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A Review of Current Calculation Methods Used to Predict Damage from High Energy Arcing Fault (HEAF) Events

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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The mission of the NEA is:

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

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

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

THE COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of senior scientists and engineers with broad responsibilities for safety technology and research programmes, as well as representatives from regulatory authorities. It was created in 1973 to develop and co-ordinate the activities of the NEA concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations.

The committee's purpose is to foster international co-operation in nuclear safety among NEA member countries. The main tasks of the CSNI are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and reach consensus on technical issues; and to promote the co-ordination of work that serves to maintain competence in nuclear safety matters, including the establishment of joint undertakings.

The priority of the committee is on the safety of nuclear installations and the design and construction of new reactors and installations. For advanced reactor designs, the committee provides a forum for improving safety-related knowledge and a vehicle for joint research.

In implementing its programme, the CSNI establishes co-operative mechanisms with the NEA's Committee on Nuclear Regulatory Activities (CNRA), which is responsible for the Agency's programme concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with the other NEA Standing Technical Committees as well as with key international organisations such as the International Atomic Energy Agency (IAEA) on matters of common interest.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

High Energy Arcing Faults (HEAFs) have the potential to cause extensive damage to the failed electrical components and distribution systems along with adjacent equipment and cables within the zone of influence (e.g. an area affected by the HEAF). Furthermore, the significant energy released during a HEAF event can act as an ignition source to other combustibles resulting in fires. Operating experience indicates that HEAF events have occurred in nuclear power plants throughout the world and in some cases affected adjacent items important to safety. Current modelling techniques are limited in characterising the risks associated with the phenomena. Because of the potential safety significance of HEAF events the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) initiated a project to provide an in-depth investigation on HEAF events in NEA member states [1].

The general objective of the study was to determine damage mechanisms, extent of areas affected, methods of protecting systems, structures and components (SSCs) and possible calculation methods for modeling of HEAF events as applicable to fire protection in nuclear power plants (NPP). However, it turned out during the task that to fully meet all objectives, large scale experiments are needed.

It has been concluded that HEAF events have occurred throughout the world in NPP’s and have shown that they have the potential to damage safety related SSCs. These events are still too small in number to allow meaningful statistical evaluation. The critical details related to determination of arc fault energy and arc durations are not always available for model development and validation. Also, variables related to electrical equipment and exposed materials are not provided by the HEAF operating experience. In addition, current methods of predicting effects of HEAF have in a number of cases under-predicted the HEAF zone of influence and resulting damage to adjacent SSC.

To be able to better characterise HEAF events it is recommended to perform a series of experiments to obtain comprehensive scientific fire data on the HEAF phenomenon known to occur in NPPs through carefully designed experiments to be able to:

- Develop a more realistic model to account for failure modes and consequences of HEAF events as well as correlations based on ignition time using variations of incident heat flux.
- Validate current models to assess SSC damage potential.
- Provide better characterisation of HEAF in fire Probabilistic Risk Assessment (Fire PRA) and assist in developing more realistic PRA tools to model the risk in PRA.
- Provide guidance in predicting potential damage from HEAF events, e.g. for regulatory oversight.

This report therefore presents:

- A review of the current calculation methods used to predict damage from HEAF events to SSC.
- A summary of the operating experience with HEAF events that have occurred in NPPs.
- Recommendations for additional research work needed to better understanding fire risks associated with HEAF events resulting from this task.

1. INTRODUCTION

In general, high energy arc faults (HEAF) in electrical equipment are initiated in one of three ways: poor physical connection between the electrical conductors, environmental conditions, or the introduction of a conductive foreign object (e.g. a metal wrench or screwdriver used during maintenance). HEAFs have the potential to cause large pressure and temperature transients inside the component cabinet leading to risk of equipment failure. Secondary fires have been observed to impact cables and other equipment in the vicinity of the event.

The operating experience from nuclear power plants (NPP) as well as from other nuclear installations worldwide has identified a non-negligible number of HEAF events and consequential fires. These incidents typically occur within high voltage components such as switchgears and circuit breakers, or at high voltage cables. Also, the operating experience appears to indicate that the numbers of HEAF incidents are increasing. A reason for this may be a result of the aging infrastructure.

Due to the potential safety significance of HEAF events, the OECD/NEA Working Group on Integrity and Ageing of Components and Structures (WGIAGE) has initiated a task on High Energy Arcing Events (HEAF) in 2009 to provide an in-depth investigation on HEAF events in NEA member countries [1].

The objectives of this task are to

- Define in technical terms a HEAF event (likely to occur on components such as breakers, transformers, etc.).
- Share between CSNI members HEAF events, experiences, research and potential mitigation strategies.
- Investigate and characterise the physical and chemical phenomena of an HEAF event from a fire dynamics perspective.
- Provide the basis for a simple model/deterministic correlation to reasonably and quickly predict the potential damage areas associated with an HEAF.
- Develop generally acceptable input criteria and boundary conditions for the Computational Fluid Dynamics (CFD) models which are likely to be accepted by industry and regulatory agencies.
- Identify needs for possible experiments/testing to develop input data, boundary conditions for HEAF events to support the development of HEAF models.

The goal of this task is to provide the basis for deterministic correlations to predict damage and to establish a set of input data and boundary conditions for more detailed modelling which can be agreed to by the international community. The output of this project may directly support development of improved treatment methods in fire Probabilistic Risk Assessment (fire PRA) for nuclear power plant applications. The expected result of the proposal is a technical report covering the aspects outlined above.

This task results in the definition of experimental needs to be addressed in a Project structure.

This report presents:

1. A review of the current calculation methods used to predict damage from HEAF events to systems, structures and components (SSC).

2. A summary of the HEAF events that have occurred in NPP.

3. Recommendations for additional research work needed to better understanding fire risks associated with HEAF events.

2. BACKGROUND

High Energy Arc Faults (HEAF) are energetic or explosive electrical equipment faults characterised by a rapid release of energy in the form of heat, light, vaporised metal and pressure increase due to high current arcs between energised electrical conductors or between energised electrical components and neutral or ground. HEAF events may also result in projectiles being ejected from the electrical component or cabinet of origin and result in fires.

The energetic fault scenario typically consists of two distinct phases, each with its own damage characteristics.

1. ***First phase:*** short, rapid release of electrical energy which may result in catastrophic failure of the electrical enclosure, ejection of hot projectiles (from damaged electrical components or housing) and/or fire(s) involving the electrical device itself, as well as any external exposed combustibles, such as overhead exposed cable trays or nearby panels, that may be ignited during the energetic phase.

4. ***Second phase, i.e., the ensuing fire(s):*** ignition of combustible material within the HEAF zone of influence. The resulting fire may be due to the ejection of hot particles or piloted ignition of combustibles.

An electrical arc is a very intense abnormal discharge of electrons between two electrodes that are carrying an electric current. The arc is created by the flow of electrons through charged particles of gas ions that exist as a result of vaporisation of the conductive material. Since arcs are usually not desirable occurrences this project describes the phenomena as an “arcing fault”.

Impact of a HEAF to its environment

The significant energy released of an electrical fault in high voltage components rapidly vaporises metal conductors and typically produces an electrical arc. The arc accompanying an HEAF releases tremendous amounts of energy in the form of heat and pressure which can lead to the catastrophic failure of electrical enclosures, ejection of burning material, fires and injury to personnel. HEAF events are of concern due to their potential to impact adjacent items important to safety and current limitations in characterising the zone of influence.

3. LITERATURE REVIEW

NUREG/CR-6850, Supplement 1 [4] currently provides the sole guidance to the nuclear industry on how to assess the risk of HEAF events through probabilistic risk assessment using both statistical and empirical fire modelling. The assessment methodology in NUREG/CR-6850 is based upon defining a potential zone of influence for HEAF events from the electrical characteristics of the components. The zone of influence is used to assess potential damage to safety related SSCs.

Other than NUREG/CR-6850 [4], the majority of commercially available electrical risk calculation methodologies are focused on protecting workers from the hazards of arc flash [5], [6], which is the electrical discharge associated with an electrical fault. In these methodologies, potential arc fault energies are calculated to assist in the selection of personnel protective equipment (PPE) requirements for worker safety [6]. Similar to the assessment of HEAF potential for damaging SSC important to safety, hazard boundaries are established around electrical equipment and specifications are established for working distances and PPE to be used. The end result is based on distance and PPE is to ensure personnel are sufficiently protected from potential arc flashes energy fluxes to prevent second degree burns. The main arc flash calculation methodologies for personnel safety are detailed in NFPA 70E [6] and IEEE 1584 [5]. Computer models are available most of which are based on the calculations provided by IEEE 1584 or in Appendix D of NFPA 70E.

In addition, NFPA 70E [6] goes further to outline specific PPE requirements within the flash-protection boundary based on the incident energy the worker may be exposed. NFPA 70E also contains a simplified approach by creating hazard/risk categories which correlate with a task-based matrix table for determining PPE requirements. These tables are not addressed in this report as they are based on workers activities and the simplified approach does not always match the empirical methods.

HEAF risk assessments in NUREG/CR-6850 [2], [3] and [4] use both statistical and empirical rule based methods (NUREG/CR-1805 [7]) to assess impact and zone of influence on nearby equipment. Recent reviews of this methodology documented the shortcomings of this method, some of which are listed below:

- 4.16 kV to 13.8 kV switchgear panels do not address fire propagation from the electrical enclosure during the energetic phase.
- How HEAF events impact fire suppression efforts and selection of fire fighting equipment is not detailed.
- The fire duration may be longer than 10 minutes to 30 minutes, which was typically analysed.
- The plant material condition and independent failures may influence the fire event sequences.
- Existing fire models may underestimate the risk of fire due to HEAF by not considering the contribution of energetic electrical arcs to fire heat release rate (HRR) values (HEAF energy release rates are reported to exceed the predicted HRR by a factor of 1000).

- Electrical safety bus and circuit breaker configuration leading to multiple accident sequences from fire induced equipment failures or operators errors is not detailed.

3.1 Overview of NUREG/CR-6850 HEAF Fire Hazard Assessment Methodologies

The following is a brief overview of HEAF treatment in NUREG/CR-6850 Fire PRA methodology for nuclear power facilities [2], [3] and [4].

Both, NUREG/CR-6850 Volume 1 [4] (summary and overview), NUREG/CR-6850 Volume 2 [3] Chapters 4 -11 (detailed methodology), and Appendix M [4] (Fire probabilistic risk assessment methods enhancements) address HEAF events and its consequences such as subsequent fires and other impacts outside the initiating cabinet/arc source. As per the methodology HEAF events are assumed to occur in electrical equipment operating at greater than 440 V based upon operating experience at the time NUREG/CR-6850 was developed.

Motor control centres (MCC) with switchgear used to directly operate equipment (e.g. MCC load centres) should be evaluated as potential HEAF sources. Based upon the methodology of NUREG/CR-6850, it is assumed for greater than 4.16 kV switchgears, HEAF events will cause impact outside the cabinet of origin and for lower voltage panels HEAF effects will remain within the panel.

NUREG/CR-6850 also proposes various zones of influence from HEAF events and fires associated with bus duct HEAF events. The zone of influence (ZOI) for HEAF events [4] is intended to capture the damage generated during the energetic phase only.

Zone of influence of segmented (non-iso-phase) bus duct fires

- The zone of influence is defined by:
    - Molten metal ejected within sphere of 0.45 m radius.
    - Molten metal spreads downward as right angle circular cone at an angle of 15 degrees (total enclosed 30 degrees).
- Combustible material within the zone of influence will be ignited unless they are protected by fire rated raceway wrap conduit or solid steel panels.
- Cable trays equipped with aluminium covers of any kind or with ventilated steel covers will be ignited by molten metal falling from above.
- Damage and ignition is assumed from time zero within the initial zone of influence.
- Fire damage is limited with the presence of fire barriers.

Zone of influence of iso-phase bus duct fires

The zone of influence is defined by a sphere of 1.45 m radius.

- Combustible material within the zone of influence will be ignited unless they are protected by fire rated raceway wrap conduit or solid steel panels.
- Here is a need to take into account burning of hydrogen gas when escaping from the bus casing.

Zone of influence of bus duct HEAF events

- The entire length of bus duct ignites any cable or combustible immediately adjacent to bus duct equipment connected to bus duct will be ignited.
- Fire damage is limited with the presence of fire barriers.

Zone of influence for electrical cabinets and switch gear HEAF events

- Initial arcing will cause destruction of the faulting device.
- Metal plasma and mechanical shock will cause adjacent switchgear within the cabinet to trip open and cabinet door blown open.
- The cabinet fire will burn with a fire intensity and severity as described from recorded experiment and documented in NUREG/CR-6850 [3], Appendix G.
- Unprotected cables will be ignited that drop into the panel in an open air configuration and any unprotected cable in the first overhead cable tray will be ignited if within 1.5 m vertical distance from the top of the cabinet and propagate to adjacent trays.
- Damage and ignition is assumed from time zero within the initial zone of influence.
- Ignition of unprotected cables (unprotected cables or armoured cables with plastic covering) or any combustible fuels will occur within 0.9 m distance horizontally from the front door of the cabinet or rear face of the panel.

3.2 Simple Model for Predicting SSC Damage

In this section, the development of a simple model and a simple correlation is discussed to predict damage to SSCs due to HEAF events based upon incident energy models such as the heat release model.

The development of an empirical correlation for incident energy and SSC damage is challenging in consideration of:

- Variables involved for assessing potential incident energy and the need to conduct an arc-flash analysis of the electrical equipment involved.
- Variables impacting the fire hazard and equipment involved.
- HEAF events having very short duration and causing very rapid increase of temperature and pressure and a rapidly expanding superheated vapour, and intense radiation are outside the range of current empirical fire models.

It is noted that a traditional plume fire models cannot be applied directly to the HEAF energetic phase to assess the heat release rate due to the contribution of the energetic electric arc. HEAF events may become fully developed fires involving multiple components depending on the electrical equipment involved and exposed materials and conditions. Fire plume models may be applied once ignition and burning is established.

Two possible approaches have been proposed based upon arc flash calculations assuming the incident energy or energy release rates can be predicted using the IEEE 1584 [5] and NFPA 70E [6] calculations methods. However, it is noted that these approaches require validation though the assessment of HEAF operational experience as it is gained and ongoing testing regimes as discussed Chapter 4 of this report.

Approach 1

- Assess the potential for ignition of nearby SSC or equipment using the point source radiation model (NUREG/CR-1805 [7], SFPE Handbook [8]).

- Assess potential for ignition of nearby SSC using the Critical Heat Flux (CHF) and then using Thermal Response Parameters (TRP), calculate estimated time to ignition (calculated in accordance with Section 3 Chapter 4 of SFPE Handbook [8], 4th Ed., Table 3-4.2) using the incident heat flux. The estimated time to ignition is then compared to the arc fault duration time to assess whether ignition is likely.

This approach is limited to situations where the arc fault is limited in duration due to upstream protective equipment and ignition though conduction (due to molten metal, burning oil, etc.) is not expected. Should sufficient data be collected, an arc flash hazard analysis is conducted to establish a range of expected arc heat flux intensities generated by the potential fault currents. Incident heat flux is then calculated at various distances using the same point source radiation model as detailed in NUREG/CR-1805 [7].

The ensuing fires can then be treated using the multiple burning objects HRR. At this stage, the fire can be treated using any of the existing room fire compartment models.

This method is summarised as follows:

- Establish vulnerable equipment around the electrical equipment; establish the *CHF* and *TRP* of each component (using the SFPE Handbook [8], 4th Ed. or NUREG 1805 [7]) and distances from potential arc fault. Conduct flash hazard analysis to calculate incident heat flux at various distances and estimated arc fault duration.

- Establish time to ignition (T_{ign}) using the incident heat flux as an input and the formula below (NUREG/CR-1805 [7] and SFPE Handbook [8]).

  $$T_{ign} = TRP^2 / (q_e - CHF)^2$$

  where
  q_e = external heat flux [kW/m^2]
  TRP = thermal response parameter [kW.s$^{1/2}$/m^2]
  CHF = kW/m^2
  T_{ign} = ignition time [s]

- If T_{ign} is higher than the calculated arc duration, equipment is not likely to ignite.

- If T_{ign} is less than the calculated arc duration, equipment is likely to ignite and contribute to the ensuing fire generated.

The above approach can be used for all applications including open box and open air applications, or closed box applications (transformers, bus ducts, cable trays, etc.). This methodology does not take into consideration the contribution of oil and oil mist from oil filled equipment. A separate evaluation should be conducted using risk techniques described in [15].

Approach 2

Another simple approach is to postulate the following:

- Closed switchgear cabinet and MCC panels will develop into a fully developed fire when the energy dissipated by the fault is 10 kW/m^2.

- Transformers and bus ducts will develop into fully developed fires when the energy dissipated by the fault current is in excess of 20 kW/m^2.

In both cases the ensuing fire will impact nearby combustibles and typical plume fire model and point source ignition models can then be used to assess the impact on nearby objects.

This is based on the following:

- Heat fluxes in the range of 10 to 20 kW/m^2 are typically considered critical heat fluxes.

- Cabinet fires will develop much faster as part of the heat released is confined within the equipment.

- 20 kW/m^2 is considered a critical heat flux associated with radiated heat energy at surfaces of a fully developed fire.

4. SUMMARY OF HEAF EVENTS OPERATING EXPERIENCE

4.1 Operating Experience with HEAF Fire Events Collected in the OECD FIRE Database

HEAF events identified in the OECD FIRE Database are documented and summarised below. The identification of the events is based on the definition developed by the FIRE Project. The OECD FIRE Database Project [9] has indicated that 48 of the total 415 fire events reported from member countries between 1979 and mid-2012 to the Database are HEAF induced fire events. Details can be found in summary in the HEAF events Twenty-three HEAF events occurred inside plant buildings and fifteen outside (typically in the switchyard/transformer yard or outside building on the plant side), the latter mainly at transformers.

Table 1 derived from [9].

Breaking down the reported events by country:

Canada	2
Czech Republic	2
Finland	2
France	6
Germany	12
Japan	4
Korea	2
Spain	3
Sweden	4
United States	11

HEAF events were not reported from nuclear power plants in the Netherlands and Switzerland.

Seventeen events occurred before 2000, eighteen between 2000 and 2005 and thirteen in the recent past between 2006 and 2011. Thirty-one of the events occurred at NPPs with PWR, thirteen at BWR, three at PHWR reactors and one at a GCR. Thirty-four (~ 70 %) events occurred during power operation, fourteen (~ 30 %) during low power and shutdown states, three of these during start-up and one during hot stand-by.

Twenty-one events were classified as safety significant or had the potential to impair nuclear safety under different configurations or conditions, due to one or more redundant safety trains being lost or adjacent compartments being affected by direct or consequential fire effects. Consequential impact to adjacent compartments is to a large part due to cable damaged by fire.

By initiating device, safety significant HEAF events occurred in:

- high or medium voltage electrical cabinets (7 events);
- bus ducts / bus bars / cable runs (5 events);
- medium/low voltage transformers (3 events);
- high voltage transformers (1 event);
- breakers (3 events);
- low voltage electrical cabinets (2 events).

The economic loss was substantial in most high voltage transformer events, even when they were not considered safety significant.

Equipment failures were among the root causes of ten safety significant events, combinations of human error and procedure deficiencies were involved in five events. Two events were solely caused by human errors during maintenance or returning to operation following maintenance.

Twenty-three HEAF events occurred inside plant buildings and fifteen outside (typically in the switchyard/transformer yard or outside building on the plant side), the latter mainly at transformers.

Table 1 HEAF events in the OECD FIRE Database, version 2012:01 [9]

Plant type	**POS**	**Component affected by HEAF**	**Voltage level**	**Location**	**Damage limited to initial component**	**Barrier deteriorated**
PHWR	FP	high voltage transformer	500 kV	switchyard, switchgear room	yes	no
PHWR	LPSD	electrical cabinet, low voltage	600 V	electrical building, switchgear room	yes	no
PHWR	FP	high voltage transformer	500 kV	outside the plant, not switchyard	yes	no
PWR	FP	high voltage transformer	500 kV	Switchyard, transformer room/bunker	no	no
PWR	LPSD	electrical cabinet, high or medium voltage	6.6 kV	turbine building, room for electrical control equipment	no	no
PWR	FP	cable run, power cable	4 kV	turbine building, room for electrical control equipment	no	no*
PWR	FP	electrical cabinet, low voltage	< 1 kV	electrical building, switchgear room	yes	no

Plant type	POS	Component affected by HEAF	Voltage level	Location	Damage limited to initial component	Barrier deteriorated
PWR	FP	breaker	n.a.	electrical building, switchgear room	yes	no
PWR	FP	high voltage transformer	400 kV	transformer yard	yes	no
PWR	FP	electrically driven pump	n.a.	intake building, process room	yes	no
PWR	FP	medium or low voltage transformer	< 50 kV	outside the plant (not switchyard)	no	yes
PWR	LPSD	medium or low voltage transformer	15 kV	outside the plant (not switchyard)	no	no
PWR	LPSD (SU)	high voltage transformer	400 kV	other building/area, process room	yes	no
PWR	FP	electrical cabinet, low voltage	< 1 kV	independent emergency building, switchgear room	no	no
PWR	FP	breaker	> 10 kV	switchyard	yes	no
PWR	FP	high voltage transformer (main transformer)	> 50 kV	other building/area, transformer room/bunker a	yes	no
PWR	LPSD	electrical cabinet, high or medium voltage	6.6 kV	electrical building, switchgear room	no	yes
PWR	FP	breaker	4.16 kV	turbine building, switchgear room	no	yes
PWR	FP	electrical cabinet, high or medium voltage	> 1 kV	diesel generator building, process room	no	no
PWR	FP	bus duct	12 kV	auxiliary building, switchgear room	no	no
PWR	FP	junction box	4 kV	outside the plant (not switchyard)	yes	no
PWR	FP	high voltage transformer (main transformer)	380 kV	other building/area	yes	no
PWR	FP	breaker	500 V	auxiliary building, switchgear room	no	no
PWR	FP	electrical cabinet low voltage	< 1 kV	electrical building, switchgear room	no	no
PWR	FP	medium or low voltage transformer - oil filled	< 50 kV	switchyard	no	no
PWR	FP	electrical cabinet, high or medium voltage	6.6 kV	electrical building, room for electrical control equipment	no	no

Plant type	POS	Component affected by HEAF	Voltage level	Location	Damage limited to initial component	Barrier deteriorated
PWR	LPSD	breaker	10 kV	electrical building, switchgear room	no	yes
PWR	LPSD	bus duct	380 V	electrical building, switchgear room	yes	no
PWR	LPSD (SU)	high voltage transformer (main transformer)	21 kV / 400 kV	outside the plant (not switchyard)	yes	no
PWR	FP	high voltage transformer (main transformer)	21 kV / 400 kV	outside the plant (not switchyard)	yes	no
PWR	FP	high voltage transformer (main transformer)	21 kV / 400 kV	outside the plant (not switchyard)	yes	no
PWR	FP	other component (current to voltage transformer)	220 kV	switchyard	no	no
PWR	LPSD	bus duct	380 V	electrical building, cable spreading room	no	no
PWR	LPSD	breaker	> 1 kV	auxiliary building, room for ventilations	yes	no
BWR	FP	medium or low voltage transformer	< 50 kV	other building/area	yes	no
BWR	FP	high voltage transformer	380 kV	other building/area	yes	yes
BWR	LPSD	breaker	6 kV	turbine building, process room	no	no
BWR	FP	high voltage transformer (main transformer)	400 kV	outside the plant (not switchyard)	yes	no
BWR	FP	cable run, power cable	10 kV	outside the plant (not switchyard)	no	yes
BWR	FP	iso-phase duct	22 kV	turbine building, process room	no	yes
BWR	FP	electrical cabinet, low voltage	< 1 kV	turbine building, process room	yes	no
BWR	FP	electrical cabinet, low voltage	< 1 kV	electrical building, room for electrical control equipment	no	no
BWR	LPSD (SU)	high voltage transformer	> 50 kV	other building/area	no	no
BWR	LPSD	bus duct	460 V	reactor building, outside containment, switchgear room	no	no*
BWR	FP	electrical cabinet, high or medium voltage	6.6 kV	electrical building, switchgear room	no	no*

Plant type	POS	Component affected by HEAF	Voltage level	Location	Damage limited to initial component	Barrier deteriorated
BWR	FP	electrical cabinet, high or medium voltage	> 1 kV	diesel generator building, switchgear room	yes	yes
BWR	LPSD	electrical cabinet, high or medium voltage	6.9 kV	turbine building, switchgear room	no	no
GCR	FP	high voltage transformer (current transformer)	6.6 kV / 400 kV	switchyard	no	no

Abbreviations:
PWR: pressurised water reactor
PHWR: pressurised heavy water reactor
GR: graphite-moderated reactor
LPSD: low power and shutdown operational states
POS: plant operational state
****:*** but consequential effects
BWR: boiling water reactor
GCR: gas cooled reactor
FP: full power operational states (> 5 %)
SU: start-up mode (cf. [9])
n.a.: not applicable

At the time being, the existing data base on high energy arcing faults (HEAF) events in nuclear installations is still too small for a meaningful statistical evaluation, critical details related to determination of arc fault energy and arc durations are mostly not available for model validation. In addition, variables related to electrical equipment and exposed materials could not be provided from the FIRE Database. However, the first rough analysis of the available operating experience gives some indications on the safety significance of this type of events, which potentially will also result in relevant contributions to the overall core damage frequency.

4.2 Operating Experience with HEAF Events from Individual Member States

In-depth details of HEAF events having occurred in German and Belgium nuclear power plants are provided below. HEAF events with fires occurring in nuclear installations in other member states are detailed in the corresponding Topical Report No. 1 provided within the OECD FIRE Database Project [10].

4.2.1 Operating Experience with HEAF from Germany

The in-depth analysis of the German operating experience with HEAF in nuclear power plants is based on a questionnaire (see Annex 1) specifically developed by GRS in the frame of the IAGE task on HEAF events for collecting information on these types of events based on discussions with national and international experts. The questionnaire was further improved based on technical discussions with specialists from German NPPs, from regulatory bodies in Germany and their corresponding counterparts from technical safety organisations in charge for this type of failure and fire safety. The final questionnaire can be found in [11] and is based on the information available corresponding to HEAF events in nuclear installations worldwide potentially applicable to German nuclear power plants.

This survey has provided in total 31 HEAF events obligatory reported to the German regulators from NPPs in Germany, 13 of these having resulted in consequential fires. The investigations are outlined in [11] including information on the components where the HEAF started and the corresponding voltage levels as well as their relevance to fire safety (see Table 2). Details on selected events from the table are given in [11].

The query provided the following insights [12] and:

- The investigations demonstrated that HEAF typically occur in a few specific components such as switchgears and transformers, electric cabinets, cables, connecting boxes and circuit breakers on voltage levels between 0.4 kV and 400 kV. In this context, high energy switchgears and circuit breakers play the most important role representing an amount of 60% of the events (18 from 31). The contribution of 10% (3 of 31) HEAF events in transformers is also significant.

- All HEAF events that have occurred so far in German NPP were immediately signaled via fire alarm or other alarm systems. Any relevant smoke release was directly detected by the fire detection systems. 35% of the high energy arcing fault events resulted in a fire.

Table 2 HEAF events in German NPP (corresponding to [11] and [12])

Plant type	POS	Component affected by HEAF	Voltage level	Damage limited to initial component	Barrier deteriorated	Root cause
BWR	FP	high voltage transformer (main transformer, oil filled)	400 kV	yes	no	T, A
PWR	FP	circuit breaker	660 V	yes	no	T
BWR	FP	high voltage transformer (main transformer)	440 kV	yes	no	T, A
PWR	FP	high voltage transformer (main transformer)	380 kV	yes	no	T
BWR	FP	motor junction box	660 V	yes	no	T
BWR	LPSD	motor junction box	660 V	yes	no	T
BWR	FP	switchgear (switchgear subassembly)	380 V	yes	no	T
BWR	LPSD	high voltage switchgear	6 kV	yes	no	T
PWR	LPSD	high voltage cabinet (conductor)	6 kV	yes	no	H
BWR	FP	high voltage cable	10 kV	yes	no	A, T
PWR	LPSD	circuit breaker (500 V injection)	500 V	yes	no	H
BWR	FP	switchgear	400 V	no	no	T, H
PWR	FP	switchgear	500 V	no	no	T
BWR	FP	switchgear	660 V	yes	no	T
PWR	FP	circuit breaker	660 V	no	no	T
PWR	FP	electrical cabinet (bus bar, breaker subassembly)	500 V	yes	no	U
PWR	LPSD	motor generator (reversible)		yes	no	T
PWR	LPSD	high voltage switchgear (injection cell)	10 kV	no	no	T

Plant type	POS	Component affected by HEAF	Voltage level	Damage limited to initial component	Barrier deteriorated	Root cause
PWR	LPSD	switchgear (injection area)	380 V	yes	no	T, H
PWR	FP	high voltage switchgear	220 kV	yes	no	T
BWR	FP	electrical cabinet (emergency diesel)		yes	yes	T, H
PWR	FP	motor of a pump		yes	no	T
PWR	LPSD	bus bar	380 V	no	no	U
BWR	LPSD	high voltage switchgear (cables)	30 kV	yes	no	H
PWR	FP	motor of a pump (safety injection pump)		yes	no	T
PWR	LPSD	circuit breaker (sub distribution board)		yes	no	T
BWR	LPSD	switchgear		yes	no	H
PWR	LPSD	contactor		yes	no	P, T, H
PWR	LPSD	generator breaker (220 kV switchgear)		yes	no	T
PWR	LPSD	switchgear (bus bar in 380 V cabinet)	380 V	yes	no	H
BWR	LPSD	switchgear (emergency switchgear)		yes	no	T, P

Abbreviations:

PWR:	pressurised water reactor	***BWR:***	boiling water reactor
FP:	full power operational states (> 5 %)	***LPSD:***	low power and shutdown operational states
POS:	plant operational state	***A:***	administrative
H:	human	***P:***	procedural
T:	technical	***U:***	unknown

The physical separation of redundant equipment of the safety trains was ensured in case of all the events. Only in very few cases (approx. 20%) the damage was not limited to the component where the HEAF occurred. Explosions initiated by the high energy arcing fault did not impair components or impact plant areas other than those where the event started. The required function of fire protection features were not affected by the HEAF event. Protective devices prevented explosions in 87% of HEAF events.

Technical causes as well as human factor (HF), mistakes in procedures and ageing represent the root causes of the HEAF events observed in German nuclear power plants. Technical root causes are the predominant failure mode (24 of the 31 events for a contribution of 77%). Erroneous human actions played a significant role for five events (16%), ageing effects affected or caused the component failure in case of three events (10%), and faulty procedures and/or administrative reasons were involved in two events (nearly 7%) together with other root causes.

For prevention of high energetic component faults the following measures are assumed to be reasonable and therefore have been or are being implemented in the plants by the German licensees, in particular, to avoid as far as practicable the occurrence of HEAF due to technical reasons and to reduce the negative consequences of HEAF:

- Replacement of components by improved ones (transformers, switchgears and breakers, cables).
- Replacement of (low amount) oil filled circuit breakers by vacuum breakers.
- Installation of electric arc detection via pressure cells together with overcurrent detection (500 ms to 100 ms).
- Oil monitoring for transformers.
- Visual inspections of relevant electric equipment (in particular cables, cable connections).
- Inspection of insulation resistances.
- Provision or optimisation of measures for pressure relief.

The analysis also revealed insights on those plant areas with components having a potential for HEAF events.

Table 3 provides those plant areas and their corresponding high voltage components potentially relevant with regard to HEAF for a BWR plant built to earlier standards.

Table 3 HEAF relevant plant areas in an exemplary German BWR NPP (from [11], [12])

Voltage Level **Plant Area**	**10 kV**	**6 kV**	**0.4 kV**
Reactor Building ZA	2		
Electrical Building ZE	2		4
Turbine Hall ZF	2		
Emergency Diesel Building ZK		3	
Circulating Water Structure ZM	2	2	
Transformer Yard	3/11**	6	
** *Note:* 3 Transformers > 10 kV (main transformer, service transformer)			

With respect to events resulting from HEAF, a short circuit failure of high voltage cables (typically 10 kV nominal voltage) in cable rooms and cable ducts (channels, tunnels, etc.) is not assumed for German NPPs at the time being. Moreover, a failure of high voltage circuit breakers and switchgears (10 kV nominal voltage or more) and the resulting pressure increase are presumed to occur and to be controlled.

Specific investigations of such scenarios have resulted in additional measures for pressure relief inside the electrical buildings of German NPPs.

4.2.2 Operating Experience with HEAF from Korea

During normal operation of the reactor with power at 100 % and the turbine generator (T/G) power at 990 MW_e a HEAF event occurred on the phase ‘B’ of the main transformer in the NPP Uljin, Unit 1 on 30 January 2001. The fault was immediately sensed by protective relays which caused a turbine trip and an automatic reactor trip. The unit was disconnected from the grid and site power automatically transferred from the unit auxiliary transformer to the start-up auxiliary transformer.

The root cause of the HEAF event was a contact failure between the tulip contactor of the upper part of the bushing and moving contactor of gas insulated bus (GIB). A coupler between the bushing of the transformer phase ‘B’ and the GIB was overheated. Cracking hot gas was formed due to the insulation deterioration of the SF6 gas on the overheated spot and a short circuit occurred between the conductor and the transformer case. The arcing induced melting of the tulip contactor of the bushing.

The following conclusion was drawn from this event:

After the failure of transformer phase ‘B’, the loss of offsite power, and the turbine/reactor trip, this event did not have any impact on plant operational safety because all safety related parameters satisfied the technical specifications set point limits.

During normal operation of the reactor with power at 100% and T/G power at 602 MW_e, a HEAF event with explosion and consequential fire occurred on the phase ‘B’ of the main transformer in the Kori NPP, Unit 1 on 22 April 2002 and caused a turbine/generator trip due to the ground failure between outlet lead wire and outer casing of the main transformer phase 'B'. The reactor tripped and stayed subcritical by the turbine trip signal and P8 (reactor power $\geq$ 30 %) signal. No radiological effects both on-site and off-site were observed. Each safety system maintained normal condition.

The root cause of the HEAF event was assumed to be a manufacture flaw. It is assumed that the connection had been damaged slowly but continuously for about 28 years since its installation in 1974 because the connection was lead-welded.

The lessons learned from this event are as following:

- Even with acceptable results from inspections of operating parameters and insulating gas analysis, this event could occur spontaneously.
- To prevent this type of event, it is necessary to inspect the selected vulnerable areas periodically and to replace the transformer through the performance evaluation.

4.2.3 Operating Experience with HEAF from Belgium

One of the most severe HEAF events occurred in Belgium at a PWR type nuclear power plant. The plant was under hot shutdown after refuelling in preparation for start-up, a breaker inadvertently opened and an arc was formed during the start of a circulating water pump resulting in an explosion in an electrical room after a few seconds. The first upstream protection did not function or reacted too late, the protection of the upstream transformer finally cut the current after 8 seconds. The damage was caused by a HEAF on the bus bars of approximately 1 second. Smoke was released and fire alarm announced in the unit control room. The event had severe consequences to the personnel working in the affected area, one person was severely burned and died some days later, three others were slightly injured.

The detailed analysis of the event gave the following findings on the event sequence:

A loss of power supply to the N1 polarity with subsequent loss of primary coolant pump No. 1 resulted in the loss of 150 kV supply to the auxiliary transformer. The emergency power supply to the S1 polarity started, a loss of room integrity was observed in total for rooms in the electrical building due to destruction and or deterioration of barrier elements, such as walls and doors.

After the start of a high voltage circuit breaker of the CW pump the protection relay was triggered on maximum current after approximately 12 seconds. Per default, the typical “Buchholz” protection on the TRa1 transformer was actuated within 8.38 minutes resulting in the opening of the circuit breaker on the 380 kV supply with subsequent transfer from 380 kV to 150 kV on N1 and S1. After another 56 seconds the maximum current on the supply from auxiliary transformer TRh1 to N1 polarity occurred followed by the opening of the 1Dg2/N1 and 150 kV circuit breaker supply to transformer TRh. The corresponding electrical scheme can be found in **Figure 1**.

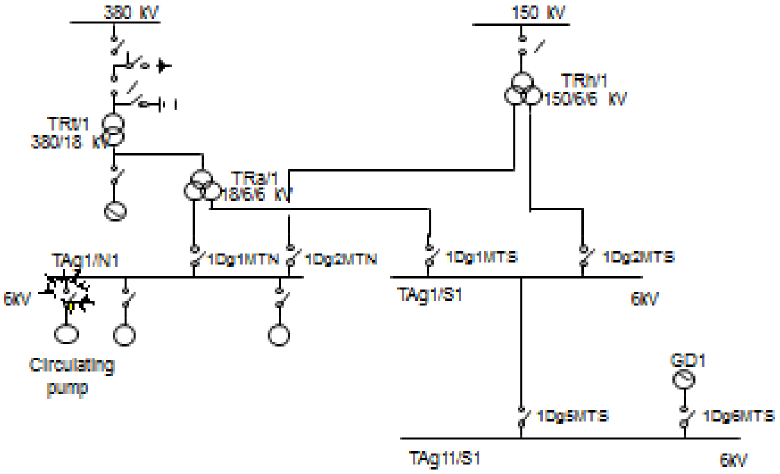

Figure 1 Electrical scheme of the circuit in the Belgium PWR HEAF event (from [13])

The status of the cubicle was the following:

In the high voltage compartment soot was observed giving evidence of fire and/or high temperature (burned paint). As well as projections of oil on the sides of the compartment, in the low voltage compartment the metal separation was still present, but fire on cables, terminal blocks and relays was observed. There was no damage in the bus bar compartment and the cables compartment.

The circuit breaker was found in open position with the central and right poles seriously damaged, the copper of the contact rods melted a length of several cm, tungsten contacts was found in cubical, the blowout chamber damaged, and indications of arcing found between two phases and with the lower parts of the mechanism. However, there was no interruption of the current to the CW motor in the two phases. A rapid pressure increase was observed in the circuit breaker housing and the relief chamber as well as arcing in the circuit breaker cubical. After a few seconds oil was ejected in the cubicle and ionised gases were released through a vent hole.

The short circuit occurred on three electrical phases with a consequential explosion. Despite expert investigations, the root cause of this breaker failure remained unknown. The explosion resulted in the severe injury and death of a worker and a loss of confinement (blasted wall and doors). Smoke exhaust dampers were destroyed; fire barriers including their active elements were damaged (cracks) as well as ventilation ducts. Inside the cubicles fire detection was inoperable.

Smoke intrusion to the control room occurred through the staircase and a spurious actuation of the spraywater deluge system at a lower level. Water impaired the I&C cabinet of the control rods converter set, and the drainage system did not operate properly. Nevertheless, there was no damage to relay contacts.

Fortunately, the overall safety of the plant was not compromised by this incident, however, safety might be impaired, if the same explosion had happened in another switchgear room. As stated by Tractebel [14], the position of the Belgian nuclear safety authority is to consider this type of explosion (arcing and failure of first upstream protective device) as a design basis accident in the sense of IEEE 308:

- For nuclear power plants in accidental situation:
  A switchgear explosion as single failure has to be postulated and the consequences have to be evaluated.

- For nuclear power plants during normal operation:

  - For the safety related trains:
    The explosion of a switchgear as an initiator has to be postulated and an additional single failure to be considered in the chain of equipment necessary to cope with the incident and the consequences have to be evaluated.

  - For non-safety related trains:
    The explosion of a switchgear has to be postulated and the consequences to be evaluated.

As a corrective measure resulting from the event, oil containing switchgears have been replaced in all Belgium NPPs so that the gas explosion component does no longer have to be considered. With respect to the adiabatic heating of air, in many cases the pressure rise due to adiabatic heating of the air leads to pressure levels higher than the resistance of structural elements. Damage of safety related equipment in adjacent trains could not be excluded. It is necessary to calculate the pressure rise more accurately.

The following main conclusions were drawn from this incident:

- The damage observed was the result of two “explosions”, first a rapid pressure rise inside the room caused by the adiabatic air heating due to energy released by the 3φ-arc, and second an oil decomposition by internal electric arcs leading to gas released through relief cap followed by an explosion of the gas mixture.

- The damage observed (broken and displaced walls) allowed for the calculation of the pressure level reached during the incident (rupture-line method of Johanson) (100 – 130 mbar).

- The blast effect of the arc generation is considered as negligible (with respect to the adiabatic heating).

First calculations in Belgium gave the indication for the adiabatic heating of air due to arcing that 40 % of the arc energy $\Delta E_{él}$ is taken into account for the adiabatic heating of air. The calculation is valid for a free burning arc in a closed empty room. With respect to the gas explosion the calculations provide the result that cracking of oil generates a volume of explosive gas of 100 cm^3/kJ (confirmed by the SEBK project) with a gas composition of 39 % acetylene, 38 % hydrogen, 20 % methane, and 3 % ethylene. Volume and gas composition were confirmed later by the SEBK project (Norway). The overpressure of the explosion was calculated by the TNT-equivalent method by means of the program INBLAST.

For the room, where the event occurred, the following results were calculated. Under the assumption of an input current of I = 36 kA, $\Delta_{électr.}$ = 43.2 MJ, the compartment volume V = 690 m^3, and at t = 1 s for the heating air a pressure difference of Δp = 100 mbar was estimated. The result for the gas explosion was a pressure difference of Δp = 29 mbar providing a total overpressure of 129 mbar for the closed room. The “pressure resistance” of the wall was assumed to be approximately 25 mbar, so the calculated pressure level is consistent with the damage observed. Weak point of the approach is that the free burning arc is considered in an empty closed room, which is not realistic, and that the TNT-equivalent method is not precise enough for explosions in closed rooms. Therefore an efficiency factor for the explosion has to be chosen, which strongly affects the final results.

This was one of the reasons that the component “gas explosion” was recalculated by using CFD software called FLACS (Flame *Ac*celerator *S*imulator) by GEXCON. In this calculation, for the same gas cloud the calculated overpressure was found to be much higher (95 mbar instead of ~ 29 mbar). The total pressure (gas explosion and adiabatic heating) of approximately 195 mbar was inconsistent with the observed damage. This may indicate that the effect of adiabatic heating was overestimated.

5. INTENDED FUTURE ACTIVITIES

The U.S. Nuclear Regulatory Commission (NRC) is currently carrying out an experimental investigation into HEAF by initiating HEAF events in switchgears donated by OECD member countries (U.S. NRC Project Code: JCN N6981) within an OECD/NEA project. The primary objective of the experiments is to obtain scientific fire data on the HEAF phenomenon known to occur in NPPs through carefully designed experiments. The goal is to use the data from these experiments and past events to develop a mechanistic model to account for the failure modes and consequence portions of HEAF events. These experiments will be designed to improve the state of knowledge and provide better characterisation of HEAF event in the fire probabilistic risk assessment (PRA) and other hazard analysis. Initial impact of the arc to primary equipment and the subsequent damage created by the initiation of an arc (e.g. secondary fires) will be examined. The equipment considered in this study primarily consists of switchgears, breakers and bussing components.

For the initial HEAF event, data is required for the blast affects, including the pressures, temperatures, and heat flux created within the switchgear component during the event. The initial impacts are important in understanding the structural integrity of the component during overpressure as well as the potential for catastrophic equipment failure for different manufacturer’s specifications (e.g. Class 1E, non-Class 1E, NEMA rating). Understanding the heat exposure effects is relevant to determining the zone of impact. Quantifying the zone influenced from a HEAF is important when analysing the arc effects on secondary combustible materials (e.g. transient combustibles, adjacent equipment, electrical cabling). This provides the basis for subsequent damage, which may result from an ensuing fire. From these data, the NUREG/CR-6850 model may be refined to more accurately represent HEAF events.

6. CONCLUSIONS

HEAF events have occurred throughout the world in NPP's and have shown that they have the potential to damage safety related systems, structures and components (SSC). These events are still too small in number to allow meaningful statistical evaluation. The critical details related to determination of arc fault energy and arc durations are not always available for model development and validation. Also, variables related to electrical equipment and exposed materials are not provided by the HEAF operating experience. In addition, current methods of predicting effects of HEAF have in a number of cases under-predicted the HEAF zone of influence and resulting damage to adjacent SSC.

Due to the relatively small sample size of HEAF events in the OECD FIRE Database, meaningful statistical conclusions with a reasonable level of confidence cannot yet be obtained. Trends and insights into HEAF events from the OECD FIRE Database indicate the following:

- The 48 HEAF fire events observed in the OECD FIRE Database up to the end of 2012 represent more than 10 % of the fire events collected in the Database.

- High voltage transformer HEAF fire events have not been observed to inadmissibly impair nuclear safety.

- HEAF incident frequencies have not increased over time except for high voltage transformers representing the highest frequency of HEAF events.

- Based upon an estimated total observation period of approximately 7000 reactor years for the OECD FIRE data collection until 2012 with an average of 80 % for plants in power operation, the conditional probability of a HEAF event with fire to occur:

  – during one year of full power operation is in the order of E-03;

  – during non-power plant operational modes it is about half an order of magnitude higher (E-02), i.e. nearly two times as high as for power operation.

The reasoning for this result needs further investigations.

- More than one third of the HEAF events in the Database (21 out of 48) have been classified as safety significant events due to a loss of the required function of one or more functionally redundant items important to safety ("loss of safety trains"), or due to adjacent compartments being affected by direct or consequential fire effects. Or the events had the potential to inadmissibly impair nuclear safety under different boundary conditions. Safety significant HEAF fire events provide a contribution of less than 5 % of the events in the Database, which is non-negligible due to the fact that at least from some member countries not only events meeting specific reporting criteria but all fires are reported to the Database.

- High or medium voltage electrical cabinets, breakers and bus ducts/cable runs mainly contribute to safety significant HEAF events with electrical cabinets have the highest occurrence frequency.

- A substantial amount of more than 40 % of the HEAF fire events in the Database did occur outside a building and do typically not jeopardise nuclear plant safety.

- The conditional probability of fire propagation to components other than those where the HEAF induced fire originated is more than two times lower than for non-HEAF fires.

- Fire barriers tended to remain intact following a HEAF event, with only two events damaging fire doors due to pressure build-up, and no events failing other fire barriers.

- All cases of direct impact to other compartments were due to propagation of hot gases or smoke penetrating fire barriers. Consequential impact was mostly due to cables damaged by fire.

The trends mentioned above are the same, if the analysis is based on the most recent version of the OECD FIRE Database with data up to the end of 2013.

All discussed measures of safety are substantially higher for HEAF initiated events than for the general population of fire events in the database, thus consistently evidencing the significance of fires initiated by HEAF events and stressing the importance of permanent research on characterisation as well as prevention of HEAF events.

7. RECOMMENDATIONS

To fully meet the objectives of the task and, in particular, to be able to better characterise HEAF events it is recommended to perform a series of experiments to obtain comprehensive scientific fire data on the HEAF phenomenon known to occur in nuclear power plants through carefully designed experiments to be able to

- Develop a more realistic model to account for failure modes and consequences of HEAF events,
- Develop correlations based on ignition time using variations of incident heat flux.
- Validate current models to assess SSC damage potential.
- Advance the state of knowledge and provide better characterisation of HEAF in the fire probabilistic risk assessment (Fire PRA).
- Assist in developing more realistic tools to model the risk in PRA.
- Provide guidance in predicting potential damage from HEAF events and for regulatory oversight,
- Answer some keys questions such as:
  - How HEAF events can be minimised or prevented?
  - How precursors to HEAF events can be detected?
  - What measures can be put in place to minimise the consequence of a HEAF event?
  - What is the best way to limit pressure phenomena and minimise failures of fire barriers?

REFERENCES

[1] Organisation for Economic Co-operation and Development (OECD), Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI), “Task on High Energy Arcing Events (HEAF)”, CAPS submitted to CSNI / IAGE and to CSNI/PRG, Version 9 October 2008 – revised with PRG Chair on 27 April 2009, Paris, France, 2009.

[2] United States Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research, NUREG/CR-6850, Volume 1, EPRI 1011989, Fire PRA Methodology for Nuclear Power Facilities, Volume 1: Summary & Overview, September 2005.

[3] United States Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research, NUREG/CR-6850, Volume 2, EPRI 1011989, Fire PRA Methodology for Nuclear Power Facilities, Volume 2: Detailed Methodology, September 2005.

[4] United States Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research, NUREG/CR-6850, Supplement 1, EPRI 1019259, Fire Probabilistic Risk Assessment Methods Enhancements, Appendix M, Appendix for Chapter 11, High Energy Arcing Faults, September 2010.

[5] Institute of Electronic and Electrical Engineers (IEEE), IEEE 1584, “IEEE Guide for Performing Arc-Flash Hazard Calculations”, IEEE, September 2002.

[6] National Fire Protection Association (NFPA), NFPA 70E, 2012 edition, “Standard for Electrical Safety in the Workplace”, 2012.

[7] United States Nuclear Regulatory Commission (NRC), “Quantitative Fire Hazard Analysis Methods for the US Nuclear Regulatory Commission Fire Protection Inspection Program”, NUREG/CR-1805, 2004.

[8] Society of Fire Protection Engineers (SFPE), SFPE Handbook of Fire Engineering, fourth Edition, Bethesda, MD, USA, ISBN-13: 978-0877658214, 2008.

[9] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI), “OECD FIRE Database, Version: OECD FIRE DB 2012:1, Paris, France, September 2013.

[10] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI), OECD FIRE Project - Topical Report No. 1, Analysis of High Energy Arcing Fault (HEAF) Fire Events, **NEA/CSNI/R(2013)6**, Paris, France, June 2013, http://www.oecd-nea.org/documents/2013/sin/csni-r2013-6.pdf.

[11] Röwekamp, M., et al., “Weiterführende Untersuchungen zum hochenergetischen Versagen elektrischer Einrichtungen mit sicherheitstechnischer Bedeutung in Kernkraftwerken“, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-A-3630, Köln, Germany, September 2011 (in German only).

[12] Röwekamp, M., S. Katzer, J. Klindt, H.-P. Berg, “Insights from Investigations of High Energy Arcing Fault ”HEAF“ Events in German Nuclear Power Plants”, Paper 54158 in: Proceedings of the 20th International Conference on Nuclear Engineering collocated with the ASME 2012 Power Conference ICONE20-POWER2012, July 30 – August 3, 2012, Anaheim, CA, USA, ASME, August 2012.

[13] Association Vinçotte Nuclear (AVN), “Explosion of a circuit breaker at the Tihange 1 NPP”, Presentation at “Four Country Information Exchange Meeting on Nuclear Fire Safety”, Warrington, United Kingdom, 1998.

[14] Aelbrecht, D., “Status on Tractebel’s activities”, HEAF–Meeting, Grainau, Germany, 30-09-2009, Tractebel Engineering SUEZ, 2009.

[15] Chille, F., and A. L. Fuglestad, “Transformer explosion risk assessment using advanced CFD tools (FLACS Code)”, in: Proceedings of Brannforum 2012, Trondheim, Norway, February 6-8th, 2012.

ANNEX 1: QUESTIONNAIRE ON HIGH ENERGY ELECTRIC (ARC) FAULTS HEAF

A-1 Background of the Questionnaire

Based on the international operating experience the state-of-the-art on the high energy electric failure (HEAF) of electric components and equipment shall be collected and assessed. In particular, potential consequences of events with this failure mechanism on adjacent equipment (particularly safety significant ones, fire protection features) and plant areas exceeding the typical fire effects (smoke, soot, heat, etc.) shall be identified.

International operating experience of nuclear installations in the near past reveals reportable HEAF events (/GRS 04/, /KOT 00/, / NRC 02/) e.g. induced by electric arcs in circuit breakers, etc. resulting in partly significant consequences to the environment of these components exceeding typical fire effects. Investigations of the events have indicated failures of fire barriers and fire protection features due to pressure build-up in the electric cabinets and/or pressure waves (/GRS 04/, /KOT 00/) as well as damage of components by missiles (/NRC 02/).

In a German NPP event with actuation of a stationary CO_2 extinguishing system resulted in deterioration and opening of a fire door caused by the overpressure in the compartment /WLN 2006/01/. The events mentioned show i.e. that fire protection has not always designed against such impacts.

A variety of fire protection features may be affected in case of HEAF events by the pressure increase and/or pressure waves (e.g. (fire) doors, fire dampers, penetrations seals and barriers, such as walls and ceilings, etc.). This results in a list of questions, which shall be answered by the licensees to evaluate the state-of-the-art, to gain insights on the basic phenomena for HEAF, and to find out, how such events can be prevented in nuclear installations.

A-2 Questions to Licensees

- Does the operating experience reveal either reportable or minor, non-reportable events interconnected to a high energy electric (i.e. arcing) failure of electric components and equipment?
  - What are the reportable events? (Short description needed).
  - What are the non-reportable events? (Short description needed).
  - In which buildings / compartments / plant areas did the event occur?
  - What type of component was the fault initiated in (e.g. switchgear, motor control center, transformer, breakers, etc.)?
  - What voltage level did the component operate at?
  - What was the nominal current load available to the component?
  - If known, what was the estimated overload current observed during the arcing fault?

  - How was the HEAF observed or detected? Directly by fire detectors, visual or auditory detection in the location where the fault occurred or indirectly by faulty/spurious signals indirect fire alarms, etc.? (An as far as feasible detailed and exhaustive event description is needed.) What were the observations and findings?
  - What was the damage? Was there high energy impact by electric causes or by others (valves, gases, etc.)? Which components/ types of equipment were affected? (short description needed).
  - What was the damage zone?
  - Was there damage by the high energy release (explosion pressure wave, etc.), or by fire or by both? What was the damage? (short description needed).
  - Which measures were available to limit the consequences of such HEAF failures?
- Did the event affect more than one component (CCF)?
  - Was the damage limited to one fire compartment or were further compartments affected?
  - Which consequences/effects (e.g. pressure waves, impact by missiles, etc.) to adjacent/nearby components (including cables) and compartments / plant areas have been observed besides the typical fire effects?
  - Which pressure peaks/amplitudes and impact durations were measured/observed?
  - Which functions of fire protection features (fire barriers and their elements as well as active means) have been impaired by the effects of HEAF, in particular by pressure waves and missiles?
  - What were the arcing durations in case of arcing being the cause?
- Fire suppression:
  - Was fire extinguishing performed?
  - If yes, which extinguishing means were applied?
  - What was (rough estimate) the total fire duration?
  - Which were successful?
- Event causes:
  - Was it possible to find out the causes of the high energy impacts observed? If yes, what were the potential causes?
  - Were the initial causes man-induced (mal-operation, errors) or purely technical ones?
  - Have the root causes been found? (please outline all the root causes)

  - Are there insights on the basic (mainly physical and/or chemical, electrical) phenomena and the interrelationships?

- Corrective actions:

  - What are the corrective actions after the event?
    - List of actions for the room/compartment or plant areas, respectively
    - Pre-fire planning depending on the equipment present in the room

  - Which measures are foreseen (originally as well as improved ones after the event) to limit the consequences of such HEAF failures?

  - Are the fire protection features implemented in the nuclear installations designed against the potential effects from HEAF of electric components and equipment or have they been upgraded (if yes, what are the improvements)?

- Preventive measures:

  - Which measures have been taken for prevention of HEAF failures in the plant design?

  - Have measures been implemented for plant improvement/upgrading to prevent those HEAF failure mechanisms, and if yes, which ones? (Have original measures been re-designed?)

  - Are further measures intended for prevention of these faults, and if yes, which ones?

  - Are the fire protection features implemented in the nuclear installations designed against the potential effects from HEAF of electric components and equipment or have they been upgraded (if yes, what are the improvements)?

- Assessment without direct observations from the events:

  - Which pressure peaks/amplitudes and impact durations may occur in the case of HEAF of electric components? Are there calculations/estimates?

  - Which insights are available on the HEFF failure mechanisms for electric equipment?

  - In which compartments/ plant areas are components and equipment available with the potential of HEAF? Are there safety significant / safety related components available in these compartments/plant areas and/or adjacent ones? If yes, which ones? What are the preventive measures there against such events?

  - What is the amount of equipment with the potential for HEAF being present in the nuclear power plant?

  - In how far are such HEAF events and their potential effects taken into account in the deterministic analysis of the installations/facilities?

  - Have the HEAF equipment and its potential failures / HEAF events been considered in the fire PSA? If yes, how and in how far?

- What are the potential effects of “aging” in the context of HEAF of electric equipment and components, can aging be assumed for those components where such events occurred?

- Which functions of fire protection features (fire barriers and their elements as well as active means) are assumed to be impaired by the effects of HEAF, in particular by pressure waves and missiles?

A-3 References

/GRS 04/ Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, “Ausfall der Eigenbedarfs- und Notstromversorgung für 2 Stunden” im taiwanesischen Kernkraftwerk Maanshan-1 am 18. März 2001, Weiterleitungsnachricht 2004/03, 2004 (in German only).

/GRS 06/ Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, “Auslösung der CO_2-Löschanlange für einen Rechnerraum mit Beschädigung einer Brandschutztür“ im Kernkraftwerk Brunsbüttel am 29.07.2005, Weiterleitungsnachricht 2006/01, 2006 (in German only).

/KOT 00/ Kotthoff, K., M. Maqua, M. Simon, “Auswahl gemeldeter Ereignisse in ausländischen Kernkraftwerken“ in Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Jahresbericht 1997, Kapitel 3.2 “Explosion eines 6-kV-Schalters im Schaltanlagengebäude“, GRS-A-2777, Köln, Germany, March 2000 (in German only).

/NRC 02/ U.S. Nuclear Regulatory Commission (NRC), Metal clad switchgear failures and consequent losses of offsite power, NRC Information Notice 2002-01, January 8, 2002.