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CSNI Technical Opinion Paper
No. 17

Fire Probabilistic Safety Assessments for Nuclear Power Plants: 2019 Update

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Fire Probabilistic Safety Assessments for Nuclear Power Plants: 2019 Update

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Foreword

Probabilistic safety assessment (PSA) has been considered a necessary complement to traditional deterministic safety analysis in nuclear power plants for more than 30 years because of its disciplined, integrated and systematic approach. The Nuclear Energy Agency (NEA) has been working to advance understanding of PSA and to enhance its use in improving the safety of nuclear installations – primarily through the NEA Working Group on Risk Assessment (WGRISK) of the Committee on the Safety of Nuclear Installations (CSNI) and via publications such as the *CSNI Technical Opinion Paper No. 1: Fire Probabilistic Safety Assessment for Nuclear Power Plants* (NEA, 2002).

Significant changes have nonetheless occurred in the area of fire probabilistic safety assessment (fire PSA) over the years. Many of the methods, models and computational tools for performing fire PSA have improved, additional fire-related operational experience has been gained and experimental results have been generated. In addition, analyses have been used to support major changes to design and operations for many plants, and research programmes have been formulated and initiated to address key, remaining issues in relation to PSA.

The purpose of the present paper, *CSNI Technical Opinion Paper No. 17: Fire Probabilistic Safety Assessment for Nuclear Power Plants*, is to provide the current international view on the state of fire PSA as performed in support of nuclear power plant design and operation. The viewpoints and perspectives contained in this technical opinion paper (TOP) are the result of the work of the WGRISK task group, which includes experts on the subject of fire PSA.[1] The report is also based on the results of an international workshop on fire PRA, organised by WGRISK in 2014 and documented in the "Proceedings of International Workshop on Fire PRA" (NEA, 2015b).

This paper takes into consideration operating experience in nuclear power plants (NPPs), particularly with regard to fire events that were collected and analysed within the NEA Fire Incidents Records Exchange Database Project (NEA FIRE). In addition, consideration has been given to recent results from fire-related experimental NEA projects, more specifically the Fire Propagation in Elementary, Multi-room Scenarios PRISME[2] project, and PRISME 2, which takes into account fire

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1. The abbreviations PRA and PSA are used synonymously in this report, consistent with usage across NEA member countries.

2 From the French "Propagation d'un incendie pour des scénarios multi-locaux élémentaires".

behaviour and spreading in nuclear specific complex geometries under different boundary conditions. The NEA High Energy Arcing Fault (HEAF) project also provides insights on high energy arcing faults with the potential of ensuing fires.

The fire PSA community generally agrees on the overall approach for performing fire PSA, with the level of realism in terms of fire PSA for an NPP often representing a trade-off between the level of modelling efforts and the needs of the plant's fire PSA application. Key sources of uncertainty in fire PSA, including potential non-conservatisms as well as conservatisms, have been identified, and many are being addressed through ongoing research and development (R&D). Continuing efforts to develop guidance and provide training are expected to improve practice and broaden the base and expertise of analysts, reviewers and potential decision makers. This opinion paper is not intended to be a guidance document for performing fire PSA, although Annex B does provide some sample guidance documents.

Fire PSA is a valuable tool that provides useful results and insights in support of risk-informed decision making. As with all risk-informed decisions, it is important that the decision makers are informed of potential biases (both conservative and non-conservative, with magnitudes that are typically uncertain) and other uncertainties associated with these results and insights.

This last point is worthy of particular emphasis. Ongoing discussions regarding the maturity and realism of fire PSA, although a positive driver for improvement activities, including R&D, database maintenance and guidance development, should not overshadow two fundamental points: fire can be an important contributor to plant risk, and fire PSA is a useful tool for risk-informed decision making. Knowledge of the uncertainties and potential biases in fire PSA can and should be included when weighing available evidence.

It should also be recognised that fire PSA judged suitable for a fire risk management issue may need to be improved when used to address an issue involving the full set of hazards relevant to plant risk. It is expected that ongoing and future improvement activities will strengthen the broad acceptance of fire PSA for a potentially wider set of applications, including enterprise risk management applications not yet widely envisioned.

Some of the key messages of this report are as follows:

- At the industry level, fire continues to be an important risk contributor for many NEA member countries.
- The risk due to fires at a particular plant site, as with many other hazards, is strongly dependent on plant-specific factors in design and operation.
- Fire PSA insights in relation to the major contributors to the total fire risk are generally aligned with operating experience and appear to be largely representative of the expected plant responses. However, some aspects of the quantitative results of modern fire PSA can be conservative. Overall, there is a wide range of views within the PSA technical and user communities regarding the realism of fire PSA and the consequent implications for the appropriate use of fire PSA results. Fire PSA methods, models, tools and data continue to improve, and the practice of fire PSA continues to mature.

The NEA recommends that organisations continue to support R&D activities on key topics identified by the fire PSA technical and user communities, as well as activities to collect, manage and provide access to quality data. Organisations should also continue to support activities facilitating the sharing of challenges, solutions, uncertainties, uses and good practices, along with activities to develop practical guidance based on these factors. Organisational support is in fact essential to ensure appropriate co-operation between the multiple disciplines and communities involved in the performance, review and use of fire PSA.

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- Nathan Siu, NRC, United States.

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List of abbreviations and acronyms

CCDP	Conditional core damage probability
CSNI	Committee on the Safety of Nuclear Installations (NEA)
FIRE	Fire Incidents Records Exchange (NEA Database Project)
HEAF	High Energy Arcing Fault (NEA Joint Research Project)
IAEA	International Atomic Energy Agency
LOOP	Loss of off-site power
MCR	Main control room
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
PRA	Probabilistic risk assessment
PRISME	Propagation d'un incendie pour des scénarios multi-locaux élémentaires (Fire propagation in elementary, multi-room scenarios, NEA Joint Research Project)
PSA	Probabilistic safety assessment
R&D	Research and development
TOP	Technical opinion paper
WGRISK	Working Group on Risk Assessment (NEA CSNI)

Chapter 1. **Introduction**

Background

Since the publication of the *CSNI Technical Opinion Paper (TOP) No. 1: Fire Probabilistic Safety Assessment for Nuclear Power Plants* (NEA 3948) in 2002, significant changes have occurred in the area of fire probabilistic safety assessment (fire PSA). Many of the methods, models and computational tools for performing fire PSA have improved, and additional fire-related operational experience has been gained and experimental results generated. In addition, analyses have been used to support major changes to design and operations for many plants, and research programmes to address key remaining issues have been formulated and initiated. Examples of these changes have been discussed at numerous international conferences and workshops, including the NEA Workshop on Fire PRA in 2014 (see "Proceedings of International Workshop on Fire PRA" – NEA, 2015b).

Recognising the inherent complexity of the phenomenological behaviour of fire and of potential plant and operator responses to fire-initiated scenarios, it is not surprising that the results of fire PSA demonstrate considerable uncertainty. With the increasing use of fire PSA in major fire-protection related applications, and with the recognition that fire PSA can play a significant role even for non-fire-related risk-informed applications, there has been (and continues to be) healthy discussion on the maturity and realism[3] of fire PSA methods, models, tools and data. Numerous stakeholders with varying points of view, including fire protection engineers, PSA analysts and senior decision makers, have been involved in the discussion. The purpose of this TOP revision is to provide a current, international view on the state of fire PSA as performed in support of nuclear power plant design and operations.

The authors of this TOP are PSA experts from NEA member countries affiliated with the NEA Working Group on Risk Assessment (WGRISK). The opinions expressed, and the arguments employed in this report are those of WGRISK members, and in

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[3] For the purposes of this TOP, the term "maturity" refers to the developmental state of a technical discipline while the term "realism" refers to the extent that the PSA model faithfully represents the response of the as-built, as-operated nuclear power plant. Though related, maturity and realism are separate concepts. Maturity refers to the global state of the technical discipline and generally depends on factors such as the characteristics of the user community, active research topics and application areas. Realism is generally discussed in the context of a specific modelling application. The degree of realism achieved often represents a trade-off between the cost and added value of additional modelling effort.

particular, of the authors. These opinions do not necessarily represent those of OECD or other international experts outside the WGRISK community. Members of nuclear safety regulatory organisations, technical support organisations and private industry concerned with the practice and use of fire PSA will find this report of particular interest. Government authorities, nuclear power plant operators and other international organisations (including CSNI working groups and members of NEA projects), as well as the general public, may also find the report of interest.

Fire complexity and challenges to fire PSA

Although the basic principles of fire behaviour are easily understood – given sufficient fuel, oxygen and heat, a fire will grow – fire is an extremely complex phenomenon to model in practice. Consider, for example, a fire in a cable tray. The availability of fuel depends on the pyrolysis of the cable jacket and insulation materials, a chemical process that depends on the physical properties of jacket/insulation (which can vary considerably), as well as the temperature of the cable surface. The transport of oxygen to the combustion zone is affected by such factors as the size and location of gaps between cables and the strength of buoyancy forces generated by the fire. Heating of the combustion zone is provided both from the flame and radiative feedback from the fire's surroundings. Under supportive conditions, oxygen flowing to the flame supports combustion, leading to heat generation which further heats the fuel (increasing pyrolysis) and increases buoyancy forces (increasing oxygen flow rates). The outcome of this positive feedback loop is fire growth. Under negative conditions, oxygen starvation (e.g. due to insufficient flow area), dissipation of heat through the cable or blockage of radiative heat feedback (due to obstructions), or simple fuel burnout can lead to fire self-extinguishment.

Furthermore, local fire physics and chemistry are not the only determinants of fire evolution and impact. The transport of heat and smoke away from the fire is affected by obstructions in the room ("clutter"), ventilation conditions, and the conditions of room boundary elements (e.g. penetration seals, ventilation dampers, doors). The effectiveness and speed of efforts to control and extinguish the fire depend on the fire detection time, the time to apply suppressants, and the effectiveness of suppressants and their application. In many cases, detection and suppression can involve plant staff actions (e.g. local detection by nearby personnel, manual actuation of installed fire protection systems, manual suppression via portable extinguishers or fire hoses). The analysis also needs to account for potential detection and suppression system unavailability (e.g. failure to restore equipment after testing) or failure during the event (including functional failures, e.g. failure of suppression systems as a result of an insufficient amount of suppressants). For severe fires, fire suppression can require the aid of off-site fire departments.

Chapter 2. Key messages and report structure

The key messages of this report are as follows.

- At the industry level, fire continues to be an important risk contributor for many NEA member countries.
- The risk due to fires at a particular plant site, as with many other hazards, is strongly dependent on plant-specific factors in design and operation.
- Fire PSA insights in relation to the major contributors to total fire risk are generally aligned with operating experience and appear to be largely representative of expected plant responses. However, some aspects of the quantitative results of modern fire PSA can be conservative. Overall, there is a wide range of views within the PSA technical and user communities regarding the realism of fire PSA and the consequent implications for the appropriate use of fire PSA results.
- Fire PSA methods, models, tools and data continue to improve, and the practice of fire PSA continues to mature.

The fire PSA community generally agrees on the overall approach for performing fire PSA, although the level of realism in the fire PSA for a plant often represents a trade-off between the level of modelling effort and the needs of the plant's fire PSA application.

Key sources of uncertainty in fire PSA, including potential non-conservatisms as well as conservatisms, have been identified and many are being addressed through ongoing R&D.

Ongoing efforts to develop guidance and provide training are expected to improve practice and broaden the base and expertise of analysts, reviewers and potential decision makers. Generally, it has been confirmed that fire PSA is a valuable tool that provides useful results and insights in support of risk-informed decision making. As with all risk-informed decisions, it is important that the decision makers are informed of potential biases (both conservative and non-conservative, with magnitudes that are typically uncertain) and other uncertainties associated with these results and insights.

The remainder of this report discusses each of these messages and concludes with some final remarks.

Chapter 3. **Fire as a risk contributor**

At the industry level, fire continues to be an important risk contributor for many NEA member countries.

International operating experience has shown that some of the most challenging precursors to a core damage accident have involved internal fires.[4]

- Browns Ferry cable fire (United States, 1975): a candle-ignited penetration seal fire spread to multiple cable trays in units 1 and 2. Multiple safety systems were affected in unit 1. Fire suppression was delayed for seven hours because of the reluctance to use water on an electrical fire. Non-proceduralised operator actions were required to achieve safe shutdown.
- Narora turbine building fire (India, 1993): a turbine blade failure led to a hydrogen explosion and severe oil fire. The ensuing scenario involved main control room (MCR) abandonment (as a result of smoke), station blackout (which lasted 17 hours), operator inability to use the unit 1 emergency control panel (due to loss of power), and a complete loss of indications for several hours. Plant operators entered unit 1 containment to obtain direct instrumentation readings and energised essential equipment to prevent core damage.
- Maanshan high energy arc fault (Chinese Taipei, 2001): salt spray and an essential bus ground fault caused a loss of off-site power. Both of the unit 1 emergency diesel generators were unable to supply power and station blackout ensued. Smoke from a high-energy arc fire (induced by the ground fault) led to heavy smoke that prevented operators from restoring one of the unit emergency diesel generators. Operators were able to connect and actuate a swing diesel, terminating the station blackout after two hours.
- Krümmel transformer fire (Germany, 2007): a long-duration main station transformer fire caused a manual reactor trip. Heavy smoke from the fire adversely affected MCR personnel in carrying out manual actions. (Ventilation was inadequate for this type of event.) Operators were nevertheless able to shut down the reactor and prevent core damage.

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4. Notable examples are included in: Nowlen, S. et al. (2011), *Risk Methods Insights Gained from Fire Incidents*; NEA (2015b), "Proceedings of International Workshop on Fire PRA"; and NEA (2016), "Combinations of Fires and Other Events – The Fire Incidents Records Exchange Project Topical Report No. 3".

- Robinson high energy arc fault (United States, 2010): a non-vital bus arc flash and fire, followed by a subsequent breaker failure, led to reactor trip, an uncontrolled reactor coolant system cooldown, and automatic safety injection actuation. Plant response was complicated by equipment malfunctions leading to loss of reactor coolant pump seal cooling and operating crew errors (including reinitiation of the electrical fault, leading to a second fire).

Numerous improvements in plant design and operations, many of which have been identified by fire PSA, have been made over time. (Some of these improvements, e.g. the installation of improved reactor coolant pump seals in pressurised water reactors, have been prompted by broad risk considerations, but have considerable impact on fire PSA results.) However, the results of many current fire PSA show that fire remains an important contributor to core or fuel damage frequencies and to large and/or large early release frequency, and therefore, public health risk (NEA, 2015b). This holds true for operations in low power and shutdown operational states, as well as during full power operation.

As discussed subsequently in this report, there are often conservatisms in fire PSA results, even after plant improvements are credited. However, there are no indications that more realistic analyses will change the essential message that fire is a hazard worthy of serious consideration in a risk-informed decision-making environment. This message has been consistently reported over the years, as summarised in multiple NEA reports on the use and development of PSA in NEA member countries and discussed at a 2014 WGRISK workshop on fire PSA (see the "Proceedings of International Workshop on Fire PRA" – NEA, 2015b). It is also reflected in the strong participation of NEA member countries in international fire-related projects (including the following NEA projects: Fire Incidents Record Exchange – FIRE; High Energy Arcing Fault – HEAF; and Fire Propagation in Elementary, Multi-Room Scenarios – PRISME), and the continuing discussion of fire PSA at major international PSA conferences.

Chapter 4. **Plant-specific fire risk**

The risk of fire at a particular plant, as with many other hazards, is strongly dependent on plant-specific factors in design and operation.

A risk-significant fire scenario generally involves weaknesses in some combination of fire prevention, fire detection and alarm, fire suppression and equipment fire separation. In such a scenario, ignition of a self-sustaining fire leads to damage of key components, and subsequent failure of plant systems and failure of operators to prevent core or fuel damage. The likelihood of each of these scenario elements is strongly affected by plant-specific features. These features include:

- fire prevention, which includes housekeeping (particularly control of combustibles), routine preventative maintenance and inerting the environments of selected critical areas;
- the location of key equipment (components and supporting electrical cables);
- separation between redundant trains of equipment important to safety by passive fire protection features (fire barriers, encapsulations), distance or a combination of the two;
- active ventilation controls (e.g. fire dampers, compartment pressurisation, smoke control and ventilation fan control);
- the location and type of fixed fire detection and suppression systems (both automatic and manually actuated);
- susceptibility to fire-induced damage of key equipment, considering both thermal and non-thermal (e.g. smoke-related) effects, and the possibility of fire-induced spurious actuations;[5]
- fire response design provisions (e.g. the location, protection and capabilities of alternate control stations);
- fire response procedures, alongside co-ordination with emergency operating procedures and associated training;
- non-fire specific plant design features (e.g. improved reactor coolant pump seals).

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[5] Note that the increased use of fibre optic cables reduces the likelihood of such actuations. Note also that a particular class of fire-induced spurious actuations – those affecting isolation valves on emergency core cooling system lines penetrating containment – can be important contributors to fire-induced containment bypass scenarios (and hence fire contributions to large release frequency).

All these features can differ significantly from plant to plant. For example, consider the location and separation of key equipment. Unlike nuclear steam supply systems (NSSS), which are largely standardised for a given reactor type, equipment layouts for safety and support systems can be highly plant-specific, especially in the case of older plants. The location of important rooms (switchgear rooms, cable spreading rooms) and passageways between these rooms (notably cable tunnels and vaults) can vary even for nominal sister plants with the same NSSS, of the same vintage and with the same architect/engineer. Some plants can have key equipment and cables in the turbine building (which poses specific fire hazards, which may include the presence of large quantities of lubricating oil and hydrogen) and others not. These particularities are typically identified by the deterministic fire hazard analysis, representing in many countries one of the basic elements for fire PSA.

Note that modern plant designs incorporate lessons from past fire studies. For example, evolutionary plant designs typically provide strong spatial separation for their redundant safety divisions. This separation is maintained up to the MCR.

The above discussion applies to the layout at the plant level. Within rooms, specific equipment locations, particularly cable routings, can vary significantly, even for newer plants. Moreover, these routings often change over time with plant equipment modifications. Such detailed differences in equipment location can be an important factor in terms of risk. For example, whether a critical set of cables is in a tray directly above a switchgear cabinet or in cable trays a few feet away will significantly impact the likelihood that a fire in that cabinet will damage those cables. For plants that lack a detailed database for cable routings, one of the major expenses of performing fire PSA involves the development of such a database.

It is important to recognise that, in addition to the effect of variability in plant-specific features, fire risk estimates can be affected by analyst choices. As discussed in Chapter 6, fire PSA is generally performed as an iterative process in order to focus analysis resources on the most important contributors to risk. For each fire scenario addressed, practical analyses typically start with conservative simplifying assumptions regarding fire extent (e.g. any fire in a room causes loss of the entire set of equipment in the room) and consequences (e.g. a main station transformer fire causes an unrecoverable loss of off-site power – LOOP). More refined analyses are performed only for those scenarios where such refinements are judged worthwhile. (This judgement is typically based on the expected impact to risk estimates.) Variations in such judgements, as well as in the resources available to perform the fire PSA, can lead to study-dependent variations in fire risk estimates and associated uncertainties.

Past NEA reports, and more recent discussions of fire risk results at international meetings, make reference to such plant-to-plant fire PSA results variations. It can therefore be emphasised that this variability is related to both plant- and study-specific features.

Chapter 5. Realism of fire PSA results and insights

Fire PSA insights in relation to the major contributors to total fire risk are generally aligned with operating experience and appear to be largely representative of expected plant responses. However, some aspects of the quantitative results of modern fire PSA can be conservative. Overall, there is a wide range of views within the PSA technical and user communities regarding the realism of fire PSA and the consequent implications for the appropriate use of fire PSA results.

When discussing the realism of PSA results and insights,[6] it is important to recognise that the notion of "risk" includes qualitative aspects as well as quantitative ones. In particular, consideration can be given to the widely-used triplet definition of risk proposed by Kaplan and Garrick (1981), in response to three questions:

- What can go wrong?
- How likely is it?
- What are the consequences?

The accident scenarios identified by PSAs appear to provide an answer to the first question. Thus, for example, some of the important insights resulting from a fire PSA include identification of the types and locations of fires, as well as subsequent equipment failures and failed actions on the part of operators that may contribute significantly to plant fire risk.

It is also important to recognise that, as discussed in Chapter 7, the results and insights of fire PSA can, in principle, be used in both fire-protection oriented risk-informed applications (e.g. the development of measures to reduce fire risk) and broader applications (e.g. the modification of allowed outage times for key equipment). Discussions of realism thus need to consider fire PSA results and insights from both a fire risk perspective and a total (all-hazard) risk perspective.

Fire risk perspective

Past fire PSA studies, taken as a whole, have consistently found that fires involving electrical cables and/or cabinets in key plant areas (including MCRs, emergency switchgear rooms, cable spreading rooms, cable vaults and tunnels) are the

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[6] See Footnote 3 for the definition of "realism" as used in this report.

dominant contributors to fire risk. In a number of these areas, the risk-significant scenarios can involve localised fires that damage important, co-located cables. However, there are some plants for which larger scale fires, e.g. turbine building fires and fires inducing MCR abandonment, are important contributors to overall fire risk. Such risk information has facilitated decisions on the prioritisation of various fire risk compensatory measures.

Past studies have also consistently shown that risk-significant accident sequences triggered by fires are generally dominated by some form of transient (e.g. loss of feedwater, LOOP and loss of various support systems). However, loss-of-coolant accidents (LOCAs), including reactor coolant pump seal LOCAs and transient induced LOCAs involving stuck open relief valves, are important contributors to risk for some plants.

From a qualitative perspective, fire PSA insights in relation to important plant locations, fire scenarios and plant response modelling appear to reasonably align with operating experience. In particular, operating experience (such as that discussed in Chapter 3) have highlighted the significant risk posed by high energy arcing fault events, fire-induced losses of off-site power, spurious equipment operation and large turbine building fires.

In recent years, many fire PSAs have moved from approaches postulating fires that immediately cause the loss of all equipment in a room to approaches postulating local fire sources that might grow and damage additional equipment (e.g. using *Fire PRA Methodology for Nuclear Facilities*, “Volume 1: Summary and Overview”, “Volume 2: Detailed Methodology” and “Supplement 1: Fire Probabilistic Risk Assessment Methods Enhancements” [EPRI/NRC 2005 and 2010], and supporting documents). Although the NEA has not undertaken a formal analysis through its Working Group on Risk Assessment (WGRISK), the understanding of WGRISK members is that the overall qualitative results of such studies are generally consistent with the above points.

Total risk perspective

There is a wide range of views within the PSA technical and user communities regarding the realism of fire PSA and the consequent implications for the appropriate use of fire PSA results. On the one hand, some users argue that the results are overly conservative and cannot be effectively used in risk-informed applications that require consideration of the risk from all hazards (including but not limited to fire). On the other hand, others argue that the objective evidence for assessing conservatisms is not definitive. Furthermore, in a truly risk-informed decision-making process, analysis limitations and uncertainties can (and should) be recognised and accommodated in a risk-informed, holistic decision-making approach (see discussion in Chapter 7).

A fire PSA that provides an overly conservative representation of fire risk, given the current state of knowledge, could bias decisions by plant and regulatory decision makers and could also inappropriately deprioritise (“mask”) hazards of greater importance. Less intuitively, an overly conservative analysis could undervalue the effectiveness of proposed fire-related improvements and lead to non-conservative decisions. More broadly, perceptions of significant departures from realism, either conservative or non-conservative, can damage stakeholder trust in fire PSA and perhaps even in non-fire-related PSA applications.

Based on discussions within the fire PSA community, and on the authors' experiences, it appears that fire PSAs, as performed using currently available tools and guidance, are providing conservative quantitative results in some analysis areas.[7] However, it has proved to be challenging to provide estimates of the degree of conservatism. Moreover, whether the degree of conservatism is excessive depends on subjective judgements, as well as the needs of the intended application. It should be noted that, similar to PSA treatments of internal events and of other hazards, there are topic areas that are difficult to model and are not yet routinely addressed in current fire PSAs. Some of the topic areas (e.g. secondary fires initiated in the course of the event, such as that seen during the Robinson fire discussed in Chapter 3) are unique to fire; others (e.g. multiple potential damage mechanisms,[8] operator errors of commission) are not. These topic areas constitute sources of uncertainty in the completeness of the fire PSA and potential sources of non-conservatism. Current use of fire PSA in support of decision making generally accounts for these factors by using a risk-informed process such as that discussed in Chapter 7.

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7. See Annex A for further details.

8. As discussed in NUREG/CR-6738, in some extreme instances, a fire event can involve explosions resulting in blast overpressures and missiles, as well as heat.

Chapter 6. Fire PSA methodology and practice

Fire PSA methods, models, tools and data continue to improve, and the practice of fire PSA continues to mature.

The complexities with fire as a phenomenon (see Chapter 1) compound the "normal" challenges associated with performing PSAs in nuclear power plants. (Examples of these normal challenges include dealing with sparse operational data, addressing the likelihood and consequences of different equipment failure modes, such as spurious operations, treating operator actions, identifying and prioritising a multitude of potential, contributing scenarios, and characterising uncertainties.) This chapter discusses the maturity and realism of current fire PSA technology (i.e. methods, models, tools and data) and practice, addressing the following key points:

- The fire PSA community generally agrees on the overall approach for performing fire PSA.
- The level of realism in the fire PSA for a plant often represents a trade-off between the level of modelling effort and the needs of the plant's fire PSA application.
- Key sources of uncertainty in the fire PSA, including potential non-conservatisms as well as conservatisms, have been identified, and many are being addressed through ongoing R&D.
- Ongoing efforts to update practical guidance and provide training are expected to improve practice and broaden the base and expertise of analysts, reviewers and potential decision makers.

It is important to emphasise that, as discussed in other chapters of this report, fire PSA is a useful tool for risk-informed decision making. The technical community's acknowledgement and discussion of uncertainties and potential biases, which ultimately leads to the identification of research needs driven by practice, is in fact an indicator of a reasonably mature discipline (see, for example, Cornell, 1981).

Consensus approach to fire PSA

The fire PSA community generally agrees on the overall approach for performing fire PSA.

In a typical fire PSA, potentially important scenarios are identified through consideration of the fire hazards (both permanent and transient combustibles and ignition sources) within the plant and of the plant equipment that may be damaged by a fire. Of particular interest are those event scenarios with fires involving the triggering of a plant transient and the response of plant systems and operators, potentially leading to core and/or fuel damage. The frequencies of such scenarios are quantified by estimating:

- the frequency of fire occurrence;[9]
- the conditional probability of fire-induced damage to structures, systems and components (SSC) given the fire;
- the conditional probability of core and/or fuel damage given fire-induced damage to SSC.

If the fire PSA is performed as part of a Level 2 PSA,[10] large (and early) release frequencies can be quantified for fire event scenarios. Many analyses consider the risk associated with low power and shutdown conditions, as well as operations at full power. General guidance documents for performing a fire PSA are provided in Annex B of this report.

Fire occurrence frequencies are typically estimated based on plant-specific and generic data from the operating experience, by applying simple statistical models for fire occurrences. The likelihood of fire damage is estimated using combinations of deterministic and probabilistic models for the physical processes of fire growth, detection, suppression and equipment damage. The likelihood of core or fuel damage is estimated using event tree and fault tree models that address the combined effect of fire-induced failures and random failures of equipment not damaged by the fire.

Trade-offs in practical analyses

The level of realism in the fire PSA for a plant often represents a trade-off between the level of modelling effort and the needs of the plant's fire PSA application.

As a result of the fundamental complexities discussed in Chapter 1, as well as the demands of characterising and treating a variety of plant-specific features identified in Chapter 4, a detailed fire PSA can require considerable resources. In practice, the fire PSA is usually performed iteratively, starting with highly simplified

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[9] Consistent with the current state of practice for fire PSA event screening, a fire event that is screened into the PSA analysis is typically assumed to result in a plant transient. This assumption may result in the overestimation of fire induced transients (compared to operating experience) if the screening process includes fire events that do not directly result in a transient event.

[10] Within Level 2 PSA models, the modelling of a plant's response to accident sequences that resulted in reactor core or fuel element damage is typically referred to as severe accident analysis.

and conservative modelling assumptions (e.g. assuming that any fire in a room will induce the failure of all the equipment in that room) and refining these assumptions (e.g. through the modelling of specific equipment and the use of detailed fire models) only for those scenarios where refinement is judged important to the final results and insights. This iterative approach enables an efficient analysis.

It is important to emphasise that fire PSA is a practical tool used to support decision making (see Chapter 7). Different fire PSA applications can have different technical support needs and therefore may require different levels of technical refinement. For example, demonstrations that a plant's fire risk meets specified criteria, demonstrations that a fire PSA has an appropriately balanced treatment of key elements in fire protection (e.g. prevention, detection and mitigation) that is capable of supporting fire programme improvements, and analyses that identify and prioritise the important contributors to overall plant risk (including non-fire as well as fire scenarios) can place different demands on the analysis. Project decisions regarding the purpose and degree of iteration will depend on the cost and added value of more detailed analysis.

Areas for fire PSA research and development

Key sources of uncertainty in fire PSA, including potential non-conservatisms as well as conservatisms, have been identified, and many are being addressed through ongoing R&D.

As discussed at the beginning of this chapter, there are many drivers to the uncertainties and biases in the results of fire PSAs. Considerable thought, reflecting lessons from a variety of sources (including past R&D, operational experience, and the performance and review of fire PSAs) has gone into the identification and prioritisation of national and international activities to improve current methods, models, tools, data and guidance. Some of the activities involve R&D, while others are aimed at maintaining or improving important infrastructure. R&D activities include, *inter alia*:

- experimental and analytical investigations of the likelihood and potential severity of high energy arcing fault (HEAF) events, particularly those involving aluminium in medium-to-high voltage switchgear and bus bars;
- experimental and analytical investigations of the growth, classification and severity of transient combustible fuel packages to refine the heat release rate methodology and fire growth profiles;
- experimental and analytical investigations to improve fire modelling techniques associated with electrical cabinets, including improvements to enclosure fire spread, enclosure effects on horizontal radiation heat transfer and alternative methods for main control board fire modelling;
- analytical investigations into the effectiveness of plant personnel detection and suppression efforts, and the relationship to fire frequency from operating experience;

- experimental investigations on the severity of electrical fires, in particular cable and electrical cabinet fires and corresponding model improvements;
- experimental investigations of fire growth within and between compartments;
- analytical and experimental investigations of the effectiveness of fire detection and suppression systems (including very early warning fire detection systems – VEWFDS – which are designed to detect incipient conditions prior to actual combustion);
- experimental investigations concerning the impact of smoke on electrical and electronic equipment;
- expert panel elicitations to interpret experimental results and develop practical inputs for fire PSA;
- expert panel elicitations to improve the heat release rate distributions for in-plant transformers (excluding large outdoor oil filled transformers);
- the development of practical screening methods to deal with fire events involving additional, secondary events (e.g. turbine failures leading to missiles, explosions and even flooding);
- the development of improved human reliability analysis methods to address the likelihood of personnel failures (including ex-control room actions, as well as actions within the MCR) during a fire scenario.

Consistent with a maturing technology, one observation is that these research activities have shifted from the general exploratory activities conducted decades ago to more focused research projects intended to address specific high risk and/or high uncertainty areas.

The infrastructure activities include support of operational experience databases (such as that administered by the NEA FIRE Incidents Records Exchange Database Project), the development of guidance, and the execution of training. Guidance and training are further discussed in the following section.

Outside of the fire PSA area, activities are underway to address more general PSA topics that are relevant to the performance of fire PSA (e.g. site level PSA dealing with multiple units and other on-site radioactive sources) and to the use of fire PSA results (e.g. the aggregation of PSA results across hazards, plant operational states and on-site radiological sources).

As can be expected, for a field where both the risks and the potential benefits of PSA improvements are believed to be significant, the fire PSA R&D environment is dynamic. Ongoing activities are being pushed to completion with high urgency in order to speed up the use of research results in practical problem solving. Unexpected research results (notably the discovery of the potential severity of HEAF events involving aluminium) and lessons from fire PSA applications (e.g. regarding modelling assumptions that appear to affect fire PSA realism) are leading to new research activities and modified priorities in terms of existing activities. It is beyond the scope of this report to comment on the nature or priority of specific elements of research plans. It has been observed that the fire PSA R&D community is paying particular attention to all the major elements of a fire scenario (i.e. initiation, growth, detection and suppression, equipment damage, plant response) and is aware of major analysis challenges identified from operational experience reviews. These challenges, some of which involve potential non-conservatisms in current fire PSAs, include the treatment of multiple hazards and events (e.g. fires induced by earthquakes or flooding), low power and shutdown operations, as well as at-power states, and multi-unit and/or multi-source impacts. Activities to address some of these challenges are at an early stage of development.

Fire PSA guidance and training

Ongoing efforts to update practical guidance and provide training are expected to improve practice and broaden the base and expertise of analysts, reviewers and potential decision makers.

In addition to analytical methods, models, tools and data, the practical performance of fire PSA requires the availability of appropriate guidance and training. With regard to guidance, a variety of current technical standards and reports are available. In addition, a number of activities are underway to develop improved guidance for both detailed issues arising during the application of a fire PSA (e.g. the modelling of cabinet to cabinet fire propagation; HEAF; and heat release rates for transformers, motors and transient combustibles) and more general fire PSA issues (e.g. analyses of fires during low power and shutdown operations). Key documents are provided in Annex B of this report.

In terms of training, several workshops have been held, covering fire PSA and related topics and aspects (e.g. electrical circuit analysis, fire modelling and human reliability analysis), and the training materials are available in a variety of forms (including slides, reports, videos and simulation model files). The International Atomic Energy Agency (IAEA) has also conducted several fire PSA training courses in various countries.

Chapter 7. Use of fire PSA in risk-informed decision making

Fire PSA is a valuable tool that provides useful results and insights in support of risk-informed decision making. As with all risk-informed decisions, it is important that the decision makers are informed of potential biases (both conservative and non-conservative, with magnitudes that are typically uncertain) and other uncertainties associated with these results and insights.

Fire PSA has a long history of supporting risk-informed decision making in the nuclear power industry. Early applications include a late 1970s analysis that supported design development for a high-temperature, gas-cooled reactor, and an early 1980s analysis that supported licensing hearings for the Indian Point nuclear power plant. Currently, fire PSA (as one part of a comprehensive PSA) is being increasingly used, even in those countries that employ a deterministic regulatory approach. Applications include the identification and prioritisation of plant changes (including specific, fire protection improvements, as well as major changes in fire protection programmes), the development of safety cases as part of the periodic safety review requirements for operating reactors in many countries, and the support of the development and approval of new reactor designs. Fire PSA results and insights are also being used to identify and prioritise R&D activities.

With the continuing use of the fire PSA, the fire PSA technical and user communities have improved their understanding of the different strengths and weaknesses of the capabilities and practice of the fire PSA. Currently, as evidenced by practical applications, it appears that there is reasonable confidence in the use of fire PSA to support applications focused on fire considerations alone (e.g. fire vulnerability assessments, ranking of fire contributors). For applications requiring relative comparisons of fire risk with other sources of risk (e.g. when aiming for a balanced design) or reasonable estimates of the absolute levels of fire risk (e.g. when using decision processes, such as those involving the modification of allowed outage times for key equipment, which rely on demonstrations that a plant has achieved a prescribed safety level), the community views are considerably more varied. This situation is providing a strong driver for efforts to better understand uncertainties and improve the usefulness of fire PSA (as discussed in Chapter 6), and it is expected that these efforts will yield useful improvements.

While there may be some limitations associated with the current state of practice for fire PSA (as discussed in Chapter 6), these limitations can be mitigated through the use of risk-informed, integrated decision-making processes that also consider traditional engineering insights, safety margins, defence in depth and analysis uncertainties. (For example, see IAEA, 2011 and NRC, 2018.) In particular, fire PSA can provide substantial decision-making support through the identification of key sources of uncertainty and their impact on the plant response.

Looking to the future, it is expected that ongoing R&D will enable new, yet untested applications for fire PSA. For example, a fire PSA could be used to support a risk-informed examination of proposed cable qualification standards. A fire PSA that addresses the frequency and consequences of scenarios leading to non-core damage, but still undesirable plant states, could also support enterprise risk management activities that might address both economic and safety risks.

Chapter 8. Concluding remarks and recommendations

In the last several years, considerable discussion has taken place on the maturity and realism of fire PSA methods, models, tools and data, with a variety of views continuing to co-exist on the subject. Although such discussions are a positive driver for improvement activities – including R&D, database maintenance and guidance development – it should not overshadow two fundamental points: fire can be an important contributor to plant risk, and fire PSA is a useful tool for risk-informed decision making. Developing a thorough understanding of the key drivers of uncertainties in the fire PSA is therefore critical for the appropriate use of risk insights that the fire PSA can provide to decision makers.

Many PSA practitioners, when comparing the fire PSA with an internal events analysis, consider fire PSA to be less mature and its results subject to greater uncertainties. As discussed in this report, the results for some areas of a given fire PSA can be conservative. Nevertheless, it is clear that the fire PSA provides a systematic analytical tool for dealing with the complex issues that need to be addressed when ensuring fire safety at a nuclear power plant. The fire PSA has proven useful for supplementing deterministic analyses on which reactor design and fire protection are based, as it highlights the strong and weak points of a plant's design and operation with respect to fire hazards, while supporting a variety of risk management applications – cable routing management being one example of an important application.

As is the case with all PSA applications, the results and insights from fire PSA should be used as part of an overall risk-informed decision-making process, rather than providing the sole technical basis for decisions. Knowledge of the uncertainties and potential biases (both conservative and non-conservative, with magnitudes that are typically uncertain) in the fire PSA can (and should) be included when weighing available evidence. One, important observation is that in such a decision support framework, a fire PSA judged suitable for a fire risk management issue may need to be improved when used to address an issue involving the full set of hazards relevant to plant risk. Ongoing and future improvement activities are expected to improve the broad acceptance of fire PSA for a wider set of potential applications, including enterprise risk management applications not yet widely envisioned.

Of course, continued improvement requires sustained organisational support. It is recommended, therefore, that organisations continue to prioritise fire PSA improvements as an essential activity, and that organisations continue to support:

- R&D on key topics identified by the fire PSA technical and user communities;
- activities to collect, manage and provide access to quality data;

- activities facilitating the sharing of challenges, solutions, uncertainties, uses and good practices;
- activities to develop practical guidance based on the above points.

In terms of sharing information, as a multidisciplinary activity, fire PSA has been demonstrated to involve the interaction of a number of technical communities. Historically, interactions between some communities (e.g. the fire PSA and operational experience communities) have been limited, and organisational support is likely needed to facilitate improved co-operation.

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Annex A. Viewpoints on conservatisms in fire PSA results

A common assertion supporting the view that fire PSA is overly conservative is that "*fire PSA results do not comport with operational experience*" (e.g. see NEI, 2017). In particular, it is argued that fire PSA over-predicts the frequency of fire-induced scenarios that pose significant challenges to plant safety as measured by the conditional probability of core damage – CCDP – a measure of "how close" a scenario comes to core damage.[11]

Empirical information from operational experience, including data on fire occurrences, characteristics and qualitative plant impacts is extremely valuable for PSA and risk-informed decision making. Additionally, quantitative measures of scenario-level operational experience, such as the CCDPs for actual events, are potentially valuable, provided that they are compared to operating experience in a technically appropriate manner using defensible statistical testing approaches. As suggested by critics of current fire PSAs, such information can be used to calibrate PSA model estimates for many scenarios. Calibration, in turn, can increase stakeholder confidence in the PSA. Even further, a calibrated model would likely be useful for additional applications, e.g. non-regulatory enterprise risk management activities to reduce the economic risk associated with non-core and non-fuel damage scenarios. Such applications could represent a "win-win" approach to safety and production concerns. It has been noted that scenario-level operational experience has been somewhat overlooked in the broader PSA community, and greater use would assist many risk-informed applications, not just those related to fire.

Of course, all sources of information used to infer the likelihood of rare events have their limitations, and scenario-level measures such as CCDP are no exception. As with conventional PSA results, CCDP generation and use require fundamental modelling assumptions regarding the applicability of the modelled events to the assessment at hand, as well as technical assumptions associated with the PSA-oriented modelling of these events. They should therefore be considered as providing an additional, rather than an alternate, perspective on risk. With respect to the comparison of fire PSA estimates with expectations based on precursor analysis results, a few cautions should be provided.

- By their nature, precursor analyses are well-suited for identifying and prioritising potential accident scenarios that are more extreme versions of observed events. These analyses can thus address important scenarios that

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[11] The CCDP measure is widely used in assessments of the severity of operational events such as those performed as part of the accident sequence precursor programmes of several NEA member countries.

involve unlikely combinations of somewhat likely failures. They are not aimed at low likelihood/high consequence scenarios for which there has been little or no warning. However, such scenarios can be important contributors to a nuclear power plant's risk profile. This caution applies especially to extreme natural phenomena (e.g. large earthquakes or external floods) but also seems applicable to fires; the lack of observations of challenging fires in sensitive locations does not necessarily mean that such fires are unimportant contributors.

- Conditional probability of core damage (or CCDPs) computed using fire PSA models and those computed using standard accident precursor models are not necessarily equivalent, because of the differing purposes of these models (and therefore their differing underlying assumptions and boundary conditions).
- As discussed in the main body of this report, although fire PSA is performed iteratively to refine initially conservative assumptions, the analysis iterations are aimed at refining total core damage frequency estimates, not at refining estimates of the frequencies of various pre-core damage plant damage states. Clearly, as currently practised, there are no guarantees of accuracy for such intermediate frequencies.

Finally, it is important to recognise that the benchmarking of fire PSA results with operational experience has a qualitative as well as a quantitative dimension, and that qualitative comparisons appear to be reasonably favourable. For example: i) scenarios identified as being important in fire PSA (e.g. fire-induced loss of off-site power) have been observed in significant fire events, and ii) significant fire events have involved mechanisms (e.g. high energy arcing fault) typically addressed by fire PSAs (which is expected since many scenarios in PSAs are developed with consideration of operating experience). However, in terms of their level of importance/applicability within a fire PSA, such conclusions can also be limited and/or overstated since a strict interpretation of such events does not address plant improvements that may have occurred since event occurrence, a fact which is particularly important for older events (e.g. the aforementioned Browns Ferry fire in 1975). In addition, operational experience can also underestimate non-conservatisms since it cannot fully capture insights from fires that did not take place (although some precursors, e.g. those associated with degraded plant conditions, may provide additional information).

Annex B. **Additional resources**

Fire PSA methodology and standards

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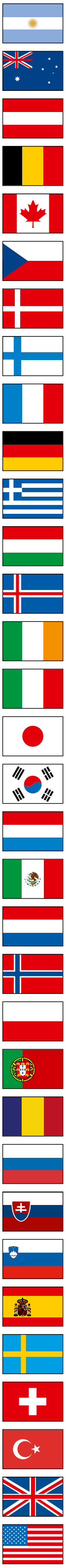

CSNI Technical Opinion Paper No. 17

CSNI Technical Opinion Paper No. 17: Fire Probabilistic Safety Assessments for Nuclear Power Plants: 2019 Update provides an authoritative review of the current status and use of the fire PSA in nuclear power plants. The report demonstrates that while fires at a particular plant site are highly dependent on plant and site specific factors, they are nonetheless an important contributor to overall risk. Insights from fire PSAs are generally found to be aligned with operating experience and to be representative of the expected plant response, making them valuable in addressing risk. This report should be useful for regulators overseeing the use of fire PSAs in nuclear installations, practitioners in understanding the considerations for performing or reviewing fire PSAs, and researchers in identifying areas requiring further study.

Nuclear Energy Agency (NEA)
46, quai Alphonse Le Gallo
92100 Boulogne-Billancourt, France
Tel.: +33 (0)1 45 24 10 15
nea@oecd-nea.org **www.oecd-nea.org**

NEA No. 7417