Research Article

Statistical Analysis of Loss of Offsite Power Events

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This paper presents the results of the statistical analysis of the loss of offsite power events (LOOP) registered in four reviewed databases. The reviewed databases include the IRSN (Institut de Radioprotection et de Sûreté Nucléaire) SAPIDE database and the GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH) VERA database reviewed over the period from 1992 to 2011. The US NRC (Nuclear Regulatory Commission) Licensee Event Reports (LERs) database and the IAEA International Reporting System (IRS) database were screened for relevant events registered over the period from 1990 to 2013. The number of LOOP events in each year in the analysed period and mode of operation are assessed during the screening. The LOOP frequencies obtained for the French and German nuclear power plants (NPPs) during critical operation are of the same order of magnitude with the plant related events as a dominant contributor. A frequency of one LOOP event per shutdown year is obtained for German NPPs in shutdown mode of operation. For the US NPPs, the obtained LOOP frequency for critical and shutdown mode is comparable to the one assessed in NUREG/CR-6890. Decreasing trend is obtained for the LOOP events registered in three databases (IRSN, GRS, and NRC).

1. Introduction

The safety systems of the currently operating nuclear power plants are mainly active requiring electrical energy for their activation and operation. The concepts of redundancy, physical separation, and functional independence are applied in the design of the electrical systems in order to achieve the required level of reliability [1].

The loss of offsite power (LOOP) initiating event occurs when all electrical power to the plant from offsite power system is lost. The NPP offsite power system is the transmission power system where the nuclear power plant is connected.

The electrical power after the LOOP is expected to be provided either by the plant generator or, in case of unsuccessful throttle down to house load, by the emergency diesel generators (EDG).

Loss of alternating current (AC) to the essential and nonessential switchgear buses in a NPP (i.e., loss of offsite electric power system concurrent with turbine trip and unavailability of the onsite emergency AC power system) is referred to as a station blackout (SBO). Station blackout does not include the loss of available AC power to buses fed by station batteries through inverters or by the alternate AC sources.

Deterministic and probabilistic safety analyses [2, 3] show that LOOP and consequential SBO are important contributors to NPP safety. The frequency of the LOOP event and the probability of restoration of the offsite power after a given time are important inputs for safety analyses.

Results of the statistical analysis of LOOP events identified in four databases are presented. The description of the databases screening methodology is given in Section 2. The description of the LOOP frequency assessment methodology is detailed in Section 3 with description of the methodology used for trend analysis in Section 4. The obtained LOOP frequencies are presented in Section 5.1. Distributions of the identified LOOP events are given in Section 5.2. The obtained results of the trend analysis are presented in Section 5.3. Main conclusions of the analysis are given in Section 6.

2. Databases Screening and Identification of Relevant Events

The four databases of operational events screened in this study for LOOP events are the database “Support à l’Analyse des Problèmes, Incidents et Difficultés d’Exploitation” (SAPIDE), owned and managed by IRSN, the database

“Vertiefte Auswertung meldepflichtiger Ereignisse” (VERA), owned and managed by GRS, the US NRC Licensee Event Report (LER) database, and the IAEA Incident Reporting System (IRS) database [4]. Identification of the relevant LOOP events in the analysed databases was performed in two steps:

- (1) First, the databases were searched to identify potential events for consideration.
- (2) Search results were reviewed with selection and classification of the relevant events.

Database searching was done with relevant “guidewords” and “keywords” identified in relation to the “LOOP” topic. All identified events in the search of the databases were analysed. The relevant events were selected and classified based on predefined criteria. The methodology for events screening and selection was also applied for analysis of the EDG failures presented in [5].

The database SAPIDE and the database VERA were screened for relevant events reported in the period from January 1, 1992, to December 31, 2011. Different reporting criteria are used in France and Germany, resulting in different type of events to be reported and inserted in the databases. 228 LOOP events from the SAPIDE database and 190 from VERA were selected as relevant for the analysis.

The US NRC LERs database and the IAEA IRS [4] database were searched to identify representative LOOP related events for the period 1990–2012. In total, 120 LOOP events were identified from the US NRC LERs database as relevant for the analysis. The widespread grid disturbance which occurred on August 14, 2003, affecting nine NPPs sites with eleven reactors, was also taken into account. Five of those events were selected and considered further in the analysis. From IAEA IRS database, 52 events were identified as relevant.

Table 1 shows the number of events identified in the analysed databases for different plant status.

Table 1 shows that the largest number of LOOP events is registered during power operation followed by cold shutdown. Different reporting criteria are used in the analysed databases. For example, the hot standby mode is classified in French SAPIDE database in on-power events while in German VERA is classified within hot shutdown mode.

From Table 1, it is apparent that very few LOOP events are reported in IRS. Indeed, IRS includes all reactors in the world and thus also France, German, and US, and hence the number of events should be higher than the sum of these three countries. It can be concluded that LOOP events are not, in general, reported to IRS and hence calculating the LOOP frequency with methodology presented in Section 3 is not meaningful in the case of the LOOP events in IRS.

The need for harmonization and unification of the reporting criteria and events description has been identified in the analysis of the identified events.

3. LOOP Frequency Assessment Methodology

Several studies have analysed data on LOOP and offsite power restoration times. The first topic report [6] summarized

the results of the technical evaluations done until 1988 and assessed major contributors to the frequency of station blackout. The following two reports document a similar study with primary objective to update the LOOP model parameters, frequency and recovery time, using US power plant event data over the periods of 1980–1996 [7] and 1987–1995 [8]. The following report [9] includes results of statistical and engineering analysis of LOOP frequencies and durations at commercial nuclear reactors in the US from 1986 to 2012 for both critical (at power) and shutdown operations.

In NUREG/CR-6890 [10], the LOOP events are classified based on the operating state of the plant at the time of the LOOP events. The LOOP events in NUREG/CR-6890 are subdivided into four types by cause or location: plant-centered, switchyard-centered, grid-related, and weather-related.

The plant-centered LOOP events include events in which the design and operational characteristics of the nuclear power plant unit are the main cause of the loss of offsite power. Switchyard-centered LOOP events are events in which the equipment, or human-induced failures of equipment, in the switchyard plays the major role in the loss of offsite power. The LOOP events in which the initial failure occurs in the interconnected transmission grid that is outside the direct control of plant personnel are included in grid-related LOOP events. Weather-related LOOP events include LOOP event caused by severe or extreme weather with forceful and nonlocalized effects.

In this paper, the same classification and categories as the ones in NUREG/CR-6890 [10] are used.

The events identified in Table 1 are classified into the LOOP categories based on the categorization given in Table 2.

The total LOOP initiator frequency per reactor critical year is calculated as follows:

$$f_{\text{LOOP-At-Power}} = \frac{\# \text{ of applicable LOOP events}}{\text{Rx critical years}}, \quad (1)$$

where # of applicable LOOP events is the sum of the events within the same category registered in a given period and Rx critical years are the sum of the reactor critical years of the operating units in the analysed period.

The LOOP initiator frequency per reactor shutdown year is calculated as follows:

$$f_{\text{LOOP-Shutdown}} = \frac{\# \text{ of applicable LOOP events}}{\text{Rx shutdown years}}, \quad (2)$$

where # of applicable LOOP events is the sum of the events within the same category registered in a given period and Rx shutdown years are the sum of the reactor shutdown years of the operating units in the analysed period.

The assessment of the LOOP frequency, as shown by (1) and (2), requires as input the total reactor critical or shutdown years in the analysed period. The reactor critical and shutdown years are calculated from the number of the operating NPP units in the analysed country in each year for

TABLE 1: Number of selected events for different plant status and database.

Plant status/database	Number of events			
	SAPIDE-IRSN	VERA-GRS	LER-NRC	IRS-IAEA
On-power	145	102	76	47
Hot shutdown	25	12	7	0
Cold shutdown	58	76	37	5

TABLE 2: Categorization of plant status into operational mode.

Mode	Plant status
Critical operation	On-power
Shutdown operation	Hot/cold shutdown

the analysed period and from the average operating factors (OF):

$$R_x \text{ critical years} = OF * \# \text{ of operating units}, \quad (3)$$

$$R_x \text{ shutdown years} = (1 - OF) * \# \text{ of operating units}. \quad (4)$$

The operating factor, expressed in percent, is defined as follows:

$$OF = \frac{\text{Online hours}}{\text{Total hours}}. \quad (5)$$

The number of the operating units in each year for the analysed period is determined from the data provided in the IAEA Country Nuclear Power Profiles website [11]. The average operating factor of the units is assessed from the Country Nuclear Power Profiles given in the IAEA Power Reactor Information System [12] as weighted average for the analysed period. The number of the operating reactors in the given year and the average operating factor (OF) for the analysed period for each country and database are shown in Tables 3, 4, and 5. The first column in these tables specifies the year with the number of operating units given in second column. The third and fourth columns include the reactor critical and shutdown years. The sums of the reactor critical and shutdown years for the total analysed period are given in the last row of the tables.

4. Trend Analysis Methodology

Accident statistics are used extensively for risk analysis of different types of accidents [13, 14]. One of the tools used within accident statistics is statistical trend analysis. The goal of a trend analysis is to investigate whether a trend is present in the data and if the data show an increase or decrease over time.

In classical statistical theory, there are a number of tests for identification of the data trends. In those tests, a typical approach is to assume that the data are realisations of Poisson distributed random variables with an expected value that, if there is a trend, may be different from year to year. A statistical hypothesis test is then used to check if the expected value is

TABLE 3: Critical and shutdown years assessed for IRSN database.

Year	Operating units	Reactor critical years	Reactor shutdown years
1992	53	42.1	10.9
1993	53	42.1	10.9
1994	54	42.9	11.1
1995	54	42.9	11.1
1996	54	42.9	11.1
1997	54	42.9	11.1
1998	54	42.9	11.1
1999	54	42.9	11.1
2000	56	44.5	11.5
2001	56	44.5	11.5
2002	58	46.1	11.9
2003	58	46.1	11.9
2004	58	46.1	11.9
2005	58	46.1	11.9
2006	58	46.1	11.9
2007	58	46.1	11.9
2008	58	46.1	11.9
2009	58	46.1	11.9
2010	58	46.1	11.9
2011	58	46.1	11.9
Average operating factor (%)			79.5
Sum of reactor critical/shutdown years		892.0	230.0

varying from year to year [15–17]. Considerable amount of data or a strong tendency in the data is required in order to apply the classical approach.

The alternative approach for the trend analysis is the utilization of the predictive Bayesian approach [18, 19].

In this study, a trend analysis of the identified events is performed with the application of approach presented in [20]. In this approach, focus is on observable quantities, and probability distributions are only used for expressing epistemic uncertainties. Four measures of data trends are introduced in the methodology as described in [20].

The T_1 measure compares averages of different parts of the data and is given in the following:

$$T_1 = \sum_{j=1}^{r-1} \left(\frac{\sum_{i=1}^j x_i}{j} - \frac{\sum_{i=j+1}^r x_i}{r-j} \right), \quad (6)$$

TABLE 4: Critical and shutdown years assessed for GRS database.

Year	Operating units	Reactor critical years	Reactor shutdown years
1992	20	16.9	3.1
1993	20	16.9	3.1
1994	19	16.1	2.9
1995	19	16.1	2.9
1996	19	16.1	2.9
1997	19	16.1	2.9
1998	19	16.1	2.9
1999	19	16.1	2.9
2000	19	16.1	2.9
2001	19	16.1	2.9
2002	19	16.1	2.9
2003	18	15.2	2.8
2004	18	15.2	2.8
2005	17	14.4	2.6
2006	17	14.4	2.6
2007	17	14.4	2.6
2008	17	14.4	2.6
2009	17	14.4	2.6
2010	17	14.4	2.6
2011	9	7.6	1.4
Average operating factor (%)			84.6
Sum of reactor critical/shutdown years		303.0	55.0

where T_1 is the trend measure, x_i is the number of LOOP events in year i , and r is the number of analysed years.

Positive T_1 indicates a decreasing trend of the observed data while a negative value indicates an increasing trend. Larger absolute values of obtained T_1 mean clearer trend in analysed data.

The T_2 measure compares the sum of the first half of chronologically ordered data to the sum of the second half:

$$T_2 = \begin{cases} \frac{\sum_{i=1}^{r/2} x_i}{r/2} - \frac{\sum_{i=r/2+1}^r x_i}{r-j}, & r \text{ even} \\ \frac{\sum_{i=1}^{(r+1)/2} x_i}{(r+1)/2} - \frac{\sum_{i=(r+1)/2+1}^r x_i}{(r-1)/2}, & r \text{ odd.} \end{cases} \quad (7)$$

Positive T_2 , the same as T_1 measure, indicates decreasing trend in data.

The T_3 measure is utilized for identification of the nonmonotonic trends and is defined as follows:

$$T_3 = \sum_{j=1}^{r-1} \left(\frac{\sum_{i=1}^j x_i}{j} - \frac{\sum_{i=j+1}^r x_i}{r-j} \right)^2. \quad (8)$$

The T_4 measure compares the observation with the mean value and is defined as follows:

$$T_4 = \sum_{i=1}^r (x_i - \bar{x})^2. \quad (9)$$

TABLE 5: Critical and shutdown years assessed for US NRC database.

Year	Operating units	Reactor critical years	Reactor shutdown years
1990	110	93.5	16.5
1991	109	92.6	16.4
1992	109	92.6	16.4
1993	109	92.6	16.4
1994	110	93.5	16.5
1995	109	92.6	16.4
1996	107	90.9	16.1
1997	104	88.4	15.6
1998	104	88.4	15.6
1999	104	88.4	15.6
2000	104	88.4	15.6
2001	104	88.4	15.6
2002	104	88.4	15.6
2003	104	88.4	15.6
2004	104	88.4	15.6
2005	104	88.4	15.6
2006	104	88.4	15.6
2007	104	88.4	15.6
2008	104	88.4	15.6
2009	104	88.4	15.6
2010	104	88.4	15.6
2011	104	88.4	15.6
2012	104	88.4	15.6
Average operating factor (%)			84.9
Sum of reactor critical/shutdown years		2062.0	365.0

Larger T_4 measure indicates larger absolute differences of the analysed observations, both positive and negative, from the mean value.

These trend measures are calculated for LOOP events registered in each database over the analysed period. The next step is to generate new datasets $x_1^*, \dots, x_r^*$ from the original data and assess trend measures for the new datasets. The new datasets are generated from the Poisson uncertainty distribution conditionally on the number of events to be equal to the identified one in data shown by (10) and equal average given with (11). Consider

$$n = \sum_{i=1}^r x_i^*, \quad (10)$$

$$\bar{x} = \sum_{i=1}^r \frac{x_i}{r}. \quad (11)$$

The new datasets should have the sum of the LOOP events equal to the sum in original data and their mean should be equal to the mean calculated for calculated data. Generating r new datasets $x_1^*, \dots, x_r^*$ is done with the utilization of multinomial distribution with r outcomes of equal probability $1/r$

TABLE 6: Plant-level LOOP frequencies assessed from IRSN database.

Mode	LOOP category	Number of events	Mean frequency	Frequency units
Critical operation	Plant	110	$1.23E - 01$	/rcry
Critical operation	Switchyard	26	$2.91E - 02$	/rcry
Critical operation	Grid	3	$3.36E - 03$	/rcry
Critical operation	Weather	6	$6.73E - 03$	/rcry
Critical operation	All	145	$1.63E - 01$	/rcry
Shutdown operation	Plant	71	$3.09E - 01$	/rsy
Shutdown operation	Switchyard	11	$4.78E - 02$	/rsy
Shutdown operation	Grid	1	$4.35E - 03$	/rsy
Shutdown operation	Weather	0	0	/rsy
Shutdown operation	All	83	$3.61E - 01$	/rsy

TABLE 7: Plant-level LOOP frequencies assessed from GRS database.

Mode	LOOP category	Number of events	Mean frequency	Frequency units
Critical operation	Plant	81	$2.67E - 01$	/rcry
Critical operation	Switchyard	2	$6.60E - 03$	/rcry
Critical operation	Grid	16	$5.28E - 02$	/rcry
Critical operation	Weather	3	$9.90E - 03$	/rcry
Critical operation	All	102	$3.37E - 01$	/rcry
Shutdown operation	Plant	75	$1.36E + 00$	/rsy
Shutdown operation	Switchyard	1	$1.82E - 02$	/rsy
Shutdown operation	Grid	9	$1.64E - 01$	/rsy
Shutdown operation	Weather	3	$5.46E - 02$	/rsy
Shutdown operation	All	88	$1.60E + 00$	/rsy

and with the number of trials equal to n as defined by (10) and given in [20]. The routine RNMTN from Fortran Numerical Stat Library [21, 22] is utilized for the generation of the new datasets.

For each of these datasets, the values of trend measures T are calculated and compared with the observed value of T from the original data. If the observed value of T measure from the original data is among the largest or smallest predefined percentage (e.g., 5–10%) of the values of the generated data, it is concluded that there is a trend in the original data.

The trend measures are calculated for events registered during power and shutdown operation for the sum of LOOP events in the given year. In total $r = 10000$ new datasets are generated and trend parameters are determined. The generated trend parameters are compared to the calculated ones. The obtained results are given in Section 5.

5. Results

The results of the analysis of the identified LOOP events are given in the following sections. The obtained LOOP frequencies for different events categories are given in Section 5.1. The distribution of the identified events in the analysed period is given in Section 5.2, with the results of the trend analysis in Section 5.3.

5.1. Obtained LOOP Frequency. The obtained LOOP frequencies for the three analysed databases are given in Tables 6–8. The first column of the tables defines the plant operational mode (critical/shutdown) with LOOP categories given in the second column. The number of identified events for each category and mode is given in third column. The mean frequency of the LOOP events per reactor critical year (rcry) or reactor shutdown year (rsy) is given in the fourth column. The LOOP frequency is obtained from (1) and (2) for power and shutdown operation as described in Section 3.

The LOOP frequencies obtained for the French and German NPPs during critical operation, as shown in Tables 6 and 7, are of the same order of magnitude. The frequencies of the LOOP events are twice larger for German plants compared to the French NPPs. Tables 6 and 7 show that plant related events are the dominant contributors to the LOOP events in the IRSN and GRS databases.

The difference of the assessed LOOP frequencies, between the French and German NPPs, is even larger for shutdown operations. A frequency of at least one LOOP per shutdown year is obtained for the German nuclear power plants. This partly can be attributed to the reporting criteria together with the different structures of NPP's fleets and a higher amount of operating NPPs in France. No data from previous studies was available for comparison of obtained mean frequencies given in Tables 6 and 7.

TABLE 8: Plant-level LOOP frequencies assessed from US NRC database.

Mode	LOOP category	Number of events	Mean frequency	Frequency units
Critical operation	Plant	14	$6.79E-03$	/rcry
Critical operation	Switchyard	42	$2.04E-02$	/rcry
Critical operation	Grid	7	$3.39E-03$	/rcry
Critical operation	Weather	12	$5.82E-03$	/rcry
Critical operation	All	75	$3.64E-02$	/rcry
Shutdown operation	Plant	13	$3.56E-02$	/rsy
Shutdown operation	Switchyard	23	$6.30E-02$	/rsy
Shutdown operation	Grid	4	$1.10E-02$	/rsy
Shutdown operation	Weather	5	$1.37E-02$	/rsy
Shutdown operation	All	45	$1.23E-01$	/rsy

Results obtained for the event in US LER database are given in Table 8.

For LOOP frequency during critical operation, a value of $3.64E-02$ /rcry is calculated for the US NPPs, as indicated in Table 8, which is comparable to the frequency $3.59E-2$ /rcry assessed in NUREG/CR-6890 [10]. The LOOP frequency of $1.23E-01$ /rsy obtained for shutdown operation is also comparable to the frequency of $1.96E-1$ /rsy in NUREG/CR-6890 [10]. The smaller value of the grid-related events during critical operation in Table 8 can be attributed to the consideration of selected events in the analysis.

The results in Tables 6–8 show that obtained LOOP frequencies during shutdown operation are larger compared to obtained LOOP frequencies for critical operation.

The maintenance activities on the electrical systems of the NPP in the largest extent are done during shutdown mode of operation. The electrical equipment and systems are removed for test, inspection, and maintenance during outage resulting in decreased redundancy of the NPP electrical system and increased susceptibility to LOOP events. Assessed LOOP frequencies during critical and shutdown operation are given in per year frequency unit. The longest period of shutdown operation of the NPP is in most cases during the refuelling outage which generally is shorter compared to the critical operation.

5.2. Distribution of the Events. Figures 1 and 2 show the distribution of events per unit in given year in the primary axis and the number of operating units in the secondary axis for the French IRSN and German GRS databases, respectively.

An average rate of 0.2 events per unit in year is obtained for the French NPPs and 0.53 events for the German plants.

Figure 3 shows the distribution of events registered in the US NRC database.

The number of the reported events normalized to the number of units in US, as shown in Figure 3, is one order of magnitude smaller compared to the events registered in Germany and France. The plant related LOOP events are dominant contributors to the events registered in France and Germany. The switchyard failures are dominant contributors to the events registered in US. This indicates that larger number of registered events for French and German plants

FIGURE 1: Distribution of events at French units.

FIGURE 2: Distribution of events at German units.

can be attributed to the plant specifics including power system design and maintenance policies.

The distribution of the events registered in IAEA IRS database is given in Figure 4.

5.3. Trend Analysis. The results of the trend analysis are given in Tables 9, 10, 11, and 12. The first column defines the mode of operation, with the trend measure and obtained

FIGURE 3: Distribution of events in the US NRC LERs database.

FIGURE 4: Distribution of events in the IAEA IRS database.

value given in second and third column. The percentage of the trend measures obtained from the generated datasets that are smaller (in case of positive measure) or larger (in case of negative measure) than the analytically assessed measure is given in last column. These percentages indicate the confidence level of the assessed trend in the analysed data.

Table 9 shows the results obtained for the events registered in the IRSN database. The positive T_1 for all three modes (critical, shutdown, and combined events) indicates a decreasing trend in the LOOP data. A large percentage of generated datasets have a smaller value than the measured value obtained from the original data, indicating that there is a trend in the analysed data. The smaller percentage of T_4 for shutdown mode indicates large deviations compared to the mean value of events in analysed period. This result is expected considering the large number of registered events in year 1996, as shown in Figure 1.

A decreasing trend is also identified for events from the GRS database for all modes of operation, as shown by the results given in Table 10. Small percentage is obtained for T_4 resulting from large deviations of observations in years 1994 and 2000 compared to the mean value, as shown in Figure 2.

A decreasing trend is also identified for events registered in the US NRC LER database as shown in Table 11. The last column in Table 11 shows that the calculated measures are within the 10% of the largest values obtained from the simulation. The only exceptions are the T_2 and T_3 measures assessed for critical operation. A large difference between events registered in the first and second half of analysed period is indicated by the smaller confidence level obtained

TABLE 9: Trend parameters for IRSN database.

Mode	Parameter	Calculated value	Percentage of smaller/larger simulated values
Critical	T_1	65.7	99.94%
Critical	T_2	5.1	100.00%
Critical	T_3	320.3	99.95%
Critical	T_4	409.8	100.00%
Shutdown	T_1	24.9	94.84%
Shutdown	T_2	1.5	96.12%
Shutdown	T_3	55.3	89.74%
Shutdown	T_4	82.6	59.19%
Both	T_1	90.6	99.99%
Both	T_2	6.6	100.00%
Both	T_3	628.0	100.00%
Both	T_4	676.8	100.00%

TABLE 10: Trend parameters for the GRS database.

Mode	Parameter	Calculated value	Percentage of smaller/larger simulated values
Critical	T_1	37.5	98.62%
Critical	T_2	1.2	90.17%
Critical	T_3	85.5	94.67%
Critical	T_4	81.8	32.93%
Shutdown	T_1	35.9	98.88%
Shutdown	T_2	1.2	91.61%
Shutdown	T_3	73.9	94.87%
Shutdown	T_4	72.8	39.24%
Both	T_1	73.4	99.93%
Both	T_2	2.4	96.70%
Both	T_3	301.2	99.67%
Both	T_4	235.0	83.52%

for T_2 and T_3 measures for the events registered during critical operation.

The calculated T_1 for the events registered during critical operation in the IAEA database given in Table 12 is negative, indicating an increasing trend in the data. The obtained values of the T_1 and T_2 measures are within the smallest 10% of the values assessed from the simulations confirming the increasing trend in the data. The lower confidence level of the T_4 measure indicates very large deviations of the registered events in the analysed period from their mean value. The positive value of the T_1 trend measures for events registered during shutdown operation in Table 12 indicates a decreasing trend of LOOP events during shutdown.

The trend of the combined events reported in the IAEA database is increasing. As a result of the differing trends obtained for events registered during critical and shutdown operation, the trend of combined events has small confidence level and therefore it is not possible to confirm/verify the trend in the data.

TABLE 11: Trend parameters for the US NRC database.

Mode	Parameter	Calculated value	Percentage of smaller/ larger simulated values
Critical	T_1	24.1	94.86%
Critical	T_2	0.5	78.03%
Critical	T_3	43.4	88.71%
Critical	T_4	130.4	98.72%
Shutdown	T_1	30.1	99.65%
Shutdown	T_2	1.8	99.97%
Shutdown	T_3	65.1	99.64%
Shutdown	T_4	71.0	96.95%
Both	T_1	54.1	99.83%
Both	T_2	2.3	99.47%
Both	T_3	192.1	99.82%
Both	T_4	257.9	99.91%

TABLE 12: Trend parameters for the IAEA database.

Mode	Parameter	Calculated value	Percentage of smaller/ larger simulated values
Critical	T_1	-19.6	4.56%
Critical	T_2	-1.1	3.86%
Critical	T_3	25.5	88.05%
Critical	T_4	63.0	91.86%
Shutdown	T_1	7.41	97.47%
Shutdown	T_2	0.25	96.91%
Shutdown	T_3	3.91	94.72%
Shutdown	T_4	3.96	0.00%
Both	T_1	-12.16	16.10%
Both	T_2	-0.83	10.55%
Both	T_3	15.54	60.19%
Both	T_4	61.33	81.98%

Final conclusion from the analysis is that decreasing trend of registered LOOP events is identified in the analysed databases, with the exception of the events registered in IAEA IRS. The analysis of events in the IAEA database showed that different trends are identified during critical and shutdown modes, with no trend observed for the whole set of data.

6. Conclusions

This paper presents the results of the statistical analyses of LOOP events registered in four databases of operational events. The reviewed databases are SAPIDE managed by IRSN (Institut de Radioprotection et de Sûreté Nucléaire) and VERA by GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH) over the period from 1992 to 2011. The Nuclear Regulatory Commission (NRC) Licensee Event Reports (LERs) database and the IAEA International Reporting System (IRS) database were also reviewed for relevant events registered in the period from 1990 to 2012.

In total, 228 LOOP relevant events were identified in IRSN SAPIDE, 190 in GRS VERA, 120 in US NRC LERs, and 52 in the IAEA IRS database. These LOOP events were classified considering the mode of operation (critical and shutdown) and by cause or location (plant-centered, switchyard-centered, grid-related, and weather-related).

The statistical analyses of the identified events include assessment of the LOOP frequency, distribution of events in the analysed period, and trend analysis of the events.

Results of the LOOP frequency assessment show that comparable frequency of LOOP events during critical operation was obtained for events in the IRSN SAPIDE and GRS VERA databases. The LOOP events reported in IAEA IRS are not considered as representative for the LOOP frequency assessment and not analysed further.

Plant-centered events are identified as dominant contributors to the LOOP events in both databases. A frequency of at least one LOOP event per shutdown year is obtained for the GRS VERA database. For US NPPs, the obtained LOOP frequency for critical and shutdown operation is comparable to those in previous studies [10]. The switchyard-centered related LOOP events are dominant contributors to the LOOP frequency during critical operation assessed for US NPPs. The obtained LOOP frequency during shutdown mode is larger compared to frequency for critical mode in three analysed databases (IRSN, GRS, and NRC). The obtained result is attributed to the maintenance activities on electrical system during shutdown operation and consequential LOOP events.

Results of the trend analysis show that decreasing trend is obtained for the LOOP events registered in three databases (IRSN, GRS, and NRC). The decreasing trend in these databases was obtained for events registered during critical and shutdown operation as well as combined (sum) events. Different trends were identified during critical and shutdown modes of operation for the LOOP events registered in the IAEA database. Combined events reported during critical and shutdown modes show no trend.

Disclosure

The scientific output expressed in this paper may not in any circumstances be regarded as stating an official position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of this publication.

Competing Interests

The authors declare that they have no competing interests.

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