Results
- Conclusions
- Questions

2

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Motivation

- Nuclear Power Plant Extended Life Operation (Beyond 40 Years)
- Concrete Containment Structure Vital Part of Nuclear Power Plant
  - Withstand P&T of DBA w/o exceeding leak rate
  - Missile Shield and Fission Product Barrier
- Augment Existing Inspections and Testing
  - Effective Condition Assessment Requires Knowledge of Design and Expected Degradation
- Detect, Track and Trend Degradation
  - Obtain quantitative and repeatable data on the performance of the containment structure.
- Structural Integrity Test
  - Accurately measure behavior of the concrete surface during the SIT
  - Data can be taken again at the next SIT to confirm that the structural behavior of the containment has not changed.

LPI

3

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What is DIC?

- Digital Image Correlation (DIC) is an optical method that employs pattern matching and image registration techniques for accurate two- and three-dimensional measurements
- System defines unique correlation areas, known as ***facets*** (typically 5-20 square pixels in size)
- Image correlation software tracks facets from successive images with **sub-pixel accuracy**

100	100	0	100	100
100	100	0	100	100
0	0	0	0	0
100	100	0	100	100
100	100	0	100	100

Time t

100	100	100	0	100
0	0	0	0	0
100	100	100	0	100
100	100	100	0	100
100	100	100	0	100

Time t'

LPI

4

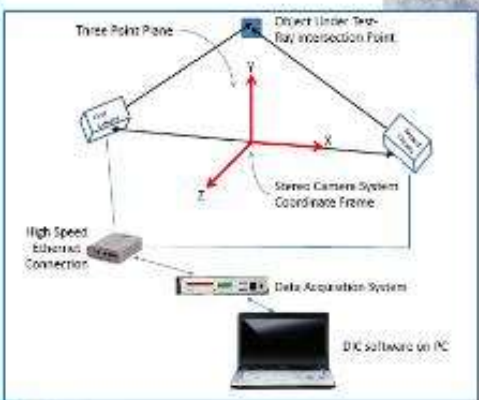
What is DIC?

- Sensitivity with 3D DIC is **1/30,000** the field of view
- Used to Measure
  - Changes in Shape
  - Deformation
  - Displacement
  - Strain
- Data can be taken for static or dynamic tests
- Common Example of DIC?
  - The Optical Mouse

5

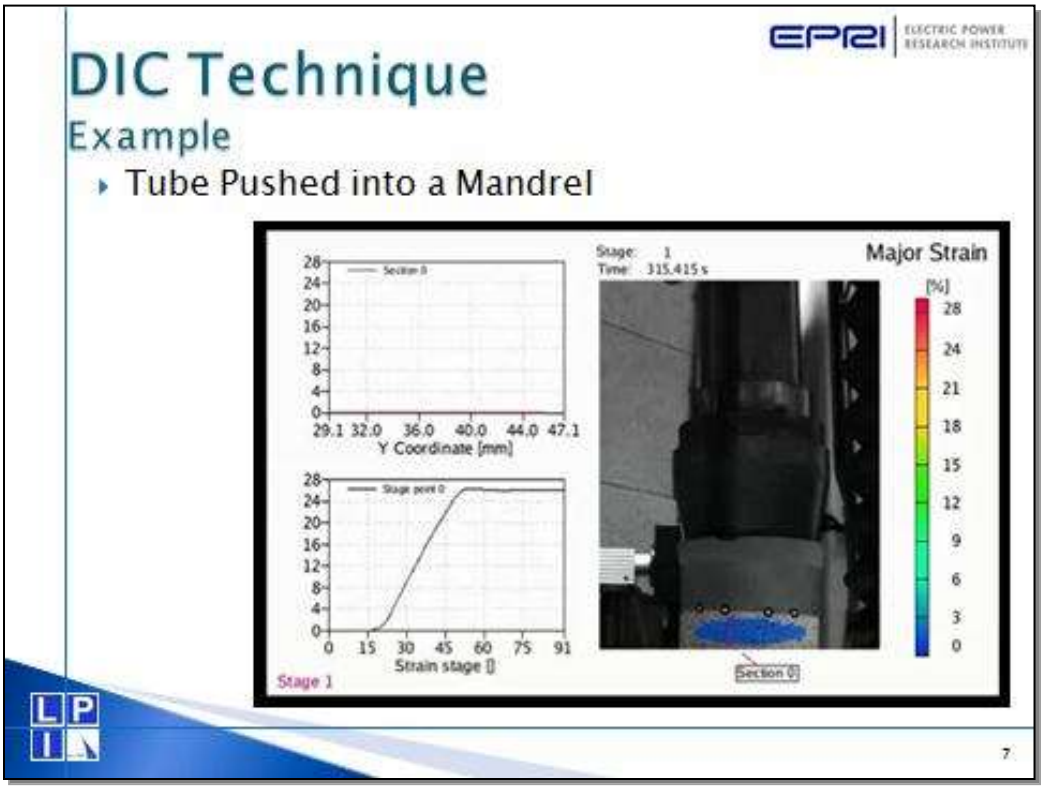
DIC Technique

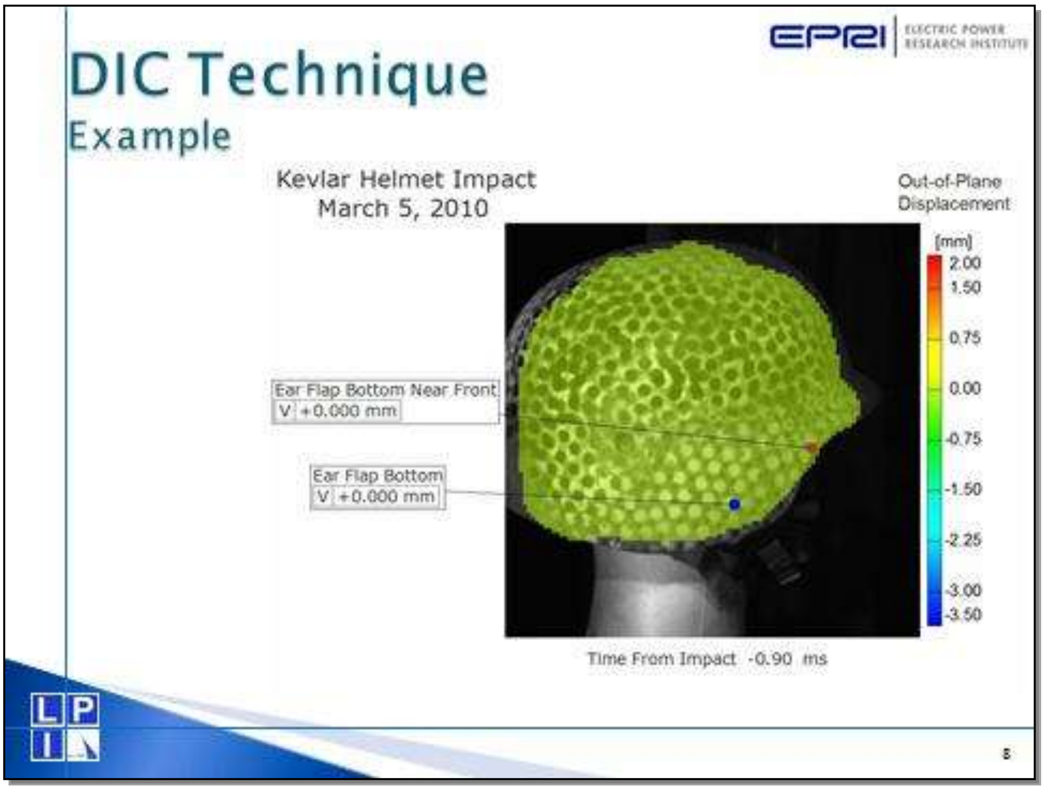
3D Technique Overview



- Apply Non-repetitive Isotropic High-contrast pattern to object under test
- Set up 2 camera system - 3D vision
- Calibrate Camera System
- Data Acquisition system collects data
- DIC software interprets data

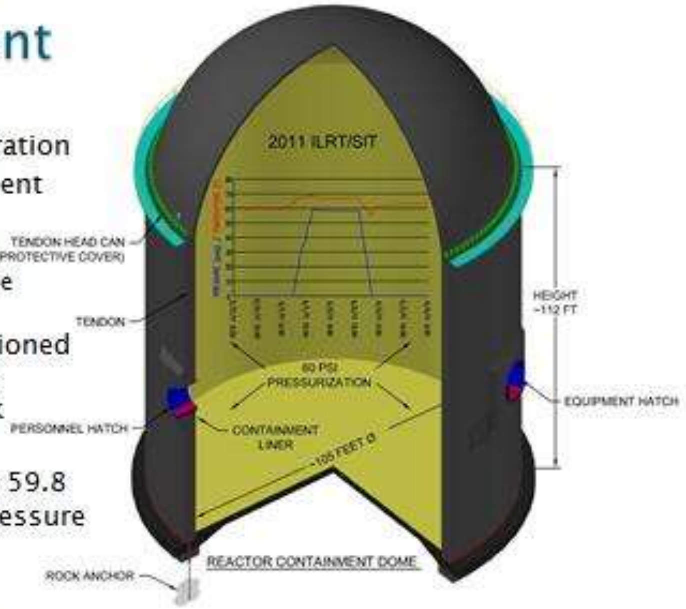
6


DIC Technique
Example
Tube Pushed into a Mandrel
Section 0
Y Coordinate [mm]
Stage point 0
Strain stage []
Stage 1
Stage: 1
Time: 315.415 s
Major Strain
[%]
Section 0
7


DIC Technique
Example
Kevlar Helmet Impact
March 5, 2010
Out-of-Plane Displacement
[mm]
Ear Flap Bottom Near Front
V +0.000 mm
Ear Flap Bottom
V +0.000 mm
Time From Impact -0.90 ms
8

Pilot Plant Containment

- 2 Loop PWR
- >40 years of operation
- Vertical containment cylinder
  - 112ft (34m) high
  - 105 ft (32m) inside diameter
- Axially post-tensioned with 160 tendons connected to rock anchors
- SIT performed to 59.8 psi (0.41 MPa) pressure

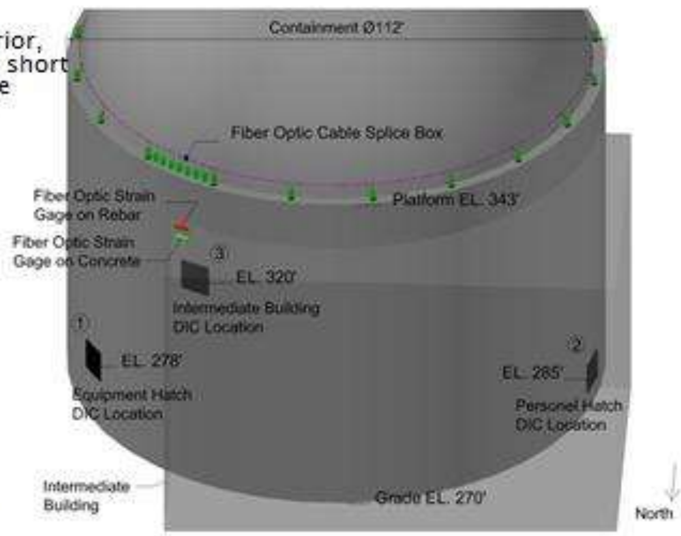


9

Pilot Plant

DIC Test Setup

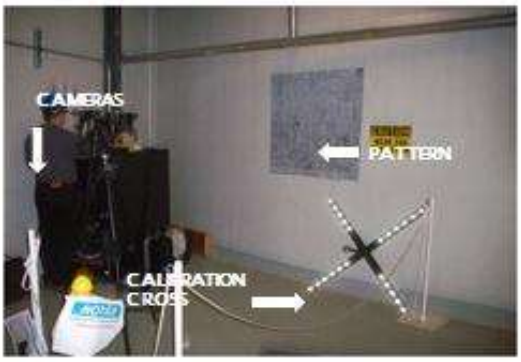
- DIC at Three locations
  - Monitored just prior, during, and for a short time following the pressurization of containment
- Monuments affixed for future comparison



10

DIC Test Setup

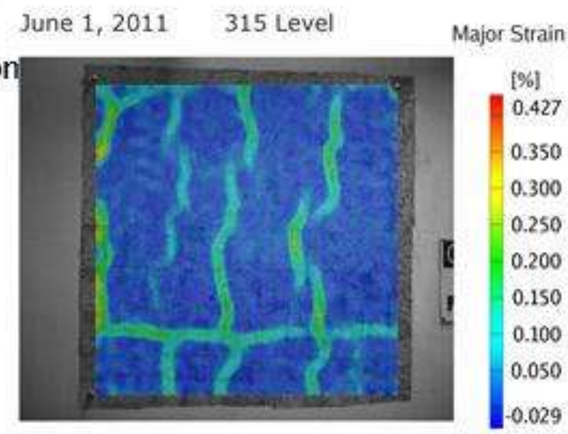
- Test area approximately 3 ft (~1m) square
- Working distance of 5ft (1.5m)
  - Angle between two DIC cameras 15-25 degrees
- Two DIC systems utilized for testing
  - One system mounted at personnel hatch to monitor response behavior during entire SIT pressurization and depressurization.
  - One system used to measure displacements at the two other locations – equipment moved between locations during hold times.



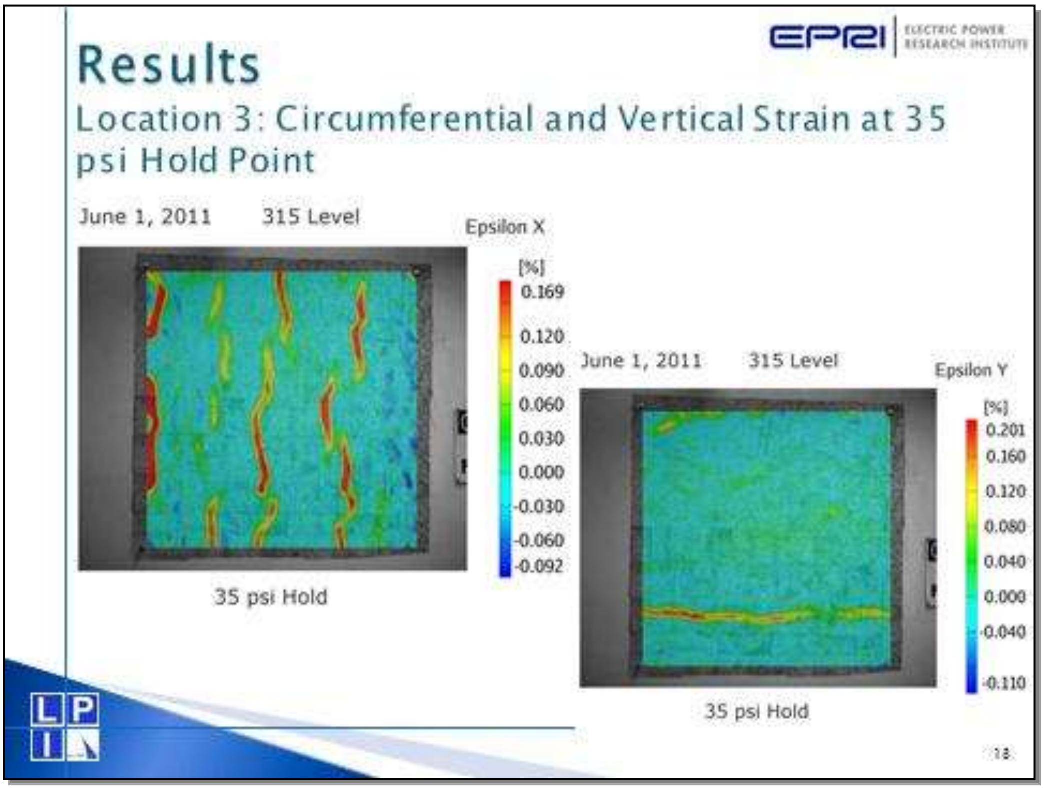
Results

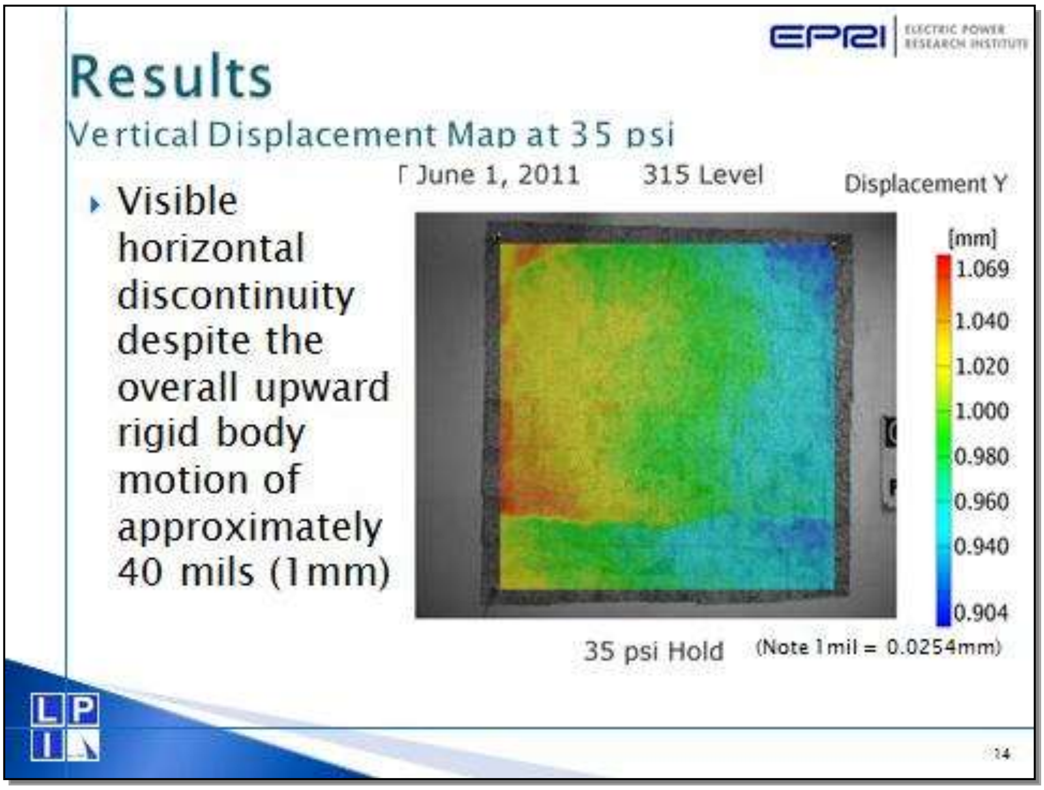
Location 3: Principal Strain at 35 psi Hold

- The "principal strain" is the maximum strain independent of direction
- Significant strain "fingers" observed at locations of hairline cracks in surface of concrete
- The higher strain value on the left side means that the crack is wider there



35 psi Hold

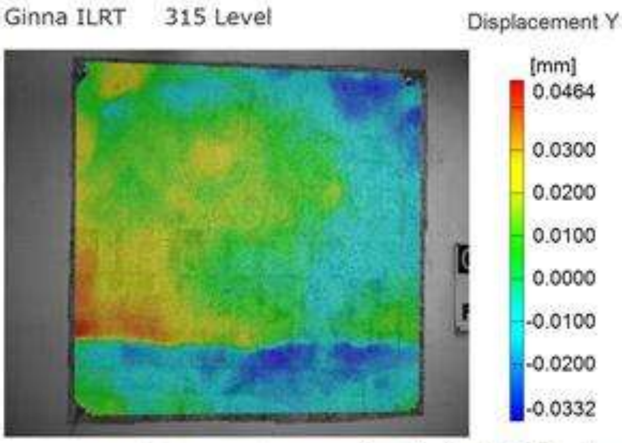

EPRI ELECTRIC POWER RESEARCH INSTITUTE
Results
Location 3: Circumferential and Vertical Strain at 35 psi Hold Point
June 1, 2011 315 Level
Epsilon X
[%]
0.169
0.120
0.090
0.060
0.030
0.000
-0.030
-0.060
-0.092
35 psi Hold
June 1, 2011 315 Level
Epsilon Y
[%]
0.201
0.160
0.120
0.080
0.040
0.000
-0.040
-0.110
35 psi Hold
13


EPRI ELECTRIC POWER RESEARCH INSTITUTE
Results
Vertical Displacement Map at 35 psi
Visible horizontal discontinuity despite the overall upward rigid body motion of approximately 40 mils (1mm)
June 1, 2011 315 Level
Displacement Y
[mm]
1.069
1.040
1.020
1.000
0.980
0.960
0.940
0.904
35 psi Hold
(Note 1mil = 0.0254mm)
14

Results

Vertical Displacement Map at 35 psi after Rigid Body Movement Correction

- Shows only the local relative displacements



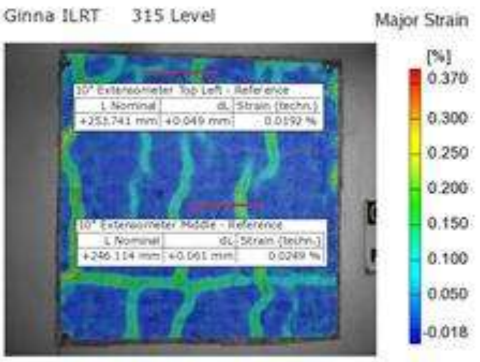
35 psi Hold (Note 1mil = 0.0254mm)

15

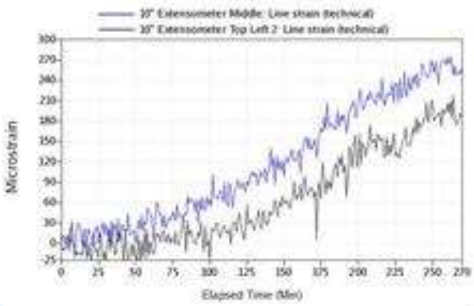
Results

10" Long Extensometers

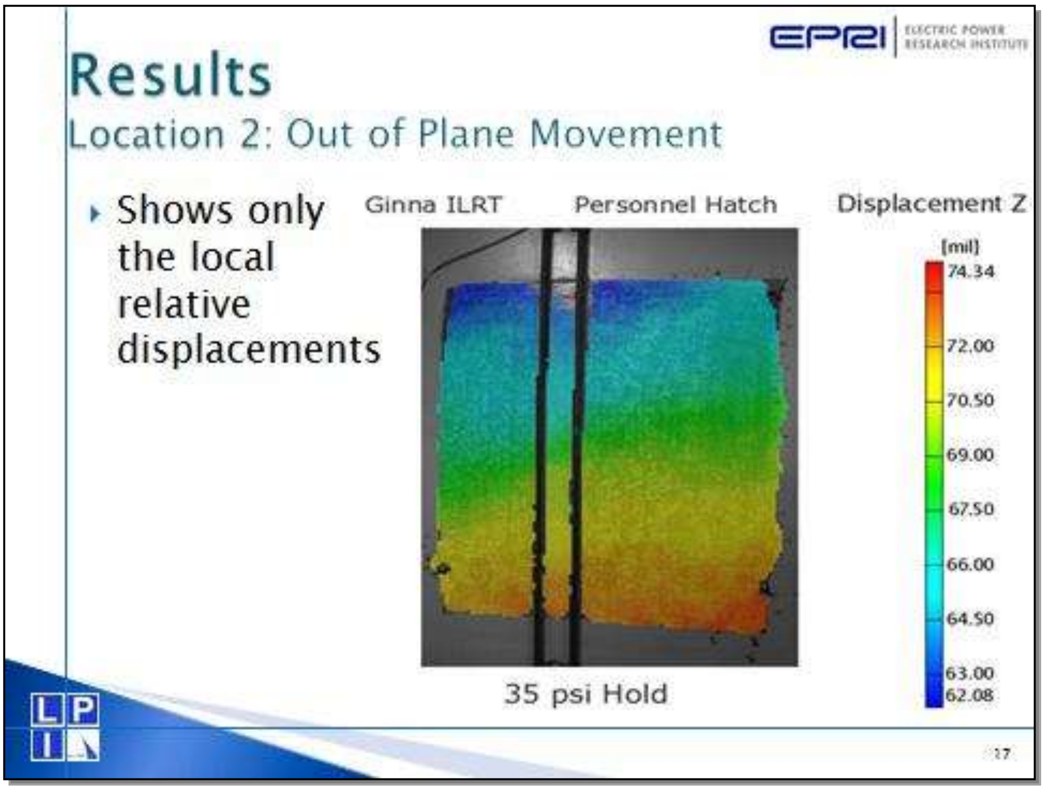
- Strain data calculated by DIC software
- "Virtual" strain gages set-up to compare with future DIC data.
- Compares well to Fiber Optic Strain Concrete Gage Near this Location ~ 190με

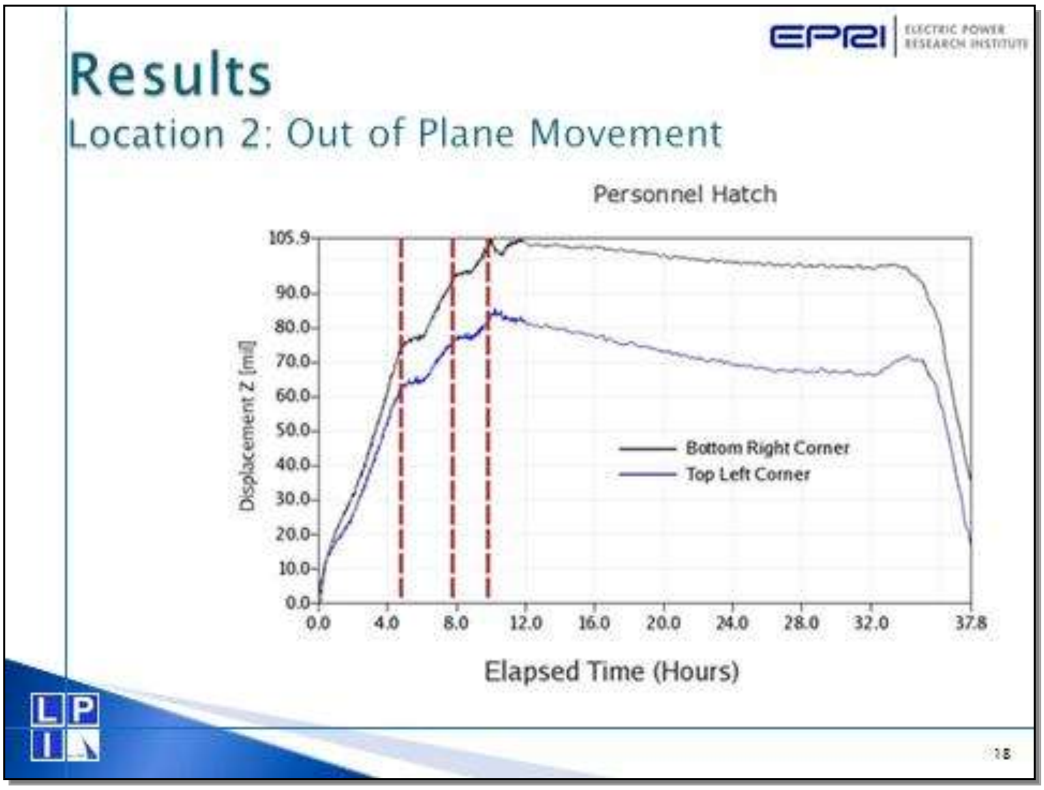


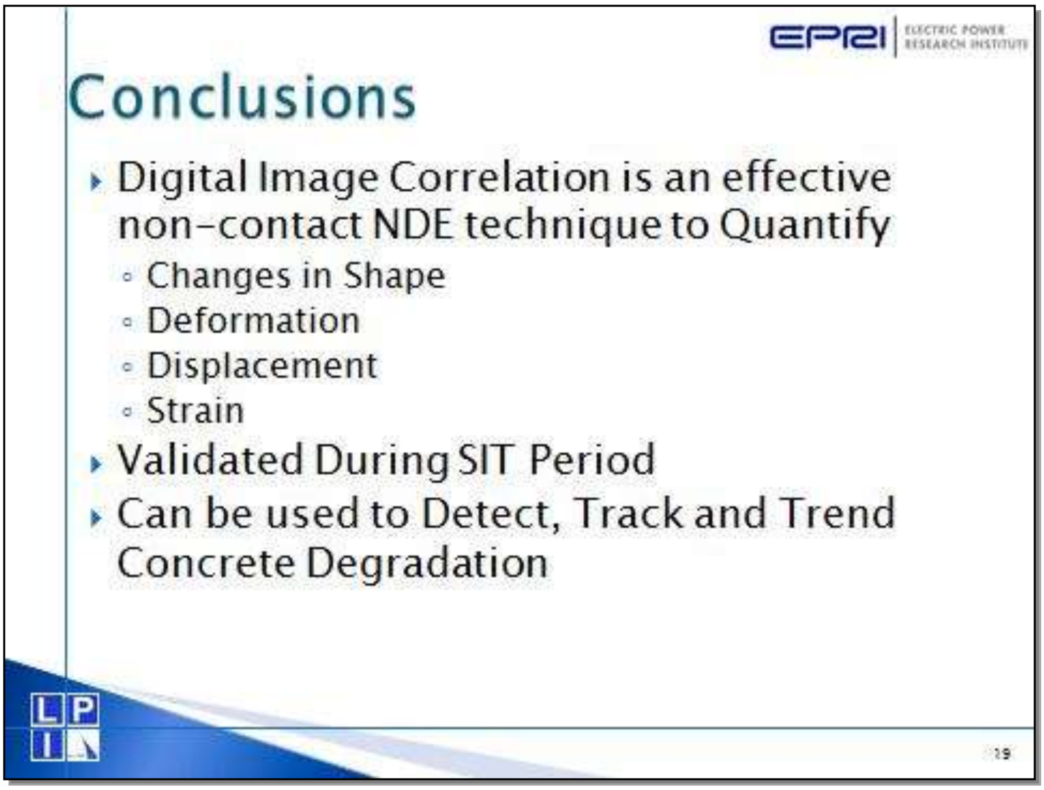
35 psi Hold



16


Results
Location 2: Out of Plane Movement
Shows only the local relative displacements
Ginna ILRT
Personnel Hatch
Displacement Z
[mil]
74.34
72.00
70.50
69.00
67.50
66.00
64.50
63.00
62.08
35 psi Hold
17


Results
Location 2: Out of Plane Movement
Personnel Hatch
Displacement Z [mil]
105.9
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
37.8
Bottom Right Corner
Top Left Corner
Elapsed Time (Hours)
18


Conclusions
Digital Image Correlation is an effective non-contact NDE technique to Quantify
Changes in Shape
Deformation
Displacement
Strain
Validated During SIT Period
Can be used to Detect, Track and Trend Concrete Degradation
19


Questions
20

Centrum výzkumu Řež s.r.o.

Project Dealing with Radiation Damage of Concrete at the LVR-15 Research Reactor

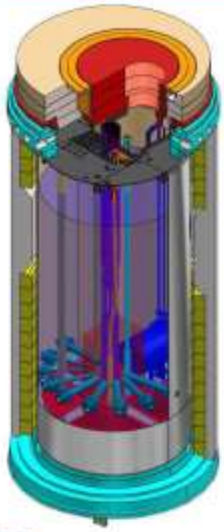
M. Marek, Z. Lahodová, M. Koleška, O. Frýbort, J. Vít, P. Hájek Jr.,

OECD NEA Workshop „NDE of NPPs Concrete Structures", Prague, September 17-19

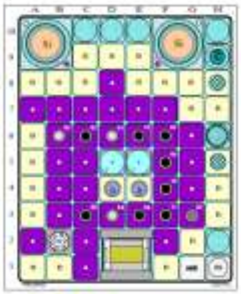
Outlines

- LVR-15 Research Reactor
- Preparation of Concrete Irradiation Project
- Mock-up
- Discussion

LVR-15 Research reactor at CV Rez



Reactor type	Tank
Pressure	Atmospheric
Average temperature	45 °C
LEU	IRT-4M 19.7% ^{235}U
Coolant	demineralized water
Reflector	beryllium
Nominal power	10 MW
Thermal flux	1.5 x 10^{18} n/m²s
Fast flux	2.5 x 10^{18} n/m²s



- **Material research**
  - Rigs - CHOUCA, Flat rigs, TW3
  - Loops - 2x BWR, 2x PWR
- **Isotope production**
  - Medical application – ^{99}Mo
  - Defektoskopy – ^{192}Ir
- **Si doping (NTD)**
  - 2 irradiation facilities- „DONA"
- **Horizontal channels – basic research**
  - BNCT Facility
  - Neutronography
  - 8 beams – neutron diffraction, scattering, neutron interactions

Material Irradiation at CV Rez

- Design of experimental facilities
  - Loops
  - Rigs – inert gas,
  - Autoclaves
- Irradiation in LVR-15 reactor
- Irradiation experiments oriented on research of material changes and influence of chemical parameters and radiation (VGB, Hitachi, MHI, TVEL,…)
- Irradiation in epithermal neutron beam - materials of storage casks - CASTOR/CONSTOR, concretes (GNB-GNS)

Material Irradiation at CV Rez

Loops
- PWR (RVS-3)
- BWR (BWR 1 and BWR 2)
- Zinc injection rig
- RVS-4 (Hydrogen / ammonia)

Special Loop Channels
- SSRT (slow strain rate testing) of PWR pre-irradiated samples
- IASCC – static / cyclic load
- 1 CT and 2 CT,
- Electrically heated fuel rods

Control of water chemistry
- system for gas dosing
- orb sphere – H2/O2 measurement
- Dionex ion - chromatograph

Irradiation Rigs
- Inert gas He, Ar
- Temperature control from 200℃ to 350℃, ±10 ℃
- CHOUCA rig - Charpy V, tensile, SSRT, 0,5 CT
- Flat Rigs – 1 CT, 2CT specimens (total irradiation volume 40x120x450mm)

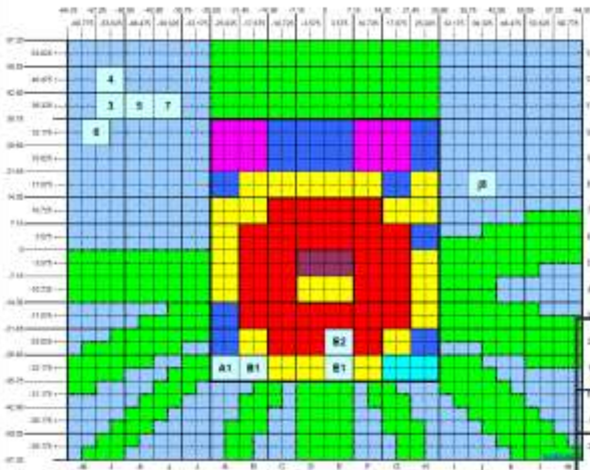
- ***Reactor dosimetry***
- Neutron monitors
- Calculations
- Mock - up experiments

Irradiation Conditions

- **We will use a 5cm diameter cylindrical sample, 10 cm long**
- **Concrete mix is still to be determined**
- **The sample will be housed in an He-filled, water cooled aluminum, casing**
- **Thermocouples will measure the sample core and surface temperatures**
- **The sample will be irradiated**
  - Neutron fluence1.5E+20 n/cm^2, E>0.1 MeV
  - The sample temperature will be bellow 90℃
- **The sample will be removed from the reactor for PIE and NDE**

- J. Wall, Nuclear Power Council Advisory Meeting, 08/26/13 – 08/29/13

Irradiation possibilities for concrete



Neutron spectrum in the LVR-15 reactor differs from the neutron spectrum in the concrete of PWR reactor especially the ratio of the neutron flux above 1 MeV to that above 0.1 MeV.

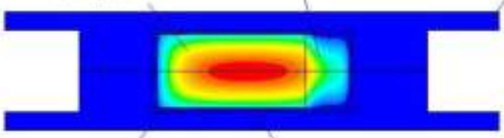
- Neutron fluence and gamma dose will be monitored during irradiation.
- 1.5E+20, E>0.1 MeV

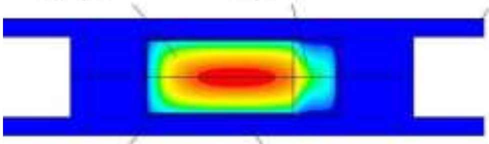
Position	$\Phi_{E>0.1MeV}$ [$cm^{-2}s^{-1}$]	Irradiation time [days]	Heating [W/g]
A1	1.42E+13	122	1.6
B1	1.73E+13	100	2
E2	8.70E+13	20	3.1
E1	4.83E+13	36	2.8

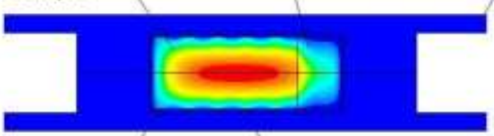
6

CFD Calculations for Concrete Sample Cooling

- **Models of cooling**
  - #1 – helium gap
  - #2 – full contact
  - #3 – partial contact
- **Four types of concrete –**
  - density 2.42 to 3.56 g/cm^3







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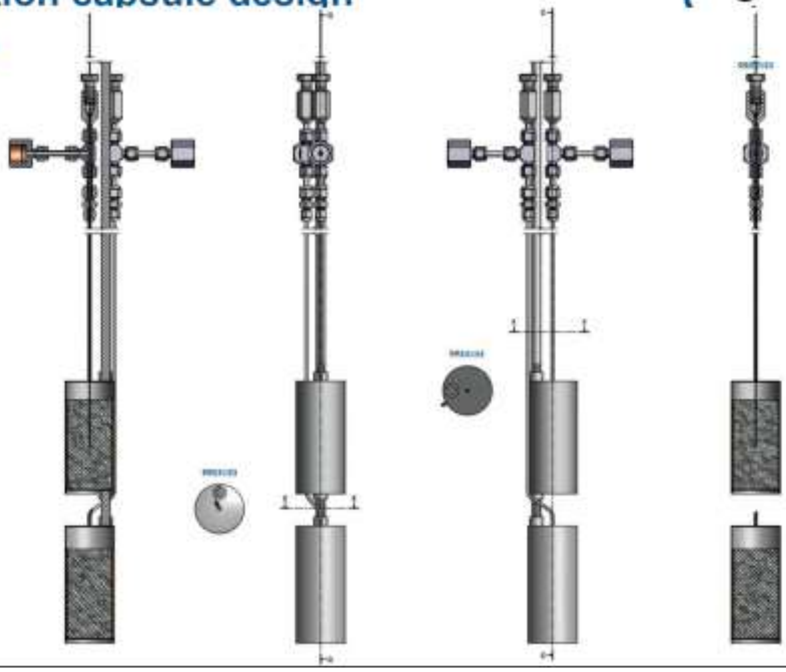
CFD Calculations for Concrete Sample Cooling

density [g/cm³]	Conductivity [W/mK] (Estimation)	Heat source [W/g]	Model #1 – helium gap	Model #2 – full contact	Model #3 – partial contact
			Max. Temperature [℃]		
3.56	1.7	0.1	91	78	80
	3.2	0.1	76	63	64
	3.2	0.2	-	-	84
2.46	1.7	0.1	76	68	69
	1.7	0.2	108	91	94
2.42	1.7	0.1	-	-	69
2.44	2.5	0.1	-	-	69
	2.5	0.2	-	-	79
	5.0	0.1	-	-	54
	5.0	0.5	-	-	89

Irradiation possibilities

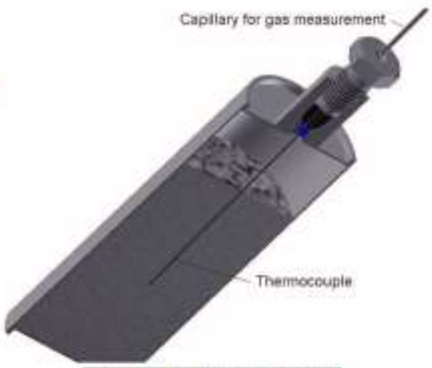
- **At present**
  - Based on contemporary knowledge of concrete parameters
    - Conductivity
  - Position out of core – in reflector area
- **Proposed action**
  - Mock-up test for irradiation - used to verify the thermal conductivity of the considered concrete and composition (impurities) of the material
  - Reactor availability
    - In 2014 – since Feb.
- **Modified irradiation arrangement**
  - Special irradiation cell with Bi shielding to decrease gamma heating in concrete
  - Irradiation time – ~100 days

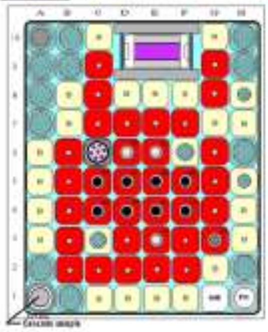
Irradiation capsule design



Mock-up experiment

- Aim:
  - Determination of thermal condition – reactor power
  - Test of gas measurement
  - Composition of the concrete – for the mock-up the Temelin type of concrete will be used.
  - Test of concrete release
- Design:
  - Simple case with thermocouple and capillary
  - Position in the core – A1
- Program
  - Temperature measurement
    - at different power levels – case in central position
    - at 10 MW – case moving up
  - Activity measurement
    - Released gas
    - Concrete sample





Discussion

- **Preparation of specimens and capsules**
  Design of the case - according to the mockup design
  Concrete will be cast in the metallic case with/without thermocouple
- **Irradiation**
  Evaluation of the mock-up and comparison of thermal conditions in the sample using gamma heating calculation
  Determination of the irradiation condition and time
  Additional gamma shielding in the irradiation channel is considered
- **Gas release**
  Gas pressure measured on-line using capillary
  Collection of gas after irradiation
- **Removal of concrete specimen from metallic case – has been tested**

12

Thank you

13

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The Use of Fiber Optic Sensors for Monitoring Loads in Post-Tensioned Containment Tendons

September 18, 2013

Sontra Yim, Tom Esselman,
Paul Bruck, Bahaa Elaidi (Lucius Pitkin, Inc.)
James Wall (Electric Power Research Institute)

Lucius Pitkin, Inc.
Consulting Engineers

1

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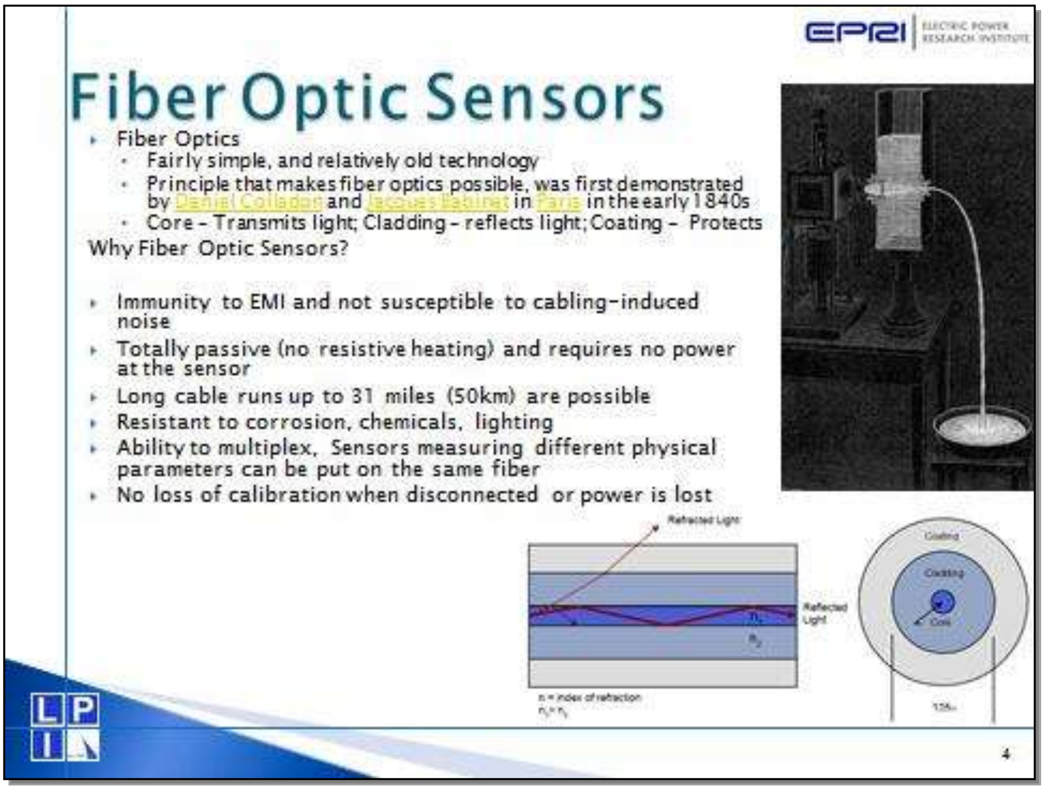
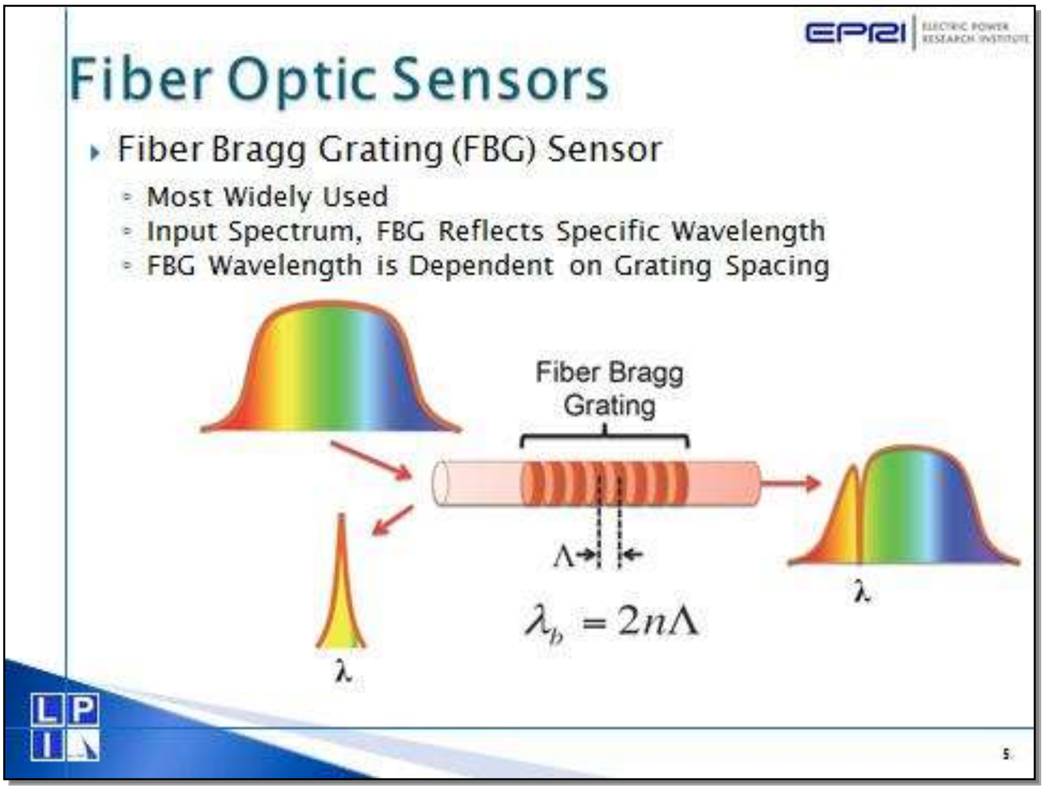
Introduction

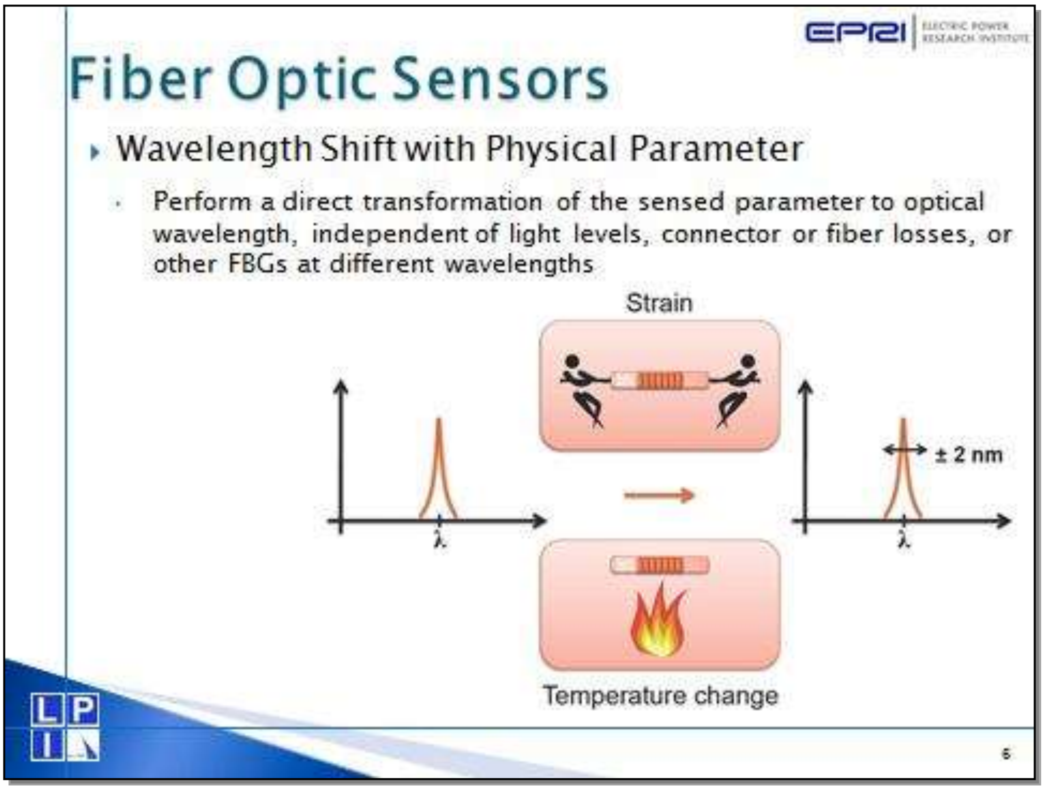
- Motivation
- Fiber Optic Sensors
- Case study at Pilot Nuclear Plant
- Results
- Conclusions
- Questions

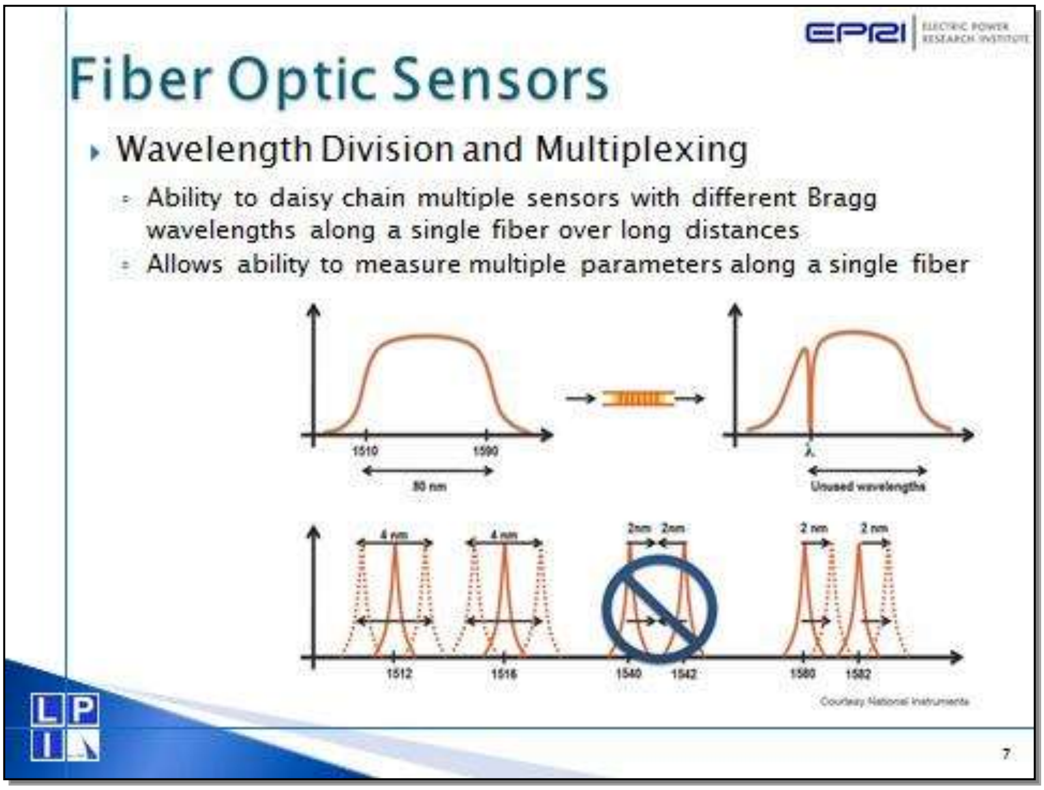
2

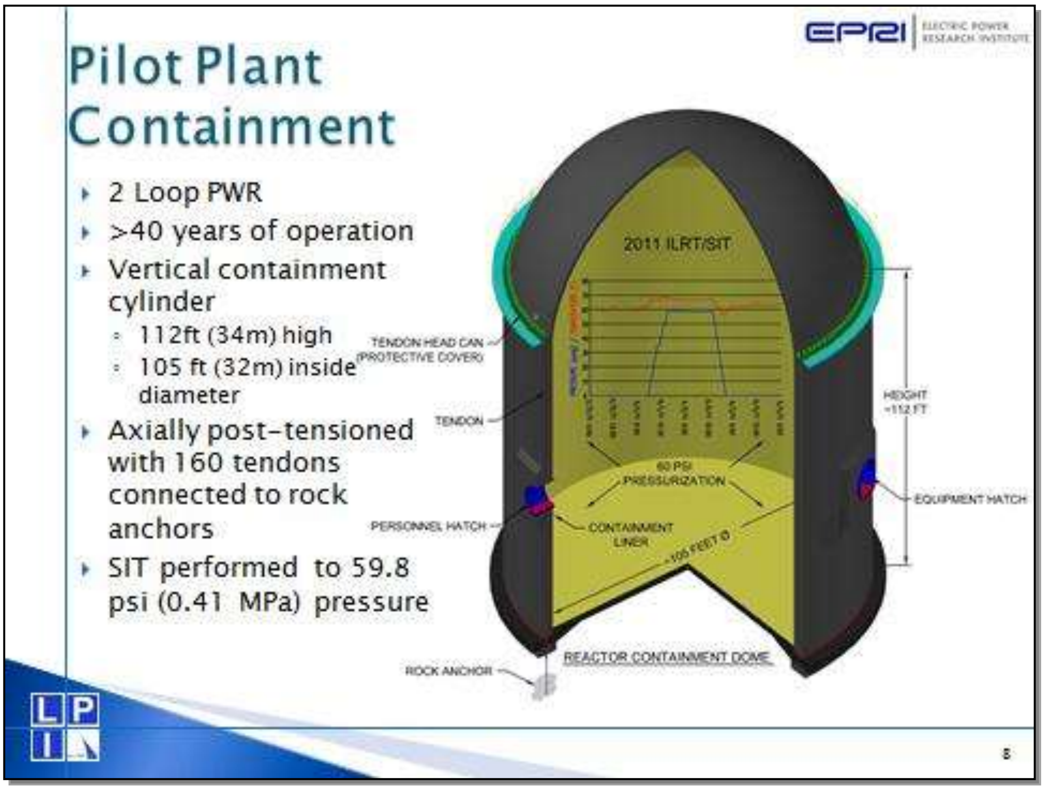

Motivation
Nuclear Power Plant Extended Life Operation (Beyond 40 Years)
Augment Existing Inspections and Testing
Effective Condition Assessment Requires Knowledge of Design and Expected Degradation
Concrete - Good in Compression; Poor in Tension
Post-Tensioned Tendons Verified by Lift Off Testing
Costly, time and labor intensive, requires special equipment. Load 700,000 lb (~3,114kN)
Potentially Alleviate Need to Perform Lift-Off Testing
Robust Real-Time Monitoring
Via Foil Based Load Cells - Not Robust
Electrical sensors susceptible to transmission loss and EMI (noise)
Detect, Track and Trend Degradation
Detect Wire Break, Relaxation, Loss of Anchor
3


Fiber Optic Sensors
Fiber Optics
Fairly simple, and relatively old technology
Principle that makes fiber optics possible, was first demonstrated by Daniel Colladon and Jacques Babinet in Paris in the early 1840s
Core - Transmits light; Cladding - reflects light; Coating - Protects
Why Fiber Optic Sensors?
Immunity to EMI and not susceptible to cabling-induced noise
Totally passive (no resistive heating) and requires no power at the sensor
Long cable runs up to 31 miles (50km) are possible
Resistant to corrosion, chemicals, lighting
Ability to multiplex, Sensors measuring different physical parameters can be put on the same fiber
No loss of calibration when disconnected or power is lost
Refracted Light
Reflected Light
n = index of refraction
Coating
Cladding
Core
4


EPRI ELECTRIC POWER RESEARCH INSTITUTE
Fiber Optic Sensors
Fiber Bragg Grating (FBG) Sensor
Most Widely Used
Input Spectrum, FBG Reflects Specific Wavelength
FBG Wavelength is Dependent on Grating Spacing
Fiber Bragg Grating
Λ
$\lambda_b = 2n\Lambda$
λ
λ
LPI
5


EPRI ELECTRIC POWER RESEARCH INSTITUTE
Fiber Optic Sensors
Wavelength Shift with Physical Parameter
Perform a direct transformation of the sensed parameter to optical wavelength, independent of light levels, connector or fiber losses, or other FBGs at different wavelengths
Strain
± 2 nm
λ
λ
Temperature change
LPI
6

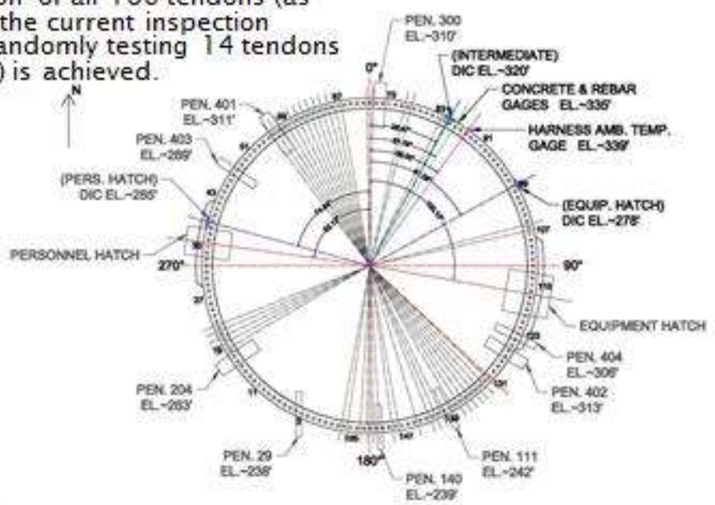

Fiber Optic Sensors
Wavelength Division and Multiplexing
Ability to daisy chain multiple sensors with different Bragg wavelengths along a single fiber over long distances
Allows ability to measure multiple parameters along a single fiber
1510
1590
80 nm
λ
Unused wavelengths
4 nm
4 nm
2nm 2nm
2 nm
2 nm
1512
1516
1540
1542
1580
1582
Courtesy National Instruments
7


Pilot Plant Containment
2 Loop PWR
>40 years of operation
Vertical containment cylinder
112ft (34m) high
105 ft (32m) inside diameter
Axially post-tensioned with 160 tendons connected to rock anchors
SIT performed to 59.8 psi (0.41 MPa) pressure
2011 ILRT/SIT
TENDON HEAD CAN (PROTECTIVE COVER)
TENDON
PERSONNEL HATCH
ROCK ANCHOR
HEIGHT ~112 FT
EQUIPMENT HATCH
60 PSI PRESSURIZATION
CONTAINMENT LINER
~105 FEET Ø
REACTOR CONTAINMENT DOME
8

Pilot Plant

Monitored Tendons

- Selected 20 of 160 Tendons
  - Statistically sufficient confidence (98.5%) in the condition of all 160 tendons (as compared to the current inspection program of randomly testing 14 tendons every 5 years) is achieved.

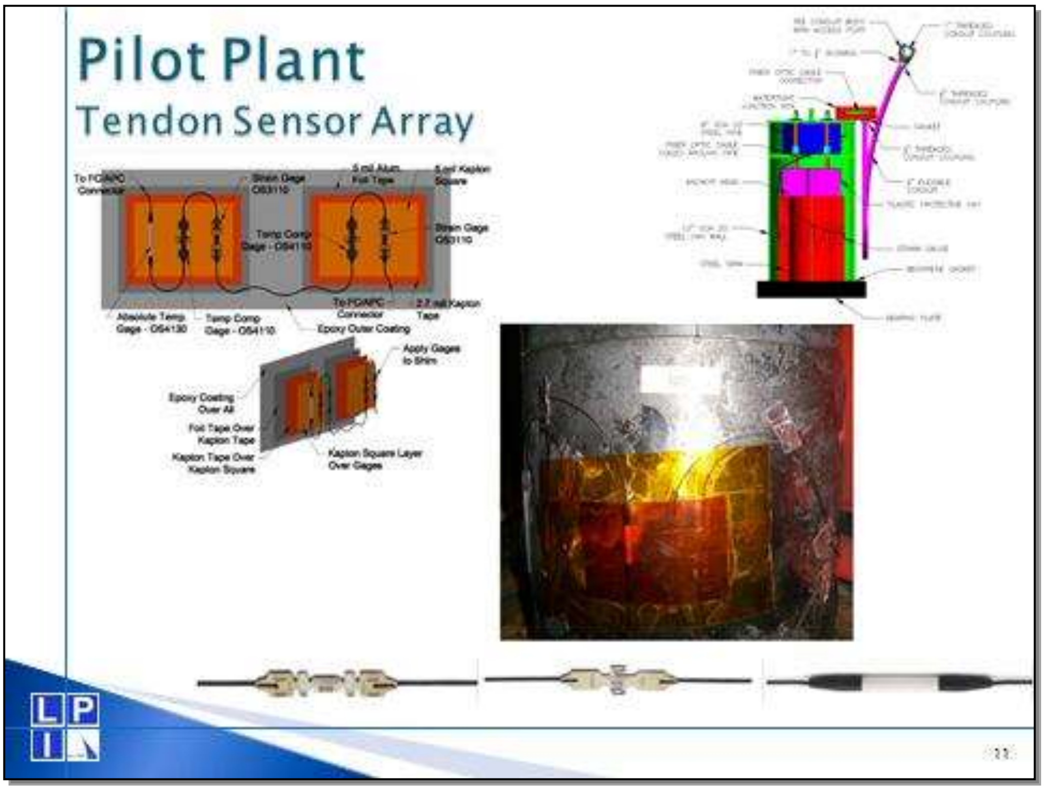


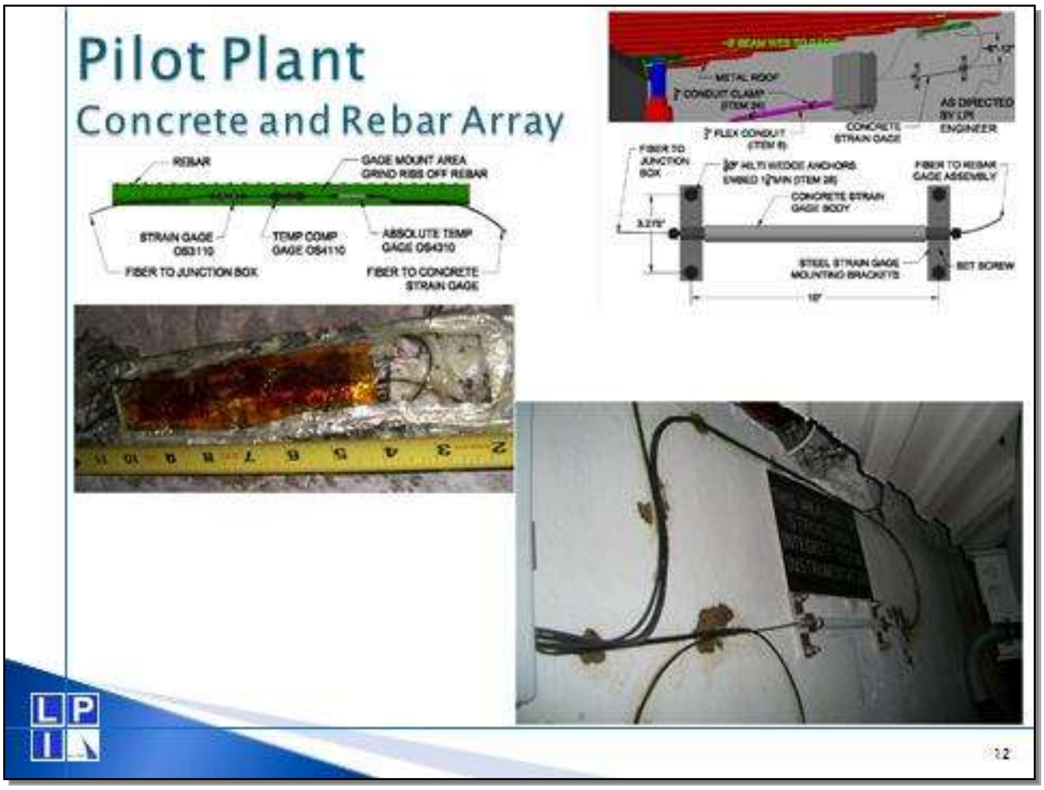
9

Pilot Plant

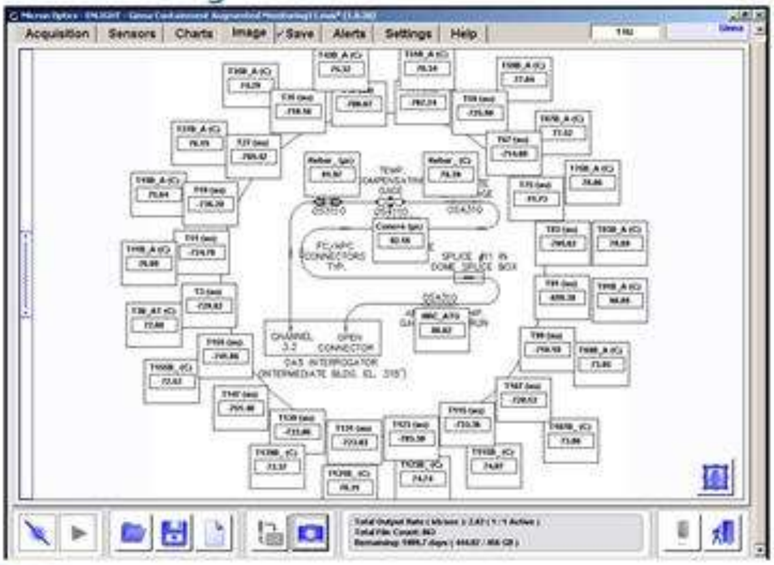
Tendon Anchor Head Design

10


Pilot Plant
Tendon Sensor Array
To FC/APC Connector
Strain Gage OS3110
5 mil Alum. Foil Tape
5 mil Kapton Square
Temp Comp Gage - OS4110
Strain Gage OS3110
Absolute Temp Gage - OS4130
Temp Comp Gage - OS4110
To FC/APC Connector
2.7 mil Kapton Tape
Epoxy Outer Coating
Apply Gages to Shim
Epoxy Coating Over All
Foil Tape Over Kapton Tape
Kapton Tape Over Kapton Square
Kapton Square Layer Over Gages
11


Pilot Plant
Concrete and Rebar Array
REBAR
GAGE MOUNT AREA GRIND RIBS OFF REBAR
STRAIN GAGE OS3110
TEMP COMP GAGE OS4110
ABSOLUTE TEMP GAGE OS4310
FIBER TO JUNCTION BOX
FIBER TO CONCRETE STRAIN GAGE
METAL ROOF
CONCRETE STRAIN GAGE
AS DIRECTED BY LPI ENGINEER
FIBER TO JUNCTION BOX
CONCRETE STRAIN GAGE BODY
FIBER TO REBAR GAGE ASSEMBLY
STEEL STRAIN GAGE MOUNTING BRACKETS
SET SCREW
12

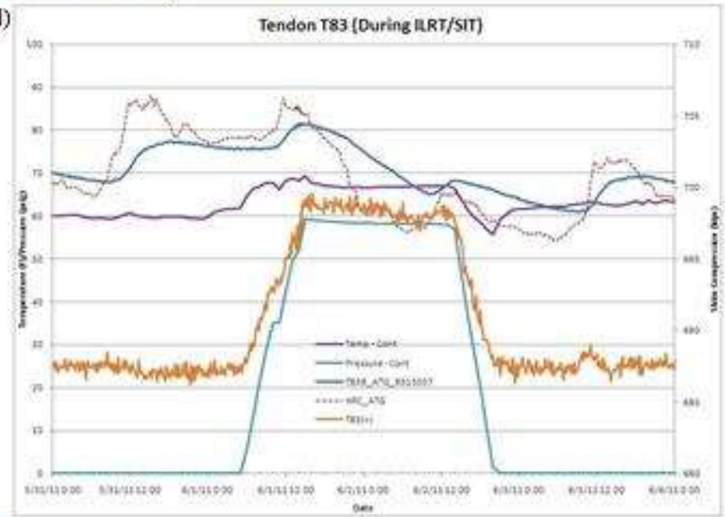
Results
Real-Time Monitoring



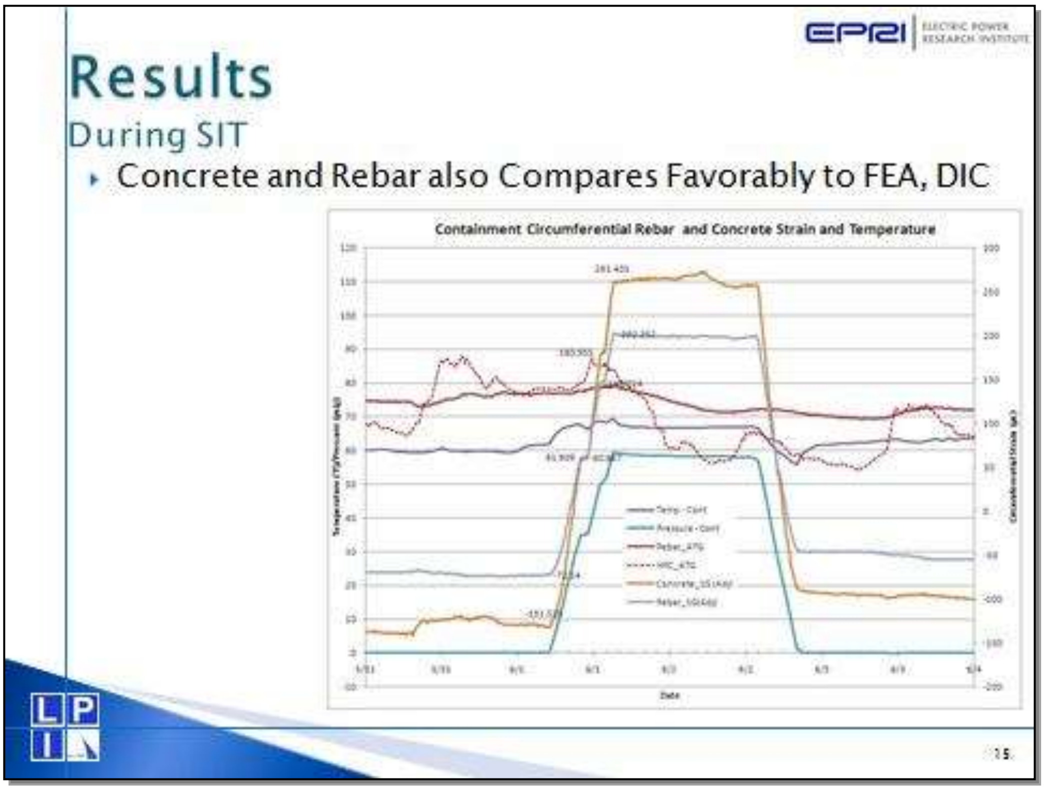
13

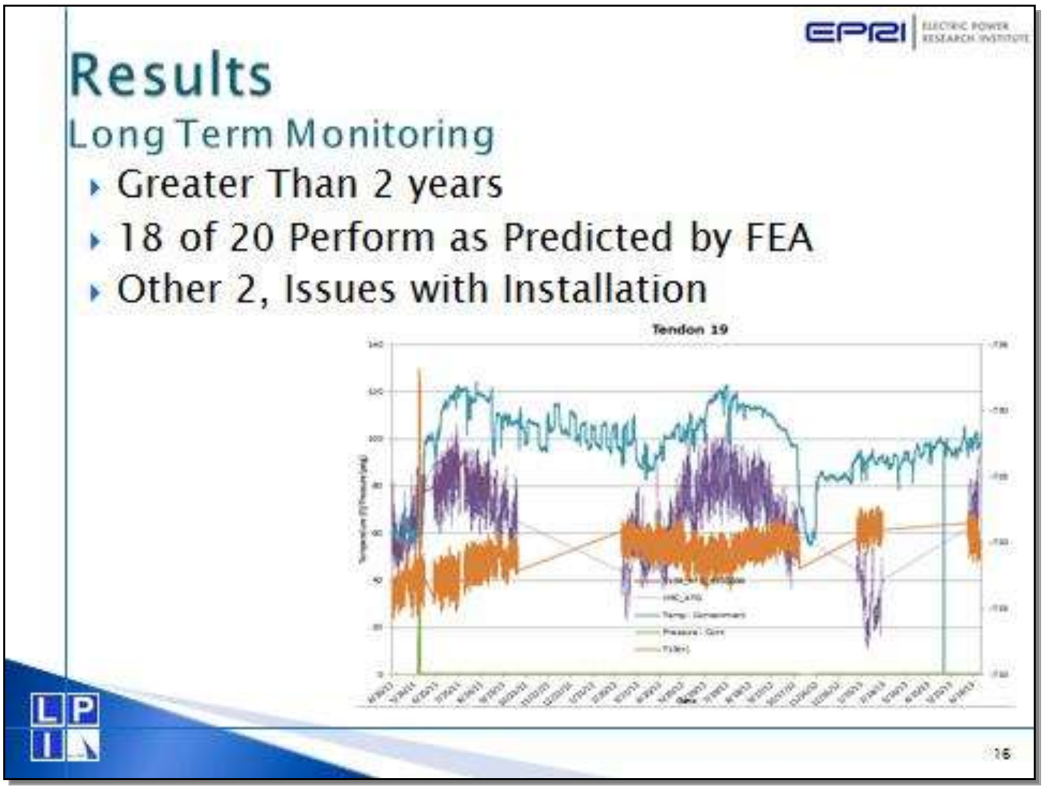
Results
During SIT

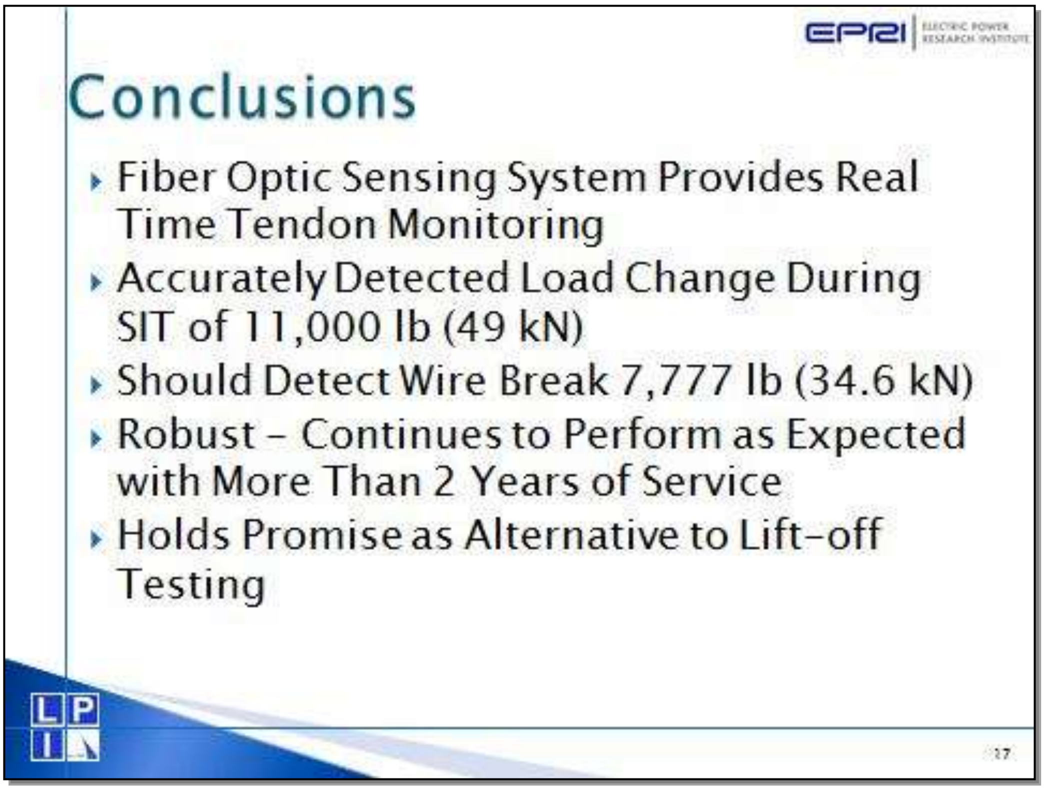
- Compares Favorably to FEA
  - 11 kips (49 kN)



14


Results
During SIT
Concrete and Rebar also Compares Favorably to FEA, DIC
Containment Circumferential Rebar and Concrete Strain and Temperature
15


Results
Long Term Monitoring
Greater Than 2 years
18 of 20 Perform as Predicted by FEA
Other 2, Issues with Installation
Tendon 19
16


Conclusions
Fiber Optic Sensing System Provides Real Time Tendon Monitoring
Accurately Detected Load Change During SIT of 11,000 lb (49 kN)
Should Detect Wire Break 7,777 lb (34.6 kN)
Robust – Continues to Perform as Expected with More Than 2 Years of Service
Holds Promise as Alternative to Lift-off Testing
EPRI
17


Questions
EPRI
18

SESSION FOUR

Hydraulic Exciter of Vibrations
Josef Machac

Experimental Stand UVJ Rez for Probability of Detection Evaluation
Ladislav Pecinka

Hydraulic vibration exciter

Ing. Josef Machač

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Dynamic measurement

- vibration exciter
- three dimensional velocity sensors
(or acceleration sensors, or displacement sensors)

- modal analysis (fourier transformation)
- natural frequencies, mode shapes

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Equation of motion

$$K \cdot r(t) + C \cdot \dot{r}(t) + M \cdot \ddot{r}(t) = F(t)$$

stiffness
displacement

damping
velocity

mass
acceleration

loading
vibration exciter

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Hydraulic vibration exciter

- horizontal or vertical movement
- frame 0.8 x 2.0 m
- maximal force ± 10.0 kN
- weight of frame 750 kg, weight of moving mass up to 900 kg
- weight of attached engine 1200 kg

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Dynamic load test of bridges

Nuselsky Bridge in Prague
485 m long, 26.5 m wide
prestressed concrete

box girder bridge
subway and road traffic

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Dynamic test of exhauster in Trbovlje

Power plant Trbovlje

360 m high exhauster
tube in tube construction

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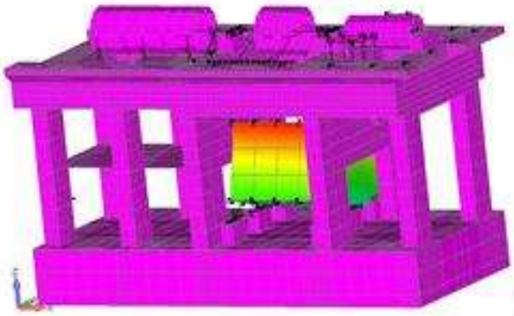
Dynamic test of turbine and generator foundations



Power plant Pocerady
270 MW

aprox. 37 m long, 15 m wide, 15 m high

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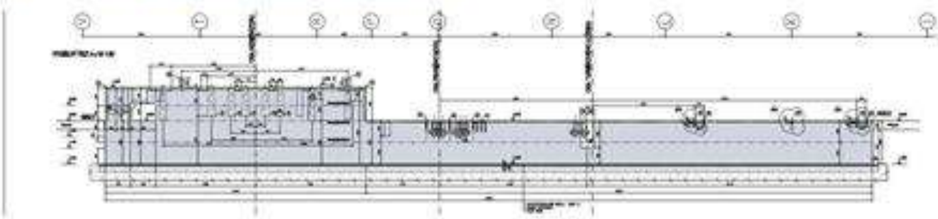
Dynamic test of gas turbine foundations

Power plant Pocerady
gas turbine 284 MW

42 m long, up to 8.6 m wide, 2.4 m high (4.3 m high)



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Comparison between experiment and simulation

- comparison of calculated natural frequencies and in-situ measured frequencies
- improving numerical model
  - realistic boundary conditions
  - overall structural stiffness (Young modulus)
  - prestress concrete simulation
  - damping coefficient

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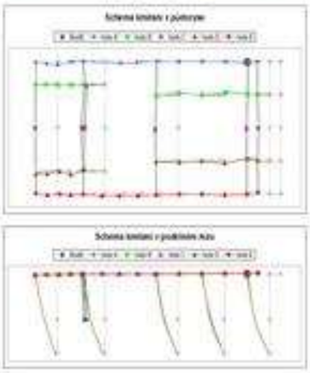
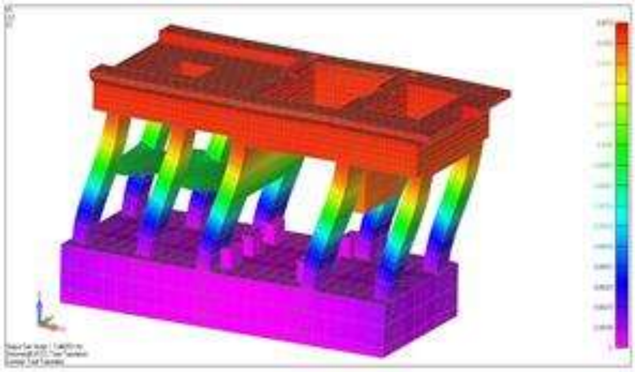
Comparison between experiment and simulation

First natural frekvency





- measured frequency 3.40 Hz
- calculated frequency 3.45 Hz
- variance 1.47%

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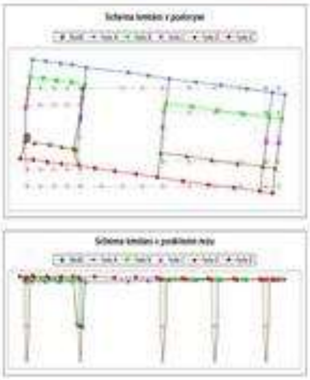
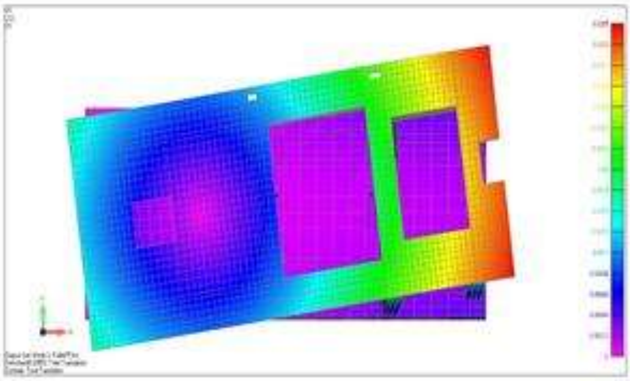
Comparison between experiment and simulation

Second natural frekvency





- measured frequency 5.70 Hz
- calculated frequency 5.44 Hz
- variance 4.68%

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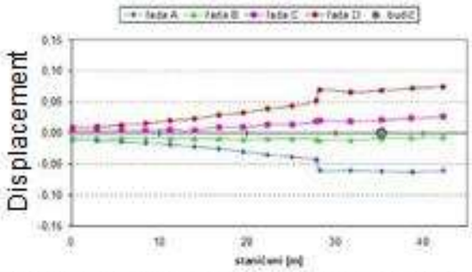
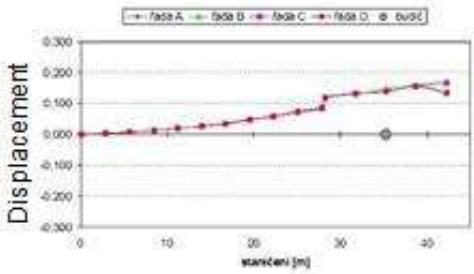
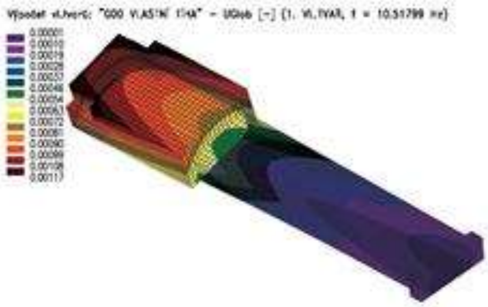
Comparison between experiment and simulation

Vertical direction



Horizontal direction





- measured frequency 10.9 Hz
- calculated frequency 10.5 Hz
- variance 3.8%

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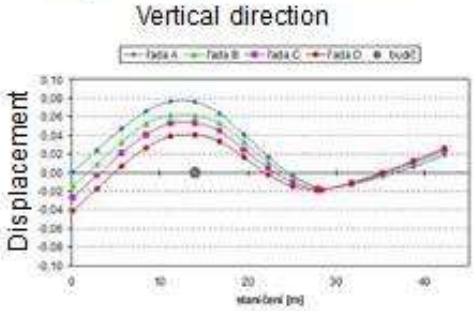
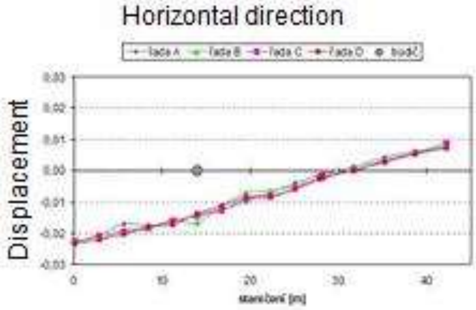
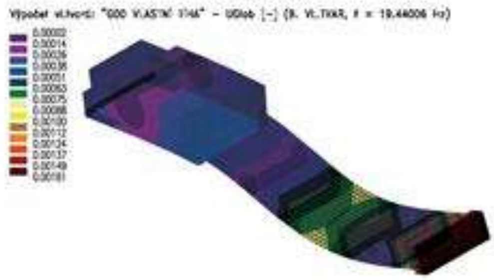
Comparison between experiment and simulation







- measured frequency 18.9 Hz
- calculated frequency 19.4 Hz
- variance 2.6%

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Experimental examination of damage structure

- degradation processes (chemical, mechanical degradation, cracks or corrosion) change stiffness of whole structure (or structural part)
- vibration characteristics of the structure change according to degradation processes and can be measured

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Experimental examination of damage structure

Article: Dynamic behaviour comparison of the damaged bridge before and after its reconstruction, prof. ing. Michal Polák, CSc., CTU in Prague

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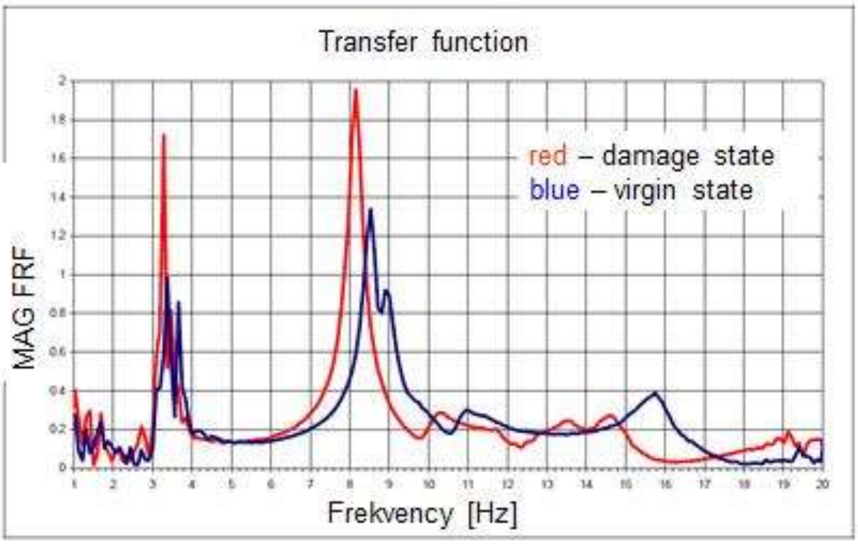

Article: Dynamic behaviour comparison of the damaged bridge before and after its reconstruction, prof. ing. Michal Polák, CSc., CTU in Prague

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Containment structure examination

- vibration exciter can be used for in-situ measuring structural natural-frequencies and modal shape
- experimentally measured values can be compared with the numerical modeling (mass and stiffness of a whole structure)
- repeated measurements (with time period 5 - 10 years) can be used for the monitoring of temporal changes and for the estimation of concrete degradation (overall loosing of stiffness)

Thank you for your atention

ÚJV Řež, a. s.

EXPERIMENTAL STEND UJV REZ FOR PROBABILITY OF DETECTION ASSESSMENT

Ladislav Pecinka

OECD-NEA WORKSHOP NDE OF NPPs CONCRETE STRUCTURES
PRAGUE, 17-19 SEPTEMBER 2013

GOAL OF PRESENTATION

- WHAT IS PROBABILITY OF DETECTION (POD)
- LESSONS LEARNT FROM NDE EXPERIMENTS IN UJV REZ

1

CONTENT

- BASIC IDEAS
- POD EXPECTED INDICATIONS
- UJV EXPERIMENTAL STEND
- SOME RESULTS OF NDE
- POD VERSUS NDE METHODS
- CONCLUSIONS

2

BASIC IDEAS

- POD DEMONSTRATION TEST AND ANALYSIS IS THE BEST AVAILABLE TECHNIQUE FOR QUANTIFYING THE DETECTION CAPABILITY OF A NDT SYSTEM
- DEPARTMENT OF DEFENSE MIL-HDBK-1823A: NON-DESTRUCTIVE EVALUATION SYSTEM REALIABLITY ASSESSMENT:

PROBABILITY OF DETECTION IS THE FRACTION OF TARGETS OF NOMINAL SIZE, A EXPECTED TO BE FOUND, GIVEN THEIR EXISTENCE

- IN GENERAL, POD IS EXPECTED TO INCREASE AS TARGET SIZE (THAT IS, INDICATION SIZE) INCREASES
- A POD DEMONSTRATION TEST IS TYPICALLY CONDUCTED USING A SET OF STANDARD SPECIMENS OF THE SAME GEOMETRY AND MATERIAL THAT HAVE A KNOWN NUMBER AND DISTRIBUTION OF INDICATION SIZES

3

BASIC IDEAS – cont. 1

- DATA GENERATED BY A POD TEST ARE EITHER BINARY OR MEASURABLE, DEPENDING ON THE RESPONSE PRODUCED BY THE NDT SYSTEM
- THEORETICAL BACKGROUND
  - STATISTICS IS THE FIELD IN WHICH THE THEORY IS DEVELOPED
  - NDT IS THE FIELD IN WHICH THE THEORY IS APPLIED
- THE SUCCES OF POD, AS WELL AS FUTURE ADVANCEMENTS, DEPENDS ON THE PARTNERSHIP FORMED AND COLLABORATION BETWEEN STATISTICS AND NDT
- FOR THE DETAIL INFORMATIONS SEE THE JOURNAL OF THE AMERICAN SOCIETY FOR NONDESTRUCTIVE TESTING „MATERIALS EVALUATION“, Vol.70, No. 4, pp 421-426, April 2012:

  Jennifer Brown: IT TAKES MORE THAN A STATISTICIAN TO DO PROBABILITY OF DETECTION

4

POD-EXPECTED INDICATIONS

- DEFECTS, i.e.
  - QUALITY OF CONCRETE (DENSIFICATION, MOISTURE etc)
  - CRACKS
  - DELAMINATION
  - VOIDS
  - DEBONDING BETWEEN LINER AND CONCRETE
  - CREEP
- SHRINKAGE
- INTERNAL STEEL COMPONENTS AS LINER etc.
- REBARS
- DUCTS OF PRESTRESS TENDONS
- TECHNOLOGICAL CHANELS

5

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND

6

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 1

SPECIMEN № 1

7

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 2

SPECIMEN № 2

8

EXPERIMENTAL STEND

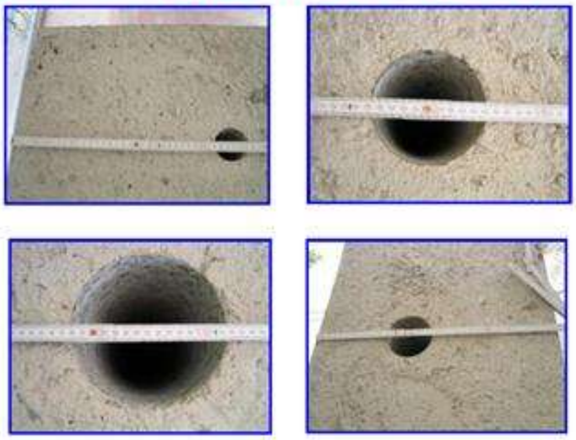
DESCRIPTION OF THE STAND – cont. 3

INTERNAL LINER WITH DEFECTS

9

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 4



SPECIMEN № 3

EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 5

SPECIMEN № 4 WITH GRID OF REBARS

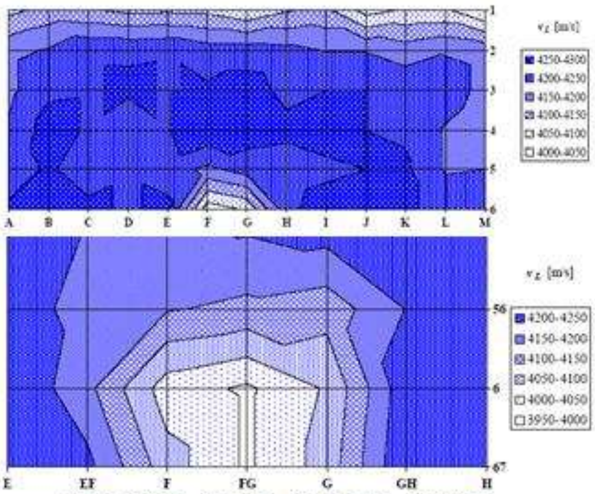
EXPERIMENTAL STEND

DESCRIPTION OF THE STAND – cont. 6

SPECIMEN № 5: CONTAINMENT WALL WITH REBARS AND DUCTS

12

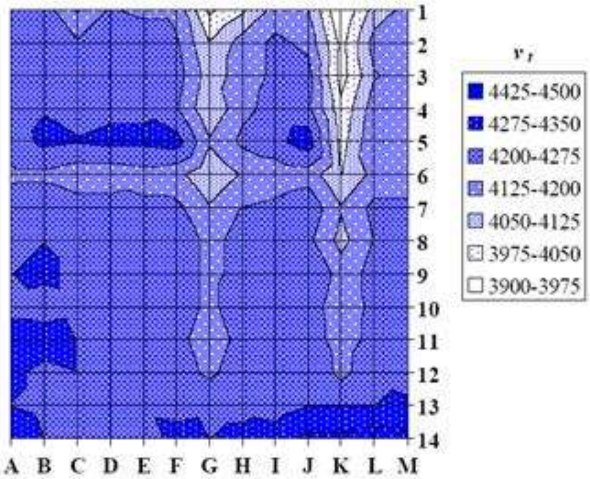
SOME RESULTS OF NDE



DETECTION OF THE ARTIFICIAL CAVITY

13

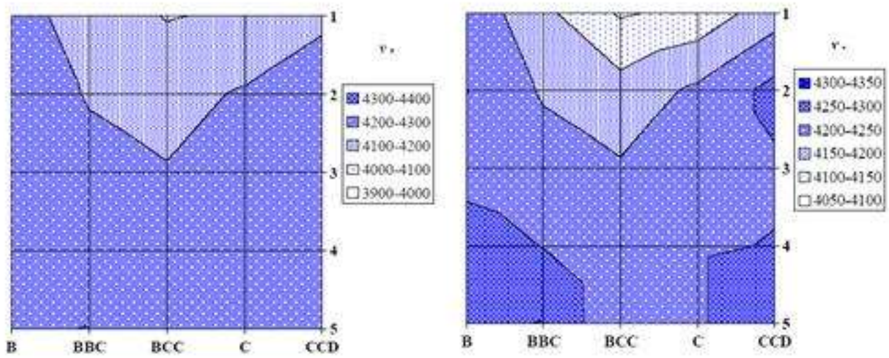
SOME RESULTS OF NDE – cont. 1



DETECTION OF HOLES ø 150 AND 100 mm

14

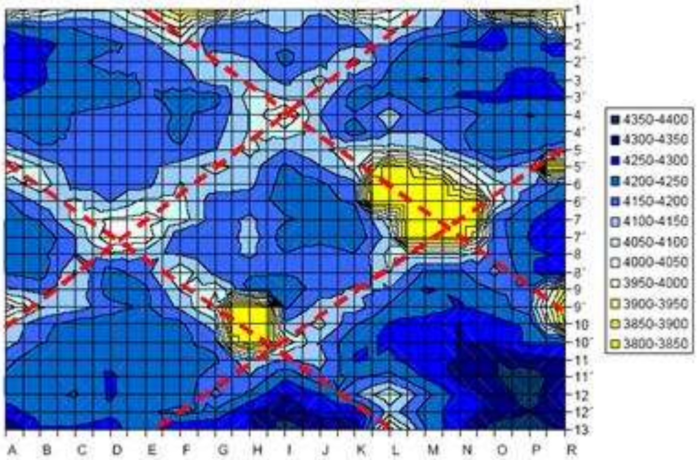
SOME RESULTS OF NDE – cont. 2



HOLE WITH ø 50 mm

15

SOME RESULTS OF NDE – cont. 3



DETECTION OF THE DUCTS

16

POD VERSUS NDE METHODS

- IN OUR EXPERIMENTS THE FOLLOWING METHODS HAVE BEEN USED
  - ULTRASOUND
  - GROUND PENETRATION RADAR
  - IMPACT ECHO
- APPLICATIONS WITH HIGH VALUE OF POD

NDE METHOD	SUCCESFUL APPLICATION TO
UT, Impact Echo, Laser	Delamination
UT, Impact Echo	Cracks
GPR, Impact Echo, UT	Voids, Channels
GPR	Cover depth
GPR, Impact Echo	Reinforcement
UT	Concrete properties
GPR, Impact Echo	Internal Liner

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CONCLUSIONS

- NDE IS VERY IMPORTANT TOOL FOR AGEING MANAGEMENT AND PLEX OF NPPs
- DETERMINISTIC OR PROBABILITY BASED APPROACHES ARE POSSIBLE
- PSA APPROACH NEED AS INPUT DATA PROBABILITY OF FAILURE AND/OR POD
- CALCULATION METHODS OF CONCRETE STRUCTURES FAILURE PROBABILITY ARE WELL KNOWN
- POD CALCULATION REPRESENT NEW CHALLENGE
- QUESTION: IS IT POD, MI-HDBK-1823A „NON DESTRUCTIVE EVALUATION SYSTÉM RELIABILITY ASSESSMENT“ GUIDE ONLY ONE?
- IF YES, EXISTS POSSIBILITY TO OBTAIN HIM AND DISTRIBUTE TO FAMILY OF IAEG MEMBERS?
- IT IS EVIDENT THAT IN POD FIELD NDE PEOPLES MUST COOPERATE WITH STATISTICIENS

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THANK YOU

FOR YOUR

ATTENTION

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