Nuclear Safety
NEA/CSNI/R(2013)6
June 2013
www.oecd-nea.org

OECD Fire Project – Topical Report No. 1

Analysis of High Energy Arcing Fault (HEAF) Fire Events

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Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development

25-Jun-2013

English text only

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

OECD FIRE Project - TOPICAL REPORT No. 1
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JT03342348

Complete document available on OLIS in its original format

NEA/CSNI/R(2013)6
Unclassified
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The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

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, as well as
- 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 Committee on the Safety of Nuclear Installations (CSNI) shall be responsible for the activities of the Agency that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations, with the aim of implementing the NEA Strategic Plan for 2011-2016 and the Joint CSNI/CNRA Strategic Plan and Mandates for 2011-2016 in its field of competence.

The Committee shall constitute a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It shall have regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee shall review the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensure that operating experience is appropriately accounted for in its activities. It shall initiate and conduct programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It shall promote the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings, and shall assist in the feedback of the results to participating organisations. The Committee shall ensure that valuable end-products of the technical reviews and analyses are produced and available to members in a timely manner.

The Committee shall focus primarily on the safety aspects of existing power reactors, other nuclear installations and the construction of new power reactors; it shall also consider the safety implications of scientific and technical developments of future reactor designs.

The Committee shall organise its own activities. Furthermore, it shall examine any other matters referred to it by the Steering Committee. It may sponsor specialist meetings and technical working groups to further its objectives. In implementing its programme the Committee shall establish co-operative mechanisms with the Committee on Nuclear Regulatory Activities in order to work with that Committee on matters of common interest, avoiding unnecessary duplications.

The Committee shall also co-operate with the Committee on Radiation Protection and Public Health, the Radioactive Waste Management Committee, the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle and the Nuclear Science Committee on matters of common interest.”

EXECUTIVE SUMMARY

Operating experience from nuclear installations has shown a non-negligible number of reportable events with non-chemical explosions and rapid fires resulting from high energy arcing faults (HEAF) in high voltage equipment such as circuit breakers and switchgears. Such electric arcs have led in some events to partly significant consequences to the environment of these components exceeding typical fire effects. Investigations of this type of events have indicated failures of fire barriers and their elements as well as of fire protection features due to pressure build-up in electric cabinets, transformers and/or compartments.

Due to the high safety significance and importance to nuclear regulators OECD/NEA/CSNI has initiated in 2009 an international activity on ‘High Energy Arcing Faults (HEAF)’ to investigate these phenomena in nuclear power plants in more detail as to better understand fire risk at a nuclear power plants. It is believed that this is better accomplished by an international group that can pool international knowledge and research means.

The main objective of the current analysis is to examine if HEAF is a common phenomenon and how HEAF develops, in order to extend the existing knowledge of this particular fire phenomenon, and to improve electrical safety standards and to design proper preventive measures.

The report presents the results of the analyses of the HEAF events in the OECD FIRE Database **[1].**

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1. INTRODUCTION

The purpose of the OECD FIRE Database Project is to provide a platform for multiple countries to collaborate and exchange fire data and thereby to enhance the knowledge of fire phenomena and in turn improve the quality of risk assessments that require fire related data / knowledge[2]. In the light of this, the project aims to:

1. Collect and analyze fire events in order to prevent fires by better understanding their causes,
2. Provide means to acquire better knowledge (both qualitative and quantitative) of fire phenomena, e.g., by designing the database such that it can support qualitative analyses and the quantification of the data,
3. Develop mechanisms and/or tools to gain feedback of nuclear power plant experience on HEAF events in an efficient manner.

The Topical Reports are developed by members of the OECD participating in the OECD FIRE Database Project. The selections of the topic and of the participant member who is going to undertake the task are agreed upon during the OECD FIRE Database Project meetings.

In the following, a list of proposed topics to be analyzed in the frame of the OECD FIRE Database Project is given:

- Challenging fires in areas relevant to safety, such as switchgear fires, relay room fires, MCR fires;
- High Energy Arcing Fault (HEAF) fire events;
- Combinations of fires and other hazards, such as seismic, flooding, or explosions;
- Fire suppression analysis;
- Rare events;
- Various applications related to, e.g., deterministic fire hazard analysis, Fire PSA;
- Database use in front of the background of modernization projects and changes in regulations.

This Topical Report presents the results of the analyses of the HEAF events in the OECD FIRE Database [1]. It has been developed in line with the OECD FIRE Database Project Quality Assurance (QA) Manual, and terms that are agreed upon.

Previous Topics

This is the first Topical Report to be provided by the OECD FIRE Database Project.

Topics under Discussion

The second Topical Report will provide a comparison of fire protection standards in member countries. A third Topical Report is intended on event combinations of fires and other hazards.

2. OBJECTIVES

From the nuclear safety point of view vital safety systems and/or safety related systems can be damaged severely by HEAF events so that their intended function may be degraded or lost. High energy arcing fault (HEAF) events can produce an arc blast, lead to significant pressure waves and/or cause high speed metal projectiles all of which may impair or damage building systems, structures or components (SSC). Therefore, the objectives of this study are:

- Investigate HEAF fire events in the OECD FIRE Database that have indicated failures of fire barriers and their elements as well as of fire protection features due to pressure build-up in electric cabinets, transformers and/or compartments;
- Determine if HEAF is a common phenomenon and how HEAF develops, in order to extend the existing knowledge of this particular fire phenomenon, and to improve electrical safety standards and to design proper preventive measures;
- Determine if these events provides sufficient insights on HEAF related events to prevent them and to provide a better understanding of their causes.

3. SCOPE

The scope of this Topical Report is to identify:

- The HEAF events in the OECD Nuclear Energy Agency (NEA) fire incident database "OECD FIRE",
- The specific equipment/components involved in the HEAF event,
- The duration of arcing time,
- The rooms where the HEAF event and associated fire (if applicable) took place,
- The interaction of human beings before, during and/or after the HEAF event,
- The effects of the HEAF event on systems and/or components that are electrically connected to the component or equipment in which the HEAF event occurred, and
- To present the results of these events.

4. DEFINITION OF HIGH ENERGY ARCING FAULTS (HEAF)

The following definition has been provided by the OECD/NEA Task Group IAGE (2009)5 on high energy arcing faults (HEAF):

High Energy Arc Faults (HEAF) are energetic or explosive electrical equipment faults characterized by a rapid release of energy in the form of heat, light, vaporized metal and pressure increase due to high current arcs between energized electrical conductors or between energized 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 fire.

The energetic fault scenario consists of two distinct phases, each with its own damage characteristics and detection/suppression response and effectiveness.

- ***First phase:*** short, rapid release of electrical energy which may result in 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.
- ***Second phase, i.e., the ensuing fire(s):*** is treated similar to other postulated fires within the zone of influence.

An arc is a very intense abnormal discharge of electrons between two electrodes that are carrying an electric current. Since arcing is not usually a desirable occurrence, it is described as an “arcing fault”. The arc is created by the flow of electrons through charged particles of gas ions that exist as a result of vaporization of the conductive material.

5. BACKGROUND

The operating experience of nuclear power plants (NPP) and other nuclear facilities has shown a non-negligible number of reportable events with non-chemical explosions and rapidly growing fires resulting from high energy arcing faults (HEAF) having occurred at high voltage components and equipment such as circuit breakers, switchgears or transformers. Such electric arcs have led in some events to partly significant consequences to the environment of these components exceeding typical fire effects. Investigations of this type of events have indicated failures of fire barrier elements and fire protection features due to pressure build-up and/or pressure waves in the electric cabinets, transformers or compartments.

According to international fire testing standards [3] fire barrier elements are designed predominantly against the thermal impact of fires given by the standard fire curve according ISO 834. The pressure build-up due to a HEAF is not considered as fire barrier design load. Several events have identified impairment or failure of fire barrier elements such as fire doors being opened or deformed by a HEAF.

Due to the high safety significance and importance to nuclear regulators, in 2009 OECD/NEA/CSNI has initiated an international activity on ‘High Energy Arcing Faults (HEAF)’ to investigate these phenomena in nuclear power plants in more detail to better understand fire risk at NPP. It is believed that this is better accomplished by an international group that can pool international knowledge and research means.

In order to demonstrate that events resulting from HEAF induced by electric arcs in circuit breakers, switchgears, etc. could exceed typical fire effects the national German database on reportable events as well as the international databases IRS (*I*ncident *R*eporting *S*ystem) and INES (*I*nternational *N*uclear *E*vent *S*cale) provided by IAEA (*I*nternational *A*tomic *E*nergy *A*gency) have been analyzed. That systematic query provided strong indications that a non-negligible number of reportable events with electrically induced explosions and fast fires resulting from HEAF may lead to significant consequences to the environment of the initiating equipment or components.

More detailed investigations of these events have identified failures of fire barriers and fire protection features due to pressure build-up and/or pressure waves in the electric equipment or component in which the HEAF event initiated. These initial findings were underlined by investigations performed by the French Technical Safety Organization IRSN (*I*nstitut de *R*adioprotection et de *S*ûreté *N*ucléaire) in the early 2000s where a very preliminary and coarse probabilistic safety assessment came up with a relatively high rough estimate for the relative contribution of the mentioned mechanisms to the core damage frequency (CDF).

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 barriers such as walls and ceilings and their active elements, e.g. fire doors, fire dampers, penetration seals, etc.) or from fires caused by the HEAF. Such events with high energy faults have high safety significance and may have the potential of event sequences strongly affecting the core damage frequency as outlined in the French case.

International operating experience of nuclear power plants and other nuclear installations, such as reprocessing plants, reveals reportable HEAF events [4] in the past, which were e.g. induced by electric arcs in circuit breakers, etc. Some of these have resulted in safety significant effects on the environment of these components exceeding typical fire effects. This type of information will form the basis of the state-of-the-art report.

Different expert institutions have meanwhile carried out investigations regarding those events indicating failures of fire barrier elements as well as of other fire protection features resulting mainly from the pressure build-up, e.g. in the electric cabinets, and/or pressure waves (cf. [4]) as well as damage of components by missiles [5]. It became obvious that a variety of structures and components may be affected in case of HEAF events by the pressure increase and/or pressure waves, such as (fire) doors, fire dampers, penetrations seals and barriers, e.g. walls and ceilings.

As a result of the evaluation of the above mentioned international databases IRS and INES, it appeared reasonable to develop a questionnaire that should provide a list of questions, which mainly shall be answered by the licensees. This questionnaire should provide insights on the basic phenomena for HEAF and allow the evaluation of such events as well as the identification of preventive measures in the future.

Such a questionnaire [4] and [6] has been developed under the lead of German experts from GRS on behalf of the Federal German regulatory body and from Germanischer Lloyd (GL) Bautechnik GmbH working on behalf of a local state authority with the aim to collect the necessary data as a prerequisite for assessing the PSA significance of HEAF events. The respective analysis has been performed on a national basis. The German query provided the following results:

- HEAF typically occur at specific components such as switchgears, transformers, electric cabinets, cables, connecting boxes and circuit breakers at voltage levels between 0.4 kV and 400 kV. High energy switchgears and circuit breakers account for approx. 60 % of the German HEAF events; the contribution of transformers is about 10 %.
- HEAF events, which occurred in German NPP, were immediately detected by fire detection and alarm systems. In particular, relevant smoke release was detected by the fixed fire detection systems. One third of the HEAF events resulted in a fire.
- Only in few cases the damage was not limited to the component where the HEAF occurred. Explosions initiated by the HEAF did neither impair components or plant areas other than those where the event started nor the required function of fire protection features.
- Technical causes as well as human factor (HF) performance, mistakes in procedures and ageing represent the root causes of HEAF events observed in German nuclear power plants.
- Some reasonable measures against recurrence of high energetic component faults have been or are being implemented by the German NPP licensees.

- Failure of high voltage ($\geq$ 10 kV) circuit breakers and switchgears 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 electrical buildings of German NPP.

The operating experience from nuclear installations in OECD/NEA member countries collected in a database has been analyzed in more detail. The state-of-the-art with respect to high energy faults of electrical components and equipment to be investigated shall be evaluated. In particular, the potential effects on specific plant areas and the plant partitioning, on components and fire protection equipment in the near vicinity of the HEAF components that may exceed the typical well known fire effects such as heat, smoke, and soot, shall be identified.

The insights of these investigations shall be generically processed and the feedback from the national as well as international operating experience be forwarded to the licensing and supervisory authorities as well as to the licensees.

The arc accompanying an HEAF produces tremendous amounts of energy and can cause substantial fires, pressure build-up and injury to personnel. The significant energy released in the fault of a high voltage component rapidly vaporizes the metal conductors involved and can destroy the equipment involved. The intense radiant heat produced by the arc may cause significant destructions. Additionally, fires can be induced as a result of the HEAF in adjacent components and/or equipment with combustibles.

From a nuclear safety point of view vital safety systems and/or safety related systems can be damaged severely by a HEAF event so that their intended function may be degraded or lost. High energy arcing faults can produce an arc blast, and lead to significant pressure waves with the capacity to damage or destroy elements of the building structures. They can also cause high speed metal projectiles impairing safety related equipment and/or structural elements, hence causing damage and injury or even death.

6. RESULTS FROM THE OECD FIRE DATABASE WITH RESPECT TO HEAF

6.1 Identification of HEAF Fire Events in the OECD FIRE Database

A list of HEAF events with fire identified in the OECD FIRE Database [1] is presented below in Table 6-1. The identification of such events is based on the definition of HEAF accepted for this task. The examination of the OECD FIRE Database (cf. [1]) has indicated a non-negligible contribution of 48 out of the in total 415 fire events collected in the Database up to mid-2012 representing HEAF induced fire events. Details can be found in Table 6-1.

At the time being, the existing data base on HEAF fire events in nuclear installations is still too small for a meaningful statistical evaluation. 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.

Table 6-1: HEAF events in the OECD FIRE Database [1]

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
CAN002	20050415	Unit 6 forced outage due to M.O.T. failure	PHWR	FP	high voltage transformer	500 kV	switchyard, switchgear room	flammable liquid (transformer insulating oil)	yes	no	fixed extinguishing system, automatically actuated	< 00:08
CAN004	20051015	Electrical arc resulting in injury	PHWR	LPSD	low voltage electrical cabinet	600 V	electrical building, switchgear room	cable insulation materials	yes	no	on-site plant fire brigade	< 00:05
CZE003	19940203	Fire of the station service load transformer 3BT02 caused by a defect on the power part of the branch lines switch followed by an explosion	PWR	FP	medium and low voltage transformer - oil filled	15.75 kV / 6 kV	outside the plant, not switchyard, voltage transformers near to main transformer	flammable liquid	no	no	on-site plant fire brigade	00:16
CZE003	20100217	Fire at 0.4 kV switchgear	PWR	FP	switchgear	0.4 kV	electrical building, switchgear room	cable insulation materials	yes	no	on-site plant fire brigade	00:05
FIN001	19910412	Fire at 6.6 kV switchgear	BWR	FP	electrical cabinet, high or medium voltage (current transformer inside cabinet)	6.6 kV	electrical building, switchgear room	cable insulation materials, other insulations	no (multiple components)	no	on-site plant fire brigade	00:37

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
FIN002	20060927	Voltage transformer fire due to human error during maintenance outage	PWR	LPSD	medium or low voltage transformer - oil filled	15.1 kV	outside the plant (not switch yard), voltage transformers near to main transformer	hardly inflammable liquid,; other insulations	no (multiple components)	no	on-site plant fire brigade (one fire); self-extinguished (another fire)	00:05
FRA008	20010119	Incipient fire on ultimate emergency diesel generator	PWR	FP	high or medium voltage electrical cabinet	6.6 kV	diesel generator building, electrical / process room	other insulations, plastics / polymeric materials	no (multiple components)	no	self-extinguished	00:05
FRA012	20100725	Automatic shutdown of the reactor following an explosion and a consequential fire on the main power transformer	PWR	FP	high voltage transformer (main transformer)	225 kV	switchyard (transformer room / bunker)	hardly inflammable liquid, cable	no	no	fixed extinguishing system, automatically actuated; on-site plant fire brigade; external fire brigade participated	02:45
FRA022	20010918	Loss of 400 kV power supply following a fire in the 6.6 kV AC normal distribution system cubicle	PWR	LPSD	high or medium voltage electrical cabinet	6.6 kV	electrical building, switchgear room	hardly inflammable liquid, plastics / polymeric materials	no (multiple components)	yes	shift personnel; external fire brigade participated	01:11

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
FRA024	20030830	Explosion of an oil-filled current transformer leading to a fire in the 400 kV platform	GCR	FP	high voltage transformer (current transformer)	6.6 kV / 400 kV	switchyard	hardly inflammable liquid	no	no	fixed extinguishing system, manually actuated; shift personnel; external fire brigade participated	00:48
FRA035	20040929	Electric fault on the main transformer leading to a reactor trip	PWR	LPSD (SU)	high voltage transformer (main transformer)	> 50 kV	other building	cable insulation materials	yes	no	shift personnel	00:20
FRA042	19901030	Loss of a 6.6 kV emergency switchboard.	PWR	FP	high or medium voltage electrical cabinet	6.6 kV	electrical building, switchgear room	cable insulation materials	yes	no	shift personnel	00:07
GER001	19890908	Short circuit in the auxiliary electrical system	PWR	LPSD	high voltage switchgear (10 kV injection cell); circuit breaker	10 kV	electrical building, switchgear room	cable insulation materials; plastics / polymeric materials	no (multiple components)	no	on-site plant fire brigade	00:26
GER003	20080314	Fire in a circuit breaker and switch-off of the emergency busbar FB	PWR	FP	high voltage circuit breaker	660 V	electrical building, switchgear room	plastics / polymeric materials	yes	no	on-site plant fire brigade	00:34

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
GER009	20021030	HEAF with consequential fire occurred by exchange of a 0.4 kV switchgear subassembly	BWR	FP	switchgear	400 V	electrical building, room for electrical control equipment	cable insulation materials	no	no	self-extinguished	< 00:03
GER009	20040823	Failure in the auxiliary power supply with consequential reactor scram	BWR	FP	high voltage cable	10 kV	outside the plant, not switchyard, other cable room	cable insulation materials	no	no	self-extinguished	n. a.
GER011	19860530	Damage of the 380 V busbar CR (auxiliary power supply of train 4) by a fire	PWR	LPSD	bus bar	380 V	electrical building, cable spreading room	cable insulation materials; other insulations	no	no	on-site plant fire brigade	00:25
GER014	20070628	Reactor trip caused by a temporary loss of station service supply due to a short circuit with a subsequent fire in a generator transformer	BWR	FP	high voltage transformer (main transformer)	400 kV	other building / area, other type of room	flammable liquid, paper, wood	yes	no	fixed extinguishing system, automatically actuated; on-site plant fire brigade; external fire brigade participated	06:58
GER017	19960208	Disconnection of a main bus due to a short circuit in a switching module	PWR	FP	electrical cabinet (busbar, breaker subassembly)	500 V	auxiliary building, switchgear room	cable insulation materials	yes	no	on-site plant fire brigade	00:17
GER017	20020811	Fire in the 500 V switchgear of one train of the independent emergency system	PWR	FP	switchgear	500 V	independent emergency building, switchgear room	cable insulation materials	no	no	on-site plant fire brigade	01:25

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriora ted	Extinguished by (all means involved)	Duration [h:min]
GER022	19870909	Short circuit in the exciter system of an emergency diesel generator unit	BWR	FP	high or medium voltage electrical cabinet (emergency diesel)	unknown	electrical building, switchgear room	cable insulation materials	yes	yes	on-site plant fire brigade	00:09
GER024	19880419	Short circuit in the 220 kV/380 kV switchgear with consequential loss of offsite power	PWR	FP	high voltage switchgear	220 kV	switchyard	hardly inflammable liquid	yes	no	on-site plant fire brigade	00:46
GER025	19890517	Electric arc at a feeder control panel in the 380 V switchgear	PWR	LPSD	switchgear (380 V switchgear, injection area)	380 V	electrical building, switchgear room	cable insulation materials	yes	no	people available in the fire area	00:12
GER027	19790811	High energy electric arc at circuit breaker and isolator	PWR	LPSD	circuit breaker (sub-distribution board)	…	auxiliary building, room for ventilation	cable insulation materials	yes	no	self-extinguished	unknown
JPN022	20110311	Seismic induced arcing fault in non-emergency metal clad (M/C) switchgear cabinet	BWR	FP	high or medium voltage electrical cabinet	6.9 kV	turbine building, switchgear room	cable insulation materials	no	no	on-site fire brigade	07:58
JPN029	19960907	Fire of the bus-duct in the power supply room for the emergency diesel generator	BWR	LPSD (hot stand-by)	bus duct	460 V	reactor building, EDG switchgear room	cable insulation materials	no	no	shift personnel; external fire brigade participated	00:42

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
JPN044	19850831	Fire at the cabinet containing 6.9 kV bus for start-up	BWR	LPSD	high or medium voltage electrical cabinet	6.9 kV	turbine building, switchgear room	cable insulation materials	yes	no	fixed extinguishing system, manually actuated; external fire brigade participated	02:14
JPN047	20070716	House transformer fire induced by the Niigata-Chuetsu-Oki earthquake	BWR	FP	medium or low voltage transformer - oil filled	19 kV / 6.9 kV	outside	flammable liquid	yes	no	fixed extinguishing system, manually actuated; external fire brigade participated	01:55
KOR001	20020422	Fire on the main transformer leading to a generator trip	PWR	FP	high voltage transformer (main transformer)	> 50 kV	outside	flammable liquid	yes	no	fixed extinguishing system, automatically actuated,	00:13
KOR010	20010130	High energy arcing fault on phase ‘B’ of the main transformer which led to the reactor trip	PWR	FP	high voltage transformer (main transformer)	22/345kV	outside plant buildings	insulation material	yes	no	self-extinguished	00:00

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriora ted	Extinguished by (all means involved)	Duration [h:min]
SPN001	19880622	Trip of main transformer, followed by fire in phase "S" due to manufacturing defect. Subsequently, turbine trip and, with permissive P-7, reactor trip	PWR	FP	high voltage transformer (main transformer)	20 kV / 400 kV	outside plant buildings (not switchyard)	hardly inflammable liquid	yes	no	fixed extinguishing system, actuated; on-site plant fire brigade; shift personnel	00:58
SPN001	19880820	Trip of main transformer, followed by fire in phase "S" due to manufacturing defect. Subsequently, turbine trip and, with permissive P-7, reactor trip	PWR	FP	high voltage transformer (main transformer)	20 kV / 400 kV	outside plant buildings (not switchyard)	hardly inflammable liquid	yes	no	fixed extinguishing system, actuated; on-site plant fire brigade; shift personnel	00:15
SPN001	19881202	Main transformer tripped, followed by fire in phase "R"	PWR	LPSD (SU)	high voltage transformer (main transformer)	20 kV / 400 kV	outside plant buildings (not switchyard)	hardly inflammable liquid	yes	no	fixed extinguishing system, actuated; on-site plant fire brigade; shift personnel	
SWD007	20021030	Auto fire alarm about an arc event in a rectifier. The failure led to stop of one turbine, after the generator started emitting	BWR	FP	rectifier	600 V	turbine building, process room	other solid material; plastics / polymeric materials	no (multiple components)	no	on-site plant fire brigade; external fire brigade participated	02:31

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
SWD007	20060915	Fire in a 6 kV electrical cabinet in room D2.21, cabinet feed power to the pump 725 P1. A breaker in the cabinet is burning	BWR	LPSD	electrically driven pump	6 kV	turbine building, process room	other solid material	no	no	on-site plant fire brigade	01:05
SWD008	20110510	Fire in the reactor containment: Arc in an electrical part in the portable vacuum cleaner	PWR	LPSD	vacuum cleaner	unknown	containment	plastics / polymeric materials	no	no	self - extinguished	unknown
SWD010	20061114	Fire in transformer supplying the 6 kV on-site electrical systems train A and C from the generator 20 kV busbar c	PWR	FP	medium or low voltage transformer - oil filled	6 kV / 20 kV	outside plant buildings	hardly inflammable liquid	no	yes	on-site plant fire brigade; external fire brigade participated	02:40:00
USA027	20100328	Plant trip due to electrical fault	PWR	FP	cable run (self-ignited): power cables	4 kV	turbine building	cable insulation material	no	no	on-site plant fire brigade; people available in the fire area	00:15
USA034	20040618	Iso-phase bus duct two-phase electrical fault and fire with secondary fires	BWR	FP	bus duct	22 kV	turbine building and outdoors	flammable liquid, hydrogen; other solid material	no	no	fixed extinguishing system, on-site plant fire brigade, external fire brigade participated	00:37

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
USA036	20000515	Unit 1 unusual event due to a 12 kV bus fault and fire	PWR	FP	busbar / bus duct	12 kV	auxiliary building, switchgear room	other solid material; plastics / polymeric materials	yes	no	on-site plant fire brigade	01:18
USA039	19991009	Undervoltage actuation due to a loss of reserve station service transformer	PWR	FP	busbar	4.16 kV	outside turbine building	cable connector / insulation materials	yes	no	on-site plant fire brigade	00:09
USA041	19990105	Unit main transformer fault and fire	PWR	FP	high voltage transformer (main transformer)	> 50 kV	transformer yard	hardly inflammable liquid	yes	no	on-site plant fire brigade	00:14
USA043	20070406	Automatic reactor trip due to a turbine generator trip caused by a fault on the 31 main transformer phase B high voltage bushing	PWR	FP	high voltage transformer	34.5 kV	transformer yard	hardly inflammable liquid	yes	no	on-site plant fire brigade	00:12
USA059	20020612	Switchyard fire in 34.5 kV circuit breaker	PWR	FP	high voltage breaker	34.5 kV	switchyard	flammable liquid	yes	no	on-site plant fire brigade	unknown
USA064	20051029	Reactor trip due to main transformer fault and fire	BWR	FP	high voltage transformer	> 50 kV	outside the plant building (not switchyard), main transformer	hardly inflammable liquid	yes	no	fixed extinguishing system; on-site plant fire brigade	unknown
USA066	20061212	Automatic reactor trip due to circulating water pump surge capacitor failure	PWR	FP	electrically driven pump	12 kV	intake building, process room	capacitor, insulation material	yes	no	on-site plant fire brigade	00:34

Plant	Date	Event Title	Plant Type	Plant State	Component	Voltage Level	Location	Fuel	Damage limited to initial component	Barrier deteriorated	Extinguished by (all means involved)	Duration [h:min]
USA086	20010203	Fire and RPS/ESF actuations caused by the failure of a non-safety related 4.16 kV circuit breaker	PWR	FP	circuit breaker	4.16 kV	turbine switchgear room	cable insulation, solid materials	no	no	on-site plant fire brigade, external fire brigade participated	2:57
USA095	20021003	Failure of start-up transformer ST 20	BWR	LPSD (SU)	high voltage transformer	> 50 kV	transformer yard	hardly inflammable liquid	yes	no	fixed extinguishing system	< 00:10

Abbreviations:

PWR: pressurized water reactor ***BWR:*** boiling water reactor
PHWR: pressurized heavy water reactor ***GCR:*** gas cooled reactor
GR: graphite-moderated reactor ***FP:*** full power operational states (> 5 %)
LPSD: low power and shutdown operational states ***SU:*** start-up mode (cf. Coding Guidelines)

6.2 Details on the HEAF Events Identified in the OECD FIRE Database

6.2.1 Event 1 – CAN002 – 20050415

On April 2005, a Turbine tripped due to an electrical fault and fire on the Main Output Transformer (MOT). A catastrophic failure occurred on the blue phase winding of the MOT with simultaneous catastrophic failure to red phase isolated phase bus potential transformer (surge arrester) cubicle (explosion but no fire). The fire was extinguished by transformer deluge system.

The reactor was manually shut down following notification of the event. Due to rupture of transformer casing, 68, 200 L of transformer insulating oil spilled to environment over 1 - 2 hours. Prior to MOT failure, there were no indications (alarms, adverse temperature trends) in the MCR of anything wrong with transformer. Semi-annual oil analysis indicated normal results. GE Hydran gas-in-oil monitor did not indicate significant gas increase until failure occurred. There were no switching/transients on the grid system immediately prior to failure. The Blue phase winding had been overhauled in 2000.

Root Cause Analysis: available evidence points to material failure in the MOT, forensic disassembly was arranged to determine failure mode, red phase surge protector failure caused by voltage surge introduced by voltage imbalance/repetitive arc strikes caused by blue phase failure. Unable to dissipate generated heat, underwent failure, pressure of which removed doors from transformer cubicle, deformed cubicle, opened fused links.

6.2.2 Event 2 – CAN004 – 20051015

On October 2005, an Electrical arc / fireball occurred when a 600 V AC 1600 A Class 4 breaker (6-53300-CB3C) was racked into its cubicle. As the breaker was moved to the connect position, an electrical fault occurred which resulted in a catastrophic failure of the breaker. Failure caused an electrical arc and fireball to erupt from the switchgear with burns sustained to the employee. As 6-53300-CB3C was tie breaker between Class 4 buses 6-53300-BUC and -BUF, electrical protection trips occurred on these buses. The employee was moved and treated for 1st and 2nd degree burns on the thighs. The fire was immediately extinguished by emergency response team. Breaker had been repaired and tested three times in the test position before permission was obtained from the ANO to rack it to the connect position. The breaker compartment door was in place and screws were engaged at the time of breaker failure; hot gases and flames vented through louvers to burn employee.

Corrective Actions, many improvements to protocol and equipment design and verification processes implemented. Shutter (prevents inadvertent contact b/w component and buses during maintenance) design improvement opportunities jointly investigated by manufacturer / Engineered materials/manager-supply chain, broken shutters to be removed from breaker cabinet, staff training on technical advice verification, team of electrical experts assembled to address inadequacy of protective clothes in such an event, emergency communication protocol improved.

6.2.3 Event 3 – CZE003 – 19940203

On February 3, 1994 at 7:14 h a HEAF event with explosion followed by the fire occurred on the transformer to supply house load of the unit 3 of a Czech nuclear power plant during full power operation.

The 15.75 kV / 6 kV transformer failure caused an outage of the 400 kV power line. The unit was then powered from the reserve power supply. The reactor was gradually shut down by operator according the emergency response plan.

Fire fighting was started at 7:19 h by NPP on-site fire brigade. At 7:30 h the fire was under control.

A very small leakage (approx. 16 kg) of oil diluted with extinguishing agents into the environment occurred after the event.

The probable cause was the fault of the power contacts of the branch switch of the transformer. HEAF was created between phases L1 and L3 before total short circuit. As a result of the failure a large amount of heat was released, followed by the explosion. Part of the transformer vessel was destroyed and branch switch particles were ejected from the transformer.

6.2.4 Event 4 – CZE003– 20100217

On February 17, 2010 at 12:37 h a HEAF event followed by fire occurred at the 0.4 kV switchgear of the unit 3 of a Czech nuclear power plant during the operation at 98 % of full power.

The fire of the switchgear did not affect the operation of the unit or other equipment and had no significant safety impact. The fire was extinguished by the on-site fire brigade of NPP 5 min after its occurrence. The damaged switchgear was repaired within two days.

The fire occurred after an inter-phase short circuit in the busbar compartment of the switchgear. According to the nature of damage to switchgear equipment the short circuit and subsequent arc (HEAF) were initiated inside the circuit breaker.

Based on a detailed examination and dismantling of equipment the failure was detected in the internal power contacts of circuit breaker. The insulation was overheated and degraded due to imperfect contact between the phases inside the circuit breaker followed by HEAF.

The arc and the fumes did not extend beyond the electrical bus of the switchgear. The design of the switchgear showed sufficient separation of the electrical buses and resilience against the arc.

The root cause of the incident was inappropriate conduct of regular thermo vision controls. Thermo vision control of the affected terminals 0.4 kV was not applied under load and it was not possible to detect any deterioration of the terminals.

6.2.5 Event 5 – FIN001 – 19910412

On April 12, 1991, a severe electric arc and fire took place in a 6.6 kV house load switchgear cabinet during power operation.

The power measurement of one 6.6 kV house load switchgear indicated a faulty value and the personnel started to examine the reason. Some damaged terminal blocks / overheated connections were detected in the secondary circuit of the current transformer. In order to disconnect the damaged terminal blocks, the power supply to the busbar was connected to the 110 kV grid (via start-up transformer). As the terminal block replacement was started, the equipment in the switchgear cubicle started to smoke and the fire brigade was alarmed. An electrician informed the main control room about the situation and all house load switchgears were connected to be supplied from the 110 kV grid and shutdown of the plant was prepared.

Due to the smoke generated inside the switchgear cabinet an electric arc occurred and caused a fire. The overload protection device opened the circuit breaker feeding the switchgear. The plant transformer's overload protection tripped the generator relay protection, which led to a turbine trip. One diesel generator started up as designed and provided power to the associated safety related busbar, which lost normal power supply via the damaged 6.6 kV switchgear. Later on, the fire/smoke spread to the neighboring cubicle containing the cable terminal from the start-up transformer (the breaker itself was opened due to the overload protection) and caused a short circuit by arcing: the differential protection device of the start-up transformer opened 1) all circuit breakers still supplying the 6.6 kV house load busbars and also 2) the breaker in the primary side of the start-up transformer, leading to total loss of supply from the grid. In these conditions, the turbine’s condenser system was not available any more resulting in the reactor scram. After loss of supply from the grid, three additional diesel generators started and provided power to the safety related switchgears, as designed.

The fire brigade extinguished the fire using manual extinguishers, within about 30 min. The extinguishing was hampered by the uncertainty about potential voltage inside the switchgear cubicles. Furthermore, the closed structure of the cubicles hampered extinguishing. Three cubicles were destroyed almost totally and one cubicle was destroyed partially.

After the fire was extinguished, efforts to regain external supply from the 110 kV to the three not affected 6.6 kV house load switchgears were started. Before regaining voltage, the failed busbar had to be separated from the transformers by opening the terminals of the connecting cables at the transformers (the cable terminal was destroyed inside the ignited switchgear). The work took approximately 6.5 h including cleaning of the one switchgear which was located in the same room with the ignited one. Then the two house load switchgears were re-connected to the 110 kV grid. The third house load switchgear was connected to the external grid on April 16, 1991.

The initial cause for the event was a break in a current transformer’s secondary circuit causing overheating of the terminal blocks and later on a short circuit in a neighboring voltage transformer’s circuit, which started to smoke and ionized the air inside the cubicle. The smoke was able to spread also into the neighboring cubicles in the same row causing another electric arc inside that cabinet. The initial break in the current transformer’s secondary circuit was assumed to occur in connection with relay testing during the annual maintenance outage in 1990.

Corrective actions:

- The damaged switchgear was restored with new cubicles and cables.
- The maintenance of switchgears was improved.
- Second start-up transformer was installed and disconnectors were mounted in the supply connections to reduce vulnerability of the power supply from start-up transformer.
- Fixed CO_2 extinguishing systems were installed into the switchgears.
- Separation walls between the switchgear cubicles were improved.
- Generator breaker was replaced.

6.2.6 Event 6 – FIN002 – 20060927

On September 27, 2006, a short circuit, an electric arc and an explosion occurred, affecting voltage transformers connected to the 15 kV busbars between generator and main transformer.

Refueling outage of the unit was ongoing on September 27, 2006 (cold shutdown). The electric power was supplied via the reserve auxiliary transformer (110/6 kV). After the maintenance, the main transformer #2 was connected to the 400 kV grid at 15:21:34 h and the auxiliary transformer #2 became energized, as well. Approximately 30 s prior to this, several signals on shorts to ground came up and were gone during 1 s until the short to ground protection triggered at 15:21:05h. The short to ground protection aims to disconnect the main transformer only from the generator's side; it worked as designed. However, the generator breaker was not needed to be disconnected, as it was already in the open position. Further on, the short to ground alarm and protection came up and went away during the next 2 min. Finally, at 15:35:37 h, the differential protection was actuated and the main transformer #2 was disconnected from the 400 kV grid, which de-energized also the auxiliary transformer #2. Disconnection of the main transformer generated an automatic fire warning at about 15:40 h and triggered an alarm for the on-site fire brigade.

One minute after the automatic alarm (at 15:41 h), the fire brigade received a fire alarm from the plant's security center. Plant personnel arriving to the site had notified the security center on a fire near the auxiliary transformer. On arrival to the fire location (at 15:43 h), the firemen noticed smoke and flames between the main and auxiliary transformer. The flames died out quickly and after assuring the main transformer was de-energized, the firemen extinguished a small oil pool fire using a portable CO_2 fire extinguisher (at 15:45 h). The extinguished fire was located on one of the three protective casings containing the voltage transformers below the generator busbars (the busbars' voltage level is about 15 kV), the fire occurred about 4 m above the ground level. The firemen isolated the area and protective foam was laid on the oil, which had leaked down on the yard (approx. 20 l). Some oil remained also inside the protective casings and it was absorbed. The firemen returned to the plant fire station at 17:10 h.

Two out of the three voltage transformers had exploded and transformer oil as well as insulation material had caught fire. All three voltage transformers and part of the capacitors and overvoltage protectors located inside the protective casings were badly damaged. The protective casings made of thin steel plate suffered mechanical damages due to the explosion caused by an electric arc. Some smithereens of the insulators of the overvoltage protectors were found approximately 30 m away from the protective casings. The main and auxiliary transformers are located just a few meters away from the scene, but they were not damaged. No damages occurred due to smoke or secondary effects. The incident did not affect power supply of the unit, because a reserve auxiliary transformer was in use.

The cause for the incident was a human error during the maintenance outage (the ground wire was mounted erroneously in the voltage transformer of the Phase R forming a short circuit in the secondary side of the voltage transformers, which caused overheating of the equipment and finally, a high voltage short circuit / electric arc / explosion occurred and the differential protection actuated). As corrective actions, procedure modifications were done and the importance of adequate post-maintenance inspections was highlighted. The area to be isolated around the main transformer was decided to be enlarged due to the smithereens being found 30 m away (this refers to the situation when the main transformer is to be energized after maintenance).

There are two main transformers and two auxiliary transformers per unit located on the yard next to the turbine building. These are equipped with an automatic water extinguishing system. However, the location of the failed components and fire is not covered by any fire detection or extinguishing system.

6.2.7 Event 7 – FRA008 – 20010119

On January 19, 2001, a HEAF event occurred at a French plant with PWR in the electrical room of the diesel generator building of the nuclear power plant.

At the time of the event, a periodical test of the ultimate emergency diesel generator set (6.6 kV Emergency Supplied Distribution System) was in progress. The ultimate emergency diesel generator set was coupled with a test load. It worked for 45 minutes and the load was two times 700 kW.

The auxiliary operator heard the diesel speed falling off, then a noise sounding like an explosion, and the generator set completely stopped. He came to the electrical room and saw smoke coming from the doors of the 6.6 kV cubicle. Then he immediately called for emergency. Five minutes later, a member of the second line response team arrived, opened the door, and noticed the presence of smoke, but the fire seemed to be extinguished. Then he called for the external fire brigade.

As the power cut had made the fire detection unavailable, the fuel tank was drained to minimize the risk. Concerning the diesel generator set, one phase was out of order, another was damaged and one isolator had to be replaced. Concerning the test load, two phases were out of order and all the isolators had to be replaced.

6.2.8 Event 8 – FRA012 – 20100725

On July 25, 2010, at 01:14, a HEAF event with explosion and consequential fire occurred on the main power transformer of the unit 2 of a French nuclear power plant during full power operation.

The loss of unit power supply by the step-down transformer caused the automatic switchover of 6.6 kV switchboards on the auxiliary transformer. It caused an automatic shutdown of the reactor by low speed of primary coolant pump. The internal emergency plan was launched due to the fire.

The spraying start-up made it possible to contain the fire in the pole compartment.

It was impossible to clarify the root causes. However, there were indications of a potential fault of the bushing of the main power transformer resulting in the formation of an electrical arc. It was assumed that bushing insulation was affected before the incident, which probably might result from CU2S attack. Presence of copper sulfide is not explained.

6.2.9 Event 9 – FRA022 – 20010918

On September 18, 2001, the reactor was in refueling shutdown. At about 04.04, the first primary coolant pump was started up. Immediately, the alarms concerning the 6.6 kV AC Normal Distribution System's switchboard and the 6.6 kV AC Normal Distribution System's overcurrent defaults appeared. A few minutes later, fire alarms regarding areas 405, 406 and 407 (7 m level, switchboards of trains A and B) started. The presence of smoke was noted.

The first line response team was instantly sent to confirm the fire, then the security instruction was put into practice, and the second line response team (which has a specific fire fighting formation) and the external fire brigade were called. The second line response team tried to put out the fire with three CO_2 fire extinguishers, which they finally achieved with the help of the firemen and a dry chemical fire extinguisher.

The internal emergency plan was launched short time after. The fire was due to the roller and cage assembly ensuring the electric mobile contact: the contact degradation led to a short circuit current in the circuit breaker, and the oil vaporization caused the cubicle's fire. Then the oil breaker exploded and the fire doors were damaged by the blast. The 400 kV power supply became unavailable and this caused a switchover to the 225 kV power supply.

In order to avoid a similar incident, a contact resistance measurement will be systematically taken after each maintenance inspection.

6.2.10 Event 10 – FRA024 – 20030830

On August 30, 2003, unit 2 of the affected plant site was at full power operation, when arcing occurred between the primary and the body of the oil-filled current transformer, which is on the 400 kV platform at the principal transformer outlet. The internal electric arc set fire to the oil, then the gas formation increased the pressure in the transformer, leading to the cover ejection, and oil combustion caused a fire.

Then a voltage regulator's default caused a main generator excitation power switching, and some 6.6 kV AC normal distribution system's boards were off, leading to a slowing down of the primary motor-driven pumps, and eventually to the reactor automatic shutdown because of low flow.

The electric fault was detected by the 400 kV energy evacuation surveillance protections. By switching to the 225 kV power supply, the reactor state changed to normal shutdown. This incident made the unit unavailable for two weeks and it might have hurt some people because of fire and ceramic fragments projectiles due to the explosion.

Following the incident, the ground area covered by oil had to be excavated, the three current transformers of unit 2 and a circuit breaker's pole had to be replaced, and the 24 kV coaxial skirts had to be repaired.

In order to avoid another similar incident, a control program of the unit 1 transformers was implemented and the unit 2 alternator voltage regulation was controlled.

The transformer explosion is probably a precursor according to PSA analysis.

6.2.11 Event 11 – FRA035 – 20040929

On September 29, 2004, a HEAF event occurred at a French plant with PWR in the main power transformer of the nuclear power plant, leading to a reactor trip. At the time of the event, the plant was in start-up mode, being connected.

A technical fault appeared at 01:40 h on the generator excitation and voltage regulation system. Two workshop technicians went in local and noticed heavy smoke generation coming from the main power transformer, and an electric arc on the poles of the transformer. They immediately called the control room to ask:

- to draw out of the transformer,
- to send the second intervention team,
- to call the external fire brigade.

At 01:43 h, the unit was disconnected from the grid, and a partial internal emergency plan was launched. One of the operators remained on site to perform the first intervention agent operations.

At 02:00 h, the second intervention team joined the agent, remained in local and preceded to the extinguishing of the fire, using a dry chemical extinguisher. The external fire brigade arrived 13 minutes later, but the fire has already been mastered. They installed fire fighting means for safety and inspected the fire site, to confirm everything was under control.

Finally, at 03:33 h, external helps departed and surveillance was maintained by internal agents until working hours.

The unit was put in hot shutdown mode at 04:40 h.

6.2.12 Event 12 – FRA042 – 19901030

On October 30, 1990, a HEAF event with explosion and consequential fire occurred in the electric building of a PWR plant during full power operation.

At 14:35 h, an electric arc occurred on one of the poles of a LHB contactor, supplying an essential service water system pump, and resulted in a cell explosion and fire in the emergency switchboard, leading to its destruction. LHB is the train B 6.6 kV AC emergency supplied distribution system.

A previous electrical event on the same switchboard occurred 20 min before the explosion. Due to this previous event, operating staff was in the LHB switchboard room before the second event. They were therefore able to notice the loud explosion noise in the switchboard, and to fight the fire right away. The operating crew had to cope with a situation not covered by the existing operation procedures (offsite power supply available with LHB switchboard unavailable), aggravated by a fire in a switchboard.

At 14:43 h, the unit was placed in intermediate shutdown, and RHR (shutdown cooling circuit) was connected to the primary circuit as soon as the operator extinguished the fire. At 20:17 h, the operator requested technical assistance from the Thermal Production Service (SPT) of the licensee in order to identify the safe state adapted to the situation. At around 23:15 h, the situation was under control and contacts with SPT were ended.

As a corrective action, all damper washers on contactors that had been in service for more than five years have been changed on all sites. In addition, new covers with ventilation slots for cooling the washers have been installed. Moreover, the very sensible-to-ageing washers, made of "vulkollan polyurethane", have been replaced by "Adiprene polyurethane" by the manufacturer.

Finally, concerning the loss of an emergency supplied distribution system (train A or B) a corrective procedure has been created while external power supply is still available.

6.2.13 Event 13 – GER001 – 19890908

On September 8, 1989, a HEAF event occurred at a German plant with PWR at high voltage switchgear in the electrical building. At the time of the event the plant was in a refueling outage (low power and shutdown plant operational state). When the 220 kV grid was connected, an electrical arc developed in the injection port of a 10 kV switchgear belonging to the auxiliary electrical system. Six seconds later the main feeder breaker (220 kV) opened. The electrical arc led to a smoldering fire which was extinguished by the local on-site fire brigade within 15 min (23 min according to another reference) by using portable dry chemical and CO_2 fire extinguishers. The auxiliary power supply of the plant was not affected, because the busbar was disconnected due to maintenance work.

6.2.14 Event 14 – GER003 – 20080314

The most recent German HEAF event resulting in a fire occurred at a pressurized water reactor (PWR) type plant in March 2008 inside a room of one redundant train in the electrical building during power operation. After an electric current measurement including switching on and off the high pressure discharge pump of the chemical and volume control system (CVCS), the CVCS system was to be brought back to normal operation. The measurement was performed at a subassembly (plug-in module) of a high voltage circuit breaker (660 V, 420 A) of the emergency busbar. For a final functional test the pump was again switched on, but could not be switched off again from the unit control room.

A longer lasting electric arc (approx. 6 min) in the circuit breaker of one of the discharge pumps of the operational CVCS resulted in an overcurrent of max. 2.5 kA and a smoldering fire in the subassembly detected by an automatic smoke detector. The fire was directly verified and the busbar was switched off to limit the damage. The fire was extinguished by the on-site fire brigade by means of portable fire extinguishers within approx. 30 min.

Since the affected busbar also supplies components of one safety train for residual heat removal, these became unavailable, too. At the same time, the emergency power supply of the emergency diesel generator of another redundant train was disconnected for maintenance. The maintenance activities were stopped and the respective emergency power supply train normalized within 18 min.

As corrective measures against recurrence increased controls with respect to impurities in case of breaker exchange and training of the personnel are being carried out.

6.2.15 Event 15 – GER009 – 20040823

A high energy arcing fault event initiated by a spontaneous short circuit of some seconds duration occurred in a 10 kV cable at a BWR type plant built to earlier standards on August 23, 2004 resulting in an overcurrent of approx. 30 to 35 kA during full power operation. The affected cable was routed from the station service transformer together with other cables through an underground cable channel to the electrical building. Due to the conditions in the ground, cables were partly imbedded in concrete cable cylinder blocks.

Neighboring cables were not affected. Within the time period of the electric arc PVC insulated cable including the copper conductor evaporated completely on a length of approx. 1 m (see photo in Figure 0-1).

Figure 0-1: Photos of the cable damage; left: location of the damaged cable, right: damage by the cable fire/evaporation

The pyrolysis and/or evaporation of the PVC cable insulations caused a heavy smoke release inside the cable channel. The automatic fire detectors directly gave an alarm. A smoke exhaust system installed in the cable tunnel because of the typically high air humidity in the tunnel quickly removed the smoke after actuation by the fire detectors.

The overpressure was relieved via open cable conduits to the transformer and through leakages. Unfortunately, the really occurred pressure value could not been determined. Damage to fire doors, dampers, or fire stop seals was not observed.

Ageing of the cables due to lightning protection features installed as backfitting measure resulting in insufficient heat removal from the high voltage cables in the concrete cylinder blocks was found to be one of the root causes,

The high energy arcing did not result in any fire propagation; combustion was limited to the location where the short circuit occurred. The fire self-extinguished immediately after the electric current had been switched off. The fire duration was only a few seconds, however, the smoke release was high. It has to be mentioned in this context that all cables inside the cable channel had been protected by intumescent coatings ensuring the prevention of fire spreading on the cables (see Figure 0-2).

Figure 0-2: Cables with protection by intumescent coating; left: photo of the cable channel, right: photo of the coating

As a corrective action, all safety related 10 kV cables with PVC shielding have been replaced by new ones. In addition, periodic in-service inspections with respect to the leakage resistance of the cables are being performed. Another effect of the event was the smoke propagation to an adjacent cable channel via a drainage sump. As a preventive measure, after the event each cable channel has been supplied by its own drainage system. Moreover, all the channels are now separated by fire barriers with a resistance rating of 90 min.

6.2.16 Event 16 – GER009 – 20021030

On October 30, 2002 a HEAF event with explosion and consequential fire occurred in the electric building of a BWR plant built to earlier standards during full power operation. A short circuit with an electric arc was observed when a subassembly (plug-in module) of a 0.4 kV switchgear was exchanged. The arc directly caused a flame and the worker responsible for the exchange activities was injured by the fire.

The overcurrent of approx. 36 kA at the switchgear (380 V nominal voltage) was switched off by electric protection devices. Two busbars (operational ones, not specifically protected) became unavailable.

Signals of two ionization fire detectors in the fire compartment and short circuits in the two affected busbars were announced to the main control room. The smoldering fire with duration of approx. 1 to 3 min was successfully extinguished by portable CO_2 fire extinguishers by an electrician sent from the control room to the fire compartment. Fire protection features were not impaired.

The root causes were technical ones in connection with a faulty action of personnel. As corrective measure after the event specific training measures have been carried out.

6.2.17 Event 17 - GER011 – 19860530

During the yearly refueling outage of a PWR a high energy arcing fault (380 V) occurred around a busbar section for about 8.5 s. The busbar was switched off by the feeder breaker and 7 s later the fire detection line was triggered. It also damaged the vertical busbar section and the main busbar section. The busbar is zero-redundant (i.e. not directly significant to the plant safety). A visual confirmation of the fire alarm took place after 2.5 min. A fire damper was closed, a smoke extraction vent was opened, and the fire was fought by the plant fire brigade. 25 min after the busbar had been switched off the fire was extinguished by portable CO_2 fire-extinguishers. The smoke extraction was supported by portable fans.

The reason for the arc could not be clarified.

6.2.18 Event 18 – GER014 – 20070628

Another reportable event gaining a lot of public attention was observed at an older boiling water reactor (BWR) type plant in June 2007. A short circuit caused a fire in one of the two main transformers outside of the nuclear power plant buildings but enclosed in a specific housing for such transformer. The short circuit was recognized by the differential protection of the main transformer and the circuit breaker between the 380 kV grid connection resulting in the affected generator transformer as well as the 27 kV generator circuit breaker of the unaffected transformer being opened. At the same time, de-excitation of the generator was actuated. The short circuit was thereby isolated.

In addition, two of the four station service supply busbars were switched to the 110 kV standby grid. Within 0.5 s, the generator protection system (initiating 'generator distance relay' by remaining current during de-excitation of the generator which still feeds the shot circuit) caused the second circuit-breaker between the 380 kV grid connection and the intact generator transformer to open. Subsequently the two other station service supply busbars were also switched to the standby grid. After approx. 1.7 s, station service supply was re-established by the standby grid. Due to the short low voltage signalization on station service supply busbars the reactor protection system triggered a reactor trip.

The transformer was completely destroyed by fire. Other combustibles involved besides the oil of the transformer were paper and wood. Smoke entered the electrical building trough the ventilation inlet vents. There was no automatic isolation of the ventilation system. The fire was manually extinguished by the professional on-site plant fire brigade and the external fire brigade. The fire duration was about three hours. After that, re-ignition of the transformer was prevented by further cooling.

The reactor was tripped due to the damage including loss of feedwater supply caused by the fire in the transformer.

The cause of the fire was a short circuit in the windings of the generator transformer, which probably might have resulted from ageing. For terminating the short circuit, the differential protection system of the generator transformer caused to open the circuit breaker between the 380 kV grid connection and the affected generator transformer as well as the generator circuit breaker to the unaffected transformer. The generator circuit breaker to the affected transformer did not open since the generator circuit-breakers are not able to interrupt the currents flowing during a short circuit. The opening of the circuit breaker between the second 380 kV grid connection and the remaining intact generator transformer was caused by the remaining current after de-excitating the generator.

As measure against recurrence the affected transformer was replaced and older main transformers in several German plants either replaced or equipped with new windings for backfitting.

6.2.19 Event 19 – GER017 – 19960208

On February 8, 1996 a HEAF occurred at a German PWR plant during full power operation. A short circuit occurred in a plug-in module (subassembly) of a 500 V busbar breaker of the recirculation air fan inside an electric cabinet located in the auxiliary building resulting in the opening of the feeder breaker. The high voltage short circuit initiated a consequential fire.

A shift electrician checked the cabinets and detected smoke near the breaker. Furthermore, fire detectors and dampers were actuated; the event was signaled to the unit control room. The smoldering fire was extinguished manually by the on-site fire brigade by means of CO_2 extinguishers within approx. 17 min. The fire burned cable insulation material (inside cabinet) and plastic fixtures.

It was impossible to clarify the root causes due to the level of damage observed at the busbar subassembly. However, there were indications of a series fault of the left phase in the plug-in module resulting in a transmission of the electric arc to the other three phases due to the high initial current. No corrective actions had to be taken, as the failure occurred randomly. However, similar components are being inspected on a random basis.

6.2.20 Event 20 – GER017 – 20020811

Another HEAF event with consequential fire occurred at a PWR type plant operating at full power on August 11, 2002. The fire started in the independent emergency building at a 500 V switchgear busbar of one of the redundant trains as a result of an electrical short circuit with an explosion initiated by a high energy arc. The fire was detected by alarm signals of the electrical system in the control room as well as by smoke and ionization detectors. Cable insulation, plastic fixtures, structural elements, contactors, relays, etc. were affected. An overcurrent of approx. 8 to 18 kA was roughly estimated.

Approx. 20 min after the first signal the short circuit could be terminated by manually isolating the medium voltage injection of the 10 kV busbar. The fire was extinguished by CO_2 by the professional on-site fire brigade. Smoke propagated via air ducts and entered other cabinets due to the pressure increase in the switchgear room. Several components including cables were damaged or deteriorated by fire or smoke and soot. Gas propagated to adjacent rooms until fire dampers were actuated after 30 s, resulting in soot deposition. The active overload protection (20 s delayed overload criterion) failed, because its power supply was destroyed by the fire.

Fifteen minutes after the event the plant was shut down manually because the expected repair time was too long to meet the relevant requirements for the number of redundant trains necessary to be available.

The root cause is assumed to be a faulty contact between the main bus and the pick-up of a load-break switch. As a result, intermittent short circuits occurred at several locations of the switchgear.

As a consequence of the event, additional electric insulations have been installed. The diversity was increased by short circuit protection via monitoring of the pressure relief dampers, adjustment of the short circuit protection (from 36 kA to 14.4 kA) and reduction of the overload time protection mechanisms (4.32 kA from 20 s to 10 s). In addition, the partitioning of the busbars between different phases has been achieved by insulating clearances.

6.2.21 Event 21 – GER022 – 19870909

Another HEAF event with explosion, consequential fire and deterioration of fire barrier elements was observed at a PWR plant during full power operation on September 9, 1987. The arcing occurred in an electrical cabinet of an emergency diesel generator Performing a load test during the in-service inspection (4-week intervals) of the emergency diesel generator an electric arcing fault initiated a short to ground in the electric cabinet of the of the emergency diesel generator exciter system (cf. Figure 0-3). The root cause of the arc with short to ground is assumed to be a loose screw. The ionization of air by the arc led to a short circuit within approx. 4 s resulting in the isolation of the emergency busbar after another 0.1 s.

Figure 0-3: Photographs: a) view into the exciter cabinet, in the foreground location where the screw loosened and b) view into the cabinet

1.5 s later the diesel generator breaker opened due to low voltage, another 0.5 s later the emergency power busbar was connected automatically to the offsite power busbar.

The smoldering fire resulting from the explosion initiated by the electric arc is assumed to be caused by the short circuit of the emergency diesel generator. The overcurrent observed could unfortunately not be measured. Due to the HEAF a sudden pressure increase occurred in the room (dimensions about: 3.6 m x 5.5 m x 5 m) damaging the two-wing fire door (cf. Figure 0-4).

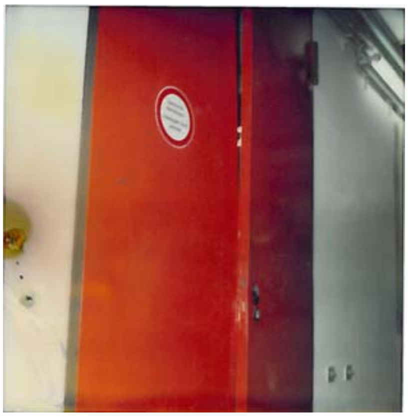

Figure 0-4: Photographs of the damaged fire door from outside the room

A combination of technical and human causes was found to be the root cause. To prevent recurrence, inspections regarding potentially loose screws were carried out for the other redundant trains.

6.2.22 Event 22 – GER024 – 19880519

In April 1988, a HEAF initiated short circuit in the 220 kV/380 kV high voltage switchgear occurred in the emergency diesel building of a PWR plant during full power operation resulting in a loss of offsite power.

The arcing occurred at the converter in one of the phases of a 220 kV outdoor switchyard. The explosion caused ionization in the 380 kV line routed in the area of the defect and thus initiated a short circuit which caused switching off this line as well as the generator transformers by the unit protection. The HEAF induced explosion destroyed the converter and ignited the released oil.

Because of the converter failure the 220 kV line was disconnected in the switchyard (breaker opening). As a result the offsite transformer lost voltage and one plant unit experienced a loss of offsite power because its main transformers were no longer supplied by the offsite transformer.

Three of the unit's diesel generators started as designed, one was out of service for maintenance. The failed converter is also integrated in the protection of the 220 kV generator transformer of the other unit (differential protection) resulting in the loss of offsite power at the second unit, too.

The event was immediately signaled in the unit control room and the on-site fire brigade was informed directly after the alarm. Three fire brigade members started to fight the fire with portable extinguishers (dry chemical). Later on additional fire fighters (in total 22) were involved suppressing successfully the fire by keeping the component, where the fire restarted again and again, covered with foam.

The affected 380 kV line is located 5 to 6 m above the 220 kV line in the switchyard. After localization of the failure and isolation of the faulty line, the 220 kV line was reenergized after half an hour and the diesels were subsequently taken out of service. The 380 kV main grid was reconnected to the unit after 90 min. The 220 kV line of the unit to the 220 kV grid remained out of service until repair work on the line was finished.

6.2.23 Event 23 – GER025 – 19890517

On May 17, 1989, an event with a high energetic arc occurred at the injection area of a 380 V switchgear in the electrical building of a German PWR type plant during low power and shutdown conditions. When the 380 V feeder breaker of an emergency power busbar was automatically connected, an electric arc developed in a subordinate connector panel. The electric arc was isolated manually after approx. 7 min, since the automatic isolation did not work due to the location of the arc and due to technical reasons.

The smoldering fire caused by the HEAF was detected by the fire alarm system (optical detectors) and extinguished by personnel present in the room using four portable CO_2 gas extinguishers. The fire duration was roughly estimated to be approx. 12 min. The damage was limited to the connector panel concerned.

The cause for the electric arc was a metallic lever for manual wind-up of the spring action memory of the switch, which had become unscrewed and had fallen into the connector panel below. The connector panel was readjusted and electrically rebuilt. As a measure against recurrence of such an event, the corresponding levers were removed from all switchgears.

6.2.24 Event 24 – GER027 – 19790811

In an older PWR an arcing fault occurred at the circuit breaker TC1 D05 of the emergency power train EV and at the switch-fuse of the emergency power sub-distribution FB in August 1979. The plant was under shutdown for the yearly outage when the event took place.

The arcing fault led to damages in the cabinet EV-7H. The plant personnel observed smoke in the room. In addition, a fire alarm signal from an optical fire detector was observed in the control room. The fire self-extinguished. The event resulted in the unavailability of the emergency power train EV for 3 - 4 days.

The reason for the arcing fault was a tapping screw and washer falling on the drawer of the circuit breaker.

1.1.1 Event 25 – JPN022 – 20110311

The "Tohoku District – Off the Pacific Ocean Earthquake" occurring on March 11, 2011 at 14:46 h caused an arcing fault in two (No. 7 and No. 8) of ten sectors of the non-emergency M/C 6-1A switchgear cabinet. The arcing fault resulted in a fire affecting all ten sectors within the cabinet. The cabinet was installed in the underground floor of the turbine building.

Prior to the earthquake, the plant was at full power operation, it was automatically shut down due to the signal of high seismic acceleration at 14:46 h.

This event can be identified as HEAF for the following reasons:

- Arcing started at the high voltage electric component (6.9 kV M/C)
- The energy was released in the form of light and high energy gas.
- Arcing was caused by short circuit and short to ground.
- This arcing fault resulted in a fire but not in missiles.
- Control cables for non-emergency components, such as feedwater pumps, condenser pumps, etc., directly above the cabinet were affected by the heat generated by the fire.
- No emergency components and cables in the room were affected.

The causes of arcing in the non-emergency M/C 6-1A may be the following (see Figure 0-5):

1. The earthquake shook Magne-Blast Breakers (MBBs), which were hung up by buses in the cabinet since MBBs were not fixed to the floor.
2. The shaking of MBBs resulted in damages of insulators and connectors. It resulted in short circuit and short to ground.
3. The short circuit and the short to ground of connectors resulted in arcing. The heat due to the arcing resulted in the fire inside the cabinet.

The fire in M/C 6-1A due to arcing caused a trip of the over-current relay at the upper stream of the startup transformer at 14:55 h. The trip of the over-current relay caused a loss of offsite power in combination with switching over of power supply system and loss of auxiliary transformer due to the earthquake (cf. Figure 0-6). The emergency buses were supplied by DG-A. After the loss of offsite power, decay heat was removed by SRV and RHR-A/C (suppression chamber cooling mode) being supplied by DG-A.

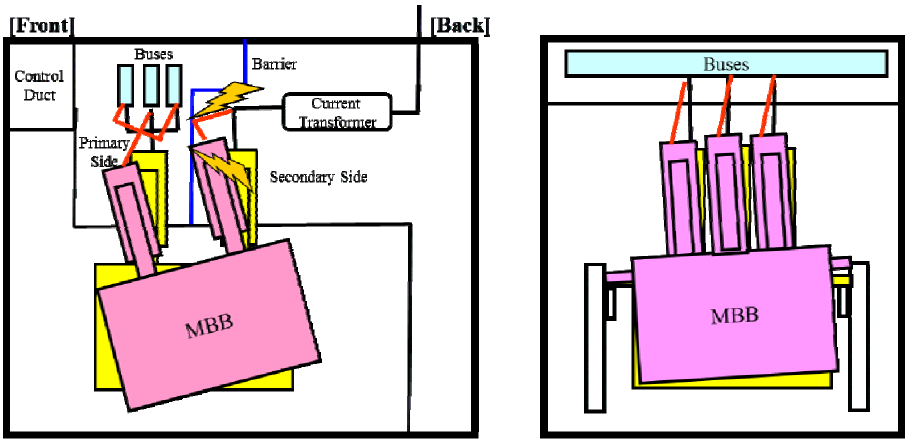

Figure 0-5: Simplified drawing for HEAF event in M/C 6-1A

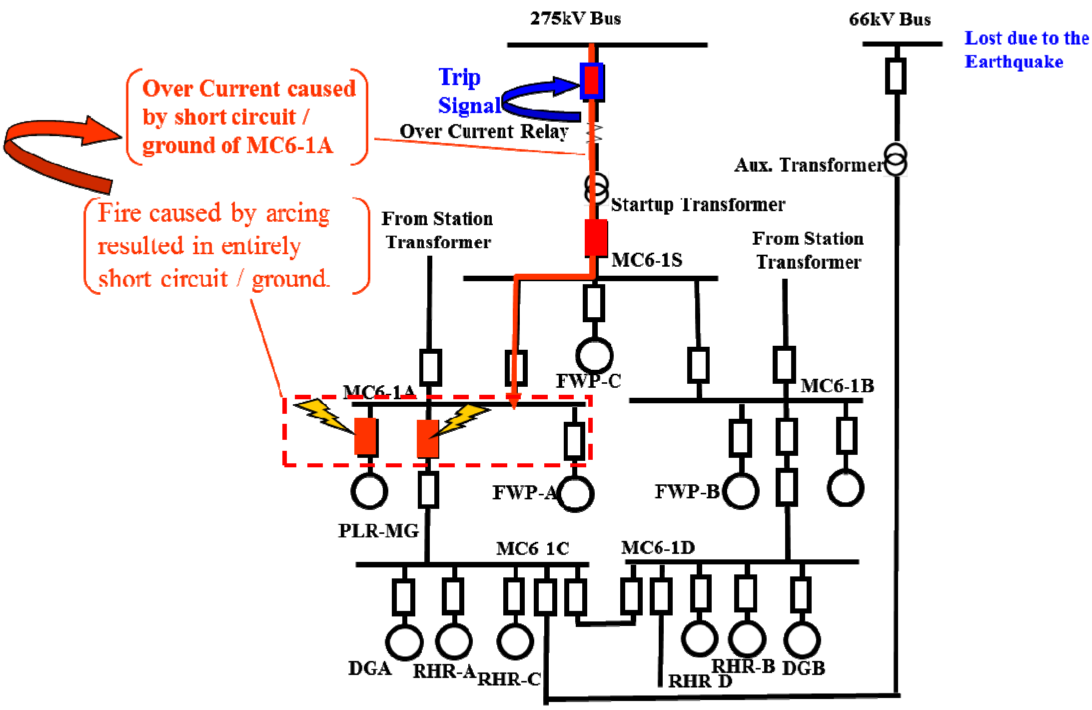

Figure 0-6: Simplified drawing for loss of offsite power by HEAF event

RHR-A/C were automatically isolated at 15:55 h due to instantaneous under-voltage of emergency bus C supplying to RHR-A/C. The instantaneous under-voltage of emergency bus C was caused by rush current from the emergency bus to auxiliary transformer damaged by the earthquake. The rush current was caused by a short circuit of synchronous detector in the non-emergency M/C 6-1A due to the fire. The short circuit caused spurious current from the non-emergency M/C 6-1A to emergency M/C 6-1C, inadvertently energizing the coil for the breaker from the emergency bus to the auxiliary transformer.

With respect to the fire sequence, the following details are important to be mentioned:

The fire was detected by an optical detector, although the on-site fire brigade could not identify the fire location due to heavy smoke at first. At 15:41 h, the public fire brigade was called. Because of damage of the access ways to the site due by the earthquake and tsunami the off-site fire brigade was however not able to come.

At 17:15 h, portable CO_2 fire extinguishers were manually used for fire extinguishing efforts in the turbine main oil tank room, the EHC room, etc. after evacuation of people from the turbine building without identification of the fire location. At 18:03 h, the on-site fire brigade started to access the turbine building BF1 with an on-spot smoke remover. The fire location and fire source could be identified at that time. Fire fighting started at 22:56 h with seven cylinders of dry chemical extinguishers.

At 22:55 h the fire was declared to be successfully extinguished. The fire duration was approx. seven hours.

The consequences of the seismically induced HEAF with consequential fire were the following:

- In the cabinet M/C 6-1A, the sector where the fire started and its adjacent one were completely damaged by arcing and fire.
- The further eight of ten sectors in M/C 6-1A were only partially damaged (upper portions of the sectors, see also Figure 0-7).
- High energy gas was released in the sector where the fire started, which could have been generated by the electric arc and fire and propagated to other sectors through the penetration of the control cable bundle (control duct) located in the upper area of the cabinet.
- Jackets and insulators of the cables above M/C 6-1A seem to be affected by the fire.
- Other components and/or cables except those just above M/C 6-1A were not affected by the fire.
- There were no missiles.
- The door of the cabinet sector, where the fire started, opened when the on-site fire brigade accessed the room. It is unknown whether the door opening is due to the earthquake or the pressurization of the cabinet.

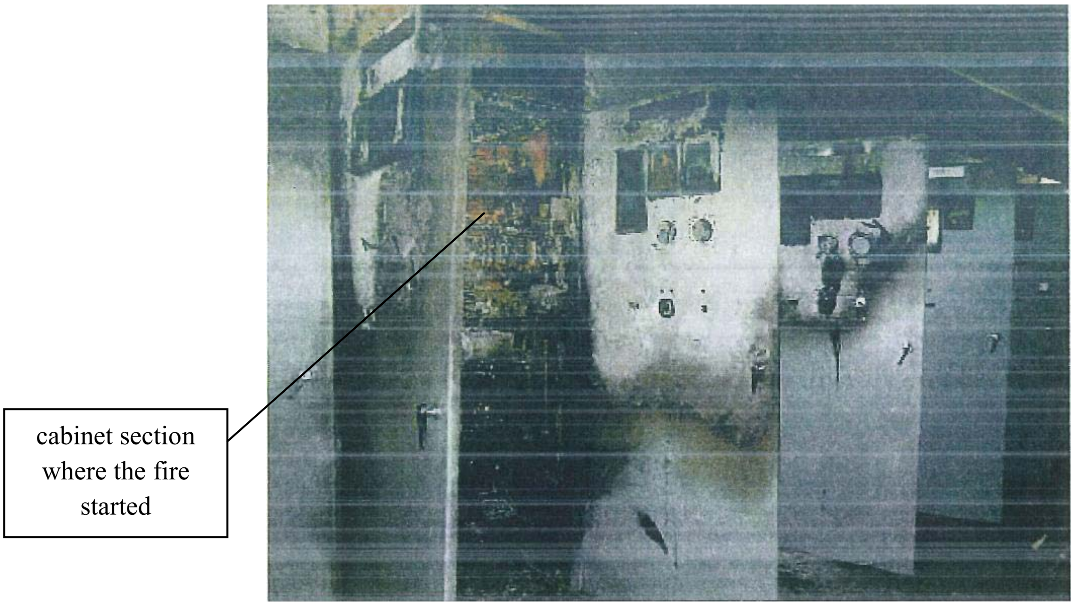

Figure 0-7: Electric cabinet with the sector where the fire started and others impaired

As a consequence of this event combination, the following corrective actions were taken:

- To prevent seismically induced high energy arcing fault and fire, it was found that MBB being hung up in M/C was the essential cause of the event. Therefore
  - MBB shall be replaced by VCB, which is fixed on the floor of the cabinet.
  - A pedestal shall be inserted between MBB and the floor of the cabinet.

  These corrective actions are also useful to prevent failure of the startup transformer.
- To prevent an instantaneous trip of the emergency bus due to fire in the non-emergency MC;
- To prevent spurious current to emergency M/C from non-emergency M/C, the licensee will install a switch between these cabinets. Since the switch will be installed outside the non-emergency cabinet, arcing fault and/or fire will not affect functions of emergency components and/or systems. This corrective action is useful to prevent the event of spurious operation of the DG breaker.

6.2.26 Event 26 – JPN029 – 19960907

At 14:12 h on September 7, 1996, for the 7th Periodical Inspection, while "The common bus SA-1 460V Earth-fault" alarm occurred during reactor depressurization and the cooling operation (reactor pressure was 6.5 kg/cm^2), the fire detector of the emergency diesel generator (A) switchgear room on the ground floor of a plant building (outside radiation controlled area) actuated. At that time, the reactor was in hot shutdown operation. Fuming from the bus duct (consisting of a tabular busbar conductor, an isolated electrode holder and its cover located in the switchgear room was observed when the operator investigated the switchgear room. The operator started the initial fire extinguishing operation. A fire fighter also joined the scene; fire extinguishing was performed in collaboration with the operator using the fire extinguisher, and extinguishment of the fire was checked at 14:54 h the same day.

This event has been identified as HEAF fire event for the following reasons:

- The event was caused by the fire due to the short circuit of the 460 V cable in bus duct.
- Plant personnel heard explosive sounds, and observed flashing and smoke in the bus duct at the event initiation.
- Molten aluminum dropped from the bus duct on the 460 V emergency cabinet causing the short circuit inside the cabinet.
- Other components around the bus duct were not affected.

The cause of the event was estimated as follows:

- The insulator in the bus-duct degraded due to stains on the insulator surface, humidity, etc.
- Airborne salt and dirt adhered to the equipment in the bus duct, to some extent the isolated decline of an isolation holder took place, and an earth fault of one phase occurred.
- The voltage of other phases increased and the two-line short (inter-phase short) occurred.
- The arcing occurred by the short circuit of the 460 V bus connected to bus-duct conductor.
- The arcing caused the melting of conductors.
- The intermittent arcing continued through the hot gas consisting of metal vapor, etc.
- Accordingly, the insulating materials and the coating materials of the duct burned.

6.2.27 Event 27 – JPN044 – 19850831

On August 31, 1985, Fukushima Daiichi unit 1 (1F1) was in shutdown operating state for periodic inspection. At 06:42 h, the alarm of “6900 V BUS / 1S GROUND” indicating that 6.9 kV bus for start-up was grounded and the fire alarm at electric equipment room (EER) occurred. Following these alarms (at 06:50 h), an operator went to the EER located in the northwest corner of turbine building and they found EER filled with smoke.

At 07:20 h, fire and corona were observed at the upper portion of the 6.9 kV metal-clad switchgear cabinet 1S for start-up.

Operators tried to extinguish the fire with dry chemical fire extinguishers. However, they gave up fire fighting and called the public fire department at 08:06 h.

The public fire engine arrived at the unit and the fire fighters started fighting the fire at 08:15 h. In the early stage of fire fighting, the fire fighters tried to extinguish the fire by squirting water into the cable duct from outside the turbine building. At 08:40 h, the fire fighters took off the cover of the cable duct corner on the roof of turbine building and injected water into the 6.9 kV metal-clad switchgear cabinet 1S via a cable duct. By the injection of water into 6.9 kV metal clad switchgear cabinet 1S3 the fire was extinguished at 08:56 h.

Due to the injection of water into the 6.9 kV metal-clad switchgear cabinet 1S, an over current relay was activated and the start-up bus was lost. Due to loss of the start-up bus lights in the turbine building and office building were lost. By the alternative electric source lights in the turbine building and in office building were recovered at 12:05 h and 16:30 h, respectively.

The estimated cause of this event is the arcing in the cabinet due to rainwater entering the building through the gap of the cable duct located at the outside of the turbine building. The rainwater injection seems to be due to a typhoon.

6.2.28 Event 28 – JPN047 – 20070716

On July 26, 2009, Niigata-Chuetsu-Oki earthquake occurred. The house transformer fire due to arcing fault succeeded the earthquake.

Operational mode prior to the fire was 100 % of full power, reactor coolant pressure and temperature were nominal values. The reactor was automatically tripped by high seismic acceleration signal prior to the fire, and was cooled down to the cold-shutdown mode without suffering any effects from the fire.

The fire started at the house transformer that was installed outside and adjacent to the turbine building, and was isolated from the other components by the fire wall.

The ignition mechanism was that the electrical arcing between the bushing and the bus duct had ignited the insulation oil leaked from the transformer to the bus duct. The analysis of the current and voltage records of the generator circuit revealed that the arc discharge was caused by the three-phase short circuit due to the contact of the bushing terminal contactor with the secondary side of the bus duct, which failed due to the large scale seismic motion. The arcing induced the melting of the upper part of the bushing. The residual magnetic field and the generator rotating due to inertia still generated electric power to the transformer. The generator voltage changed from 17.2 kV to 13.2 kV during the arc discharge as recorded. The circuit current induced by the arcing might have been 50 kA approximately, based on the records, and the insulation oil fire was induced by more than 1000 ^{0}C arc-discharge.

The fuel involved was insulation oil leaked from the transformer; flash ignition temperature of the insulation oil is higher than 130 ^{0}C according to the Japanese Industrial Standard Code. The transformer contained about 17 m^3 of insulation oil during normal operation.

The fire was detected by post-earthquake patrol of plant personnel. The fire was extinguished by chemical hydrate from the regional fire engine.

1.1.2 Event 29 – KOR001 – 20020422

On April 22, 2002, a HEAF event with explosion and consequential fire occurred on the phase 'B' of the main transformer during full power operation. During normal operation of the reactor power at 100 %, 602 MW_e of turbine/generator power, plant protection relay (86GT) was activated and caused a turbine/generator trip due to the ground failure between outlet lead wire and outer casing of main transformer phase 'B'. The reactor tripped and stayed subcritical by the turbine trip signal and AP8 (reactor power 30 %) signal. No radiological effects both on-site and off-site were observed. Each safety system maintained normal condition.

The automatically actuated fire suppression system (spraywater deluge system) extinguished the fire successfully. The operator verified that the fire was put out, and closed the spraywater isolation valve and stopped the fire pump.

The transformer was severely damaged by the fire. 'A/B/C' phase high-voltage (345 kV) side bushing, 'B/C' phase insulator on the upper side of the lightning arrester and radiator (6 era/12 era) were broken down.

The main transformer internal trouble spots were identified as follows:

- An arc developed between B phase high voltage coil lead wire and shield plate of outer casing of the transformer (cf. Figure 0-9).
- The connection between terminal lug and lead wire outside bushing broke away (cf. Figure 0-9).

Figure 0-8: Photographs of the damaged lead wire and shield plate of outer casing of transformer

Figure 0-9: Photographs of the lead wire broken away from the terminal lug

The cause of ground failure was estimated as follows:

- Fault current flowed from 4 cycles in 'B' phase, and after four cycles in 'B' phase, the fault current flowed in 'C' phase as judged by the analysis from fault recoding.

- It was assumed that the ground failure started in 'B' phase and insulation of bushing in 'C' phase broke down by the after-effect based on the trace of arc between the lead wire of 'B' phase and transformer casing.
- Presumption of the first ground failure occurrence:
  It was assumed that insulation breakdown occurred in 'C' phase bushing by the after-effect of ground failure between transformer casing insulation plate and shielding plate, due to the damage of insulation caused by partial meltdown of the welded connection between the terminal lug outside the bushing and the lead wire, with molten lead drops falling on the insulation plate for conductor support and foreign material collecting cover.

The root cause of the arcing fault was assumed to be a manufacture flaw. It is believed that the connection had been damaged slowly but continuously for about 28 years since it's installation in 1974 because the connection was lead-welded.

6.2.30 Event 30 – KOR010 – 20010130

On January 30, 2001, at 12:08 h, a HEAF event occurred in the main transformer during full power operation, leading to a reactor trip. An electrical arcing occurred on the phase ‘B’ of the main transformer (cf. Figure 0-10). The fault was immediately sensed by protective relays which caused a turbine trip, and automatically reactor trip. The unit was disconnected from the grid, and site power automatically transferred from the unit auxiliary transformer (UAT) to the start-up auxiliary transformer (SAT).

The root cause of the damage 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. The 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 (cf. Figure 0-11).

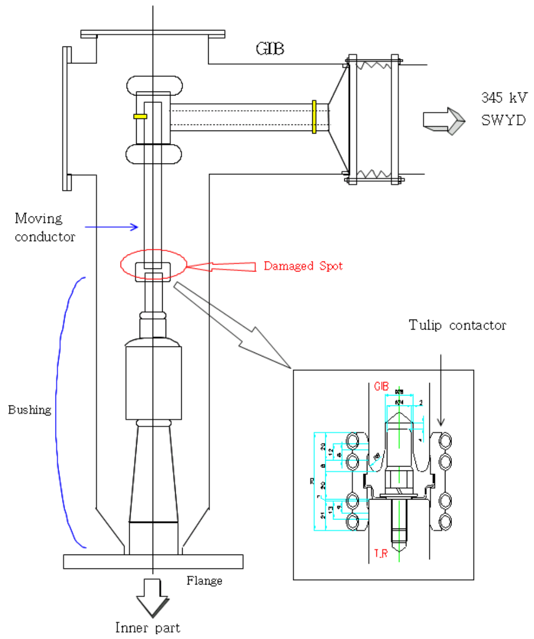

Figure 0-10: Main transformer bushing failure part diagram

Figure 0-11: Photos of the bushing damage

6.2.31 Event 31 – SPN001 – 19880622

On June 22, 1988, at 19:30 h, with unit at 100 % power the main transformer, phase S (TP-2), was ignited. It is in the open air. The area has got 3 hour fire resistant rated walls at both sides of the TP-2 (21 kV / 400 kV). TP-2 is physically located between transformers TP-1 (east) and TP-3 (west).

Immediately after the TP-2 explosion, the turbine trip occurred due to TP-2 protection actuation and, consequently, reactor trip. The response of plant systems was adequate, particularly transfers of electrical buses and start-up of diesel generator "B". The plant remained under control in hot stand-by state.

The incident started with a short circuit in the high voltage terminal (400 kV) due to an isolation failure between this terminal and the phase box. The corresponding high energy arcing event had immediate consequences:

1. The box oil exploded,
2. The isolation material (porcelain) broke up,
3. The upper part of the phase box swelled and showed a 500 mm crack, and
4. Ejection and spillage of the box oil occurred.

According to the NPP inside emergency plan, the "alert of emergency" level was declared at 19:40 h. That was because the fire lasted more than 10 min after confirmation and could potentially have affected the safety systems. The level was de-activated at 21:30 h.

The extinguishing equipment (portable means) used in the fire were three dry chemical (powder) extinguishers, two 5 kg halon extinguishers, and two gas (carbon dioxide) extinguishers.

6.2.32 Event 32 – SPN001 – 19880820

This event was the second HEAF fire event in the main transformer (TP) of a three-event series within six months' time (from June to December, 1988).

On August 20, 1988, at 16:35 h, with unit at 100 % power the main transformer, phase S (TP-2), caught fire. It is in the open air. The area has got 3 hour fire resistant rated walls at both sides of the TP-2 (21 kV / 400 kV). TP-2 is physically located between transformers TP-1 (east) and TP-3 (west).

Immediately after the TP-2 explosion, the turbine trip occurred due to TP-2 protection actuation and, consequently, reactor trip. The response of plant systems was adequate, particularly transfers of electrical buses and start-up of diesel generator "B". The plant remained under control in hot stand-by state. The fire protection system of the area was signaled as being activated in the control room. The control room manager ordered visual inspection of the transformers area to the control room. A plant field operator confirmed the fire in transformer TP-2. The shift manager called the on-site fire brigade by phone.

The incident started with a short circuit in the high voltage terminal (400 kV) due to an isolation failure between this terminal and the phase box. The corresponding high energy arcing event had immediate consequences, but not as violent as those occurring in the fire event in June 1988. The upper part of the phase box swelled, but there was no ejection or spillage of the box oil to the surroundings.

According to the NPP inside emergency plan, the "alert of emergency" level was declared at 16:45 h. That was because the fire lasted more than 10 min after confirmation and could potentially have affected the safety systems.

6.2.33 Event 33 – SPN001 – 19881202

This is the third and last fire in the main transformer (TP) of a three-event series within a six months period (from June to December, 1988).

Prior to the fire, at 05:31 h, with the NPP at 100 % power level, reactor trip occurred due to turbine trip plus permissive P-7. That was because of a 400 kV power line disturbance that made TP protection actuate.

At 19:00 h, the different inspections related to the previous reactor trip came to an end. The reactor remained in sub-critical state. At 19:51 h, the 400 kV line was energized, the TP immediately tripped and phase "R" (TP-3) burst into flames. It is in the open air. The area has got 3 -hour fire resistant rated walls at both sides of the TP-3 (21 kV / 400 kV). TP-3 is physically located between transformer TP-2 (east) and auxiliary transformer TAU (west).

Immediately after the TP-3 explosion, turbine trip occurred due to TP-3 protection actuation and, consequently, reactor trip. The response of plant systems was adequate. The plant remained under control in hot stand-by state. The fire protection system of the area was signaled as being activated in the control room. The control room manager ordered visual inspection of the transformers area. A plant field operator confirmed the fire in transformer TP-3 to the control room. The shift manager called the on-site fire brigade by phone.

The incident started with a short circuit in the high voltage terminal (400 kV) due to an isolation failure between this terminal and the phase box. The corresponding high energy arcing event had immediate consequences, but not as severe as in the fire event in June 1988.

According to the NPP inside emergency plan, the "alert of emergency" level was declared after the fire was confirmed. That was because the fire lasted more than 10 min after confirmation and could potentially have affected safety systems. The level was de-activated at 20:10 h, after the fire had been extinguished.

After the occurrence of this fire event, the licensee decided to launch a thorough investigation in order to unveil the root cause of the failures.

Due to the fire, the 400 kV line was unavailable. Only the 200 kV line was available through the outside auxiliary transformer TAE. As this situation was to remain for several days, it was decided to re-align the 110 kV line through the stand-by auxiliary transformer TAR in order to have another electrical supply alternative. Nevertheless, in the alignment maneuver, on December 3, 1988 a human error provoked the loss of the TAE transformer and, subsequently, loss of offsite power (LOOP). The LOOP cause was immediately identified and the 220 kV line was recovered in approximately .1.5 min

6.2.34 Event 34 – SWD007 – 20021030

On October 20, 2002 a HEAF fire event occurred at the Swedish NPP SWD007. An automatic fire alarm about an arc event in a rectifier in the turbine building (T12) was obtained. The failure led to a turbine trip of one turbine, after the generator started emitting sparks and smoke from the generator rotor area. Turbine hall roof was filled with smoke. The cause of the fire were bad connections on contact rails in an electrical cabinet causing a short circuit; it took also a long time for the MCR staff to turn off the power to the affected rectifier.

Fire alarm was received at 17:58 h from a turbine building. A watchman was in the neighborhood when the automatic fire alarm started. He saw that there was a fire in a rectifier cabinet. He did immediately grab an extinguisher and tried to extinguish the fire with powder, but he failed. The fire could not be extinguished at the first attack. The internal fire brigade arrived and they called also after the external fire brigade for backup.

At the beginning, big flames and sparks came out of the cabinet, but the flames decreased quickly. When the external fire brigade arrived there was no more fire, only sparks and smokes. The top of the turbine building was filled with smoke. The smoke came from an arc in a cabinet directly connected to the generator. The cause of the fire was a short circuit and an arc due to bad contact between busbars.

6.2.35 Event 35 – SWD007 – 20060915

On September 15, 2006 a HEAF fire vent occurred at the Swedish NPP SWD007. The fire started in a 6 kV electrical cabinet in room D2.21. The cabinet feeds power to the pump 725 P1. A breaker in the cabinet was burning.

The fire alarm was actuated by the heavy smoke development in the cabinet feeding power to the pump 725 P1 (the closed cooling system for turbine building). The fire was eventually extinguished, it could be observed that the damages were extensive in the cabinet, including the cables, and that the smoke had made the room very dirty. The fire had most probably started in the main contactor (breaker) for 725 P1 as an arc. The arc had in its turn caused an overheating of surrounding cables and electrical equipment. After 7 min the local fire brigade arrived to the affected room and begun the extinction of the fire, with carbon dioxide. The fire was extinguished at 16:31 h.

The fire did not spread to adjacent cabinets but the heat effects could have impacted neighboring cables.

1.1.3 Event 36 – SWD008 – 20110510

On May 10, 2011at 23:32 h the MRC (main control room) staff of the Swedish NPP SWD008 observed a temperature rise in the containment during a CAT (containment air test/ 3.16 bar overpressure). The temperature started at 24 ^{0}C and increased to 34 ^{0}C within a few minutes. Temporary heat detectors were placed on 5,14,18,27 and 33 m above the entrance level. The fire started at the entrance level. The highest temperature, 34 ^{0}C, occurred at the highest level, 33 m above the fire/entrance level.

At the same time there was a signal in the fire detection system. Because of the pressure difference of 3.16 bar between in and outside it was not possible to enter the containment. The control room staff tried to find an explanation for the temperature rise, which was causing confusion. It was not possible to verify what had happened trough the CCTV cameras since the lenses were covered with soot from the fire.

After safety discussions the decompressing started at 07:10 h on May 12, 2011. The first team went into containment at 02:45 h on May 13, 2011 and could verify that there had been a local fire at the entrance floor in the equipment that had been used mainly for decontamination of the diverse equipment. The divers where used to close the fuel transfer tube in the water filled reactor cavity at the CAT line up.

There was no possibility to enter the containment for about 50 hours because of the CAT overpressure. According to the plant operating procedure containment spray could have been used but the fire sequence was over before it was obvious to the MCR-staff that a fire had occurred.

The fire has occurred at 3.16 bar overpressure at which the oxygen content is higher. This probably led to faster flame spreading and higher combustion. At lower pressure the flame spreading is proportional to the pressure. In research reports the flame spreading is proportional to the pressure up to 2 - 3 bar (overpressure) and then it drops. However the combustion has been faster and more complete than normal so the overpressure has had a major impact on the flame spreading but to what degree is unknown.

The humidity was 80 % when the containment could be entered after the CAT. Reducing the humidity with temporary dryer had highest priority. The humidity was reduced to 40 % with three temporary dryers in four days. The delay of the possibility to take action to protect the equipment and decrease the humidity made the damage worse.

Operation mode prior to the event

Prior to the event the plant was under outage conditions. The entire fuel was in the fuel building, i.e. there was no fuel in the containment. CAT (containment air test) was going on at 3.16 bar overpressure.

Component where the fire started

It is stated by SKL (SKL - the Swedish National Laboratory of Forensic Science) that there has been an arc in a vacuum cleaner for dry and wet use. All other possibilities as fire starters are excluded. Ignition mechanism is electric arc. There was some fire load and ignition source left during the CAT in the containment. Inside the reactor containment there is only manual fire extinguishing equipment available.

Smoke influence

The whole containment from the level of fire +115 up to the ceiling +156 was colored black from smoke: The lower parts of the containment where not black but the components in those areas where effected by smoke.

Secondary effects

High levels of chlorides have been verified in the same area where smoke had effected the containment. Approximately 4300 components in the containment were cleaned and had been verified to be in proper condition before starting up the reactor.

Comments on consequence and corrective actions

During CAT no transient fire load shall be in the containment and no electrical devices shall be connected. This is the normal procedure when CAT is done at the end of the outage just before start up and the containment is cleaned to the same level as during power operation. This time the time schedule was changed and the CAT was done before the initial plan. The plant operational procedure required the same elimination of transient fire load but some equipment that had to be used for the refueling was allowed to be left in the containment during the CAT test. Due to miscommunication and unclear responsibilities for the preparatory work the fire load was larger than necessary.

6.2.37 Event 37 – SWD010 - 20061114

On November 14, 2011 a HEAF event with fire occurred at the Swedish NPP SWD010. At 00.30 h the transformer LT 310 which supplies the 6 kV on-site electrical system trains A and C from the generator 20 kV busbar caught fire. The fire was extinguished by the on-site fire brigade with assistance from local fire brigade units. Transformers are separated by passive fire protection means (No extinguishing equipment is installed, just a concrete wall between the main and local transformer. The transformers stand on a common sand bed for both main and local transformer, on the bottom of the sand bed there are piping connections to a vessel for collecting oil spill).

The cable penetration to the turbine building was most probably damaged by the explosion, and that caused smoke to leak into the turbine building, re-causing new fire alarms. Local transformer LT310 contains in total 10 m^3 of mineral oil. Main transformer T31contents are 56 m^3 of mineral oil in total.

The fire released smoke and soot into the turbine building via damaged penetrations in the wall. Fire had an impact on other components in the plant, smoke propagated to the turbine building via a cable penetration damage by the explosion (cables for different phases from the generator to the transformers) in the turbine building wall.

6.2.38 Event 38 – USA027 – 20100328

At 18:52 EDT on March 28, 2010, a feeder cable to 4 kV non-vital bus 5 failed. Specifically, cable insulation on the feeder cable failed at the 4 kV bus 5 cabinet entry point, resulting in an arc flash and cable fire in the conduit. When the fault occurred, circuit breaker 52/24 did not clear the fault as expected, and the breaker remained closed for the duration of the event. The circuit breaker failed to open because of a mechanical flaw in the trip circuit fuse, which disabled the control power to the trip circuit. Failure of the breaker to open led to internal damage to the unit auxiliary transformer (UAT) and a lockout of the UAT on fault pressure that caused the main generator lockout relay (86P) to operate.

As a result of circuit breaker 52/24 failing to open, the fault persisted on 4 kV buses 4 and 5 as the time over-current protection for 4 kV bus 4 feeder circuit breaker 52/20 began timing. The voltage for 4 kV buses 4 and 5 became significantly depressed due to the fault, and the 'B' RCP motor supplied by 4kV bus 4 slowed, actuating the low RCS flow reactor protection logic for the 'B' RCS loop, which tripped the reactor. The fault current was initially fed from the UAT. After three to four seconds, the internal failure of the UAT tripped the fault pressure protection, locking out the UAT and also the main generator. The fast transfer from the main generator lockout signal opened breaker 52/20 and closed breaker 52/19, transferring the fault from the UAT to the start-up transformer (SUT). Following transfer of the fault to the SUT, voltage for 4kV bus 3 became significantly depressed, resulting in actuation of the loss-of-voltage relays for the 480 V E-2 safety bus. The 480 V bus E-2 then separated from 4 kV bus 3, the 'B' emergency diesel generator (EDG) automatically started and connected to the 480 V E-2 bus, and the load sequencer operated as designed.

After several seconds, the time over-current relays for circuit breaker 52/19 actuated and tripped the circuit breaker, clearing the fault and ending the first electrical fault event. Plant electrical conditions following the termination of the first event left 4 kV buses 1, 2, and 3 powered from the SUT, 480 V bus E-2 powered from the 'B' EDG, station service transformer (SST) 2C de-energized, and 4 kV bus 4 and bus 5 de-energized. The entire sequence of protective automatic actions occurred within approximately 20 s.

The initial fault on 4 kV bus 5 also resulted in electrical fires at 4 kV bus 5 and at breaker 52/24 on 4 kV bus 4. The fires were extinguished by fire brigade and security personnel using dry chemical fire extinguishers. Damage to 4 kV bus 4 was initially limited to the 52/24 cubicle. Damage to 4 kV bus 5 was limited to the incoming line compartment along with the feeder cables.

Following the reactor trip and the loss of power to electrical buses described above, instrument bus 4 also temporarily lost power. The loss of Instrument bus 4 caused the flow control valve to the component cooling water thermal barrier return, to close, which isolated cooling to the RCP thermal barrier. This condition went undetected by the operating crew for a period of approximately 39 min. The power loss in the plant also prevented remote closing of the moisture separator re-heater (MSR) steam shut-off valves and opened the MSR drain tank alternate dumps to the condenser, resulting in an RCS cool down. The RCS cool down led to an automatic safety injection (SI) due to low pressurizer pressure. Station expectations are that operators should manually initiate SI if the automatic set point is being approached, but the operators were not closely monitoring pressurizer pressure or level.

The operating crew properly transitioned through the emergency operating procedures.

Following safety injection termination and plant stabilization, a transition was made to procedure GP-004, post-trip stabilization. At approximately 22:34 h, during performance of GP-004, the operating crew attempted to reset the generator lockout relay (86P), based upon procedural guidance in GP-004. The operating crew was not aware of the locked-in UAT fault pressure signal, even though a main control board annunciator was available to provide that indication. When the attempt was made to reset the lockout relay, the UAT fault pressure trip signal would not allow the logic to be reset. The lockout relay would not latch into the reset position and was released back to its tripped position by the operator. Upon release of the relay handle, the circuit breaker 52/19 anti-pump logic was reset, arming the breaker to reclose again. With the UAT fault pressure trip input to the generator lockout relay still locked in, the fast transfer contacts reclosed breaker 52/19 when circuit breaker 52/19 reclosed, it repowered 4 kV bus 4 and re-energized the faulted cable and breaker compartment from the SUT.

A fault occurred when circuit breaker 52/19 was closed. The fault lasted only a short amount of time, insufficient to trip the circuit breaker 52/19. Current was still flowing to the faulted components, but was not sufficient to trip the protective devices. Approximately 3 min later, a condition in the rear of the circuit breaker 52/24 cubicle caused a significant fault and resulted in an arc flash. The arc flash breached the rear of the circuit breaker 52/24 cubicle and caused damage to surrounding components. Circuit breaker 52/19 opened to clear the fault and isolated the faulted components.

A second fire was initiated from the arc flash. This fire was extinguished by the fire brigade using dry chemical fire extinguishers. Following the second event, the electrical conditions in the plant were: 4 kV buses 1, 2, and 3 powered from the SUT, 480 V bus E-2 powered from the 'B' EDG, station service transformer (SST) 2C de-energized, and 4 kV bus 4 and 4 kV bus 5 de-energized.

Following the arc flash and fire due to the attempted reset of the generator lockout relay, both safety related 125 V DC battery buses [BU] developed electrical grounds. At this point, the operating crew declared an Alert, based on a fire that was affecting safety related equipment, and activated the emergency response organization.

During plant stabilization and restoration, the operating crew failed to recognize the condition of the electrical distribution system prior to attempting to reset the main generator lockout relay, which resulted in re-energizing the faulted 4 kV system. The crew did not identify a control room annunciator associated with the UAT that was locked in from the initial fault. The annunciator response procedure provides the inputs to the generator lockout relay and automatic actions associated with the UAT fault signal. However; this annunciator response procedure was not referenced by the operating crew. The root cause of this aspect of the event is a lack of monitoring of key plant parameters by the operating crew.

6.2.39 Event 39 – USA034 – 20040618

On June 18, 2004 at 06:40 h, with the plant operating at full power, a HEAF occurred in the 22 kV system. The "B" phase faulted to ground in the low voltage bushing box on top of the Main Transformer, and the "A" phase faulted to ground in the surge arrester cubicle of the Main Generator Potential Transformer (PT) Cabinet through the "A" phase surge arrester

Within less than one cycle (11 ms of the initial electrical fault, the main generator protective relaying sensed the condition and isolated the generator from the grid within the following five cycles (80 ms). A generator load rejection reactor scram then occurred. Approximately 400 ms following the initial electrical faults to ground from "A" and "B" phases, arcing and ionization in the "B" phase low voltage bushing box carried over to the "C" phase low voltage bushing box on top of the main transformer . The electrical faults disrupted a flange in the oil piping between the Main Transformer oil conservator (expansion tank) and the "C" phase low voltage bushing box. The arcing or heat from the HEAF ignited the oil, resulting in a fire. Fire suppression systems activated automatically as expected.

The plant response following the scram was as expected, with the exception that both recirculation pumps tripped and other AC voltage effects were observed as a result of the voltage transient associated with the high fault current. All safety systems functioned as designed and the reactor was shut down without incident. There was no release of radioactivity and no personnel injuries.

The fire brigade was dispatched at 06:41 h. An unusual event was declared at 06:50 h due to "any unplanned on-site or in-plant fire not extinguished within 10 minutes”. The fire brigade initiated fire hose spray from a nearby hydrant and quenched the fire. Local fire departments began arriving at 07:05 h. The fire was declared under control at approximately 07:17 h and re-flash watches were established. Offsite power transmission lines and station emergency power sources were available at all times throughout the event.

The iso-phase bus flexible connector that failed (expansion joints) was part of the original bus design. All flexible connectors were replaced with an upgraded design. All of the surge arresters were replaced.

The root causes of the event were determined to be the result of a flexible connector fabrication deficiency and preventative maintenance not being performed on the surge arresters located in the generator potential transformer (PT) cabinet.

The electrical grounds that initiated the event were caused by loose material in the "B" iso-phase bus duct as a result of the failed flexible connector that allows the iso-phase bus to thermally expand and contract. The grounds raised the voltage on the "A" and "C" iso-phase busses, contributing to the failure of the "A" phase surge arrester.

6.2.40 Event 40 – USA036 – 20000515

On May 15, 2000, at 00:25 h, HEAF occurred on the 12 kV non-segregated phase bus between the auxiliary transformer and the 12 kV bus D and bus E. The fault was immediately sensed by phase differential protective relays which initiated a unit trip. The unit trip caused a turbine trip and automatic reactor trip as designed. Power automatically transferred from auxiliary to start-up power.

While the unit trip immediately opened 500 kV switchyard breakers and the main generator field breaker, it took several seconds for the voltage to decay from the main generator. Electrical current from the generator continued to feed the fault, resulting in electrical arcing and significant damage to the faulted bus and duct. The fault was in an overhead bus duct inside the 12 kV switchgear room. A 4 kV start-up bus duct located immediately above the faulted 12 kV bus was damaged by the fault and subsequent arcing. This damage to the 4 kV bus induced arcing in the 4 kV bus duct resulting in a differential trip of start-up transformer 1-2, 11 s after the initial fault. The loss of both auxiliary and start-up power to 4 kV vital buses resulted in an under voltage condition, causing EDGs to start. Vital loads on 4 kV buses F, G, and H, automatically sequenced onto their associated EDGs.

Start-up transformer 1-1 remained energized supplying power to non-vital 12 kV loads, consisting of the four reactor coolant pumps (RCPs) and one circulating water pump (CWP). The faults left non-vital 4 kV buses D and E de-energized.

At 00:43 h, the shift manager declared an UE due to the fire lasting greater than 15 min and loss of both sources of offsite power.

The on-site fire brigade requested offsite assistance as a precautionary measure. After electrical current to the fault diminished, the arcing ceased and only a small fire remained. When the fire brigade entered the room, they quickly extinguished the fire with a CO_2 extinguisher, before off-site assistance arrived. After clearing smoke from the room, the fire was declared out at 01:43 h.

The cause of the bus failure could not be conclusively determined due to the absence of physical evidence. The bus connection that failed was vaporized or melted. Several feet of conductor had burned or melted away. In order to perform an investigation, the fault location was quarantined. Detailed evidence was gathered prior to cleanup. Potential causes that were considered and eliminated include: maintenance activities, testing, sabotage, foreign material or animal, and insulation cracking.

The immediate cause is postulated to be a thermal failure of the bolted connection of the center conductor of the 12 kV bus supplied by Auxiliary Transformer. The PVC boot failed due to the excessive heat and created smoke. The radiant heat from the center conductor caused the insulation to fail on adjacent conductors. The smoke provided an ionized environment for a phase-to-phase arc from the center conductor to the south conductor. Subsequently, there was arcing between all conductors.

6.2.41 Event 41 – USA039 – 19991009

On October 9, 1999, at 12:34 h, with units 1 and 2 at 100 % power, control room overvoltage annunciators alarmed. Operators dispatched to the "C" reserve station service transformer (RSST) saw small flames at the bus bar-to-cable connections for the "A" phase of the 4160 V feeder from the "C" RSST to the station.

These connections are located adjacent to the unit 2 turbine building. Abnormal procedure "Fire Protection-Operations Response" was initiated. At 12:41 h, an electrical arc from a cable connector to the metal siding of the turbine building resulted in an "A” phase-to-ground HEAF and "C" RSST lockout. The loss of the "C" RSST caused an under voltage condition on the "F" transfer bus and a loss of the unit 1 emergency buses.

Emergency diesel generators (EDG) No. 1 and 3 automatically started in response to under voltage signals and re-energized the emergency buses. The under-voltage signals also caused the stub buses to trip and the automatic start of unit 1 charging pump and unit 2 charging pump.

Component cooling pumps, which were in the standby mode, received a trip signal in addition to the loss of the stub buses and were, therefore, rendered inoperable. Plant systems responded, as expected, and the under voltage actuations occurred, as designed.

Unit 1 remained at 100 % power and unit 2 decreased power to 96 % due to a brief interruption of control power to the Unit 2 turbine electro-hydraulic system that resulted from the loss of the emergency bus. Unit 2 was returned to 100 % power at 14:00 h. Later on, all unit conditions were verified to be stable.

The station's fire brigade quickly responded to the fire and equipment damage was limited to a single cable connection to the RSST 4160 V bus.

Plant systems performed as designed in response to the under-voltage condition on the 1 and 2 emergency buses and control room operators executed the appropriate abnormal and operating procedures to ensure unit stability.

The root cause analysis has preliminarily concluded that the vertical orientation of the failed cable connection to the RSST 4160 V bus permitted moisture to enter the protective sleeve of the connection. The moisture within the connection provided a conductive path from the cable conductor to the cable shielding. This path allowed electrical arcing to occur within the connection, which caused the overvoltage annunciator to alarm. This condition also caused an electrical arc to the adjacent metal wall of the Turbine Building, resulting in a HEAF and RSST lockout. The loss of the transformer produced an under voltage condition on the 1 and 2 emergency buses, which resulted in the automatic start and loading of EDGs No. 1 and No. 3.

6.2.42 Event 42 – USA041 – 19990105

At approximately 13:11 h on January 5, 1999, with unit 1 operating at 100 % power and no electrical switching in progress an internal fault occurred in the unit 1 main (1M) transformer. The fault caused an explosion in the transformer and unit 1 turbine trip / reactor trip. As a result of the explosion, the 1M transformer was breached and a large amount of oil was expelled and ignited in an area approximately 40 feet north of the transformer.

The fire brigade was dispatched to the site and extinguished the burning oil fire at approximately 13:25 h. As a result of the fault, explosion, and fire, both 1M and 1R (unit 1 reserve transformer) were locked out. This caused the loss of non-safeguards buses 11, 12, 13, and 14 and major equipment on unit 1 powered from these buses including both reactor coolant pumps (RCPs), both feedwater pumps, both circulating water pumps, all condensate pumps, all heater drain pumps, 11 cooling water pump, all turbine building and auxiliary building lighting (except for battery, the unit stabilized, power was restored to non-safeguards 4 kV buses and the RCPs were restarted between 7 and 8 h following the transformer fault. The unit was restored to normal power operation over the following week.

During the day of the event plant personnel started clean-up of the area where the transformer oil had burned. All remaining unburned oil, dirt, sod, and snow was scraped from the ground and placed in dumpsters for future disposal. About 2 inches of dirt that had been thawed out from the fire was removed. There appeared to be no further penetration of oil into the ground. Soil samples will be taken in the spring when the ground has thawed to verify no oil soaked into the ground. The transformer pit drains were covered to minimize the spread of the remaining oil to the transformer bay collection pit. Sampling of the oil showed that PCBs were 2 parts per million.

Following the event, the equipment of concern was checked out for damage. Power to unit 1 was transferred from 2RX and 2RY to 1R transformer (the unit 1 reserve auxiliary transformer), the unit was returned to hot shutdown, taken critical, and returned to power on January 12, 1999. Since the cause of the internal phase to phase failure of the transformer has not yet been determined, corrective actions to prevent recurrence are currently undetermined.

6.2.43 Event 43 – USA043 – 20070406

On April 6, 2007, at 11:09 h, an automatic reactor trip (RT) occurred due to a turbine-generator trip as a result of a fault on the 31 main transformer. All control rods fully inserted and all required safety systems functioned properly. The plant was stabilized in hot standby with decay heat being removed by the main condenser. There was no radiation release. The emergency diesel generators did not start as adequate offsite power remained available. Two of three 138 kV offsite power substation feeders tripped as a result of the event. The auxiliary feedwater system automatically started as expected due to steam generator low level from shrink effect. Control room (CR) operators were notified of a fire at the 31 main transformer with the fire protection deluge system actuated. The plant fire brigade responded to the fire and applied foam.

The fire brigade leader reported to the CR the fire was extinguished at 11:21 h. The CR was notified at approximately 11:40 h that a visible explosion had previously occurred. Based on the report of an explosion, the CR declared a notice of unusual event (NUE) in accordance with the emergency plan which was terminated at 12:54 h. The direct cause of the RT was due to the actuation of the relays that sensed a fault from the failure of 31 main transformer 345 kV phase B bushing. The most probable cause was a design weakness associated with the type bushing used in the Phase B bushing. Significant corrective actions included replacement of 31 main transformer, and inspection, repair and replacement of damaged components as required associated with the 32 main transformer, the unit auxiliary transformer, and high voltage components. The event had no effect on public health and safety.

The direct cause of the RT was a turbine-generator trip due to actuation of generator protection system primary and backup lockout relays (86P, 86BU) that sensed a fault from a failure of the 31 main transformer 345 kV phase B bushing.

The root cause was indeterminate as the catastrophic failure destroyed most of the evidence. Engineering postulates that the bushing fault developed internal to the bushing possibly due to thermal cycling of the bushing during its years of service that lead to gas bubbles (voids) in the bushing oil. The gas bubbles resulted in dielectric breakdown due to partial discharge until the breakdown was severe enough to result in failure to condense the voltage. The 345 kV then exited at the weakest point and arced to the steel transformer tank leaving a hole in the bushing conductor and rapid increase in combustible gases. The most probable cause was a design weakness associated with condenser type high voltage GE bushings used in Phase B whose design develops problems affecting dielectric insulation. Documented GE design weaknesses included: 1) design flaw where gaps existed at the ends of the internal insulation paper/core allowing for the formation of gas bubbles leading to partial discharge and increased dielectric losses, 2) the bushing condenser design incorporated alternate paper layers printed and plain where the ink developed capacitance properties allowing for voltage tracking across the paper causing corona action and burning, 3) the bushing flex seal design for thermal cycling would move and crack resulting in compromise of the seal, 4) age of the phase B GE type U bushing which was an original early design with 30 years of operation.

6.2.44 Event 44 – USA059 – 20020612

On June 12, 2002, at 13:45 h, the "BC" 34.5 kV circuit breaker opened and a trouble alarm for the reserve auxiliary transformer was received in the control room. This was caused by an explosion in the 34.5 kV switchyard and oil fire in the switchyard output feeder breaker which was the result of a HEAF event. As a result, the reserve feed transformer was rendered inoperable, affecting the bus of reserve feed. This resulted in a loss of the preferred offsite power source to the East essential service water (ESW) pump

Subsequent protective switching by the system load dispatcher resulted in the reserve feed transformer being de-energized, affecting the bus of reserve feed. This resulted in a loss of the preferred offsite power source to the west ESW pump.

A contributing cause was determined to be the explosion of the current transformer due to an internal fault and HEAF event.

The reserve auxiliary transformers are the preferred source of offsite power when the units are tripped or shut down. Following the switchyard event, unit 1 and unit 2 were stable with power being supplied by the unit main generator through the unit auxiliary transformers. The reserve source of offsite power was only available through a single transformer and voltage output from this transformer was below the operability range, but stable. Additionally, the switchyard and the local area grids were in a degraded voltage condition due to the tie-lines in the 345 kV switchyard being open. In this degraded condition, taking the units off line would change the electrical load flow patterns on the grid and would increase the probability of grid instability and the likelihood of a loss of offsite power. Additionally, in taking the units off line, unit loads would be transferred to the TR5 reserve transformer, further increasing the probability of a loss of power from this source due to its low voltage. Loss of offsite power would cause a significant plant transient, resulting in the emergency diesel generators (EDG) supplying the safety related electrical buses, loss of forced flow through the reactor core, and a loss of the normal heat sink for the core (circulating water cooling of the main condensers).

6.2.45 Event 45 – USA064 – 20051029

On October 29, 2005 at 13:30 h EST, unit 1 was in the run mode at an approximate power level of 2804 CMWT (100 % rated thermal power). At that time, the reactor tripped on turbine control and stop valve fast closures. The turbine and generator tripped when the main power transformer experienced a fault which resulted in a main generator neutral ground overcurrent lock-out. Following the reactor scram, water level decreased due to void collapse from the rapid reactor pressure increase, reaching a minimum of approximately sixteen inches below instrument zero (about 142 inches above the top of the active fuel). The decrease in water level resulted in closure of the group 2 primary containment isolation valves per design. The operating reactor feedwater pump restored level to its design set point. Reactor pressure peaked at approximately 1145 psig, resulting in all eleven main steam safety relief valves opening as designed to reduce pressure.

The event was caused by an internal fault in the main power transformer. Heat from the fault resulted in an explosive rupture of the transformer shell at its top edge, and a subsequent fire within the transformer. A notice of unusual event was declared, and the installed fire suppression system along with the on-site fire brigade extinguished the fire. The transformer was replaced, and all systems and components affected by the fire or the transformer fault were inspected and repaired.

This event was caused by an internal fault in the main power transformer. An ongoing investigation is underway by station personnel to determine the root causes of the internal fault.

In March 2005, a trend was identified of increasing dissolved gas in the main power transformer oil, and bi-weekly oil sampling was initiated. In July 2005, daily oil samples were begun to monitor the gas levels and the rate of gas formation. On two occasions (September 8 through September 12, 2005 and October 17 through October 25, 2005), the transformer was connected to an on-line oil processing skid to reduce total dissolved gas levels. An oil sample taken the morning of the failure indicated no unusual gas levels or rates of gas formation.

6.2.46 Event 46 – USA066 – 20061212

On December 12, 2006, at 13:22 h, while conducting power ascension operations with unit 2 at approximately 25 % power, an electrical failure occurred in the circulating water pump 12 kV motor enclosures. A loud bang and explosion was reported to licensed plant operators in the Unit 2 control room. The electrical transient experienced on the 12 kV non-vital bus actuated an under voltage protection relay tripping the load breakers.

The reactor trip signal was initiated when two out of four RCP motor breakers opened. All control rods fully inserted in response to the reactor trip and all plant systems functioned as required. The auxiliary feedwater system for unit 2 was manually actuated per plant procedures, before an auto start signal for this system was generated.

On December 12, 2006, at 13:40 h, licensed plant operators confirmed an explosion onsite. At 13:56 h, the fire department first responders reported that the fire was out.

The immediate cause of the HEAF event was the result of surge capacitor failure causing a phase to phase electrical short resulting in a 12 kV electrical discharge and localized fire.

The root cause of the surge capacitor phase-to-phase internal fault was an in-service insulation breakdown, a single random electrical failure.

6.2.47 Event 47 – USA086 – 20010203

On February 3, 2001, at 15:13 h, plant operators were increasing Unit 3's power following completion of its refueling outage. At about 15:13 h, when switching offsite power sources for unit 3, a feeder breaker faulted and started a fire. This resulted in a loss of power to non-1E systems, a turbine/generator trip, a reactor trip, and a start of both Unit 3 emergency diesel generators. Containment emergency coolers were also started. Anticipating the fire would last more than 15 min, an unusual event was declared at 15:27 h

PST. The failure of a DC breaker to function properly resulted in the unavailability of the turbine/generator lubricating oil system, causing damage to the turbine/generator.

The event was caused when the breaker 3A0712 faulted, which caused arcing, localized overheating and started a fire within the breaker cubicle. The arcing damage prevented the breaker from opening to clear the fault. Ionized gases and smoke diffused through cable passages between adjacent cubicles and entered the reserve auxiliary transformer (RAT) feeder breaker cubicle and caused a ground fault within the cubicle, which resulted in the RAT trip and loss of non-safety related offsite AC power. The fire consumed much of the breaker’s non-metallic parts and caused substantial melting of current carrying components. Consequently, the exact cause of the breaker fault could not be conclusively determined. All subsequent operations were as designed, except the DC main turbine lubricating oil pump motor supply breaker malfunctioned.

The control room annunciators failed when the breaker to their power distribution panel tripped open as a result of the fire.

Because of communication errors, the control room was informed that the fire was extinguished at 15:44 h and control room personnel closed out the unusual event at 16:20 h based on this information. At 17:38 h, fire responders informed the control room that the fire had not yet been extinguished. Control room personnel did not re-open the unusual event declaration at that time because the fire was already fully contained within the cubicle, and did not actually pose a threat to safety related or safe shutdown equipment, and assistance from offsite agencies was not required .

6.2.48 Event 48 – USA095 – 20021003

At approximately 0230 hours on October 3, 2002, a fire occurred on start-up transformer (ST) no. 20. The transformer fire was extinguished by the transformer's automatic deluge system. Unit 1 was in MODE 1 - power operation operating at 100 % power and Unit 2 was in MODE 2 - start-up. Unit 2 was manually scrammed due to a loss of both reactor recirculation pumps. Unit 1 continued operation at 100 % power. The fire was extinguished quickly and caused no significant impact to adjacent systems or structures. An emergency plan unusual event was declared at 03:15 h when it was determined that two explosions also occurred. The unusual event was terminated at 05:52 h on October 3, 2002. Station transformer no. 20 was replaced and declared operable on October 10, 2002.

The root cause was an undetectable internal fault. This internal fault could have originated from several possible sources. It was also determined that the primary and backup lockout relays did not actuate as expected during the event. The lockout relays provide electrical protection for the ST-20 start-up transformer and function automatically to protect the transformer. The failure of the primary and backup lockout relays to actuate did not cause the event. Corrective actions have been developed and implemented with sufficient breadth to address the possible causes of both the transformer and the protective relay failures. No safety barriers were affected by this event. There were no consequences to the health and safety of the public as a result of this event.

6.3 Observations and Trending of HEAF Events in the OECD FIRE Database

Analyzing the OECD FIRE Database [1] with regard to HEAF fire events, a total of 48 out of 415 events collected in the Database, representing a contribution of 11.5 %, have been found to be HEAF events with fires. However, the size of the sample of HEAF events is too small for a meaningful statistical assessment. Therefore only basic observations can be presented, which, at best, can be interpreted as tendencies.

6.3.1 General Observations

In total 48 HEAF events with fires were reported to the OECD FIRE Database from the following countries between 1979 and mid-2012:

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 observed in nuclear power plants in the Netherlands and Switzerland. However, the event database from these countries is anyhow extremely small.

Seventeen events occurred before 2000, eighteen between 2000 and 2005 and thirteen in the recent past between 2006 and 2011. 31 of the events occurred at NPP with PWR, 14 at those with BWR, 2 at PHWR reactors and 1 at a GCR.

The analysis, if HEAF fire events typically occur during power operation gave the following result: 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. As low power and shutdown plant operational states are estimated to make up only about 15 % of the total operating time, the numbers show that the conditional probability of a HEAF event to occur during low power and shutdown or start-up is more than twice as high as during full power operation.

Interesting aspects of the HEAF events with fire are their safety significance and/or the economic losses incurred by the events. Eight events either were safety relevant or had the potential to impair nuclear safety under different conditions, because safety trains were lost and/or compartments beyond those where the fire started were affected by consequential fire effects, the latter mostly by damage to cables. Safety relevant HEAF events occurred in high or medium voltage electrical cabinets (4), in medium/low voltage transformers (2) and bus ducts / bus bars / cable runs (2). Events impairing nuclear safety did not occur in high voltage transformers, breakers and switchgears; however the economic loss was substantial in most high voltage transformer events.

In all but two HEAF events equipment failures were among the root cause, only in case of four events human error also played a role. Two events were solely caused by human errors during maintenance, respectively, restoration to operation after maintenance.

The plant location where the HEAF event resulted in fires is of particular interest from a potential safety significance point of view. Investigating if any trend could be observed, the following results have been obtained: Twenty-eight events occurred inside plant buildings, and 20 outside. For details see the diagram below in Figure 0-12.

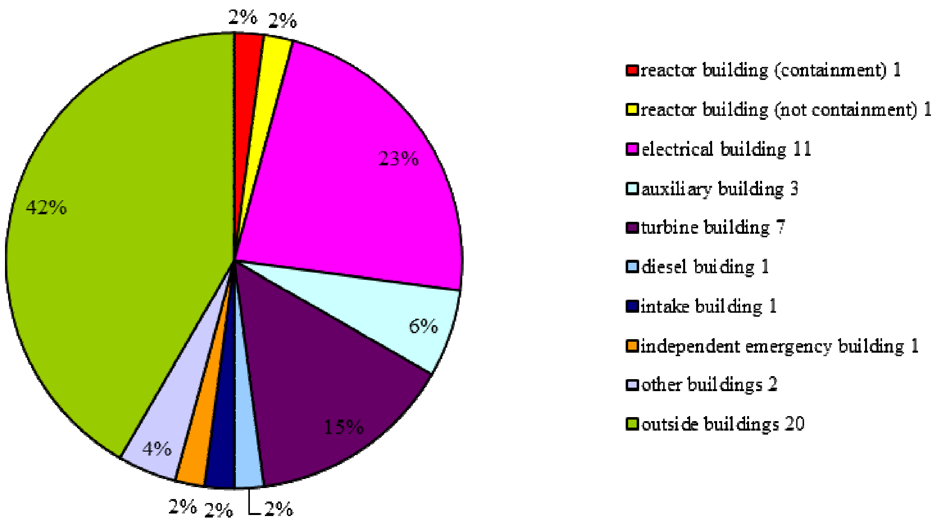

Figure 0-12: Locations where HEAF fire events occurred

In 27 events (~ 58 %) the damage was limited to the component where the fire started; in the remaining 21 events other components were also affected.

Barriers remained intact in 45 of 48 HEAF events, only in course of the three remaining events barriers were deteriorated or failed. In one case, the concrete housing of a transformer located outside plant buildings onsite, was severely damaged. The other two events occurred in electrical buildings indicating that two of the eleven HEAF events in electrical buildings, i.e. nearly 20 %, were accompanied by barriers being impaired. As barrier failure might be relevant to safety a potential for improving protection in the electrical building is seen.

In thirteen events fixed extinguishing systems were involved in fire extinguishing. In three cases extinguishing was accomplished by automatically actuated systems alone, in two more cases by automatically actuated systems in combination with the on-site fire brigade. In the remaining eight cases the fire was extinguished by manually actuated fixed extinguishing systems together with the onsite fire brigade, or in some cases also the external fire brigade.

In 29 events the fire was extinguished by the on-site plant fire brigade (24) or by shift personnel (5), and in six events the fire self-extinguished. In eleven events several differing ways of attacking the fire were needed to successfully extinguish the fire.

With respect to the components, where the HEAF occurred, the dominant contribution to HEAF events is from transformers, in particular high voltage transformers, which account for fourteen events, and medium and low voltage transformers, accounting for four events, i.e. both groups together account for nearly 40 % of the events. Details on the observations for the different groups of components are given below.

6.3.2 Component Observations

HEAF events with fire were observed at only a limited number of different components with the potential of such type of event. In the following paragraphs this is outlined in more detail. A graphical illustration of the below discussed contributions of the different components is provided in Figure 0-13.

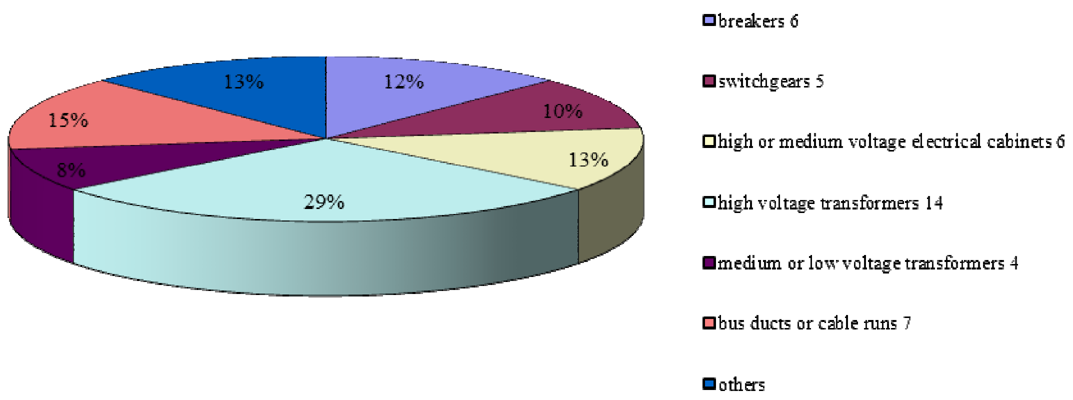

Figure 0-13: Contributions of components to the 48 HEAF events

6.3.2.1 Transformers

Transformers constitute the largest group of HEAF events with fires recorded in the Database. They make up 37.5 % of the 48 HEAF events. Furthermore, some of the HEAF fires at transformers caused the most damage at components. However, most of them were not relevant to nuclear safety. These events can be further sub-categorized in HEAF events at high voltage transformers and those at medium or low voltage transformers. The observed characteristics of the two groups of transformers differ significantly; therefore they are discussed separately in the following paragraphs.

High voltage transformers

Four HEAF events at high voltage transformers occurred before 2000, seven between 2000 and 2005 and finally three between 2006 and 2011. The relatively higher frequency of HEAF events in more recent years could be an indication of a rising impact of ageing problems such as deteriorated insulation material. This assumption is supported by the observation that ten events involved isolation failures, either between windings or between phases and ground.

Eleven events occurred at full power operation, three during start-up. Again, eleven events occurred outside plant buildings, one in a switchgear room, and two in other buildings.

In case of twelve events the damage resulting from the HEAF was limited to the transformer; in two events other components were also affected. Barriers remained intact for all events. The fire load involved was oil in twelve cases, and cable insulation material in two cases.

In two cases the fire was extinguished very quickly by fixed automatically actuated systems (spray water deluge), in another two cases the fire was extinguished manually by plant personnel within short time, in all other cases it took combinations of fixed and manual systems to extinguish the fire, mostly within short or moderately long time. In further two cases the extinguishing took several hours.

Medium and low voltage transformers

All four events at medium and low voltage transformers occurred in oil filled ones. They all occurred outside buildings. Three events were observed during full power operation, one during low power and shutdown states. All the events were caused by electrical insulation failures. In one event the damage resulting from the HEAF was limited to the transformer itself; in three cases other components were also affected. Barriers were deteriorated in one event. The fire load involved was oil in all cases.

In two of the four events the fire was extinguished quickly by the on-site fire brigade, in the remaining two cases it took combinations of fixed and manual systems to extinguish the fire within more than one hour.

6.3.2.2 Bus ducts and cable runs

Two events occurred outside, two in the turbine building, one in the electrical building, one in the reactor building, and one in the auxiliary building. Five events occurred at full power operation, one during low power and shutdown, one during hot stand-by.

In case of events the damage resulting from the HEAF was limited to the initiating component, in five events other components were also affected due to consequential functional effects. Barriers remained intact in all but one event. The fire load involved was cable insulation material in six events, and other fire loads in one event.

The fire was extinguished by the on-site fire brigade or other plant personnel in three cases within short to moderately long time, in one case however only after more than one hour. In two cases the fire was extinguished by combinations of fixed and manual systems within short or moderately long time. In one event the fire self-extinguished.

6.3.2.3 High or medium voltage electrical cabinets

Three of the HEAF events at high or medium voltage electrical cabinets occurred in the electrical building, two in the turbine building, and one in the diesel generator building. Four of the events occurred at full power operation, two during low power and shutdown plant operational states. In the case of four events the damage resulting from the HEAF was limited to the initiating component; in the case of two events other components were also affected.

Barriers remained intact in all but one event. The fire load involved was cable insulation material in the case of five events. Other fire loads were involved in only one event.

The fire was extinguished by the on-site fire brigade or other plant personnel in two cases within short time, in one case the fire self-extinguished after more than one hour. In three cases it took between more than one hour up to nearly eight hours (fire fighting hampered by earthquake influence) to extinguish the fire.

6.3.2.4 Breakers

All breaker HEAF events occurred in electrical and auxiliary buildings, four of which at full power operation, two at low power and shutdown. In four events the damage resulting from the HEAF was limited to the initiating component, in two events other components were also affected, barriers remained intact in all cases. The fire load involved was cable insulation material in case of five events, and flammable liquid in one event. In two cases it took more than one hour to extinguish the fire, in the remaining four events the fire was quickly extinguished.

6.3.2.5 Switchgears

All HEAF events with fires at switchgears occurred in switchgear rooms in electrical buildings, three of which at full power operation, two at low power and shutdown. In case of three events at switchgears the damage resulting from the HEAF was limited to the initiating component, in two events other components were also affected, barriers remained intact in all events. The fire load involved was cable insulation material in all events. In all but one event the fire was quickly extinguished by on-site personnel.

6.3.2.6 Others

From the remaining events one involved a vacuum cleaner inside the reactor containment, one a rectifier, two low voltage electrical cabinets, and finally two events occurred at electrically driven pumps.

6.3.3 Summary

Meaningful statistical conclusions cannot be obtained due to the small size of the sample of HEAF events. The findings in this section are based on observations of very small populations. At best, they can be interpreted as tendencies. The following could be concluded from the data:

- The 48 HEAF fire events constitute a significant share of nearly 11.5 % of the 415 events collected in the OECD FIRE Database [1] up to August-2012.

- Assuming a total operation time of approximately 5150 reactor years for the time period of OECD FIRE data collection until August 2012 and an average of 85 % power operation, the conditional probability of a HEAF event with fire to occur during one year of full power operation is about 0.008. For a HEAF event to occur during non-power operation it is about 0.02, i.e. about 2.5 times higher than for power operation.

- In general, there is nothing conspicuous about the occurrence dates of the HEAF events, with the only exception of events at high voltage transformers. Their occurrence dates seem to suggest a trend of increasing frequencies of HEAF in the more recent years. Maybe this can be attributed to ageing problems of electric isolation materials.

- The dominant contribution to HEAF events with consequential fires comes from transformers, with 29.2 % from high voltage transformers and 8.3 % from medium and low voltage transformers. HEAF in high voltage transformers typically lead to the destruction of the transformer and consequentially to massive economic losses. Safety significant consequences have not been observed in the events collected for high voltage transformers. The reason for this seems to be the fact that most of these transformers are located outside of buildings or plant areas relevant to safety. On the other hand, HEAF events in high or medium voltage electrical cabinet have a high potential for impairing nuclear safety.

- Regarding the location of fire origin the dominant contribution (~ 42 %) to the entire number of HEAF fire events in the Database comes from events outside plant buildings. Typically, these events are not safety significant. Another trend to be observed is that inside buildings HEAF fire events in the electrical building are most frequent (~ 23 %), particularly occurring in electric cabinets. Another observation is that the events in the electrical building have a higher potential for impairing safety and that for approx. 20 % barrier deterioration or failure was observed.

- The conditional probability of propagation of damages to components others than those where the fire originated, given a HEAF event, is significant, about 3.3 E-01. This is significantly higher than the conditional probability of 2.2 E-01 for damages caused to other components, given an OECD FIRE event. The main contributions to such propagating damages are from HEAF events in bus ducts and cable runs and in medium and low voltage transformers. On the other hand, the conditional probability that HEAF events at high voltage transformers (making up 29 % of the HEAF events) lead to damages of other components in only 1.4 E-01.

- With respect to the root causes of the HEAF fire events, in all but two events equipment failures (technical causes) were among the root causes, only in four events human error also played a role. In two events human error was the sole root cause.

- Another important observation was made regarding safety significance of HEAF events with consequential fires. Eight events (~ 17 %) were relevant to nuclear safety because safety trains were lost and/or compartments beyond those where the fire started were affected by consequential fire effects, the latter mostly by damage to cables. The highest relative share of safety significant events is observed for high or medium voltage electrical cabinets, with four out of six events resulting in safety significant consequences.

- Fire doors representing fire barrier elements separating fire compartments were damaged in case of two events due to the sudden pressure increase resulting from HEAF in high or medium voltage electrical cabinets inside electrical buildings. Outside plant buildings, a transformer housing made of concrete was severely damaged as a result of a transformer fire caused by HEAF. In all other events the barriers remained intact.

7. CONCLUSIONS AND RECOMMENDATIONS

The operating experience with respect to fires occurring as a consequence of high energy arcing fault (HEAF) events in nuclear power plants (NPP) collected in the international database OECD FIRE **[1]** from twelve OECD Nuclear energy Agency (NEA) member states has demonstrated a non-negligible amount of nearly 10 % of this type of plant internal events. These typically occur at components working at higher voltage levels such as switchgears and circuit breakers, or at high voltage cables as well as at transformers of different voltage levels.

Furthermore, the analysis of these events has shown that they have the potential to damage systems, structures and components (SSC) in NPP. However, the number of events is still too small to allow meaningful statistical evaluation.

Technical causes have been found to be the major root causes for the high energy arcing faults (see also [8]). Other causes identified from the OECD FIRE Database query are human failure, ageing effects and faulty procedures in combination with other root causes.

In some of these events, the electric arcs have resulted in partly significant consequences to the environment of the components affected, exceeding typical fire effects. In-depth investigations have shown the potential for failures of fire barrier elements such as fire doors and other protection features by such impacts induced by the extremely rapid pressure increase typically accompanying HEAF events.

The critical details related to determination of arc fault energy and arc durations are still missing, which restricts the use of these events in the HEAF scenarios for model validation. Variables related to electrical equipment and exposed materials were not provided either.

In view of the background of the potential safety significance of HEAF events and as a result of the investigation on HEAF fire events in the frame of the OECD FIRE Database Project, OECD Nuclear Energy Agency (NEA) has meanwhile initiated a task on "High Energy Arcing Faults" for in-depth investigations of this type of events in NEA member states [7], their damage mechanisms and their root causes as an important part of better understanding fire risk at NPP which is better accomplished by an international group to pool knowledge and research means.

Potential for plant improvements of passive fire protection means, in particular fire barriers, is seen in electrical buildings and, in particular in the confinement of electrical cabinets.

A major goal of this OECD/NEA task is to develop deterministic correlations for predicting damage and to establish a set of input data and boundary conditions for more detailed modeling which can be agreed on by the international community [9]. The output of the task may directly support developing improved methods for fire Probabilistic Risk Assessment (PRA) for nuclear applications.

To enable the fire expert community from OECD member states to better characterize HEAF events it has been recommended to perform experiments for obtaining comprehensive scientific fire data on the HEAF phenomena known to occur in nuclear power plants through carefully designed experiments, to be able to develop more realistic models to account for failure modes and consequences of HEAF, to advance the state of knowledge and provide better characterization of HEAF in fire PRA, and, in particular, to answer key questions, which cannot yet be answered form analyzing the HEAF events in the OECD FIRE Database. Such key questions can be how to prevent and to detect HEAF or what would be the best way for limiting pressure phenomena and minimizing fire barrier element failures.

The OECD FIRE Database project members will try to support this effort by continuously following the operating experience with HEAF fire events in their countries and providing as much detail as possible on event sequences, pressure build-up and consequential effects. Furthermore, the feedback from the experimental results shall be used by the National Coordinators of the OECD FIRE Database Project through providing corrective actions and precautionary measures to the nuclear power plant licensees and regulatory bodies in their countries.

8. REFERENCES

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