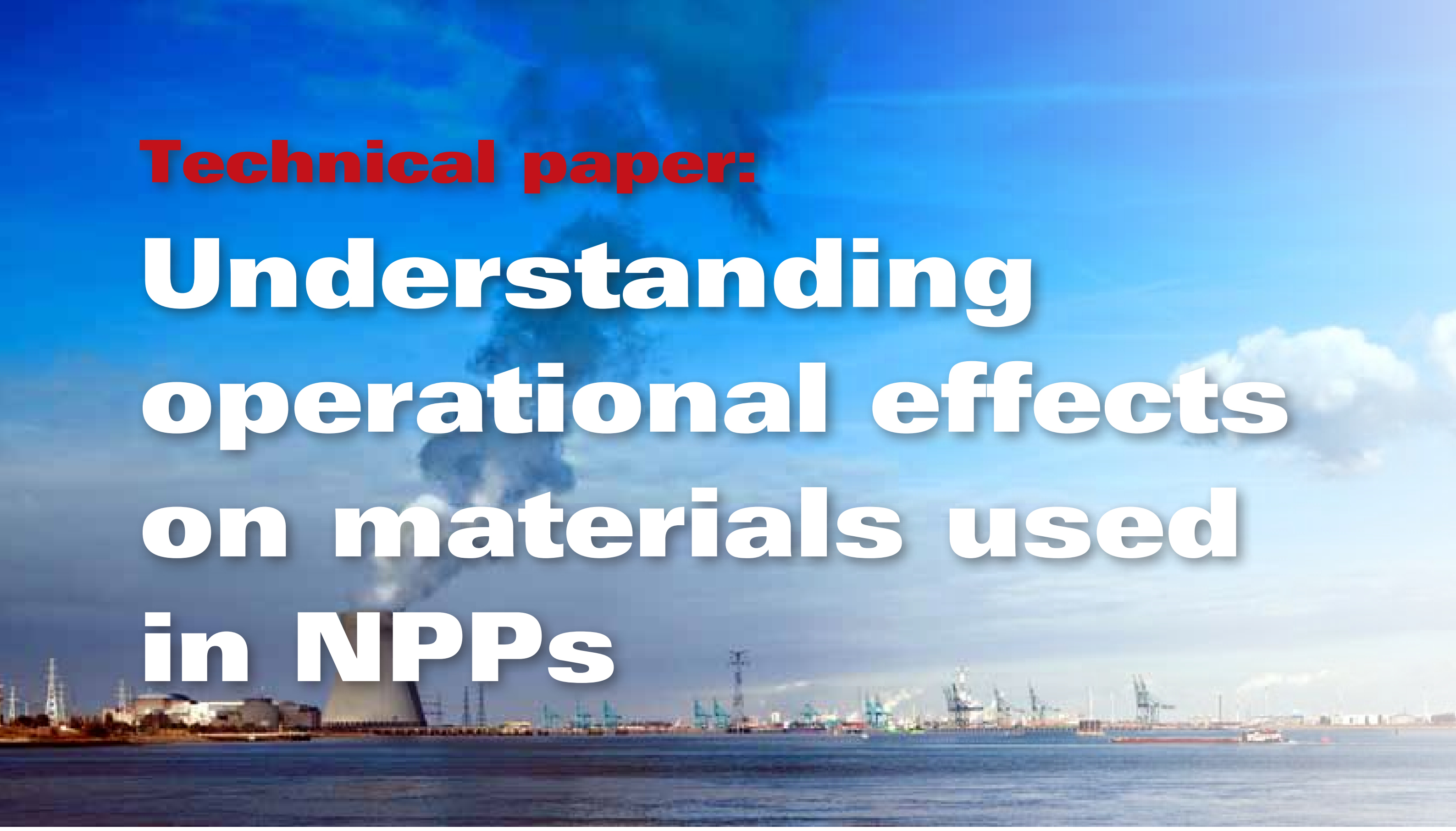

Technical paper:

Understanding operational effects on materials used in NPPs

Understanding how materials used for systems, structures and components (SSCs) behave chemically and physically in the operating environments of nuclear power plants (NPPs) is shown to be vital for implementation of robust plant-life and ageing management (PLiM and AM) strategies, and to achieve safe profitable current and long-term operation (LTO). As operating time is accrued, the NPP-SSCs are exposed to various stressors that may cause ageing degradation (AD) that could affect safety margins, induce spontaneous failures in equipment or lead to power reductions, expensive forced outages and even accidents. This paper looks at examples of important SSC-AD mechanisms and their mitigation, and the fundamental requirements of best-possible designs and materials. The roles of AM and PLiM, as parts of a feedback loop to overall operating practices (OPs), are highlighted. Efficient knowledge capture and management, as well as succession training, are recognized to be essential requirements for both the current and future nuclear power industry.

Keywords: Ageing degradation mechanisms, ageing and plant-life management, license renewal, power uprates, mitigation measures, safety culture, knowledge capture and management.

By Dr Philip G. Tipping, Nuclear Energy and Materials Consultant (NE&MC), Switzerland

The commercial nuclear power industry began in the mid-1950s and has already achieved well over 14000 reactor-years in 2011. Some of the first (Generation I) NPPs, for example, were the UK Calder Hall plants (Magnox-type, pressurized carbon dioxide gas cooled/graphite moderated and natural uranium fuelled) and the US Shippingport plant (light water cooled and moderated pressurized water reactor (PWR). Such pioneer NPPs provided much knowledge and experience upon which today's current fleet (Generation II) is based.

As in other technology-driven industries (e.g. aerospace, aviation, oil and chemical refinement), technical and operational developments have been continually added to NPPs as improved designs, better materials and increasingly effective OPs became available. Importantly, lessons-learned from plant-own and other NPP experiences have been rigorously implemented throughout the industry to benefit all aspects of operation and safety. Some actions taken were primarily driven by safety-related issues e.g. repair (overlay welds) or replacement of primary-side austentic steel (e.g. type 304) piping affected by stress corrosion cracking (SCC) with improved alloy (e.g. type 316NG) in boiling water reactors (BWRs) and secondary-side carbon (ferritic) steel piping thinned by erosion-corrosion (EC) in a PWR, and reactor pressure vessel (RPV) neutron flux reduction to lower rates of RPV embrittlement. Other measures taken were safety and economics-based (e.g. replacement of steam generators (SGs) when the number of plugged SG tubes affected by SCC, or wall thinning, became excessive, thus reducing the power output).

It is also noted that the heat transfer area of SGs in PWRs can represent over 50% of the total primary system pressure-retaining boundary, and the SG tubing is thus a significant barrier to fission product release. The SG tubing also is a barrier against steam release into the containment during a loss of cooling accident (LOCA). Further modernizations were added to plants to improve instrumentation and control (I&C), such as the introduction of digital and wireless signal technology to replace analogue systems. Operational flexibility and response times to address plant anomalies have thus benefitted. Further actions have focussed on modifying the reactor coolant water chemistry, e.g. hydrogen water chemistry (HWC) in BWRs to mitigate austentitic stainless steel core-shroud SCC rates, usually in combination with tie-rods, to maintain mechanical integrity even in the event of through-wall cracking. Fundamental research continues to provide NPP designers, manufacturers and safety authorities with science-based answers concerning SSC-AD mechanisms and also the optimum detection, mitigation, elimination and repair strategies to be used.

This paper discusses some important SSC-AD mechanisms that have been encountered in Generation II NPPs, and focuses attention on the way these plants may be kept operating in excess of their original design lives in a safe and profitable way (i.e. LTO). Benefitting from effective maintenance, robust OPs, PLiM and AM and ageing surveillance programmes (ASPs), many NPPs have already obtained license renewal (LR) status (US approach) or have permission for continued operation on the current license basis (periodic safety review (PSR) approach). The possibility of LTO for older plants is a valuable commercial opportunity, since such plants usually have low capital costs due to amortization and depreciation, even when the costs of replacement of large SSCs (e.g. SGs) or improvements to safety systems are factored in. Also, the share of nuclear-generated electrical power is currently around 16% of the world's total, and this will increase as New Generation III/IV NPPs eventually connect to the grid. In the near to mid-term (2011-2025), it will still be Generation II NPPs (current fleet 442, with an average operational life of ~ 26 years, and an increasing number thereof in, or approaching, the LTO-phase of life), which will provide the largest share (in 2011 ~375 GWe) of nuclear-generated electrical power. Furthermore, considering the issues connected with possible climate change and the availability and use of fossil-based energy, nuclear power is set to take an increasingly important role in terms of environmental acceptance (greenhouse gas-free) and overall security of cost-competitive energy supplies. The future of the nuclear power industry will be very dependent on maintaining safety in operation at all times, and the industry will therefore need to ensure that sufficient and appropriately trained personnel, with a good safety culture and proven technical abilities, are available to operate both the current and future NPP fleet.

Ageing and plant life management

A role within ageing management (AM) is to address safety-oriented issues, and consequently, AM has the goal to ensure that sufficient safety margins are maintained, or even increased, relative to original design requirements. Recognizing that large passive essentially non-replaceable items are potentially life-determining for a NPP (e.g. containment, reactor pressure vessel), AM strategies must also feature elements that manage and compensate for any insufficiencies/deficiencies in original NPP designs or inspection programmes. Unexpected SSC-ADs that have appeared during operation, and any corresponding lack in the understanding and mitigation thereof, are also addressed in AM. For example, buried cables and piping became an issue due to corrosion because of degraded protective coatings and poor backfill properties, and lack of appreciation, at the time of construction, of such effects over time. Correspondingly, appropriate monitoring and properly scheduled inspection programmes were not foreseen or implemented. Such occurrences are dealt with in affected NPP's AM programmes. Operational, engineering and maintenance actions in AM keep SSC-AD rates under control and manageable and thus ensure integrity (especially in safety-related SSCs) and that large irreplaceable SSCs (i.e. plant life-determining) are kept at levels of technical condition commensurate with safe operation. Thus AM strategies continually follow the state-of-the-art science and technology to implement qualified approaches to address current and evolving SSC-AD issues. A further goal of AM is to thus facilitate that NPPs will, at least, safely reach their original design lives.

Ageing surveillance programmes (ASPs): The identification and description of SSC-AD and the best methods to monitor, detect, inspect and mitigate it are commonly found in ASP documentation/dossiers. A specific SSC may be fully characterized with respect to its safety class, function, manufacturer, product type (e.g. forged, cast, rolled and associated welds), together with compliance certificates of chemical composition, heat treatment and fulfilment of design requirements (e.g. fracture toughness, tensile strength, chemical resistance), material type (e.g. high alloy, austenitic cladded low alloy, rubber, plastic, concrete), operating environment (chemical and physical conditions prevailing), maximum design loads/stresses allowed, known AD mechanisms (plant-own and world experience, published literature and research results). Specific restrictions on operating environments, including the use of approved lubricants (e.g. sulphide and chloride free to avoid corrosion/SCC) are also noted in ASP documentation. The ASPs are based on living documents that reflect the ever-evolving knowledge-base.

Plant life management (PLiM): The role of PLiM is basically economics-oriented insofar that PLiM is the foundation to keep NPPs operating profitably as long as possible, whilst cost-effectively maintaining safety at acceptable levels by having in place qualified methodologies to detect, eliminate or mitigate SSC-AD well before unreliable performance, spontaneous failure or forced outage can occur. PLiM (and AM) methodologies are tools for NPP owners to protect their assets, since plants that operate as long as possible, free from SSC failure, and have therefore high availability, will sell more power over a longer period of time, which, all other things being equal, will represent more profit. Asset management and protection thus encourage owners and operators to keep running their plants and, where applicable and necessary, to apply for LR or ensure that the PSR process provides proof of safety for continued operation.

Plant-specific OPs, which may include focused SSC monitoring (e.g. on-line piping wall thickness measurement), tailored maintenance schedules, special fuel management and storage procedures, coolant water chemistry control, repairs, refurbishments, replacements (RRRs) and decontamination/radwaste aspects are supported by feedbacks from AM and PLiM programmes. Issues arising due to obsolescence of SSCs and securing functionally equivalent quality assured (QA) replacements are also addressed in PLiM, as are spare part procurement, inventory maintenance and keeping plant documentation updated. Another important feature of PLiM is the optimum planning of when RRRs of SSCs should be done. When RRRs are carried out too early, they may unfavourable impact the business case, whilst overly delaying RRRs to save money could cause spontaneous failures of SSCs, which may lead to costly forced outages. It is stressed here that safety must always have precedence over any financial/profit goals of NPP operations.

NPP lifetime: The "lifetime" of NPPs may be regarded or defined from different stand-points:

- Design life: Time over which the main design requirements (particularly safety-related) are complied with, and functionally equivalent spare parts are readily available: SSC obsolescence,

as well as conceptual ageing of design have the potential to curtail the duration of a plant's originally expected life;
- Technical life: Safety and reliability requirements are met;
- Operational life: Time over which a NPP is producing electricity, ideally at a profit;
- Economic life (end of): The point in time when all plant operating/generating costs cannot be covered by sales of power;
- Regulatory life: Defined here by license status. With original license and LR or PSR approaches, the plant safety case has been approved for (continued) operation. Failure to fulfil licensing requirements will mean the end of the plant's operational life, until such a time when the license requirements, if at all possible, can be complied with or restored. (Note: extensive backfitting, RRRs of SSCs, seismic requalification and extensive changes to OPs, for example, may be required, and thus it may not be possible to justify the necessary financial outlay for future profitable operation);
- Political or legal life: When public acceptance of nuclear power is lost or legal mandates and national and international agreements to phase out certain plants come into power;
- General lifetime: The period from fabrication to retirement of a NPP;
- Chronological lifetime: Time span from site selection, construction, operation, shutdown, de-fuelling, dismantling, decontaminating and returning the site to a "green field" status.
- Long-term operational life (LTO): the operational time (granted under either LR or PSR approaches), after expiry of the original design lifetime. This may be 20 or more years, based on the license conditions.

Notwithstanding the subjective (emotional, political etc.), objective (system-technical, safety margins remaining, obsolescence etc.), business-case (amortization, profitability of operations etc.) and legal connotations associated with the term "NPP lifetime", NPPs must be kept in a safe condition at all stages of their constructional, operational and post-operational history. This observation is especially relevant when addressing radioactive waste (radwaste) conditioning/storage/disposal aspects, since radwaste issues potentially carry a long-term legacy, spanning many generations of human society, political regimes and possible geological changes. It is noted here that engineered radwaste barriers (ERBs), which include conditioning (e.g. vitrification) and defence-in-depth (DID) packaging strategies, have the function to effectively retain different types of radioactive isotopes, whilst the geological situation of final repositories robustly mitigates the case if any breakdown of the ERBs should occur.

Viewed holistically, the age structure of nuclear power technologists and regulators must also be included when discussing the industry, since the life and future of nuclear power, as a whole, will depend on having available sufficient and appropriately trained personnel to run, and regulate, the plants. It is important to ensure that a balance is kept between the experienced workforce, and younger personnel in training. An experienced NPP workforce, and specifically the know-how they possess, is a precious corporate commodity, and good succession training will be a vital facet of NPP personnel management strategies. Training and knowledge capture are thus keys to the current and future industry. Safety culture (e.g. safety awareness, adherence to written procedures, questioning attitudes, motivation to report anomalies and team-work), will serve to support OPs, AM, ASP and PLiM methodologies.

Aspects of current and long term operation

Due to AM, ASP and PLiM methodologies and effective OPs, including routine and exceptional maintenance, backfitting and RRRs, many Generation II plants are technically in a position to operate longer than their original design-lives with a relicensed status (LTO). Some NPPs have also implemented power uprates (PUs), and as a consequence, NPP-SSC materials will be exposed even longer to specific operating environments, and may thus be subject to new types, and levels, of stressors. These conditions may cause further changes in the physical and chemical properties of the materials, and it is essential to detect and follow the rates of such trends, using the most appropriate and sensitive methods available (e.g. crack size resolution levels may be higher with some tools and materials being inspected than when other methods are used), and to have science-based and engineering strategies in place to eliminate or mitigate known or newly appearing SSC-AD. It is noted, for example, that ultrasonic testing (UT) or X-ray methods may be less suitable than magnetic particle or dye penetrant tests, depending on the material, and geometry thereof, involved (e.g. non-magnetic or magnetic, wrought, cast or welded) and locality and types of flaws (e.g. surface or internal cracks or holes) being sought. The optimum choice of appropriate and calibrated inspection tools and the use of approved interpretation/analysis methods are essential to facilitate detection and quantification of defect sizes to enable the safety-relevance thereof to be assessed and the best RRR method chosen accordingly. Inspection personnel qualification is thus an essential requirement for the QA of inspection results obtained.

Power uprate (PU) categories: Increasing the licensed power level of NPPs is called power uprating, and PUs have been successfully implemented in a number of BWRs and PWRs. There are three categories of PU, namely, Measurement Uncertainty Recapture (MUR), the Stretch (SPU) and the Extended (EPU). The MUR creates power increases of typically <2% of the original licensed power. These are obtained by implementing enhanced techniques for calculating reactor power, necessitating improved monitors to more precisely measure feed-water flow which is used to calculate reactor power. More precise measurements reduce the degree of uncertainty in the power level which is used by analysts to predict the ability of the reactor to be safely shut down under possible accident conditions. A SPU covers a 2-7% increase in power output, and is characterized by altering set-points in the instrumentation. The SPU approach thus requires no major plant modifications. An EPU can create up to a 20% increase in power. This, in contrast to other PU categories, requires significant changes to plant operations and the balance of plant (e.g. new turbines and generators, generator renewal or modification to deal with steam intake increases, coolant flow-rate increase, I&C adjustments, focussed monitoring and inspection on piping, steam dryers etc.). A typical 20% EPU project could take 2-4 years to complete at a cost of around USD 300-600 million, depending on the NPP design and number of Units involved. The amortization time of PUs is relatively short (typically <10 years) and thus PUs remain commercially attractive, especially in combination with LTO.

Operational issues associated with PUs: Despite PUs being done within design tolerances and maintenance of sufficient safety margins, the new operating conditions may cause additional challenges to SSCs involved. Larger volumes of steam and increased flow-rates thereof, as well as higher levels of vibrational loading have been responsible for cracking in some BWR steam dryers. For example, the US-Quad Cities Unit 1 BWR NPP had undergone an EPU, but steam dryer cover plate cracking developed after about one year. Unit 2 at Quad Cities NPP also experienced similar problems, 15 months after its EPU. A further BWR-NPP, the Dresden Unit 3, experienced cracking in the steam dryer hood 10 months after its EPU. Affected NPPs have been repaired using thicker steam cover plates and full-length gussets instead of braces. These occurrences show that it is essential to fully analyse all expected and possible effects of any changes to NPP configuration and operating conditions in order to avoid problems with SSCs.

Current and future issues with SSC-AD: The nuclear power industry has, to date, been confronted with a variety of SSC-AD issues, and it is to be expected that the effects of time-at-temperature in various operating environments will continue to occupy designers, operators, researchers and regulators. Much has been learned over the last 55 years concerning materials behaviour in the NPP environment, and research has provided fundamental understanding of SSC-AD mechanisms, and tools to address them. Some SSC-AD mechanisms that have affected NPPs and have caused unforeseen costs or operating restrictions are discussed below.

Neutron irradiation embrittlement of reactor pressure vessels (RPVs): Neutron-induced embrittlement of RPVs is unlikely to be problematic in New Generation III NPPs due to improved (i.e. low impurity copper, phosphorus) weld and base materials The mechanisms and issues of embrittlement of RPV low alloy, tough bainitic-structured ferritic steels and welds has been studied exhaustively and a variety of solutions have been found, based on research and results from tests on RPV surveillance capsules containing fracture mechanics, Charpy (notch toughness) and tensile specimens of the RPV materials. Due to the safety significance of only placing the RPV under pressure when it is in a tough state (e.g. in the Charpy upper shelf region), the results of surveillance specimen tests are important to select the pre-heat temperature before pressurization. Neutron flux reduction (hence fluence with time) retards the rate of embrittlement, indicated by the shift in the Charpy ductile to brittle transition temperature (DBTT) as a function of temperature, and it is readily achieved by fuel element management whereby new fuel elements are placed in the core centre and those with high burn-up are used in the core periphery (i.e. "inside-out" strategy). Some RPV beltline regions have been thermally annealed (e.g. 168h at 450°C) to recover toughness levels.

Stress corrosion cracking (SCC): Stress corrosion cracking has caused many NPPs to replace piping or SGs, and can occur in virtually any alloy if specific combinations of tensile stress, microstructure and chemically active environment are present. Intergranular (IG-SCC), transgranular (TG-SCC) and irradiation assisted (IA-SCC) are all forms of environmentally assisted cracking (EAC), and the mechanisms have been studied extensively. Improvements to alloy compositions, fabrication methods of components and heat treatments and adjustments to operating conditions, including water chemistry modification, have been implemented. Mill-annealed tubing of Alloy 600 (nickel base alloy with max. 17% chromium 10% iron and 1% manganese) used in some designs of SG has been found to be susceptible to SCC. In the late 1970s, Alloy 600 tubes were subjected to a high-temperature treatment to improve the tubes' resistance to corrosion. However, NPPs with replacement SGs now commonly feature tubing of thermally treated Alloy 690TT which, to date, is proving more resistant to corrosion mechanisms.

Primary water (PW-SCC) of RPV closure head penetration cladding (in Alloy 600) of control rod drive mechanisms (CRDMs) of some PWR RPVs has necessitated closure head replacements. Notwithstanding the problems associated with obtaining new RPV closure heads, costs thereof and plant downtime, PW-SCC caused, in one notable case, leakage of borated coolant onto the external surface of the ferritic RPV, resulting in boric acid corrosive attack ("wastage"). The NPP in question was Davis-Besse, a 873 MWe PWR in the USA, which underwent a successful, if expensive (about USD 600 million in 2002-2004) recovery, which included the purchase of a new RPV closure head. Other NPPs have been affected to varying degrees, and replacements of closure heads (with PW-SCC resistant penetration cladding material Alloy 690 TT and Alloy 52/152 attachment welds) are on-going, coupled with improved monitoring systems for the early detection of any possible borated water coolant leaks in future.

Other SSC-AD, for example IG-SCC in BWR austenitic stainless steel piping, will be less problematic in Generation III NPPs, since the improved nuclear grade (NG) alloys have lower carbon levels (<0.03%) and are stabilized (e.g. with titanium or niobium added to preferentially form carbides) and thus have less propensity to form chromium carbides when subjected to a sensitizing temperature/time regime (e.g. 500-800°C) in the heat affected zone (HAZ) of welds. Sensitization, where the chromium unites with carbon to form chromium carbide ($Cr_{23}C_6$), depletes the alloy locally of chromium, thus rendering the affected area more prone to corrosion, leading to "knife-line attack". Furthermore, improved manufacturing processes and post weld heat treatments (e.g. solution annealing:1050°C for 30 minutes) will also keep levels of residual tensile stresses below critical levels and dissolve any $Cr_{23}C_6$ that may be present, returning the chromium to the matrix bulk of the alloy composition, whereby restoring its corrosion resistance.

Other SSC-AD mechanisms:

- Thermal ageing and embrittlement of valve bodies, pump casings and piping of some duplex grades of cast austenitic stainless steel (CASS), where time-at-temperature (e.g. 58000h at 280-320°C) causes changes in the alloy's microstructure (e.g. development of sigma-phase from the residual delta ferrite phase), which lowers toughness;
- High and low cycle fatigue, where repeated mechanical loading induces cracks to form and propagate, reducing the cross-section of components and thus the load-carrying capacity;
- Thermal fatigue, where rapid heating and cooling cycles result in expansion and contraction of components, leading to crack formation;
- Void swelling of stainless steels and nickel alloys in RPV internal components, where high neutron doses create voids in the materials, leading to dimensional changes (swelling);
- Cable insulation, rubber or elastomer seals degradation (safety, electrical and mechanical issues thereof, for example loss of vital safety signals, short circuits, brittleness and leaking of pumps), caused by harsh radiation (gamma), neutron irradiation and exposure to moisture ingress and heat;
- Erosion-corrosion (EC): also called flow accelerated corrosion (FAC) reducing the wall thickness in secondary-side carbon steel piping under pressure with high temperature steam/water, or thinning SG tubing. EC is caused when coolant flow changes speed and direction in pipe-bends, resulting in localized down-line 2-phase turbulence and associated continual destruction of protective oxide layers. Designs should, as far as is possible, avoid piping geometries (and flow restricting baffles) that may cause EC;
- General (galvanic) or localized (pitting) corrosion of buried piping and steel containments may impact leak-tightness and isotope retention ability;
- Loss of pre-tensioning loads due to stress relaxation in RPV internals and settlement of concrete structures;
- Containment concrete shrinkage, cracking, spalling and chemical attack (e.g. carbonate formation) and corrosion of reinforcement steel rods, which may impact DID goals for severe accident management scenarios;
- Neutron absorber material degradation in spent fuel ponds is a safety issue, since spontaneous criticality could occur, especially when also the storage water is not maintained chemically with respect to boron level. Spent fuel and safe storage conditions thereof are important planning issues for NPP operators since current, LTO and even New Generation NPPs may require further optimization/enlargement of storage capacity as part of significant back-fitting programmes.

It is a natural phenomenon that materials will, over time, tend to react with their physical and chemical environments leading to varying degrees, and types, of SSC-AD. Important tasks of designers are to select the best materials and optimum plant lay-out, and to allow for good access to SSCs for monitoring, testing and ease of RRRs. A vital task of operators is to ensure that operating conditions keep SSC-AD rates as low as possible, using inputs from research and operational experiences.

Discussion

Currently operating NPPs, irrespective of their age, continue to fulfil their licensing and design conditions and thus operate as safely and reliably as they did upon commissioning. Indeed, many older NPPs now possess improved SSCs and additional (backfitted) safety systems compared to when they first entered service. Furthermore, the improvements added since the original license was granted are credited so that the "current license basis" may differ substantially from the original one. The world's NPP fleet plant-availability factors have increased from about 75% in the 1980s to 85-90% in 2011. This reflects the continued improvements in OPs, timely and effective maintenance and the way ASPs, AM and PLiM have been used to benefit safety, reliability and profitability. The nuclear industry's reliance on good basic design concepts, DID layouts/strategies and back-up systems, and constant vigilance to identify, and eliminate, common cause failures (CCFs), (i.e. where failure of one defence layer causes failure in subsequent ones) and latent failure conditions (LFCs) has the aim to ensure that no individual/single failure, including human error, can lead, through a chain of events, to an accident. It is noted here that reportable events in NPPs are due 80% of the time to human error, the remainder are due to equipment failures. The human errors are split into organization weaknesses (70%) and individual mistakes (30%). The importance of safety culture, training of personnel and robust organizational approaches in NPPs are thus highlighted.

With LR or continued permission to operate, depending on national licensing legislation, the world's fleet of older NPPs (>40 years of full power operation) are likely to be able to operate at for least another 20 years in excess of their original design lifetime. This LTO not only assures a "low carbon" energy supply, but also facilitates plant amortization over a longer time, and increases the overall profitability and competitiveness of nuclear power over other sources.

There have been many issues concerned with SSC-AD. Whilst some were expected and allowed for in conservative design margins some were unexpected, necessitating specially adapted AM and PLiM approaches and correspondingly adjusted OPs. A variety of QA technical, chemical, engineering fixes and design measures are now in place to detect, monitor, mitigate or eliminate the known important SSC-AD mechanisms. Importantly, the use of AM, ASPs and PLiM, in a feedback loop to OPs, continues to enhance the effectiveness of detecting and addressing SSC-AD if, and when, it occurs, and the vigilance (safety culture) of the plant operating personnel is an integral part of operations to facilitate timely and cost-effective implementation of all necessary safety-related and operational measures.

Conclusions

1. Public acceptance and the future of the commercial nuclear power industry will depend significantly on its overall safety and operational reliability record, and therefore all aspects of design, manufacturing and operation of NPP-SSCs that may affect safety must be continually QA-assessed to ensure compliance with the state-of-the-art science and technology. Plants using effective OPs, AM, ASP and PLiM approaches will be safe, profitable and reliable, since the SSCs will be kept within their design and regulatory requirements in the most cost-effective way.
2. Science-based approaches and fundamental research to understand how materials behave under service conditions, and the robust integration of research results to mitigate or eliminate SSC-AD in a QA way are key to safe, reliable and profitable operation of NPPs.
3. Good OPs and allowing enough time for work to be carried out properly (i.e. time pressure can never be allowed to lead to short-cuts in analyses, inspections/procedures etc. and thus impact QA) have higher priority than lowering costs and increasing power production levels, and this tenet remains pertinent also for future Generation III/IV NPPs.
4. When a NPP implements a PU it is essential to fully analyse all chemical and physical effects due to changes in the overall plant operating conditions in order to avoid SSC-AD issues.
5. The use of AM, ASPs, PLiM and continually upgraded OPs will facilitate LTO since the plants will maintained effectively, be safe and reliable and thus will have optimum pre-conditions to obtain LR or permission to continue operation with PSR approaches.
6. SSC-obsolescence and problems associated with the supply of functionally equivalent (QA) spare parts has the potential to affect current and LTO of NPPs (also future New Generation plants); the industry must plan well ahead for such contingencies and the importance of original and updated plant documentation is hereby emphasized.
7. There is an urgent need for the commercial nuclear power industry, and its regulation, to address the shortage of skilled human resources in some areas. With older plants going into their LTO phase and the coming Generation III/IV NPPs expected to operate for 60+ years, strategies to encourage young persons to make a career in all branches of nuclear power technology must be developed and implemented in the near-term. Knowledge capture and management are essential pre-conditions for the future of the entire industry.
8. The contribution of nuclear-generated electrical power to the world's total (~16%) is significant and will increase as New Generation III/IV NPPs connect to the grid. In the interim, the Generation II NPPs will still supply the largest share. It is therefore essential to ensure these remain safe and profitable (also in their LTO-phase) and thus contribute to environmentally friendly and secure supplies of cost-competitive power. By understanding materials behaviour and operational effects in NPPs these important goals will be reached for both the current and future NPP fleet.

References available. More technical articles can be found in the webshop at: http://webshop.kci-world.com

Acknowledgement

The author wishes to thank Dr. Baldev Raj of the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam-603102, India for his valuable comments and suggestions.

About the author

Dr. Philip G. Tipping is a nuclear energy and materials consultant, and was formerly a senior metallurgist and materials specialist at the Swiss Federal Nuclear Safety Inspectorate (ENSI). He was Chairman of the IAEA Technical Working Group for the Life Management of Nuclear Power Plants (TWG-LMNPP) between 2004-2008. Email: ingphil@ymail.com