Digital Twins for Improving the Accuracy of Thermal Fatigue and Environmental Qualification Time Limited Aging Analyses

Track 1 – LTO

Miguel A. Calatayud
Aging Management and LTO Manager for Cofrentes NPP
T. +34 606 593 801. M. mlm@iberdrola.es

David Galbally
Chief Engineer, Innomerics
T. +34 677 744 821. M. dgalbally@innomerics.com

NIC 2024
June 5-6, 2024
Amsterdam, Netherlands

Miguel A. Calatayud

He received his master degree in Chemical engineering by the University of Zaragoza and Electrical engineering by the University of Valencia, Spain.

In 1999 he started his professional career in the Nuclear Industry in Iberdrola as Electrical and I&C Engineering Design, supporting Cofrentes NPP activities for 21 years. From 2011 to 2019 he collaborated with the International Atomic Energy Agency in the IGALL (International Generic Ageing Lessons) project, developing the IAEA SRS 82 "*Ageing Management in Nuclear Power Plants. IGALL*", acting as a Chairman of the Working Group of Electrical and I&C components; at the same time, Senior Expert in the Electrical and I&C area for the IAEA SALTO (Safe Aspects of Long Term Operation) Peer Review Services.

During 2020 collaborated with WANO in the developing GP 2020-31 "Excellence in Ageing Management". Since 2022 Head of Aging Management and Long Term Operation for Cofrentes NPP.

David Galbally

David holds a master degree in electromechanical engineering from ICAI School of Engineering in Madrid and a Master of Science in Aeronautics and Astronautics from the Massachusetts Institute of Technology (MIT)

He began his career with GE Nuclear Energy in San Jose, CA in 2001. He was involved in the development of new NDE technologies for inspecting reactor internals (4 international patents), as well as the development of new numerical and empirical methods for characterizing the response of steam dryers subjected to flow induced vibrations (2 international patents).

After spending 6 years at Iberdrola as manager of the Materials, Lifecyle Management and PSA Group, he co-founded Innomerics, where he is currently president and Chief Engineer. He has co-authored highly cited publications on numerical methods for real-time simulations, and leads the development of innovative software that is used by clients throughout the world to ensure safe and reliable operation of nuclear power plants

Summary

- **Motivation**: why do nuclear power plants need more accurate monitoring solutions to support aging management programs as they extend their original design life?
- **Solution**: digital twins as a method to reduce uncertainty in the characterization of degradation mechanisms that govern aging of critical nuclear power plant components.
- **Ingredients**: description of the elements that form a digital twin.
- **Application examples**: thermal fatigue and environmental qualification.

Motivation

- Nuclear power plants were originally designed using a set of operating conditions and events that were postulated to occur during the life of the plant.
- Many of the postulated conditions used to design safety-related components of nuclear power plants are based on an underlying assumption regarding the number of years that the plant was assumed to operate when it was designed (i.e. its design life).
- As plants exceed the reference time used to develop their design conditions, it is necessary to re-evaluate the validity of the original design calculations in those cases where degradation mechanisms are time-dependent. For example:
  - Fatigue damage accumulation increases as a function of operational transients which, in turn, increase with the number of operating cycles of the plant.
  - Thermal aging of polymers increases as a function of the number of hours that the component has been subjected to elevated temperatures which, in turn, increase with operating time.

Alternatives to Justify Design Adequacy

- During the design phase, adequacy of the design (i.e., compliance with acceptance criteria under postulated design conditions) was demonstrated using a variety of methods, including analysis and testing.

- The adequacy of the design beyond the original design time can also be demonstrated using a variety of methods, including additional testing, inspection, reanalysis, etc.
  - An effective method to demonstrate adequacy of the original design beyond the originally postulated design life is to characterize the actual operating conditions that equipment, systems and components are subjected to during plant operation.
  - Since actual operating conditions are usually less severe than those postulated during the design phase, margin between actual and postulated conditions can be used to extend the plant life.

Digital Twins: Bridging the Gap Between Design and Operation

Analysis tools used during the design phase

- **High fidelity geometric modeling**
- **High fidelity multiphysics modeling**
- Hypothetical operating conditions (“design conditions”)
- Applications are complex to use. Require experienced analysts
- Very long calculation times

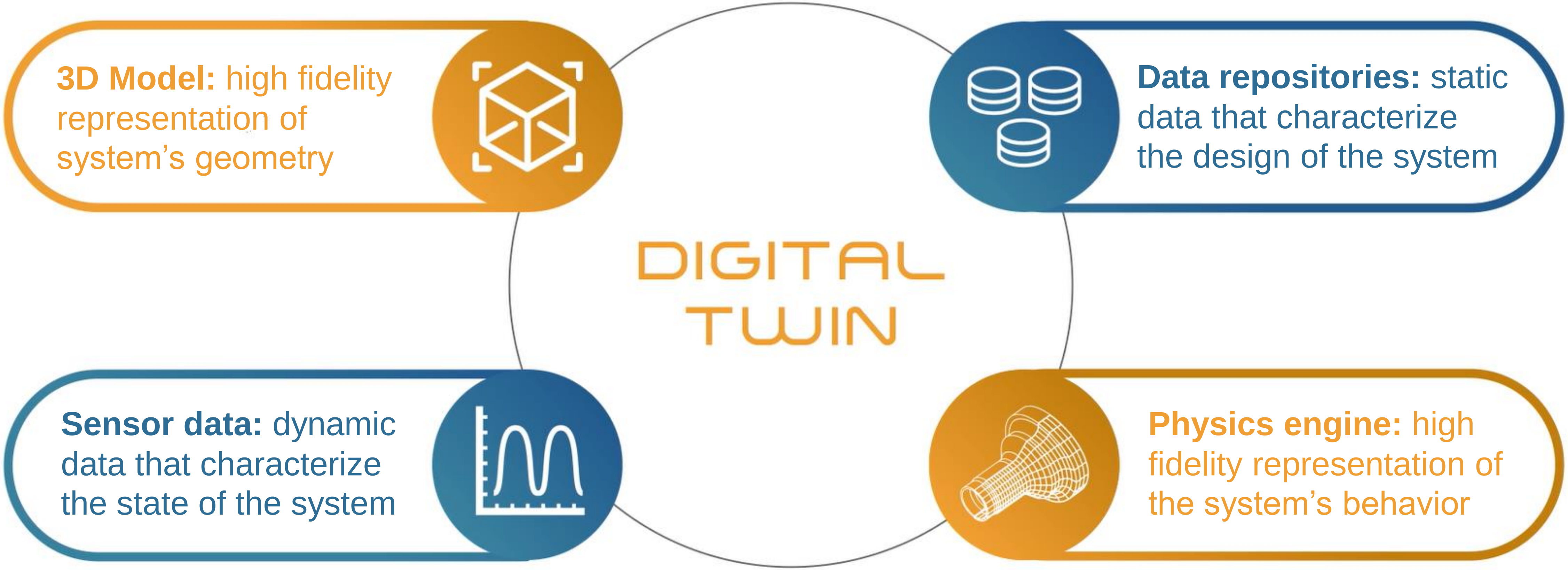
Analysis tools used during the operating phase

- Simple models that are invalid outside limited range of applicability
- Lack of spatial discretization (1D “black boxes”)
- **Actual operating conditions based on sensor data**
- **Large volumes of input data under multiple operating conditions**
- **Easy to use (no need for expert users)**

Digital Twins: High-Fidelity and Real-Time Analyses

- **High fidelity geometric modeling**
- **High fidelity multiphysics modeling**
- **Actual operating conditions based on sensor data**
- **Real-time computation**
- **Easy to use. Only configured once, since the geometry and system construction remain constant**
- **Allow performing predictive analyses under off-design operating conditions**

Elements of a Digital Twin



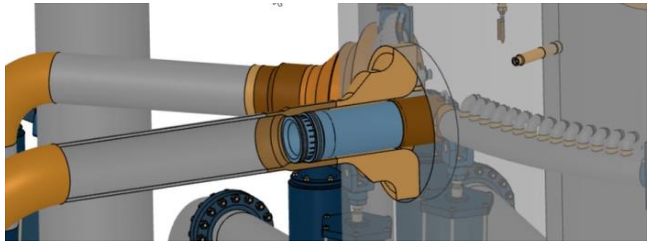
Application Example: Fatigue Damage in Feedwater Nozzles of BWR

- **The problem**: Design basis transients used to demonstrate adequacy of feedwater nozzles are not realistic.
  - Hypothesis of instantaneous thermal shock during transients that involve large changes in feedwater flow (e.g., plant start-up, plant shutdown, etc.) are not representative of actual physical phenomena that occur in the actual plant.

- **The solution**: Development of a digital twin of the feedwater nozzles, to characterize actual thermal-hydraulic phenomena that occur inside the nozzles at low feedwater flows.

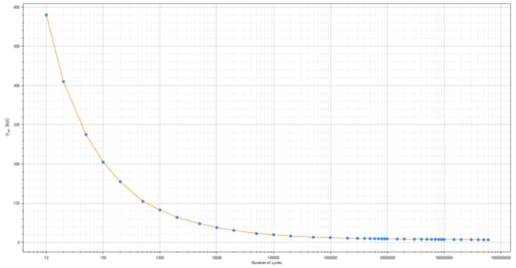
Elements of the Digital Twin

3D Model



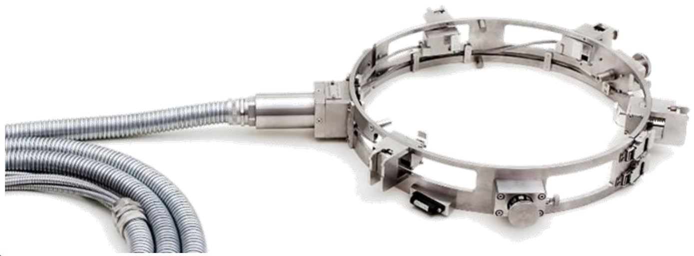
Model of the components of interest, including nozzle, sparger and feedwater lines

Data repositories



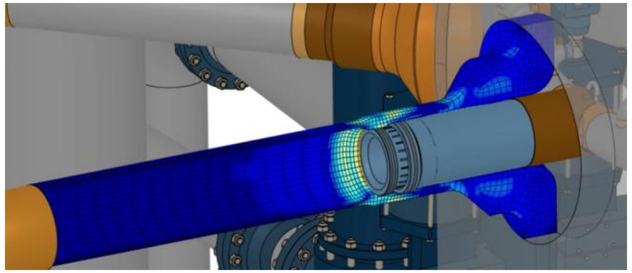
Design information, including material properties and fatigue damage model

Sensor data

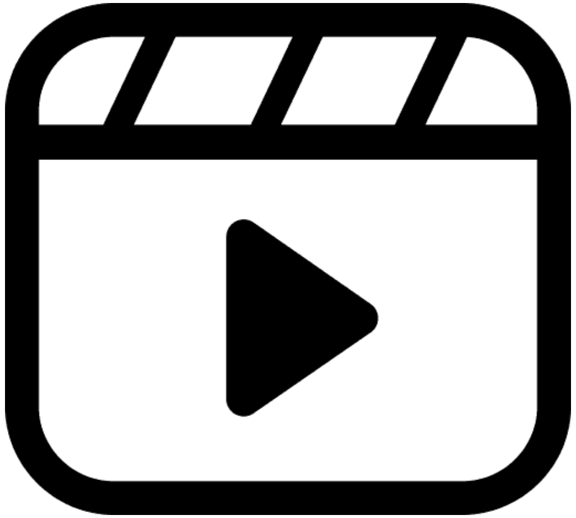


Thermocouple sensors installed on the feedwater pipes and feedwater nozzles

Physics engine



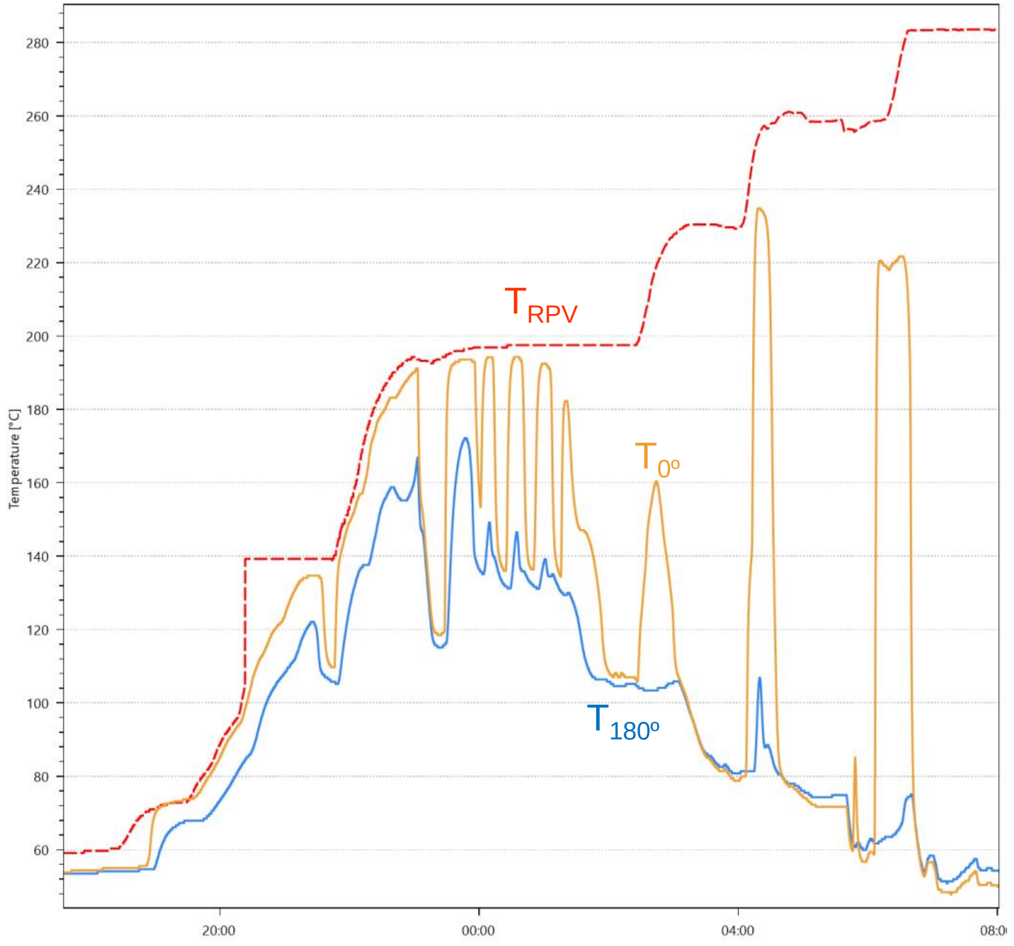
Thermomechanical finite element model, reduced basis approximation and inverse problem framework



Video

Results

- True characterization of each plant operating transient.
- Some transients are very different from those postulated in the design bases (not possible to compare true transients with design transients).
- Accurate determination of stresses, strains and fatigue damage during each operating condition.

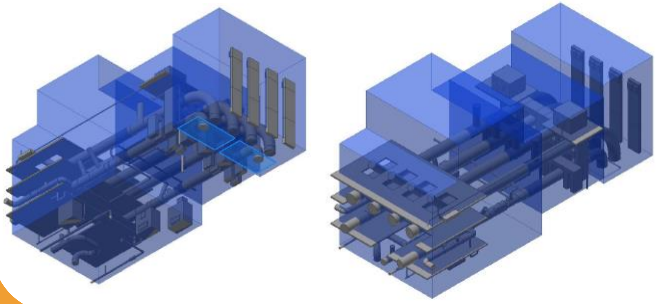


Application Example: Environmental Qualification of Equipment

- **The problem**: environmental qualification of equipment in non-accessible areas often relies on overly conservative assumptions based on maximum temperatures recorded for the entire area.
  - The majority of equipment and components subject to EQ requirements are not located in the most unfavorable location of each room.
- **The solution**: Development of a digital twin of non-accessible areas (drywell and steam tunnel) of a BWR to fully characterize environmental conditions at all locations of interest during plant operation.

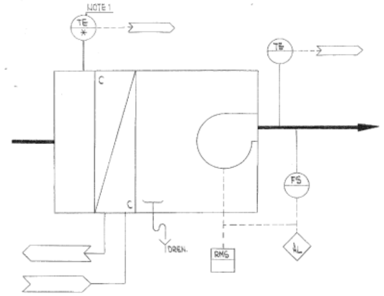
Elements of the Digital Twin

3D Model



Model of the equipment, structures, systems and components contained in each area

Data repositories

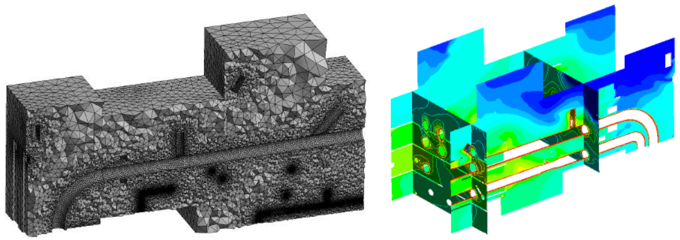


Design information, including HVAC performance curves, EQ information of each component, etc.

Sensor data

Data loggers distributed throughout the areas of interest, in conjunction with plant instruments

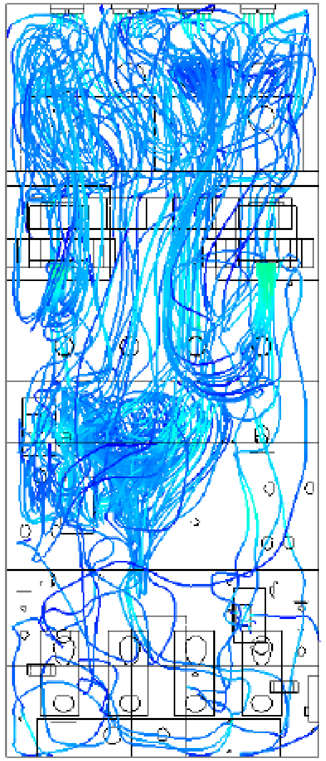
Physics engine

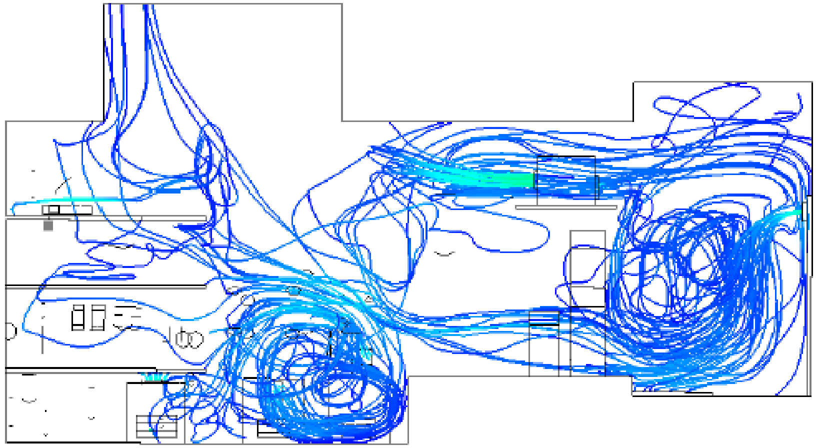


CFD heat convection model, reduced basis approximation and inverse problem framework

Results

- Determination of accurate ambient temperatures at each location, based on actual HVAC operating conditions, weather, plant operation, etc.
- Validation of predicted temperatures using sensor data.
- Accurate calculation of aging for each component subject to environmental qualification requirements.





Conclusions

- As plants exceed the reference time used to develop their design bases, it is necessary to re-evaluate the validity of the original design calculations in those cases where degradation mechanisms are time-dependent.

- An effective method to demonstrate adequacy of the original design beyond the originally postulated design life is to characterize the actual operating conditions that equipment, systems and components are subjected to during plant operation.

- Digital twins take the best features from tools that have been traditionally used in the design context, such as high fidelity modeling of the phenomena of interest, and allow their use in a monitoring context, thereby enabling the characterization of the response of the system under actual operating conditions, instead of postulated design conditions.

Thank you for your attention!

Any questions?

Miguel A. Calatayud
Aging Management and LTO Manager for Cofrentes NPP
T. +34 606 593 801.   M. mlm@iberdrola.es

David Galbally
Chief Engineer, Innomerics
T. +34 677 744 821.   M. dgalbally@innomerics.com