CONSIDERATION OF EVENT COMBINATIONS OF FIRES AND OTHER EVENTS IN FIRE PRA - INSIGHTS FROM THE OECD FIRE DATABASE

Heinz-Peter Berg[1], Eunate Armañanzas Albaizar[2], Nicole Fritze[3], Marina Röwekamp [4]

[1] *Bundesamt für kerntechnische Entsorgungssicherheit (BfE): Willy-Brandt-Straße 5, 38226 Salzgitter, Germany,* Heinz-Peter.Berg@bfe.bund.de
[2] *Consejo de Seguridad Nuclear (CSN): Calle de Pedro Justo Dorado Dellmans, 11, 28040 Madrid, Spain,* eaa@csn.es
[3] *Bundesamt für kerntechnische Entsorgungssicherheit (BfE): Willy-Brandt-Straße 5, 38226 Salzgitter, Germany,* Nicole.Fritze@bfe.bund.de
[4] *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH: Schwertnergasse 1, 50667 Köln, Germany,* Marina.Roewekamp@grs.de

The international database OECD FIRE on fire incidents in nuclear power plants (NPP) has been recently investigated regarding the operating experience in the participating member countries with respect to event combinations of fires and other events. Causally related events, either fires and consequential events or initiating events and consequential fires, have been observed as well as combinations of fires and other events having occurred independently of each other at the same time.

The fact that the amount of such event combinations is more than 10 % of the entire 448 event records in the database, of which the majority are fire events without safety significance, is notable.

In total 49 event combinations have been identified in the FIRE Database up to the end of 2015, the vast majority of them representing combinations of initial internal hazards, such as high energy arcing faults (HEAF), explosions or missiles, and consequential fires. Approximately 1 % of the entire events collected in the FIRE Database are fires resulting from external hazards. Approximately one quarter (12 events) of the above mentioned 49 event combinations recorded are fires and consequential events: seven of these initial fires resulted e.g. in an internal flooding as a consequential event.

The number of records of fire event combinations with more than one consequential event, of which at least one represents a fire, is seven representing 15 % of all event combinations identified in the database. This number is non-negligible and also indicates potential domino effects which may impair nuclear safety.

One general conclusion from this study is that event combinations fires and other events (hazards) and their potential consequences to plant safety need to be more systematically analyzed and considered in probabilistic risk assessment (PRA). They have also to be adequately addressed in the plant design. This underpins similar lessons learned from post-Fukushima investigations. Combinations of a majority of internal and external hazards not exceeding the design basis have already been accounted for in the plant fire safety concepts and are also addressed in the regulations of several countries. However, some consequences of fires, in particular flooding from extinguishing activities, need more systematic consideration. Moreover, the consequences of event combinations involving HEAF and fire need further in-depth investigation. This may result in plant modifications in the future including improved procedures.

I. INTRODUCTION

Cascade effects are the dynamics present in accidents in which the impact of a hazard or the development of an initial technological or human failure generates a sequence of events. Thus, an initial impact can trigger other phenomena leading to severe consequences. Cascade effects are complex and multi-dimensional and evolve constantly over time. They are associated with a high degree of vulnerability.

The domino effect occurs in many major accidents, increasing significantly both their complexity and their final effects and consequences. Although in recent years the interest in this aspect has received more attention, the research achievement is still modest compared to other aspects of industrial accidents. This is the reason that its main features are still insufficiently known.

Hazards typically occurring on a specific site cause or induce other hazards to occur. In particular, individual natural hazards are rarely observed alone. Thus, it is very important to note that almost any event combination of hazards is possible and that it is necessary to identify these interactions and find ways to mitigate the effects of hazard combinations.

In (Ref. 1), the state-of-the-art with regard to available approaches for modelling, assessment, prevention and management of domino effects and natural hazards triggering industrial accidents is described. Nevertheless, the relevant work carried out during past studies still needs to be consolidated and completed, in order to be applicable in a real industrial framework. Therefore, enhanced tools and methods have to be developed to assist the progress towards a consolidated and universal methodology for assessment and prevention of cascade events, contributing to enhance safety and sustainability of chemical and process industry.

Combinations of events have already been investigated in the process/chemical industry for many years because several major accidents occurred, often damaging equipment enclosures. The domino effect of event combinations can be investigated by different methods (Ref. 2). The significance of domino effects in chemical accidents is demonstrated in (Ref. 3). A domino effect can occur in various types of scenarios. However, an essential aspect is whether it is confined to a single plant or area or progresses to others.

Operating experience from different types of industrial installations has shown that event combinations of fires and other events occur throughout their entire lifetime. A recent study (Ref. 4) has addressed the main features of domino effect accidents in process/storage plants and in the transportation of hazardous (flammable) materials through an analysis of 225 accidents. One of the goals of this study was to analyze the domino effect sequences applying probability event trees. The most frequent sequences were explosions inducing fires (27.6 %), fires inducing explosions (27.5 %) and fires inducing secondary fires (17.8 %) for these specific types of installations.

Similarly, nuclear operating experience from the recent past underlines the necessity to take into account event combinations in the safety assessment of nuclear power plants, because the required function of systems, structures and components (SSCs) important to nuclear safety may be impaired in case of the occurrence of event combinations of fires and events. This may result in degradation or loss of their intended functions. In principle, causally related combinations of events such as earthquakes and consequential fires may significantly impair or even totally disable SSCs and may be not limited to one reactor unit at multi-unit sites.

Therefore, also in a recent document of the International Atomic Energy Agency (IAEA) regarding the design of nuclear power plants (Ref. 5) it is required: "*Where the results of engineering judgment, deterministic safety assessments and probabilistic safety assessments indicate that combinations of events could lead to anticipated operational occurrences or to accident conditions, such combinations of events shall be considered to be design basis accidents or shall be included as part of design extension conditions, depending mainly on their likelihood of occurrence. Certain events might be consequences of other events, such as a flood following an earthquake. Such consequential effects shall be considered to be part of the original postulated initiating event.*"

II. CATEGORIZATION OF COMBINATION OF FIRES AND OTHER EVENTS

The international OECD FIRE Database on fire incidents in nuclear power plants (Ref. 6) has been recently investigated regarding the operating experience in the participating member countries with respect to event combinations of fires and other events. Causally related events, either fires and consequential events or initiating events and consequential fires, have been observed as well as combinations of fires and other events having occurred independently of each other at the same time. The detailed results of these investigations can be found in the corresponding Topical Report (Ref. 7).

The following insights have been gained:

- Only internal hazards have been observed to occur as consequence of a plant internal fire, while fires may be induced by several internal or external hazards.
- Combinations of fires and independently occurring hazards represent rare event combinations.
- Only very few external and internal hazards have to be considered to be significant.

This investigation resulted in the following list of potential combinations, only some of which have been observed from the operating experience of nuclear power plants in those member countries participating in the OECD FIRE Database Project:

- Causally related event combinations of fires and other events:
  - Fire and consequential event:
    - Fire and consequential fire;
    - Fire and consequential explosion;
    - Fire and consequential (internal) flooding;
    - Fire and consequential high energy fault of electrical, mechanical or pressurized components with the potential of impairing item important to safety;
    - Event chains of multiple events with fires and more than one consequential event;
  - Event and consequential fire:
    - Internal hazard and consequential fire:

        - Internal explosion and consequential fire;
        - High energy fault of electrical, mechanical or pressurized components with the potential of impairing items important to safety and consequential fire;
        - Internal flooding and consequential fire;
    - Natural external hazard and consequential fire:
        - Earthquake and consequential fire;
        - Weather induced natural hazard and consequential fire, e.g.:
            - Hydrological impact (from rain, flooding);
            - Lightning;
        - Biological impact and consequential fire;
        - Wildfire (if not man-made);
        - Other natural hazard and consequential fire;
    - Man-made external hazard and consequential fire:
        - External fire and consequential fire;
        - External explosion and consequential fire;
        - Aircraft crash and consequential fire;
        - Other man-made hazards and consequential fire;
    - Event chains with fires as one of the consequential events;
- Fire and another event occurring independently of each other, but simultaneously, one during the mission time of the other:;
    - Internal hazard and independent fire:
        - Fire and independent fire,
        - Internal explosion and independent fire,
    - External hazard and independent fire:
        - Earthquake and independent fire;
        - External flooding and independent fire.

III. RESULTS FROM INVESTIGATING THE OECD FIRE DATABASE RECORDS

The analysis has shown that out of the 448 events reported to the OECD FIRE Database up to the end of 2014 (Ref. 6), 49 event records have been identified as event combinations of fires and other events (see Figure **1**). This contribution of approximately 11 % is non-negligible.

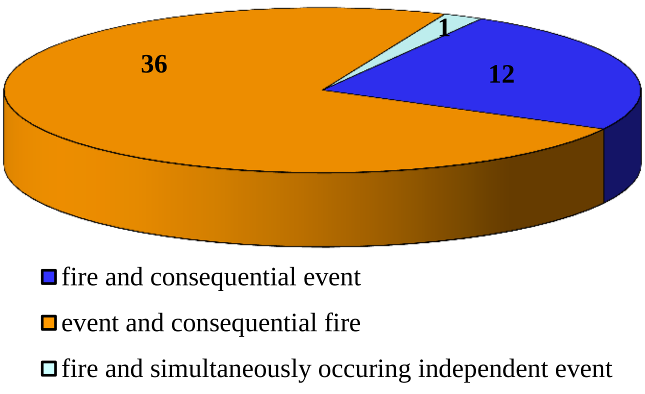

Figure 1. Fire event combinations in the OECD FIRE Database version 2014:2 (Ref. 6)

Seven of these combinations (more than 14 % of all 49 event combinations) are combinations of multiple events (so-called event chains). Two examples of the combination of an earthquake with more than one consequential events, one of these being a fire, can be found in the Database. In both event sequences a sequence of steps of the fire event can be observed for the combination of an earthquake and consequential fire. Not surprisingly the earthquakes caused a high energy arcing fault (HEAF), which resulted in a consequential fire. The fact that two of 49 event combinations (4 %) are cascading hazard combinations is a clear indication that such event combinations have to be systematically addressed in safety assessment and that these are relevant for probabilistic risk assessment (PRA, often used synonymously for probabilistic safety assessment, PSA). The analyses have resulted in corrective actions, such as plant specific design modifications, and, in one case, the implementation of an additional fire engine including full time operators for this equipment.

In the first of the above mentioned multiple-event combinations, an earthquake occurred with the consequence that the reactor was automatically tripped from 100 % of full power by high seismic acceleration signals prior to the fire, and then was cooled down to the cold shutdown mode without suffering any effects from the consequential fire. The fire started at the house transformer installed outside of buildings on the plant area being isolated from other components by a fire wall. The ignition mechanism was an electrical arc between the bushing and the bus duct igniting the insulation oil leaking from the transformer to the bus duct. The transformer contained about 17 m^3 of insulation oil. The fire was detected by post-earthquake patrol of plant personnel. It was successfully suppressed by chemical hydrate from the regional fire engine.

In case of the second multiple-event combination, the earthquake caused a high energy arcing fault in two of in total ten non-emergency switchgear cabinets. The HEAF resulted in a fire affecting all ten 6.9 kV cabinets of the switchgear. The cabinets were installed in the underground floor of the turbine building. Prior to the earthquake, the plant was at full power, it was automatically shut down due to the signals of high seismic acceleration. The fire was detected by an optical smoke detector, although the on-site fire brigade first was not able to identify the fire location due to heavy smoke. In addition, the alerted public external fire brigade was unable to support the on-site fire brigade because of access ways to the site being blocked as a consequence of the earthquake and tsunami. The fire duration was nearly eight hours, one of the highest fire durations observed so far from events in the OECD FIRE Database. The information on these two event combinations is briefly summarized in Table 1.

Table 1. Event combinations of seismic events with consequential HEAF and subsequent fire, from the OECD FIRE Database version 2014:2 (Ref.6)

Event Title	**ID**	**Plant State Before / After Fire**	**Component Where the Fire Started**	**Fuels**	**Plant Area / Building Where the Event Combination Occurred**	**Root Causes**	**Extinguished by (all means involved)**	**Duration [h:min]**
House transformer fire induced by the “Niigata-Chuetsu-Oki Earthquake”	361	PO / SD	medium and low voltage transformer (voltage < 50 kV): oil filled	flammable liquid	outside plant	E	external fire brigade; fixed system – manual actuation	01:55
Seismic induced arcing fault in non-emergency metal clad (M/C) switchgear cabinet	410	PO /SD	electrical cabinet: high or medium voltage (HEAF ≥ 1 kV)	cable insulation materials	turbine building	E	on-site plant fire brigade; fixed system – manual actuation	07:58

Note:

In this table, the following abbreviations are used:

PO: power operation SD: shutdown mode E: equipment

Information similar to that given in Table 1 is provided for all 49 combinations of fires and other events in the OECD FIRE Database. Details can be found in (Ref. 7).

Although the combinations listed in Section II are considered possible or have been observed in the operating experience from other industries as well as from the Fukushima Dai-ichi reactor accidents, only a few of these potential event combinations have been reported to the OECD FIRE Database so far. The corresponding distribution of event combinations is provided in Figure 2.

24 out of 49 events combinations are fires consequential to HEAF, additional six event sequences are HEAF induced by an initial hazard (including fire) with subsequent fire.

It has to be mentioned in this context that for most of the different types of combinations, only one or very few events have been reported so far to the OECD FIRE Database. The vast majority of these combinations have been identified as combinations of HEAF events with consequential fires solely (24 events, representing 5 % of all events in the Database and nearly 49 % of the combinations) or as event chains (six event combinations, 12 % of the combinations). These multiple event sequences cover initial fires with consequential HEAF and subsequent fire (two events), HEAF inducing a consequential fire resulting in subsequent internal flooding (one event) and HEAF induced by external hazards (earthquake or rain) with consequential fire (three events). Thus, the available operating experience gives some indications that these event combinations may need special attention with respect to preventive measures.

Nine out of 49 event combinations (more than 18 %) are fire events resulting in consequential internal flooding, mostly due to fire extinguishing activities. One of these event combinations was a missiles induced fire, another one was a HEAF causing fire with consequential flooding. The contribution of these events representing nearly 2 % of all fire events in the 2014:2 Database version (Ref. 6) shows that some improvement could also be made to account for this type of event combination. Hazards PRA has to address this issue adequately.

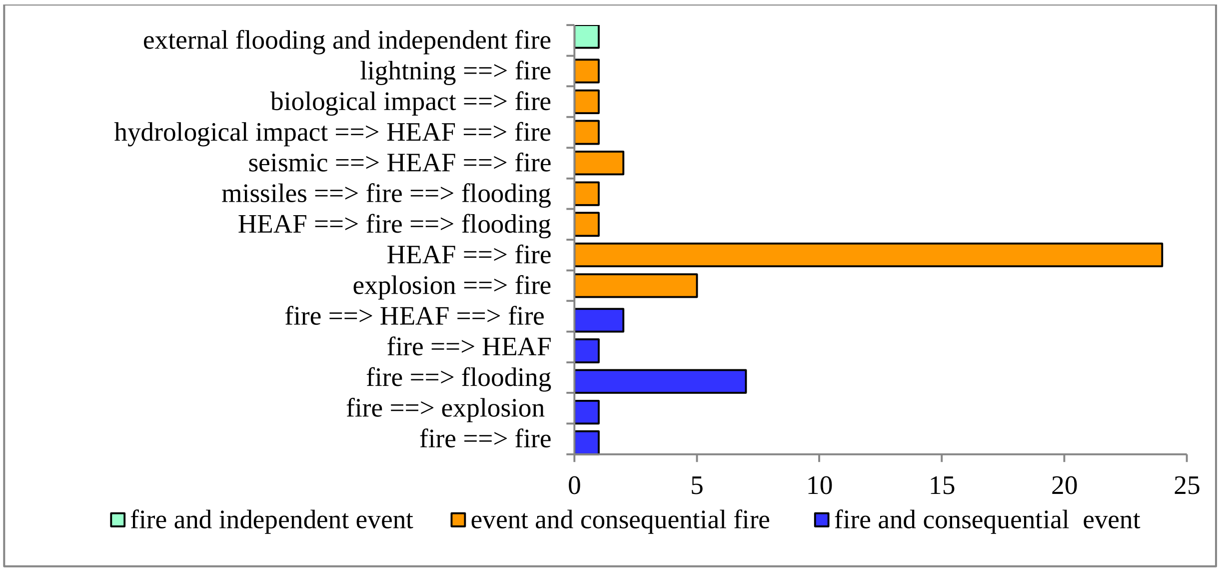

Figure 2. Event combinations observed in the OECD FIRE Database (version 2014:2, (Ref. 6))

Up to the end of reporting to the 2014:2 Database version (Ref. 6), only one event combination of a fire and another event occurring independently but concurrently with the fire has been recorded. This event is an external flooding and a simultaneously, however independently occurring fire, demonstrating that such combinations do occur, although their occurrence frequency is very low. At the time of the internal fire, the plant was in cold shutdown and had already reported the impacts of the flood. In total the external flooding lasted about four weeks. Licensee fire brigade personnel as well as personnel of the local fire department responded to the fire. The fire resulted in a loss of power to six of nine safety related 480 V AC buses and two of four safety related 4160 V AC buses leading to the loss of the spent fuel pool cooling function. The significance of this event is non-negligible, since this might have caused the loss of a safety function or multiple failures in systems used to mitigate an event in case the event would have occurred at power. Considering such event combinations in Hazards PRA may provide more detailed insights on potential weaknesses and the effects of improvements on the plant safety.

In principle, this combination of events shows the need to be aware of the possibility of a fire and an independently occurring event. In case of the external flooding plant accessibility is needed to enable technical support from outside the plant, e.g. to allow for a change of the personnel on-site or access of the external local fire brigade. Plant access has to be ensured, even under such extreme circumstances, and should be addressed in the PRA.

Figure 3 shows the components where the fires started in case of the event combinations analyzed. A majority of the events recorded occurred at transformers (nearly 41 %) and electrical cabinets (approximately 18 %). The trend seems to be increasing, particularly for HEAF events at transformers with consequential fires as approximately 60 % of these events occurred between 2000 and 2015 versus 40 % in the period between 1985 and 2000. Probably, this could be due to ageing of e.g. transformer windings or bushings.

With regard to the severity of the events, there are indications either provided by information on how many safety trains were affected or lost or by the information on change of the plant operational mode as a consequence of the event sequence. In case of eight of the 49 event combinations recorded in the Database (representing approximately 16 % of the event combinations), one safety train and in case of two event sequences (4 %) more than one safety train was lost. For 33 of the 49 event combinations (67 %) the plant operational mode changed. This contribution is even higher (79 %) when considering that for plants under construction or in shutdown (7 events in total) the plant mode cannot change.

The consequences of the event combinations recorded so far in the FIRE Database on the plant operation mode are shown in Figure 4 and Figure 5. In these figures, the following abbreviations are used:

PO: power operation
SU: start-up mode
HS: hot stand-by
SD: shutdown mode

CP: construction phase

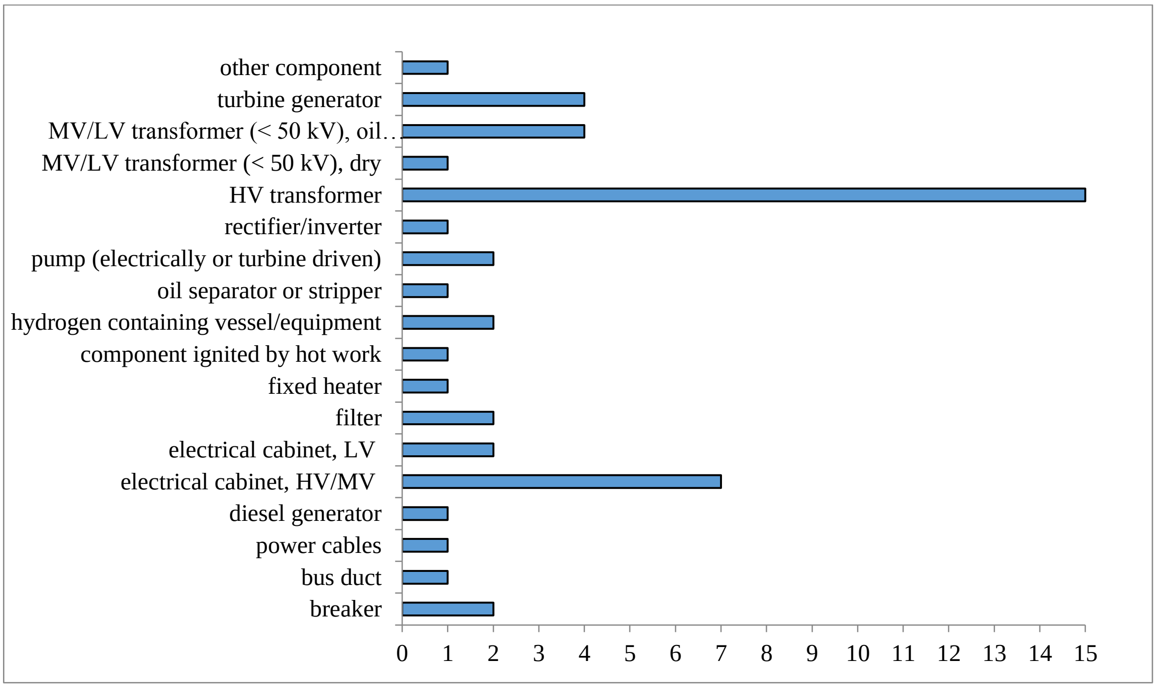

Figure 3. Event combinations - component where the fire started, from (Ref. 6)

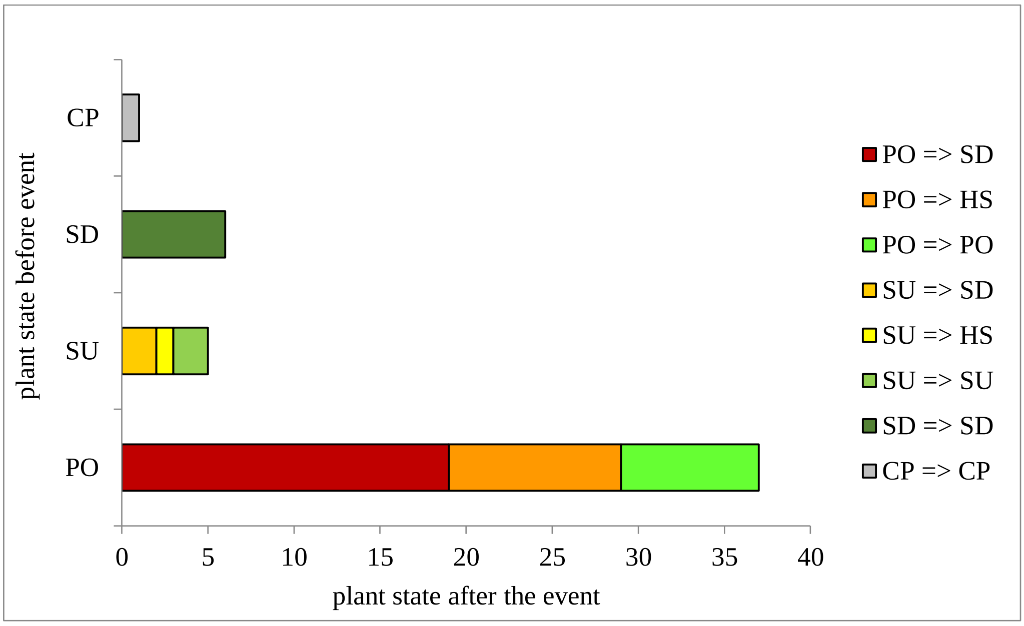

Figure 4. Operational mode before the start of the event combination and after the event, from (Ref. 6)

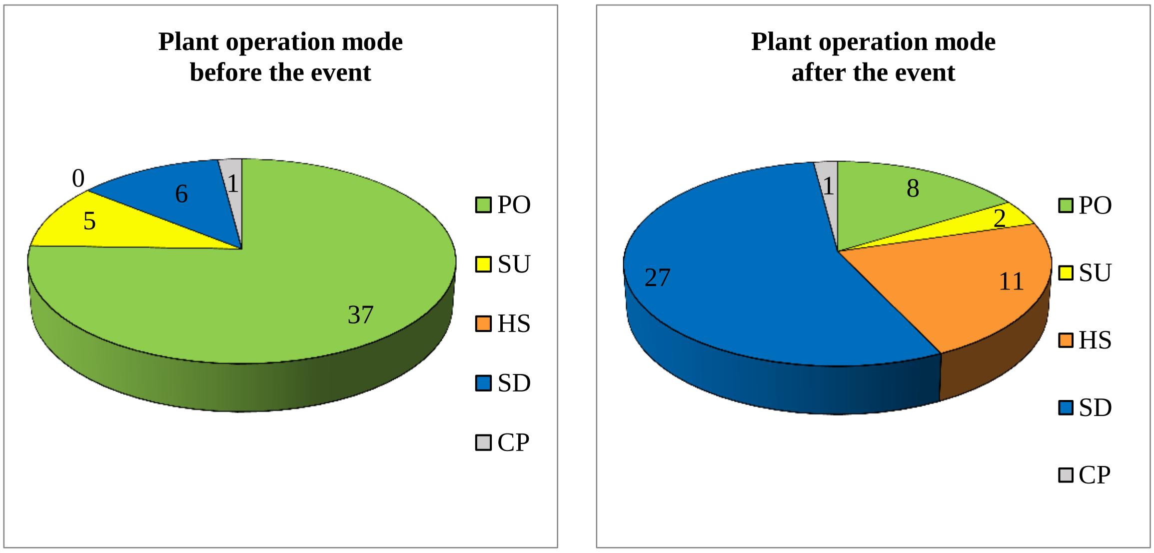

Figure 5. Operational mode changes for the event combinations, from (Ref. 6)
(left: before the event, right: after the event)

In case of 37 out of 49 events (nearly 76 %) the plant operated at full power when the initial event occurred, in 8 of these the plant remained at full power, while in case of 10 events the mode changed to hot stand-by and in 19 events to shutdown as a result of the fire. The contribution of more than two thirds of all event combinations during power operation mode having resulted in a plant operation mode change is notable. The result differs strongly from that for individual events (no event combinations) in the Database, where for 60 % of the events the plant operational mode remains unchanged at full power and changes to hot-stand-by or shutdown for only 37 % of the events.

In case of plants in shutdown conditions (six events) or under construction (one event) the plant operation mode of course trivially remained unchanged, while for plants under start-up (in total five events) the operation mode changed to hot stand-by (one event) or shutdown (two events), and remained unchanged only for two events. No event combination involving fire has been recorded at present in the Database for plants in hot stand-by.

IV. CONCLUSIONS AND OUTLOOK

Nearly 11 % of the entire 448 fire events recorded in the OECD FIRE Database up to the end of 2014 (Ref. 6) have been identified as event combinations of fires and other events. This contribution is non-negligible.

Notably, 24 out of 49 events combinations are fires consequential to HEAF. Thus, HEAF events resulting in fires are the most important contributors to event combinations, among them HEAF at transformers and at electrical cabinets representing the highest contributions.

One further HEAF event resulted from an initial fire, two HEAF events from earthquakes and another one resulted from impact of heavy rain. The entire fire events correlated to HEAF are presented in the set of event combinations. A majority of such correlations of HEAF and fire have resulted in more severe consequences and a change of the plant operational mode. One of the lessons learned from this result is that HEAF phenomena were not well known when a majority of the existing nuclear power plants were designed. According to the recent insights safety improvements to adequately consider potential HEAF events in the design and operation of nuclear installations are needed. The relevance of HEAF events for fire safety and the need to address these in Fire PRA has been recognized on an international level having resulted in an OECD Nuclear Energy Agency (NEA) experimental project in order to perform in-depth investigations. Results are expected to be publicly available in the near future and may affect Fire PRA approaches.

The experience from event combinations also indicates that only a few explosions caused a consequential fire and that most of these did not result in a change of the plant operational mode indicating that the plant design against internal explosions has already considered the possibility of such consequential fires and their potential effects on plant safety.

Nine out of 49 fire events in the FIRE Database (Ref. 6) resulted in internal flooding. In most of these events the flooding was due to fire extinguishing activities. The non-negligible contribution of event combinations finally resulting in subsequent internal flooding events indicates that some improvements may be possible in the plant design regarding the protection against fire and consequential flooding. Combinations of fires and consequential flooding need to be systematically addressed in Fire PRA.

At least one example of a fire and a simultaneously, but independently occurring hazard has been observed underlining that such combinations do occur, even if the occurrence frequency of such an event combination is low.

In total five event sequences in the OECD FIRE Database show a domino effect: fire with consequential HEAF causing another fire, missiles causing a fire resulting in subsequent flooding, two event sequences with seismically induced HEAF and subsequent fires, and, last but not least, rain causing HEAF and subsequent fire.

It has also to be mentioned that none of event combinations observed in the FIRE Database resulted in a loss of all safety trains. Moreover, the events were limited to one plant unit in case of multi-unit sites. However, this may be due to the fact that a majority of the event records in the Database represent events without safety significance and that in most cases passive fire protection means have ensured that fires occurring inside buildings are at least limited to the respective building.

One general conclusion is that event combinations of events from internal as well as external hazards with fires need to be more systematically analyzed. Moreover, they should be addressed in the site specific plant design. This was also one of the lessons learned from the post-Fukushima reactor accident analyses. The investigations of the operating experience collected in the OECD FIRE Database as provided in (Ref. 7) clearly underpin this lesson learned.

While combinations of a majority of internal hazards and those external hazards not exceeding the design basis have already been accounted for in the plant fire safety concepts, some consequences of fires, in particular flooding from extinguishing activities, may warrant a more systematic consideration regarding potential secondary effects from fire extinguishing media already during the design of the fire protection features and before establishing fire management strategies.

In addition, the in-depth investigation of event combinations of fires and other events has clearly demonstrated that some improvements in the Database, particularly for statistical use, but also for consistency in coding and a harmonized understanding of complex event scenarios is needed (e.g. regarding the consideration of fire spread or consequential fire). The potential improvements already identified will be implemented in the next version of the Database to be distributed in the first year of the Phase Five of the OECD FIRE Database Project.

Regarding the use of the OECD FIRE Database for Fire PRA there are still limitations due to inconsistencies in reporting between member countries according to differing national reporting criteria. However, the data – as indicated in the case of combinations of fires and other events or hazards – provide already valuable insights for probabilistic considerations.

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