DOCTORAL PROGRAM IN RADIATION SCIENCE AND TECHNOLOGY

Chair:
Prof. Carlo Bottani

The thesis works that are presented in this Yearbook are very representative of the multi-disciplinary research activity performed within the context of the PhD educational and research program in Radiation Science and Technology (RST). The latter is specifically designed to provide the student with the state-of-the-art in a wide range of research fields related to the application of nuclear and non-ionizing radiations, to foster the growth and strengthening of research skills in our young researchers, to fully integrate their efforts made by our young researchers within the research performed in our Department of Energy, which is aimed both at obtaining basic results in RST through innovative instrumentation and methods, and at developing and testing effective technological solutions for specific applications. In the last decades the research activity was mainly devoted to:

- Planning and development, by means of analytical-numerical methods, empirical models, and experimental studies, of innovative nuclear plants for energy conversion, aerospace, and fusion applications.
- Methods of safety and reliability analysis applied to the design and diagnostic of nuclear systems, and in general of high risk environments.
- Radio-protection for environmental monitoring, nuclear plants decommissioning, radioactive waste disposal, underground dispersion of contaminants.
- Development of innovative high-performance radiation detectors, and their applications to R&D fields such as space science, synchrotron radiation, high-energy physics, or to topics of interest for the large community such as medical investigations, cultural heritage preservation, environmental monitoring, nuclear safety.
- Synthesis by ionic implantation or pulsed laser ablation of innovative materials, such as nanostructures and "soft" materials, and their structural characterization by radiation scattering techniques (Raman, Brillouin, X-ray, neutron, and quasi-elastic light scattering), or tunnel/atomic force microscopy.

Starting with the new 25-th doctoral cycle (2010) this doctoral program and the Energy doctoral program are unified in the new Energy and Nuclear Science and Technology doctoral program.

For what concerns the specific thesis works presented in what follows, Stefano Buzzaccaro investigated systems of colloidal particles interacting via very short-ranged attractive forces and obtained valuable and often unforeseen insights on the contingency of the liquid state and on the origin of metastable gel or glassy phases with relevant potential applications in the fields of crystallization and competitive adsorption of proteins, percolation in microemulsions, flocculation and renneting. Valentino Di Marcello developed a multi-physics approach to the modelling and analysis of nuclear reactor core behaviour and applied it to the study of the dynamics of Molten Salt Reactors (MSR). In the last years, this kind of nuclear reactors has been the subject of a growing and renewed interest from the scientific community in the framework of the Generation IV International Forum. The thesis work of Fabio Donati focused on the development of new Scanning Tunneling Microscopy and Spectroscopy (STM and STS) tools (both theoretical and experimental) and on their application in the investigation of magnetic surfaces. Spin polarized STM (the technique used in this work in an innovative way) is a very hot topic in both surface physics and nanotechnology. Paolo Ferrari worked in the field of organ dose conversion coefficients for neutrons and photons, investigated with voxel (3D) models and Monte Carlo simulations and validated through the irradiation of complex anthropomorphic phantoms. He obtained useful results in view of radiotherapy applications. The thesis work of Vito Memoli dealt with the modeling, again based on the multiphysics approach, of three different innovative nuclear reactors. In particular, the developed models are aimed at performing both static and dynamic analyses of reactor core. The three systems considered in this work are the space reactor SURE, the Lead cooled Fast Reactor and the Molten Salt Reactor. All these systems cannot rely on previous experience and require a major effort in terms of system modeling and simulation. Nicola Pedroni developed advanced Monte Carlo simulation methods and neural network regression for the reliability analysis of nuclear passive systems. The methods have been tested on a case study involving the natural convection cooling in a Gas-cooled Fast Reactor after a Loss of Coolant Accident. Giovanni Sansavini analyzed critical infrastructures with respect to their vulnerabilities to random failures and targeted attacks. Critical infrastructures are large scale, spatially distributed, complex systems which provide vital services for modern society, such as energy supply, transportation, information and telecommunication, drinking water distribution, including wastewater treatment. The work of Daniele Vigolo had the purpose of investigating nonequilibrium effects arising in "complex fluids" (nanometer-size latex particles, surfactant micelles or polymer suspensions) in the presence of thermal gradients. A successful application of thermophoresis as a microfluidic separator was also tested.

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CONCEPTUAL CORE DESIGN STUDY FOR A GENERATION-IV

Lead-cooled Fast Reactor Demonstrator

Sara Bortot

The object of this thesis work consists in the development of a preliminary core configuration for a Generation-IV Lead-cooled Fast Reactor (LFR) demonstrator (DEMO).
A great interest is currently focused on the combined technologies of fast reactors and associated closed fuel cycles, due to their potential to significantly foster a more effective utilization of uranium resources, while enabling the transmutation of minor actinides. R&D on the most promising concepts is currently being coordinated at an international level by initiatives such as the Generation-IV International Forum. Moreover, the European Community has defined its own strategy and priorities for systems that are the most likely to meet Europe's energy needs. In particular, attention to heavy liquid metal coolants (HLMC) has arisen in several countries, as their advantageous characteristics and associate technologies have gradually been recognized. Two pool-type reactor concepts have been selected as candidates for international cooperation and joint development: the Small Secure Transportable Autonomous Reactor (SSTAR), and the European Lead-cooled System (ELSY).
With the existing experience base, the need to construct and operate a LFR demonstrator has been recognized, aimed at successfully proving specific LFR technologies and to lay a foundation for further commercial deployments.
In this context, two different LFR demonstrators targeting two diverse aims have been developed, reflecting the significant differences between the ELSY and SSTAR missions and designs. The first is based upon the ELSY reference configuration, and is expected to both prove the viability of technology to be implemented in a first-of-a-kind industrial power plant, and serve as an irradiation facility for accelerated fuels and materials testing, thus requiring a high neutron fast flux. The second consists in a first-of-a-kind demonstration of an improved modular natural circulation STAR, named the SUstainable Proliferation-resistance Enhanced Refined Secure Transportable Autonomous Reactor (SUPERSTAR), intended for international or remote deployment and with features for near-term realization.
Two conceptual core configurations have been developed starting from the very beginning of the projects by applying a same method. In particular, a preliminary broad-spectrum analysis of the technical issues that would accompany an early LFR demonstration has been first performed, in order to identify a set of general objectives and requirements properly defining the meaning of "demonstrative".
Then, attention has been concentrated on neutronics, and an *a priori* core design methodology has been set up and applied to establish a number of geometrical parameters on the basis of demonstration goals and technological constraints. Scoping analyses have been then performed, followed by optimization studies leading to the reference core configurations.
A complete neutronics characterization, involving fuel cycle calculations and evaluation of reactivity coefficients and kinetic parameters (required for the subsequent study of core and primary loop dynamics) has been accomplished. Once established a core configuration for the two demonstrators, preliminary thermal-hydraulic analyses have been performed to verify *a posteriori* that safety limits were respected and postulated criteria were fulfilled.
As far as DEMO is concerned, conventional MOX has been considered as the reference fuel, according to the needs of both meeting a reasonably early schedule and pursuing the major goal of ELSY representativeness. Nevertheless, a U-Pu-Zr ternary alloy fuel core has been investigated as an alternative option, since the superior safety response to operational transients and postulated accidents that metal provides, compared to oxide, may eliminate the practical need for certain safety features such as the capability to withstand core melting scenarios or energetic core disruption.
The resulting core designs feature a 300 MW_{th} core, composed by 24 ductless fuel assemblies (FAs) with pins arranged on a square lattice, organized into two radial enrichment zones, ensuing from criticality assessment and power flattening needs. The foremost goal of designing a high power density LFR DEMO assuring a high fast neutron flux has been successfully accomplished while complying with all the reference criteria: a peak total neutron flux nearly three times as high as ELSY one has been achieved while respecting all the technological constraints in both configurations.
Concerning SUPERSTAR concept development, a core design investigation has been carried out by incorporating also the use of hot channel factors as well as margins for other uncertainties, seeking four essential requirements: a long core lifetime, transportability, near-term deployment, and natural circulation cooling up to 15 % overpower. Design studies have emphasized reducing the power distribution through the use of multiple enrichment zones, limiting the burn-up reactivity swing to less than 1 $ compatibly with a unitary conversion ratio, and providing sufficient shut-down reactivity, while always complying with the strict radial dimensional constraint. Moreover, the design of innovative control rods denser than lead, thus sinking in lead under gravity following release, has been undertaken in order to guarantee safety.
A preliminary core configuration complying with all the design goals have been suitably accomplished: the reference design fulfills quite satisfactorily the two key neutronics goals, as the a long-life core has been designed featuring a reactivity swing matching the target figure of 1 $ while assuring a very flat power distribution all over its lifetime.
Investigation of DEMO kinetics and dynamics has been finally undertaken, in order to provide a helpful and flexible tool in this early phase of the reactor conceptual design, in which all the system specifications are still considered as open design parameters, allowing a relatively quick analysis of fundamental dynamics and stability aspects that cannot be left aside when refining or even finalizing the system configuration. In this perspective, reactor dynamics is of primary importance for the study of plant global performance and for transient design-basis analysis, since it provides fundamental feedbacks on safety and stability, as well as prospects of using different core materials possibly helping make a definitive choice concerning fuel type and design parameters, and useful guidelines for the conception of an appropriate control system.
Calculations have been carried out using a first principles analytical model, *ad hoc* developed, as well as the SAS4A/SASSYS-1 Liquid Metal Reactor Code System. Both core and primary loop models have been developed, and the reactor transient response following postulated accident initiators has been studied. MOX and metallic fuel dynamic performances have been compared, confirming the expected superior safety characteristics of the latter, and a very good agreement has been found between the outcomes of the simplified analytical model and SAS4A/SASSYS-1 results.
The transient simulation has brought a fundamental finding: the high core pressure drops (due to the small hydraulic diameter coming from the need of a very compact lattice with small pin diameters to reach very high power density values) compromise an effective cooling by natural circulation, which consequently cannot be relied on whether an accident occurs, in particular for MOX fuel. As a main consequence and feedback on core design, it is stated that a high flux demonstrator needs to incorporate alternative additional systems to guarantee an effective core cooling in the case of loss of pumping power. On the contrary, if priority is to be given to the demonstration of natural circulation cooling effectiveness in accidental conditions, then the very ambitious goal of a high power density design must be necessarily relaxed.

HELIUM PRODUCTION AND BEHAVIOUR IN LWR OXIDE NUCLEAR FUELS

Pietro Botazzoli

The context of the present thesis is the characterization and the modelling of the nuclear fuel behaviour in reactor. The work has been developed in the framework of a collaboration between the Politecnico di Milano and the Joint Research Centre/Institute for Transuranium Elements (JRC/ITU).
The study of the thermo-mechanical behaviour of fuel rods (fuel rod performance) is of paramount importance for the design, safety and licensing of nuclear fuels. In fact, the fuel rod is the first barrier against the release of fission products. The thermo-mechanical behaviour of the fuel rod is influenced by many phenomena coupling the fuel pellets and the cladding. The synergy of the different phenomena can be studied only by means of expensive and demanding integral irradiation tests, with the support of fuel performance codes. Many fuel performance codes have been developed in the last 40 years. Among them, TRANSURANUS, developed at the JRC/ITU, is one of the most qualified tool. Although it is more than 30 years old, it is continuously under development in order to improve its prediction capabilities in view of increasing burn-ups and with the employment of new materials. For this end, the properties of new materials have to be implemented and semi-empirical correlations have to be replaced by more flexible physics-based models based on a multi-scale approach. The lifetime extension of a fuel rod at high burn-up, the fuel performance modelling in such conditions, and the improvement of the multi-scale approach applied to the behaviour of nuclear materials are important issues, which are supported by many International Projects (e.g., IFPE - International Fuel Performance Experiment, FUMEX-3 - FUel Modelling at EXtended burn-up, and F-BRIDGE - Basic Research for Innovative Fuel Design for GEN IV systems, sponsored by OECD/NEA, IAEA and the European Commission, respectively).
Among the issues currently investigated, the behaviour of inert gases in oxide fuels at high burn-up is one of the most relevant. In particular, the present thesis contributes to the study and the modelling of the He behaviour (from its production to the release) in oxide nuclear fuels for LWRs. He behaviour can influence the in-reactor performance and the long term storage of nuclear fuel. During the irradiation, He trapped in the pellet can contribute to the degradation of the properties of the fuel. On the other hand, the fraction released in fuel rod free volume influences the inner pressure with consequences for the safety. This is especially relevant for Mixed OXide fuels (MOX), which are envisaged to be employed for a better sustainability of the nuclear energy resources (closed fuel cycle) and for the management of military grade Pu (e.g., Fissile Material Disposition Program).
In fact, He production increases exponentially with the burn-up and it is more relevant for MOX fuel, since the initial presence of Pu leads to a larger production of α emitters. To this end, in the present thesis, models relevant for the performance of LWR UO_2 and MOX fuels at high burn-ups have been developed, coupled and implemented in TRANSURANUS.
As a first step, a model for the production of He has been developed and implemented in the TRANSURANUS Burn-up module (TUBRNP). The model takes into account the He produced by α decays, (n,α) reactions and ternary fissions.
At first, it has been verified through neutron-transport depletion calculations, performed by means of the VESTA Monte Carlo-depletion code (developed at the Institut de Radioprotection et Sûreté Nucléaire). Finally, the model has been validated against experimental data. In particular, a good agreement has been found in terms of average concentrations and radial profiles of the main α emitters produced in UO_2 fuels.
However, further experimental data are needed for a complete validation of the model.
The most important missing information is the He produced. Moreover, isotopic compositions and relative radial nuclide profiles of LWR MOX fuels, especially at high burn-up, are also relevant.
As a second step, the microstructure of oxide fuels has been studied, since it is relevant for the behaviour of the gases. More precisely, grain growth of UO_2 and MOX fuels has been investigated. In fact, grain boundaries strongly influence the diffusion process in the grains.
As far as the UO_2 is concerned, experimental data of unirradiated fuel pellets available in the open literature have been analysed and interpreted by means of different models. However, the experimental data are too dispersed to draw definitive conclusions, since they are influenced by many parameters, which are not always available (e.g., O/M, porosity fraction, pore size).
As far as MOX fuel is concerned, due to the lack of experimental data, tests have been carried out by the author at JRC/ITU in order to study for the first time the influence of Pu content (0, 3.7, 9, 25 %wt) and fabrication technique (SOLGEL, SBR, MIMAS) on the grain growth of stoichiometric MOX fuels annealed at different temperatures (1350-1750°C). Both grain size distributions and average values have been measured. On one hand, it has been found that normalized size distributions did not change significantly during the annealing and were similar among the different samples. On the other hand, large differences have been noticed in terms of growth kinetics. The slowest kinetics has been experienced by the SBR sample, followed by MIMAS and UO_2, while the two SOLGEL samples had the largest growth. No dependence on the Pu content has been found and the predominant effect has been attributed to the pore size.
In fact, SBR MOX is characterized by the largest and slowest pores, while SOLGEL is characterized by the smallest and fastest pores. All things considered, grain growth kinetics of the analyzed samples lies within the large scatter of the values available in the open literature for UO_2 fuels, and the only correlation proposed in open literature for stoichiometric MOX is in agreement with the growth experienced by the SOLGEL samples, which is faster than commercial fuels. This means that the adoption of this correlation for commercial MOX leads to an overestimation of the grain growth, with consequences for the estimation of fission gas and He releases.
For the fuel performance, on the basis of the large scatter of the experimental data, the same correlation developed for UO_2 can also be used for MOX fuels. However, a quantification of the effect of porosity and fission gas bubble on the grain boundary movement could be further investigated, for example by means of mesoscale simulations.
As a final step, the transport of He in the fuel has been investigated. A model for the He release in the rod free volume has been developed. In a simple but physics-based way, it takes into account the intra- and inter-granular behaviour and the absorption. The model has been implemented in TRANSURANUS and preliminarily validated on the basis of pressurized and unpressurized fuel rods. The agreement is satisfactory although some discrepancies have been noticed. More experimental data are needed for better assessing the model parameters (diffusion coefficient, solubility) and for a proper validation.
In summary, the behaviour of He in LWR fuel has been studied and modelled, considering the production, the release in the fuel rod free volume and the absorption. In order to do this, grain growth has been investigated. Some data would be useful for a complete validation of the He production and release models, as well as for the in-pile grain growth of LWR MOX fuels.
Although related to LWR conditions, the present work could be extended to fast reactors. This could be achieved by including specific one-group cross sections in the He production model, by considering the columnar grain growth and the corresponding release process from columnar grains.

COMPUTATIONAL METHODS FOR MAINTENANCE POLICY OPTIMIZATION IN COMPONENTS OF ELECTRICAL SYSTEMS

Michele Compare

Managing an industrial plant entails evaluating and trading off the conflicting objectives of economic service and safe operation. In this context, maintenance plays a significant role: knowing when and how to inspect, repair and renovate the components of a system is fundamental to reduce failures, for safety reasons, and unplanned downtime, for economic reasons.
The relevance of maintenance in the strategic paradigms of competitiveness of modern businesses has accentuated the need of measuring its contribution to achieving the goals set, which typical include: maximization of production, cost reductions, optimization of maintenance resources, optimization of capital equipment life, minimization of inventory on hand, minimization of energy usage. While these goals do not form an exhaustive list, they highlight the contribution that the proactive management of maintenance can bring to the productive operation of a company. Such management of maintenance entails that the goals sought be measured through the introduction of adequate maintenance key performance indicators. The quantification of these indicators, and thus the optimization of a proactive maintenance plan or the verification of its adequacy, can be made by more or less sophisticated modeling. Thus, the increasing importance of maintenance in practice has led also to a growing interest for modeling and optimization in support of effective maintenance decisions, which has steered research efforts towards the development of mathematical models and computational methods aimed at identifying a policy of intervention that typically maximizes the production profit and minimizes all losses, including assets ones, while fulfilling the safety goals and the regulatory requirements.
In spite of the many research efforts in the direction of building models in support of maintenance decision making, it seems fair to say that in many practical cases the situation is not so brilliant: maintenance policies are in many instances still based on the maintenance schedules recommended by the vendor, which are usually conservative or are only based on qualitative information driven by experience and engineering rationale. In particular, the simplicity of the assumptions of a single component operating in a fixed environment and affected by a single degradation mechanism which is exactly known, compared to the complexity of the reality of multi-component systems in a changing environment in presence of imprecision, is often put forward to explain the lack of success of maintenance modeling in practice; this simplicity can be regarded as a consequence of the distance between research and industry.
In this context, the objective of the present PhD work has been the development of innovative computational methods in support of maintenance decision makers in real industrial (especially nuclear) applications. These methods have been developed to address real case studies provided by industrial partners, in an effort t o bridge the gap between the academic and industrial worlds. In particular, these case studies are characterized by a common feature: lack or corruption of available data. This situation is typical of the real industrial contexts, but usually it is not given due account in maintenance modeling.
In particular, three challenges have been faced:

- Assess the performance of a maintenance policy when the stochastic model of the behavior of the component is completely known, but it depends on a number of ill-known parameters elicited from experts.
- Assess the performance of a maintenance policy when the model of the degradation process is not known, and thus it has to be derived from the information elicited from experts.
- Build reliable diagnostic tools based on a dataset containing corrupted data.

Namely, in the first case, the uncertainties associated to the information provided by the experts have been represented by possibility distributions. Then, an hybrid Monte Carlo-Possibilistic method has been exploited to propagate the epistemic uncertainty on the parameters jointly with the aleatory uncertainty, which is encoded by the stochastic process that models the behavior of the maintained component. This has allowed to estimate the uncertainty on the considered indicators of the performance of the maintenance policy to be assessed (i.e., the component mean unavailability and total cost over the mission time). The novelty of the contribution of this part of the thesis lies in the particular combination of techniques taken from the literature and their application in the context of maintenance performance assessment.
A novel framework that captures the expert knowledge about the degradation processes affecting the components and exploits this information to build fuzzy degradation models has been proposed to addressed the second issue. These fuzzy models are then embedded in a Monte Carlo (MC) simulation scheme in order to estimate the considered indicators of the performance of the maintenance policy to be assessed such as the mean unavailability and cost. To do this, an innovative computational solution has been devised: an hybrid Fuzzy Logic - Monte Carlo method. Thus, the contribution of this work is twofold: on one side, the expert-knowledge-based approach to build the models of the degradation processes; on the other side, the techniques to simulate these models within the Monte Carlo scheme.
In regard to the third issue (i.e., diagnostics), a novel methodology has been devised to build a reliable empirical classifier for diagnosing the degradation state of electrical components, in the situation (again, very common in real world applications) in which the dataset available to train the classifier contains errors that undermine the performance of the diagnostic tool. In turn, the methodology is made up of two steps: in the first one, the errors are identified and removed from the dataset (which constitutes the novelty of the contribution), whereas an empirical classifier is built in the second part, on the basis of the cleaned dataset.

COMPUTATIONAL METHODS AND SOFT COMPUTING MODELS FOR RELIABILITY, AVAILABILITY, MAINTAINABILITY AND SAFETY ANALYSIS OF NUCLEAR SYSTEMS

Francesco Di Maio

Reliability, Availability, Maintainability and Safety (RAMS), as well as risk analysis, are big issues in old and modern Nuclear Power Plants (NPPs) of developed and developing countries. In this context, China represents one of the most strategic market for the nuclear energy industry. However, in the development of such plan, the safety of NPPs is still considered a critical issue for the public acceptance of nuclear energy and, thus, a lot of collaborative research is done for improving the safety standards of old and modern NPPs.
As a result, the work presented in this Ph.D. thesis has been performed at the Department of Energy of the Politecnico di Milano in tight collaboration with the Institute of Nuclear and New Energy Technologies (INET) of Tsinghua University, Beijing (China), within a Joint Ph.D. Agreement signed by both Institutions.
In this context, the goal of the Ph.D. work here presented is to propose the use of advanced simulation techniques (e.g., Monte Carlo) and soft computing methods (e.g., Artificial Neural Networks (ANN), Genetic Algorithms (GA) and Fuzzy Logic (FL)) for addressing four main topics that are problems and challenges related to the power plants design (topics 1 and 2), operation (topic 3) and life extension phases (topic 4), respectively:

1. Reliability analysis of passive safety systems
2. Reliability analysis of Digital Instrumentation & Control (I&C) systems
3. Condition monitoring for failure prognostics of components
4. Uncertainty analysis in Thermal-Hydraulics (TH) computer codes

Reliability analysis of passive safety systems

Common to most innovative reactor concepts is the transition from active to passive safety systems, that, for their operation, only rely on natural forces, such as gravity or natural convection. This is widely reckoned to bear some important advantages. However, a fundamental issue, still to be resolved, is the quantification of their reliability, which still requires considerable computational efforts. This calls for the implementation of fast and transparent TH models for a clear interpretation of the system response. The speed of calculation would allow for extensive scenario analysis and for systematic methodologies for addressing all the uncertainties involved, within a rigorous, transparent, traceable, but at the same time manageable, effort of analysis. In this thesis, a simulation framework of analysis is presented aiming at evaluating the safety performance of the Residual Heat Removal system (RHRs) of the Chinese High Temperature Gas-Cooled Reactor – Pebble Bed Modular (HTR-PM) under uncertain operation conditions, and components and equipments failures.

Reliability analysis of Digital Instrumentation & Control (I&C)

Existing and future NPPs are making a transition from analog to digital technology of Instrumentation and Control (I&C) components, because digital technology has many merits, compared with analog type. However, since digital technology makes use of software for signal processing and operation, there are various technical issues to be solved, such as challenges that exist in modeling the dynamic interactions between the plant systems and processes due to the many unique attributes of these systems. Thus, to assess the impact of digital I&C on NPPs safety, quantifiable reliable models are needed. This entails the simulation of a number of scenarios much larger than that considered for the classical Event Tree/Fault Tree (ET/FT)-based analysis, with the post-simulation retrieval of information becoming quite difficult and burdensome. In this thesis, the results of some investigations with respect to the classification of the numerous accidental scenarios generated in the dynamic safety analyses of a Level Control Dynamic system (LCDs) and a Lead Bismuth Eutettic – eXperimental Accelerator Driven system (LBE-XADS) equipped with digital I&C are presented.
The methods investigated are based on a Fuzzy C-Means (FCM) clustering algorithm in which the classification takes into account not only the final system states reached at the end of the accidental scenarios but also the timing of the occurring events, the fault magnitudes and the characteristics of the process evolution.

Condition monitoring for failure prognostics of components

Existing NPPs strive to improve safety, maintain availability and reduce operation and maintenance costs by attempting at monitoring NPPs health.
This is why failure prognostics is becoming attractive in RAMS applications. The primary purpose of a prognostic system is to indicate whether the equipment of interest can perform its function throughout its lifetime with reasonable assurance; and in case it cannot, to estimate its Residual Useful Life (RUL), i.e. the lifetime remaining before it can no longer perform its function. The problem of inferring the system state from the measured parameters can be tackled by two general approaches: the model-based and data-driven approaches.
In thesis, a data-based similarity approach for the on-line estimation of the RUL of a system is presented. The novel approach consists in predicting the remaining time before failure of a given failure scenario developing in the system, by comparing by fuzzy similarity analysis its evolution data to a library of reference trajectory patterns. The prediction on the failure time is dynamically updated as time goes by and measurements of signals representative of the system state are collected. For illustration, a case study is considered regarding the estimation of RUL in failure scenarios of the LBE-XADS.
The same approach is tested on the degradation trajectories of a component subjected to fatigue failure crack growth. This latter case study is also considered for showing the capabilities of an additional approach developed in this thesis, that consists in an original combination of data-driven (i.e., Relevance Vector Machines (RVM)) and model-based approaches to prognostics, where particular attention is given to the adequate representation and propagation of the uncertainty in the estimates of the RUL.

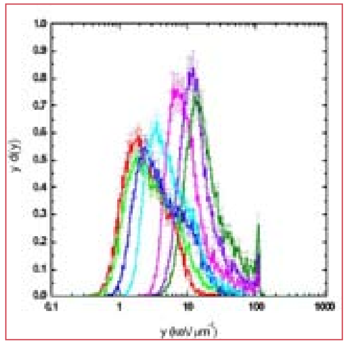
Uncertainty analysis in Thermal-Hydraulics (TH) computer codes

Uncertainty analysis is required when *i*) checking design solutions of new NPPs whose safety analysis relies on newly developed models and codes and *ii*) analyzing requests for power uprates and life extensions of existing NPPs, because the combination of the uncertainties of the system under analysis may increase the risk of accidents. Conservative calculations are traditionally performed for the verification of the safety performance of a NPP. Recently, the conservative approach is being challenged by a more realistic, Best-Estimate (BE) analysis, which sets forth the calculation of safety margins with realistic models and BE assumptions to account for the consequences related to the failures in some protective barriers. This requires a revision in probabilistic terms of the concept of safety margins and repeated model runs for the associated sensitivity and uncertainty analyses. In this thesis, a set of frameworks of analysis is presented for the estimation of probabilistic safety margins: Order Statistics (OS), Bootstrap Techniques (BT) and Artificial Neural Networks (ANNs) are exploited to tackle the problem of the computational burden related to the large number of model runs needed for the accurate estimation of safety margins and their confidence intervals. Furthermore, different case studies are also presented with respect to the complete blockage accident scenario of one Group Distribution Header (GDH) of a RBMK-1500 nuclear reactor, the partial/total failure of a passive Residual Heat Removal system (RHRs) of the High Temperature Reactor – Pebble Modular (HTR-PM), and the Loss Of Coolant Accident (LOCA) in the RHRs of a Pressurized Water Reactor (PWR).

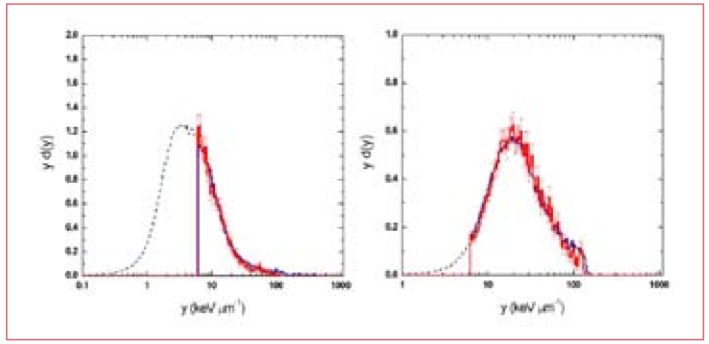
SILICON DETECTORS FOR HADRONTHERAPY APPLICATIONS

Maria Vittoria Introini

Hadrontherapy, a radiotherapeutic treatment carried out with hadrons (e.g. protons and carbon ions), is one of the most promising treatments for some kind of tumours, especially for those highly resistant to conventional treatments like surgery, chemotherapy and radiation therapy with photons and electrons. The effectiveness of a hadrontherapy treatment is strictly related to the energy deposited at the cellular level by the irradiation beam.
This local deposition triggers a complex sequence of processes inducing the biological effect. Therefore, an accurate treatment requires a detailed physical knowledge of the local energy distribution of the therapeutic beam and an accurate and complete beam quality assessment.
For this purpose, many efforts are required for developing instruments and methods capable of integrating the information derived by a typical dosimetric approach, in order to obtain a more comprehensive physical knowledge of the local energy deposition.
Microdosimetry, a field of radiation physics dealing with the description, the measurement and the analysis of the statistical fluctuations of energy imparted locally by radiation to matter, can accomplish this task with high accuracy. Microdosimetric measurements are typically performed by using tissue-equivalent proportional counters (TEPCs). However, a simple and widespread use of these devices for the characterization of hadrontherapy beams is limited by practical difficulties in the management and the maintenance of the associated systems. These limitations led to study alternative detection systems capable of measuring microdosimetric spectra similar to those acquired by TEPCs.
The aim of this thesis was to verify the possibility of characterizing a therapeutic proton beam by exploiting a silicon device based on the Monolithic Silicon Telescope technology, recently proposed by the Laboratory of Nuclear Measurements of the Politecnico di Milano for microdosimetry applications. This device, fabricated by ST-Microelectronics (Catania, Italy), is characterized by two different stages: a thin ΔE stage (of about 2 µm in thickness) and a thick E stage (of about 500 µm in thickness).
The ΔE stage, coupled to a tissue-equivalent converter, can be in principle exploited as silicon microdosimeter.
A prototype device with a ΔE stage segmented in a matrix of micrometric cylindrical diodes about 2 µm in thickness and 9 µm in diameter (coupled to a thick stage E about 500 µm in thickness) was firstly characterized within quasi-monoenergetic neutron fields.
The aim was to test the capability of this device of reproducing microdosimetric spectra similar to those acquired by a reference TEPC. A systematic comparison was performed between the lineal energy spectra derived with the two detection systems.
The results of this comparison were satisfactory. In order to test the response of the monolithic silicon device to an intense hadron beam, a numerical study with FLUKA simulations was performed.
A comparison of the numerical results with experimental data acquired at the 100 MeV un-modulated proton beam of the Loma Linda University Medical Centre was carried out and gave confidence about the use of this device for the characterization of a hadrontherapy beam.
The segmented detector was then irradiated at different phantom depths with a clinical proton beam at the Centro di AdroTerapia e Applicazioni Nucleari Avanzate (CATANA), the first Italian protontherapy facility. Simulations with the FLUKA Monte Carlo code were also performed (Fig.1) and numerical results were compared with experimental data. Moreover, a systematic comparison between the lineal



1. Lineal energy spectra obtained with FLUKA simulations at different depths in PMMA.



2. Fig.2: Example of the comparison between the microdosimetric spectra obtained with the silicon telescope (red curve) in the proximal part (left) and in the distal part (right) of the SOBP and those obtained with a reference TEPC, truncated at 6 keV µm^{-1}(blue curve) and complete (non-normalized, dashed black line).

energy spectra derived with the segmented telescope and literature data acquired with a reference TEPC was finally carried out (Fig.2).

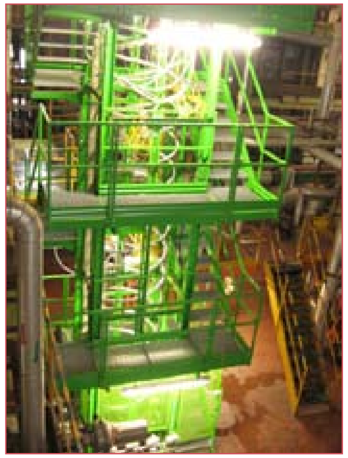
The results of these measurements demonstrated the capability of the silicon device of measuring microdosimetric spectra of proton beams similar to those derived with a TEPC at lineal energies higher than 6 keV µm^{-1} and at beam currents about two order of magnitudes lower than clinical ones. These limits prevent the acquisition of lower-LET events in the proximal part of the SOBP, therefore hinder the measurement of low-energy deposition events associated to high energy clinical proton beams. In order to improve the performance of the silicon-based system, a new detector design is in progress and will be the subject of a future research.

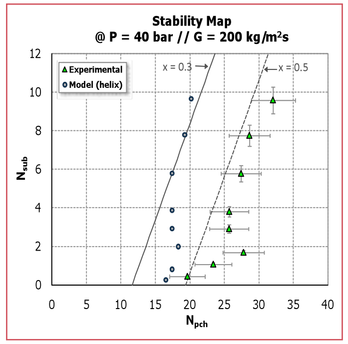
The possibility of performing a heavy-ion beam characterization by exploiting the double-stage structure of the Monolithic Silicon Telescope was finally investigated with preliminary irradiations on a low-energy carbon beam. The detector was placed at different depths inside a PMMA phantom and irradiated with 62 AMeV carbon ions. Preliminary results highlighted the possibility of performing the dosimetric and microdosimetric characterization of light ion beams. It should be underlined that data about microdosimetry of 62 AMeV carbon ions are not available in the literature. Moreover, this ion energy is not suitable for treatment because of the limited range in tissue (about 8 mm).
In order to perform a systematic comparison with reference data, further measurements at the carbon ion energies usually employed for cancer treatments (290 AMeV, 400 AMeV) are necessary and will be matter of future work.

MODELLING AND EXPERIMENTAL INVESTIGATION OF HELICAL COIL STEAM GENERATOR FOR IRIS SMALL-MEDIUM MODULAR REACTOR

Davide Papini

New technological solutions are being envisaged within the nuclear reactor projects of Generation III+ and Generation IV, aimed at simplifying the plant layout and fulfil at the same time higher safety requirements. Different concepts of Small-medium Modular Reactors (SMRs) are currently under development, where all the primary system components are located inside the reactor vessel (integral layout).
The adoption of helically coiled tube steam generators fits well with such integral approach to reactor design. As a matter of fact, the helical geometry results in more compact steam generators and efficiency improvement through better heat transfer characteristics.
With reference to the Generation III+ project IRIS (International Reactor Innovative and Secure), the dynamic behaviour of the helically coiled steam generator (and related safety systems as well) has been dealt with in this thesis, by means of the development of suited modelling tools, both analytical and numerical.
Analytical lumped parameter model based on the moving boundary concept has been developed to study the dynamics of a once-through steam generator (IRIS kind).
With respect to literature models, the innovative feature of the developed model is to prescribe the temperature at steam generator primary side inlet, hence to simulate a realistic fluid-heating process. Testing of the model has been realized via coupling to a reactor core model. Depicted transient responses on the coupled system (reactor model and steam generator model) confirmed that the considered moving boundary approach is appropriate for the study of boiling channel dynamics.
In the framework of IRIS scaling analyses, several issues regarding containment modelling by means of the RELAP5 code have been addressed.
The RELAP5 transient analysis code is widely used in the nuclear area and is designed as the reference thermal-hydraulic code for calculations with water-steam mixtures in 1D "pipe-oriented" systems. Application of the code in large volumes (such as reactor containment drywell volume), standing outside its validation matrix, has been investigated. The GOTHIC code, dedicated for containment analysis, has been considered to validate – with fair quantitative agreement – the RELAP5 predictions.
Density wave instability phenomena have been then major topic of investigation, as the parallel channel instability (physically of density wave kind) might be triggered among the parallel channels of the once-through steam generators, where boiling process occurs within tubes (secondary-side). Flow instabilities must be avoided in the design and operation of the various industrial systems, as the thermally induced oscillations of the flow rate and system pressure can cause mechanical vibrations, problems of system control, thermal fatigue and thermal crisis occurrence as well.
The study of density wave instabilities has been dealt with by applying the sound modelling approach tested preliminarily on the steam generator global behaviour. Both, analytical modelling and numerical modelling have been considered, in order to represent the complex interactions between the variables triggering the instability.
A theoretical lumped parameter model – moving boundary kind – has been developed, based on the integration of mass, energy and momentum 1D equations. The model has been plentifully tested dealing with the simplified vertical tube geometry, also owing to the availability of similar works in the open literature for validation purposes.
Several sensitivity studies have been provided, identifying most critical parameters to model for a correct prediction of the instability threshold. Theoretical predictions from analytical model have been then successfully compared with numerical results obtained via the RELAP5 thermal-hydraulic code and the COMSOL multi-physics code as well, which proved to be capable of predicting DWO occurrence.
Moreover, parallel channel instability has been studied also experimentally, with respect to the helical-coiled tube geometry featured by the IRIS steam generator. A full-scale open-loop experimental facility has been specifically built and operated at SIET labs in Piacenza (Italy), comprising two helical tubes (connected by means of two common headers) in simulation of the helically coiled steam generator of the IRIS reactor (Fig. 1).
The experimental campaign has showed the peculiar influence of the helical geometry on instability thresholds in parallel channels. A thorough threshold database useful for model validations has been provided as well. The effects of system pressure, flow rate and inlet subcooling on the power at the onset of instability have been investigated, clustering the data in dimensionless stability maps.
The experimental results have showed that the shape of the stability boundary with helical coil tubes differs from classical one, valid for straight tubes.
A different behaviour in the low-subcooling region occurs, and can be ascribed to the effect of the centrifugal field induced by tube bending. Discrepancies with respect to the classical theory have been also observed in terms of period of the oscillations.
Finally, the appearance of Ledinegg type instabilities (triggered by the provided parallel channel boundary conditions) has been depicted. Some Ledinegg transients have been taken into account, showing even superimposition phenomena with density wave oscillations.
The final task of the thesis has been devoted to the simulation and interpretation of the experimental results, by adapting to the dimensional characteristics of the facility both, the analytical lumped parameter model and the RELAP5 code.
Best results have been obtained via the analytical model, on the basis of a modified form of the widespread and sound Lockhart-Martinelli friction multiplier tuned on the frictional characteristics of the system.
Though a systematic underestimation of the instability onset (which is indeed a conservative feature), satisfactory qualitative agreement with the experimental stability boundary has been reached.
Fig. 2 shows an example of such comparison between model and experimental results, highlighting a pretty good simulation of the stability boundary shape.
In conclusion, proper reproduction of the stationary pressure drop distribution within the investigated helical-coiled system is depicted as mandatory, prior to provide any accurate instability calculations.


1. Global view of the full-scale experimental facility simulating the helical coil steam generator (SIET labs).



2. Comparison between theoretical model and experimental results in terms of stability map (P = 40 bar; G = 200 kg/m²s).

ENSEMBLE-BASED CLASSIFIERS AND INCREMENTAL LEARNING TECHNIQUES FOR FAULT DIAGNOSIS OF COMPLEX SYSTEMS

Roozbeh Razavi-Far

Introduction

There has been an increasing interest in fault diagnosis in recent years, as a result of the increased degree of automation and the growing demand for higher performance, efficiency, reliability and safety in complex systems. The work in this thesis has been motivated by the desire to develop ensemble-based classifiers and incremental learning techniques for fault diagnosis of complex systems.

To maintain a high level of performance and reliability in complex system, errors, component faults and abnormal system operation must be detected quickly. The source and severity of each fault must be diagnosed so that corrective action can be taken promptly. Faults in process equipment can result in off-specification production, increased operating costs, the chance of line shutdown and the possibility of detrimental environmental impact. Therefore, early detection and diagnosis of process malfunctions are strategically essential for companies to remain competitive in world markets. Furthermore, many system malfunctions do not have safety or life-threatening consequences but may seriously influence the ecology.

In this thesis, recent approaches to fault diagnosis for complex systems are studied. The use of ensemble-based classifiers and incremental learning techniques are considered important extensions to the classification approach for fault diagnosis in dynamic and complex systems.

The problem of diagnosing faults can be tackled resorting to many different approaches based, for example, statistical approaches; principal component analysis; quantitative approaches; frequency domain analysis; expert systems; computational intelligence approaches.

However, in complex systems, quantitative models and fault-symptom relationships are not readily available; classification or pattern recognition can be used for fault diagnosis. Pattern recognition methods for classifying faults are usually based on time-series data of various signals in static environments. However, the quantity of training data and their representativeness of the underlying distributions are of paramount importance for good performance of these pattern recognition methods.

In complex or large scale systems, it is common for the data to be collected in large volume or small size. Moreover, the complex decision boundaries that exist between the different classes are difficult to be learned by a single classifier. Ensemble of classifiers offers a potentially valid framework to handle above situations.

On the other hand, collecting adequate and representative data is often a dynamic process of successive data acquisition campaigns. In such dynamic environments, the datasets become available successively, over a period of time. Moreover, datasets collected in subsequent installments may contain patterns of new classes of fault that were not present in prior datasets.

Therefore, fault classification problems require a solution that needs to be incrementally updated over a period of time. An effective way for performing incremental learning for fault diagnosis is that of using an ensemble of fault classifiers. However, incremental learning procedure becomes more complicated by the appearance of new classes of fault.

The purpose of this thesis is to develop ensemble-based classifiers and incremental learning techniques for fault diagnosis of complex systems. This work introduces three novel ensemble based classifiers and incremental learning algorithms. Ensemble-based classifier is developed for fault diagnosis and transient identification in case studies with different sizes and difficulties along with a method for confidence estimation. Then, a classifier-ensemble incremental-learning procedure is proposed for fault diagnosis in different operating conditions. Finally, dynamic weighting ensemble algorithm is designed specifically for incremental learning and diagnosing new classes of fault through dynamically adjusting the combination weights of the classifiers' decisions. A novel class detector is also developed along with dynamic weighting ensemble algorithm for new class fault detection. These three algorithms are investigated through a series of experiments and case studies. The results are presented and compared.

Conclusions

The thesis discusses the properties and practical value of several novel ensemble-based classifiers and incremental learning algorithms for fault diagnosis of complex systems. These algorithms are all developed to solve various fault diagnosis problems in dynamic and complex systems and investigated through a series of experiments and case studies.

1) Bagged ensemble of Fuzzy C-Means (FCM) classifiers is developed for fault diagnosis in case studies with different sizes and difficulties along with a method for confidence estimation. The experimental comparison between bagged ensemble and a single supervised, evolutionary-optimized FCM classifier shows that the bagging ensemble performs as well or slightly better than the optimized FCM classifier on classification of medium and large datasets and outperforms the optimized FCM classifier in the classification of small datasets. Then a method is developed for estimating the confidence of the bagged ensemble system. The confidence in the final classification is obtained by exploiting the nature of the ensemble itself, to compute the Bayesian posterior probability of the class by a softmax approach.

In particular, very few patterns classified with high confidence values are misclassified, whereas, as expected, low classification performances are obtained when considering the few patterns classified with low confidence values.

Thus, majority of correctly classified instances had very high confidence estimates while lower confidence values were associated with misclassified instances.

2) A classifier-ensemble incremental-learning procedure is proposed for fault diagnosis in different operating conditions. In particular, the algorithm is inspired primarily by the Bagging algorithm and developed for learning in dynamic environments; new classifiers are added to the ensemble to learn the new data while keeping the previous classifiers to retain the existing knowledge. However, the classifiers are trained on subsets of the known classes, and thus are doomed to misclassify instances from classes on which they were not trained.

3) Dynamic weighting ensemble algorithm is designed specifically for incremental learning under the harshest learning conditions and diagnosing multiple new classes of fault. The algorithm uses the concept of dynamically adjusting classifier voting weights based on the hypotheses of other classifiers. This novelty allows classifiers to discuss with each other and determine which ones are likely to correctly identify a given instance based on the classes on which they are trained. Classifiers then adjust their voting weights accordingly. Incidentally, the algorithm overcomes the outvoting problem and prevents proliferation of unnecessary classifiers by reinitialization of distribution based on the performance of the current ensemble on the new data. Hence, the algorithm focuses on that portion of the new data space that has not already been learned by previous classifiers.

A novel class detector is also developed along with dynamic weighting ensemble algorithm for new class fault detection.