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Statistical analysis of nuclear power reactor outages as sources of elevated radioxenon releases

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INTRODUCTION AND MAIN RESULTS

Detection of radioxenon from NPPs by the IMS noble gas network is critical for nuclear event assessment. The assumption of continuous radionuclide releases from nuclear power plants is not consistent. Elevated discharges are most often associated with periods of significant power variation, particularly during reactor shutdowns, outages, and subsequent restarts. Our statistical analysis across reactor types shows that refueling combined with maintenance (Cause C) is the dominant driver of prolonged xenon emissions, while shorter maintenance-only or refueling-only outages contribute episodically. Our analysis shows PWRs/BWRs dominate global xenon contributions, while GCRs, PHWRs, and LWGRs play significant regional roles. These findings provide IMS experts with reactor-specific patterns essential for distinguishing civilian sources from potential nuclear test signals.

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Introduction

Radioxenon discharges from nuclear power reactors (NPPs) are frequently detected by the noble gas monitoring systems of the International Monitoring System. However, the standard assumption of continuous releases is not realistic. It has been demonstrated that ramping power down and up during operations are occasions of elevated discharges, which are most likely to be observed. Despite this, only limited information is available about these relevant NPP operations.

This study utilizes comprehensive outage data from the International Atomic Energy Agency's Power Reactor Information System (PRIS) to statistically analyze the frequency and duration of outages. The analysis focuses on planned full outages, during which reactor units are disconnected from the grid for purposes such as inspection, maintenance, repair, refueling, or a combination of these activities. The statistics are presented by reactor type, including Boiling Water Reactors (BWRs), Gas-Cooled Reactors (GCRs), Pressurized Water Reactors (PWRs), Pressurized Heavy Water Reactors (PHWRs), and Light Water Graphite Reactors (LWGRs). The results of this study support event screening and expert technical analysis of radiological events of interest, helping to distinguish reactor emissions from nuclear test signals and enhancing the understanding of the operational sources of elevated radioxenon releases.

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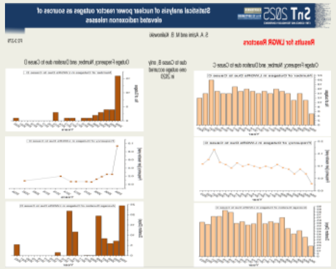
Results

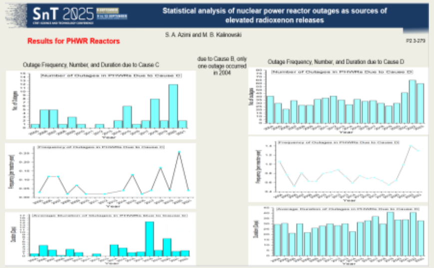
The statistics are applied to outages that affect the reactor core and require the power to be ramped down.

- **Cause B**:Refuelling without maintenance
- **Cause C**:-Inspection, maintenance or repair combined with refueling
- **Cause D**: Inspection, maintenance or repair without refueling.

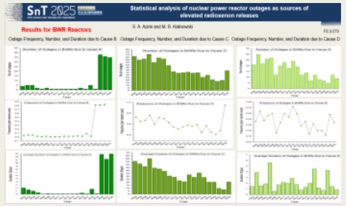
LWGR



PHWR



BWR



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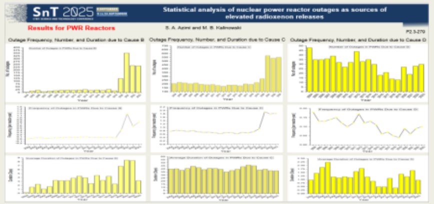
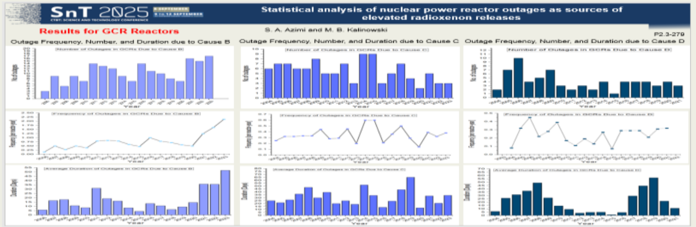


GCR



Summary and Conclusion

Reactor Type	Outage Cause	Number of Outages	Average Outage Frequency (per reactor-year)	Average Outage Duration (Days)
LWGR	Cause B	1	0	0.1
	Cause C	269	0.9	56.7
	Cause D	35	0.1	5.5
PHWR	Cause B	1	0	0
	Cause C	54	0.1	2.6
	Cause D	676	0.7	29.2
BWR	Cause B	143	0.1	1.7
	Cause C	785	0.6	36
	Cause D	326	0.2	2.2
PWR	Cause B	1235	0.2	3.7
	Cause C	4885	0.9	40.3
	Cause D	589	0.1	1.21
GCR	Cause B	178	0.6	13.7
	Cause C	97	0.3	31.1
	Cause D	61	0.2	19.9

All numbers apply cumulatively for all reactors of the given type and over the years 2004 to 2023.

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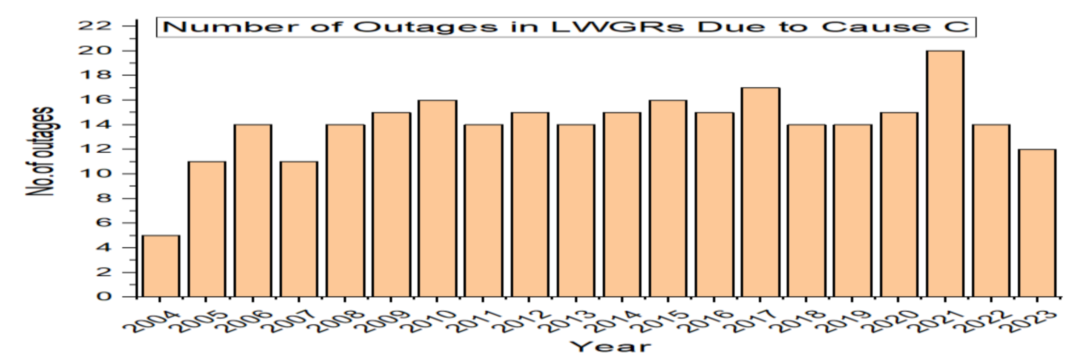
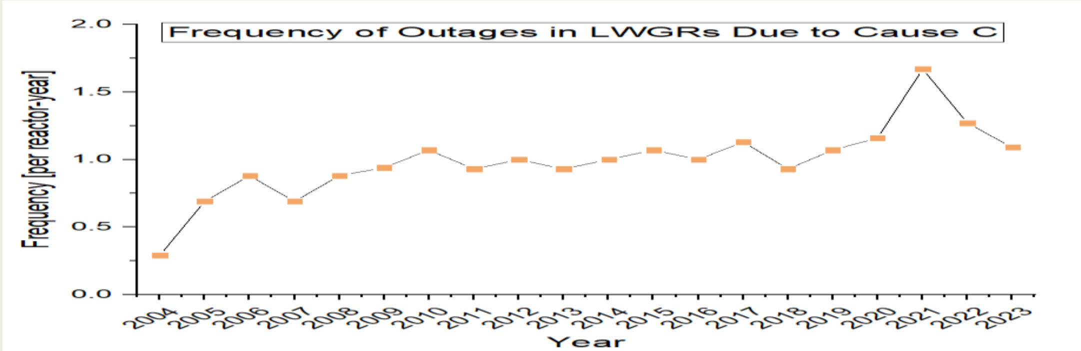
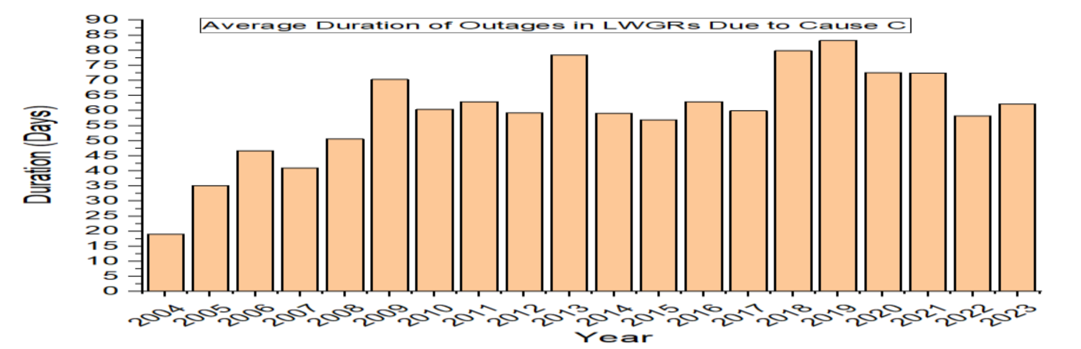
Results for LWGR Reactors

Outage Frequency, Number, and Duration due to Cause C

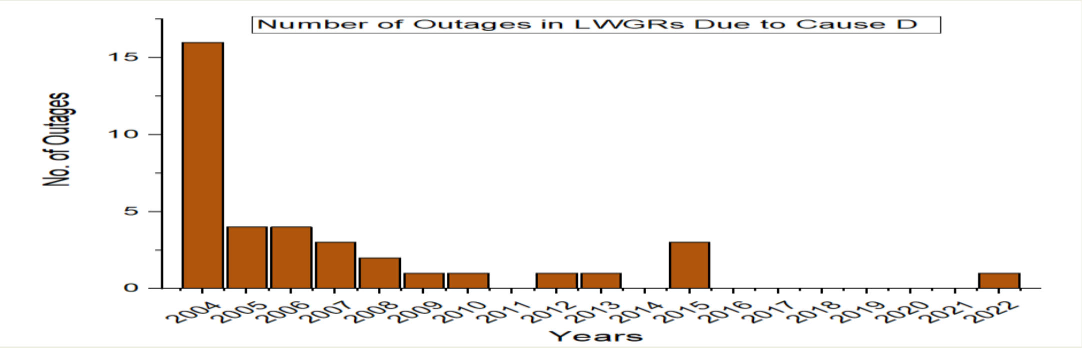


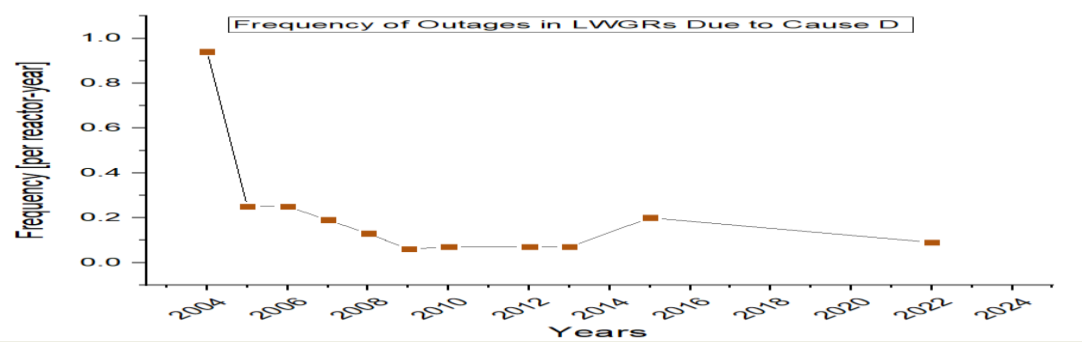


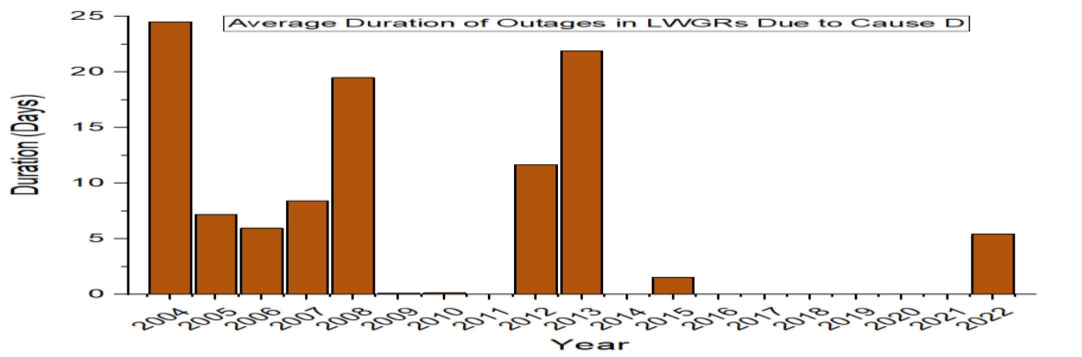


due to Cause B, only one outage occurred in 2020

Outage Frequency, Number, and Duration due to Cause D







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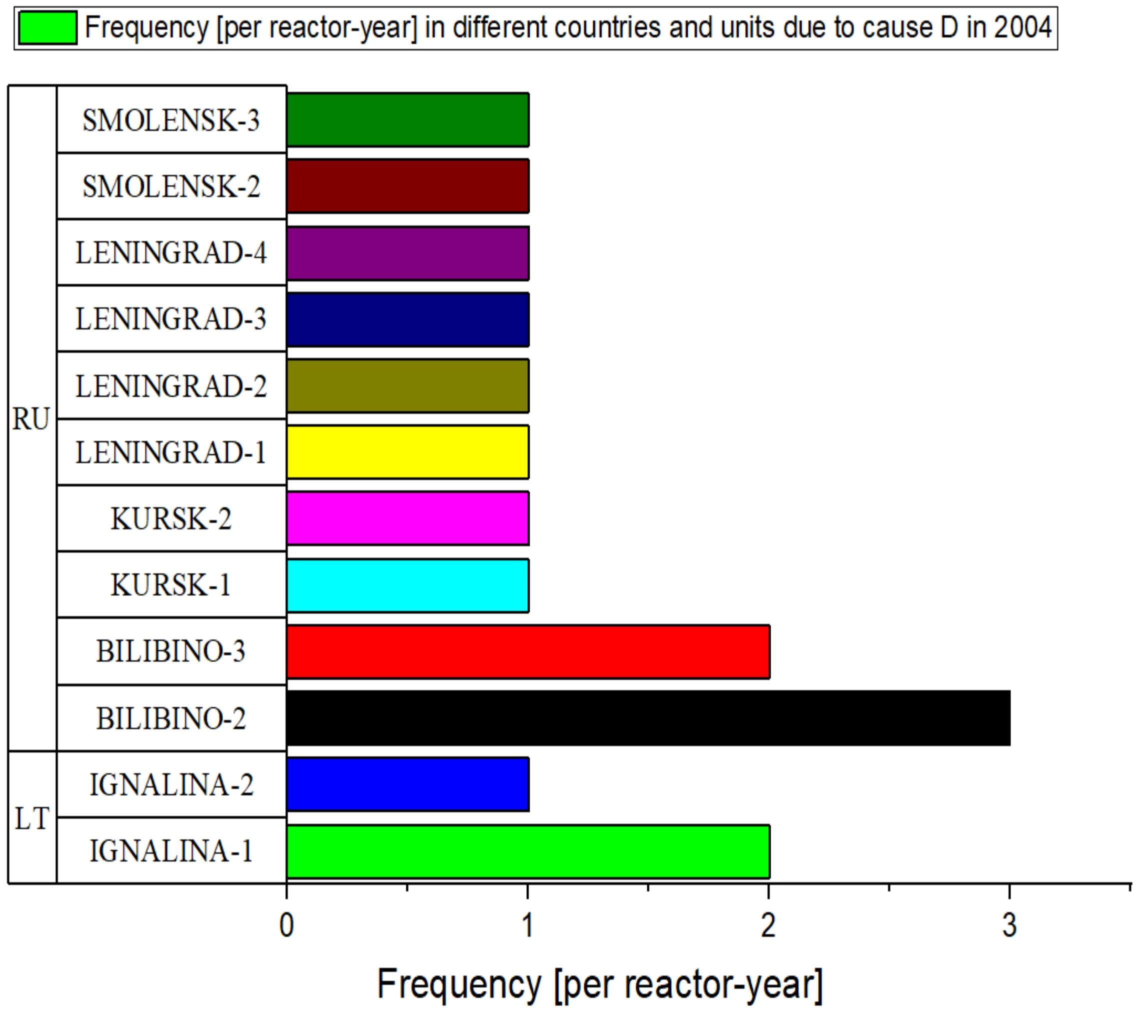
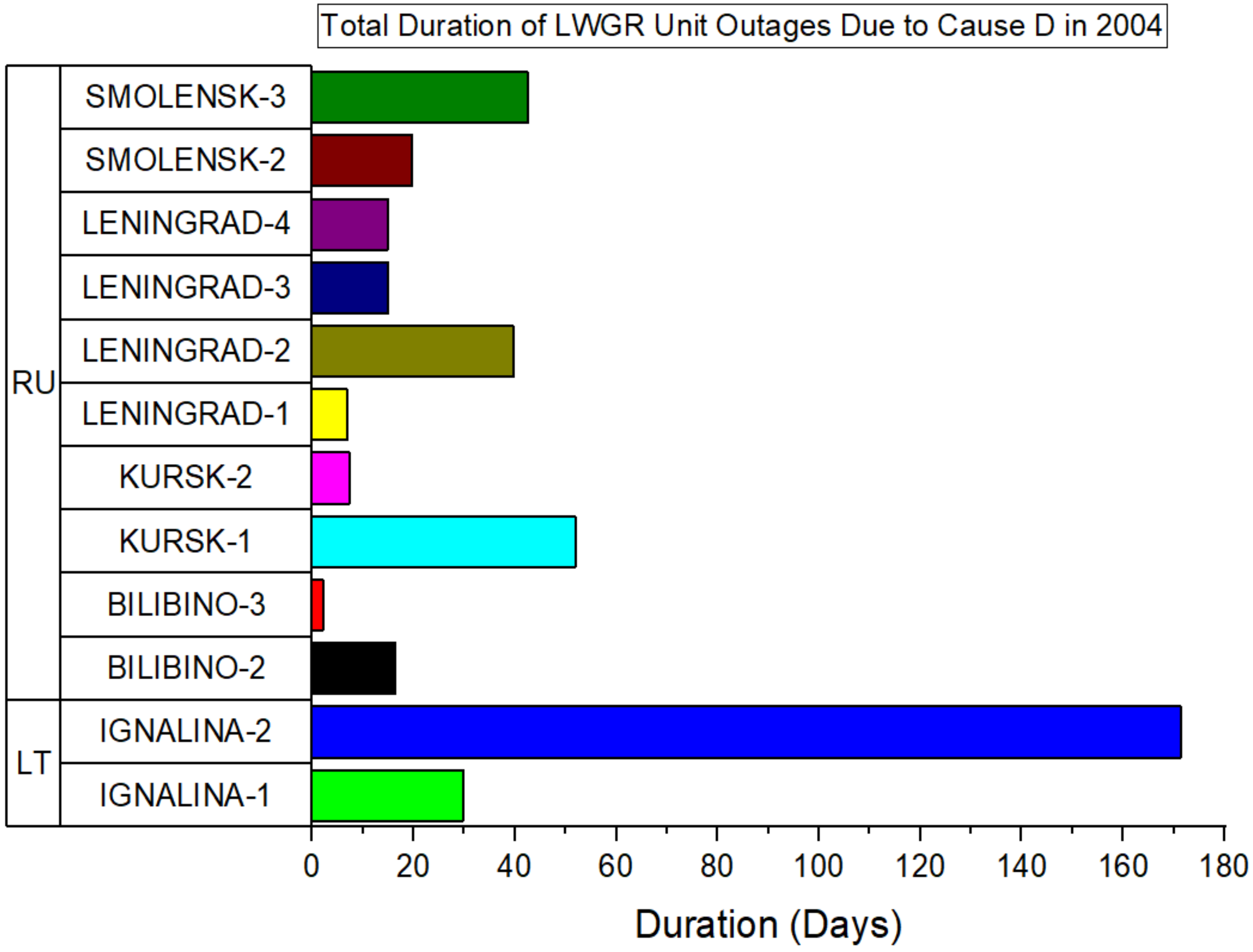
Results for LWGR Reactors

Outage Frequency in corresponded units due to Cause D



Total duration in corresponded units due to Cause D



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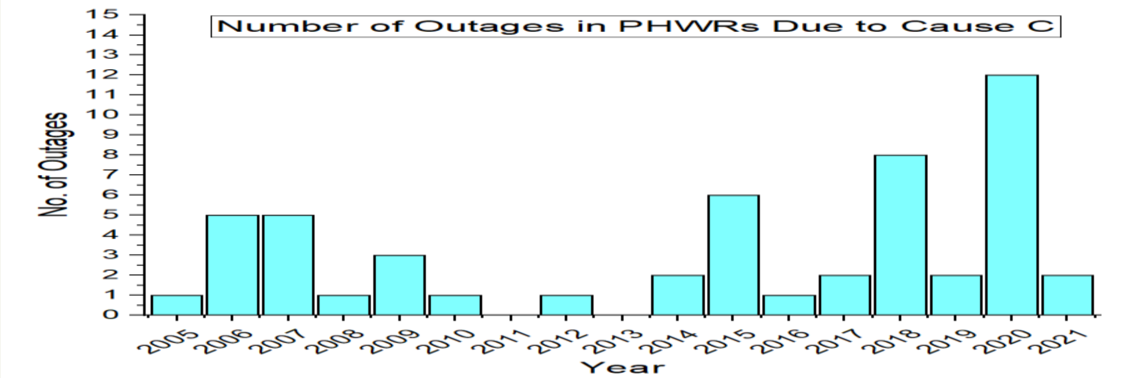
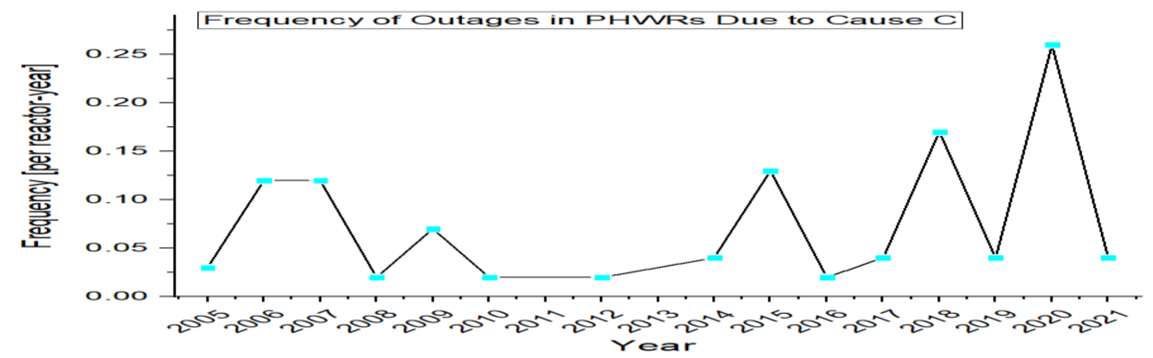
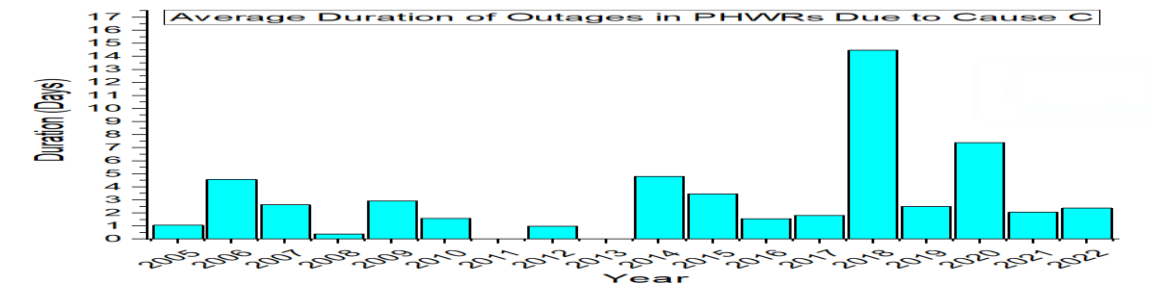
Results for PHWR Reactors

Outage Frequency, Number, and Duration due to Cause C

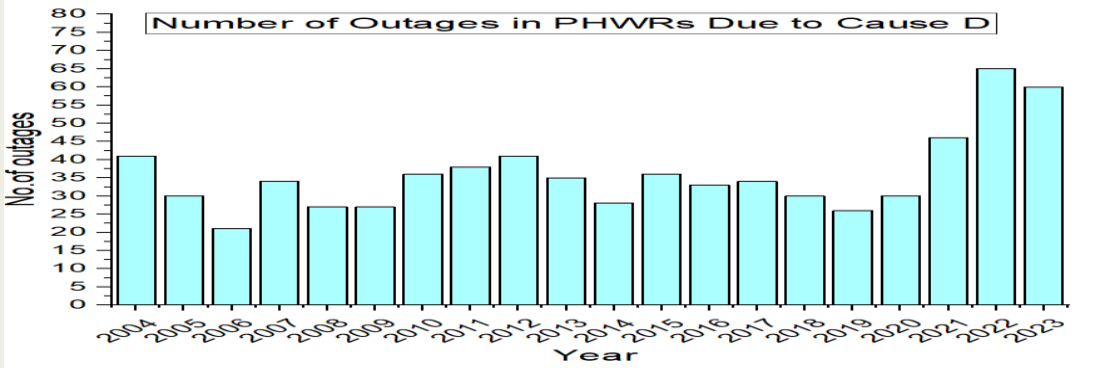


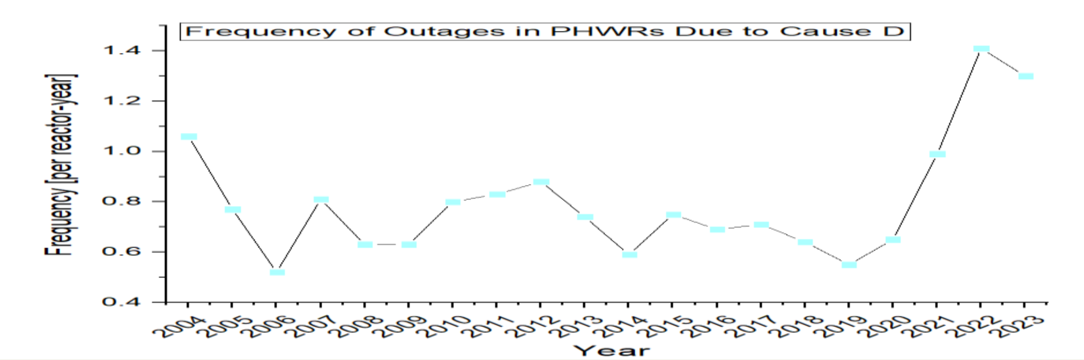


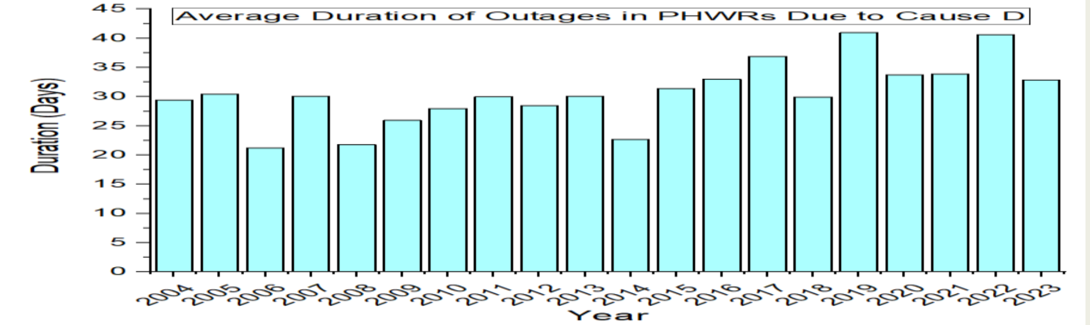


due to Cause B, only one outage occurred in 2004

Outage Frequency, Number, and Duration due to Cause D







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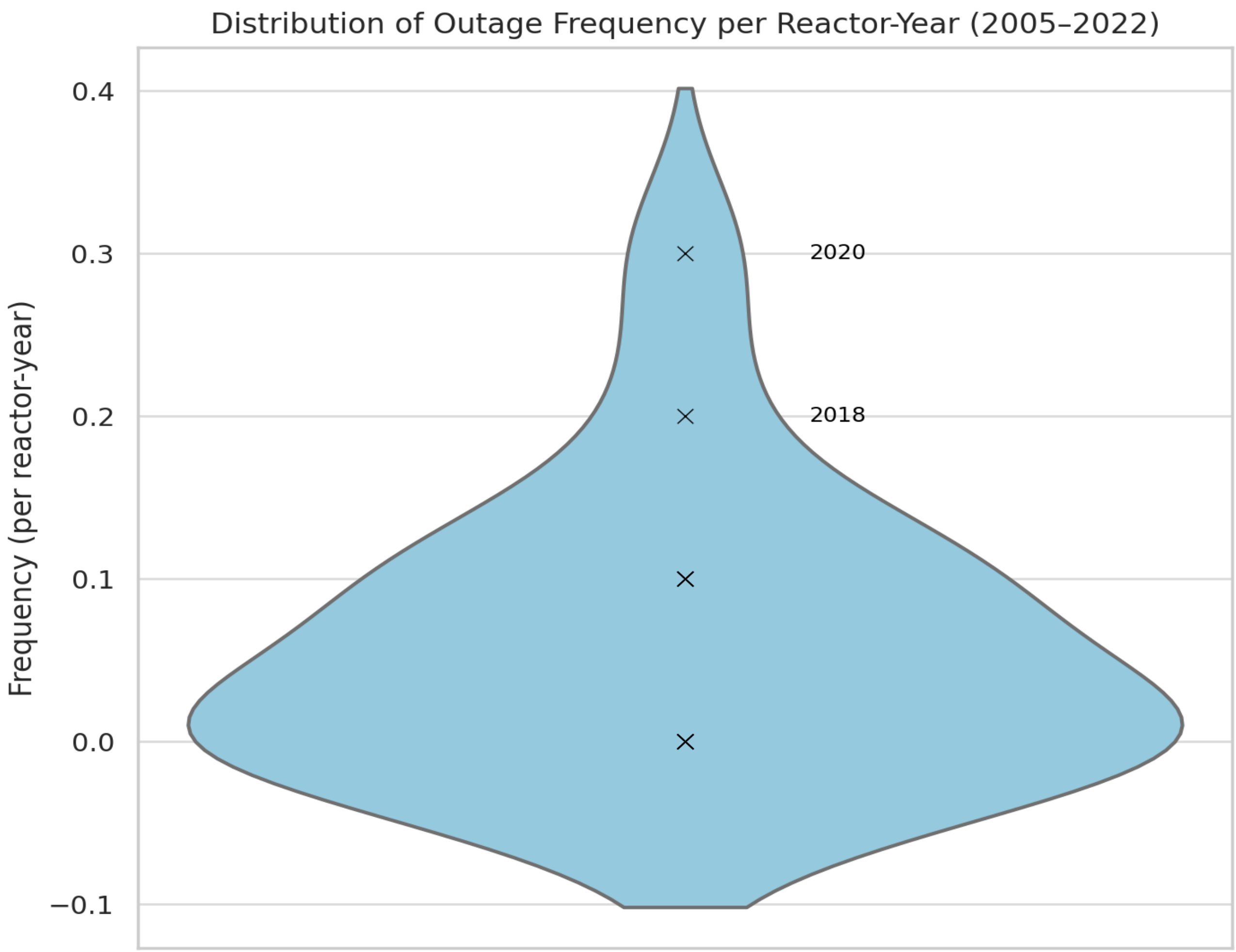
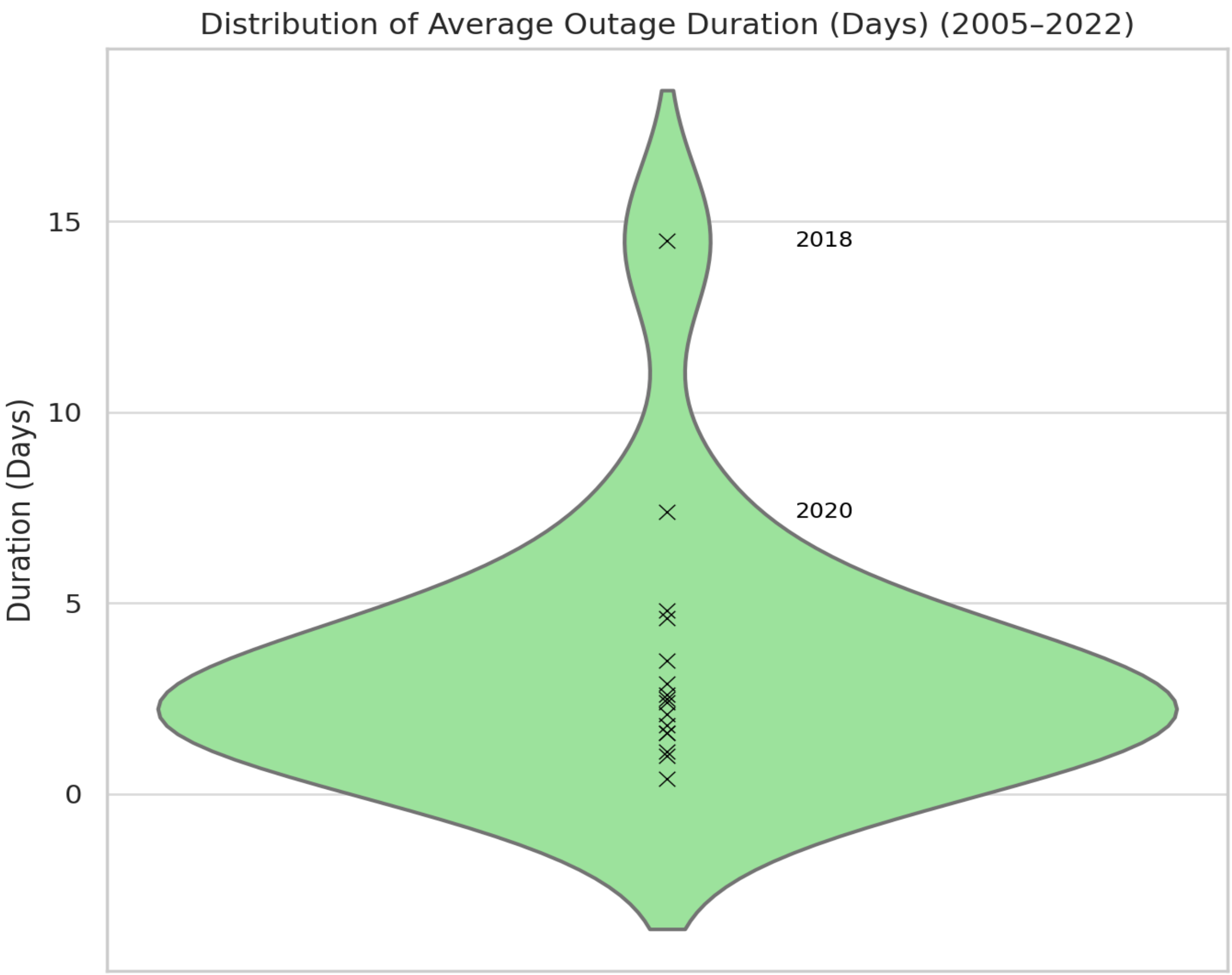
Statistic results for PHWR Reactors

Violin Plot of Outage Frequency Due to Cause C



Violin Plot of Average Outage Duration Due to Cause C



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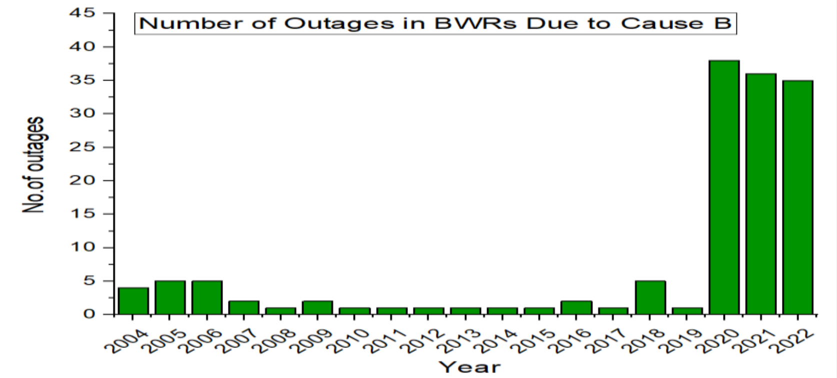
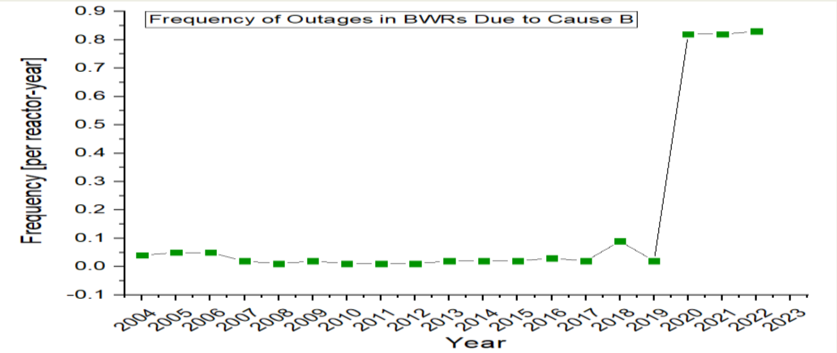
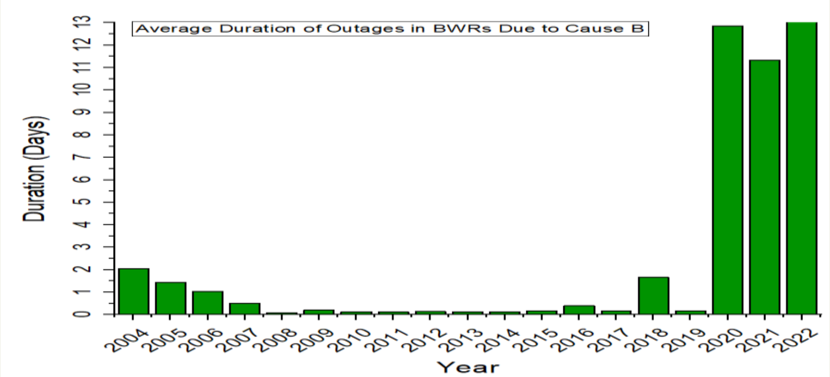
Results for BWR Reactors

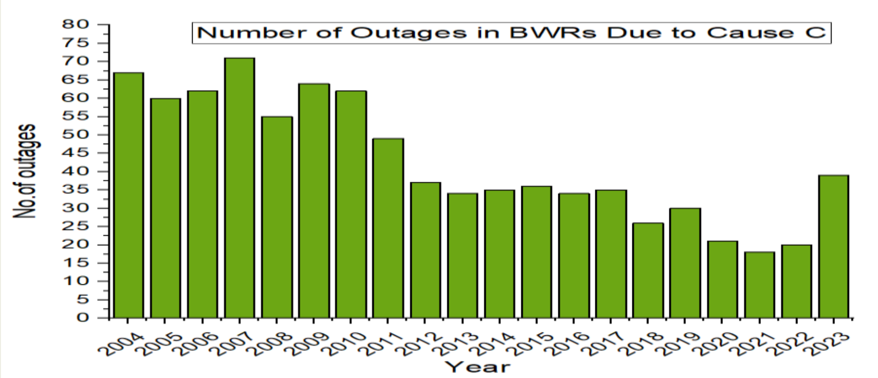
Outage Frequency, Number, and Duration due to Cause B

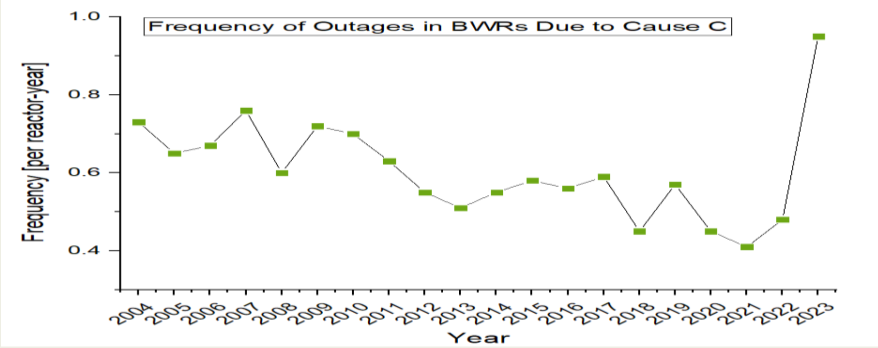


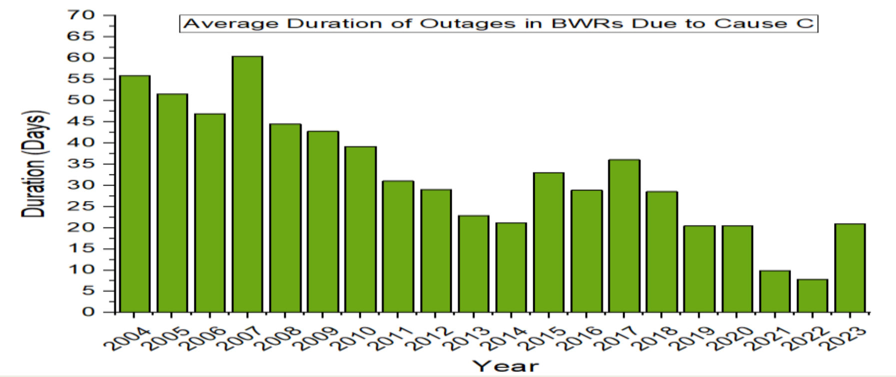




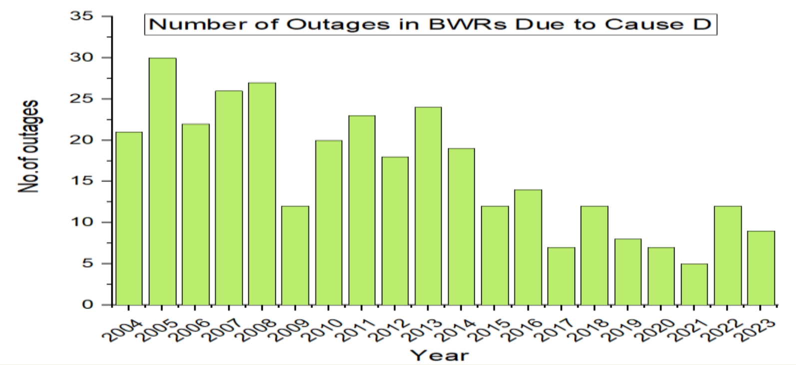
Outage Frequency, Number, and Duration due to Cause C

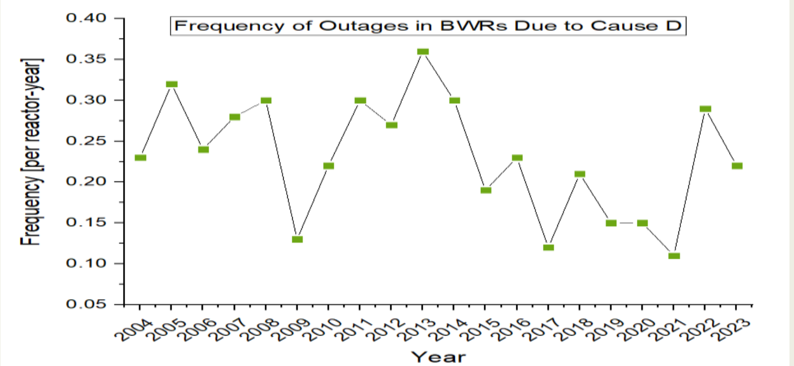


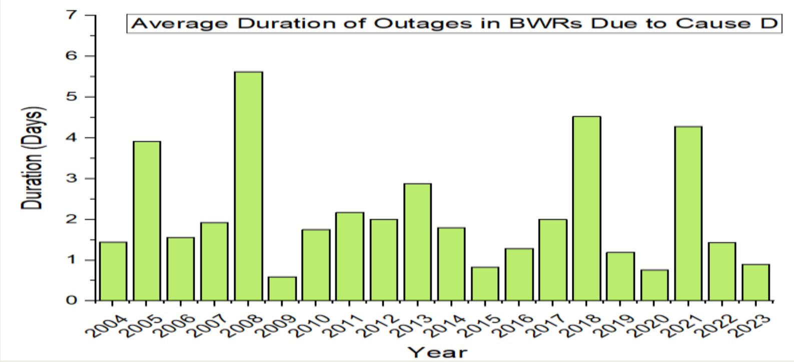




Outage Frequency, Number, and Duration due to Cause D







Comparison of Results in BWRs

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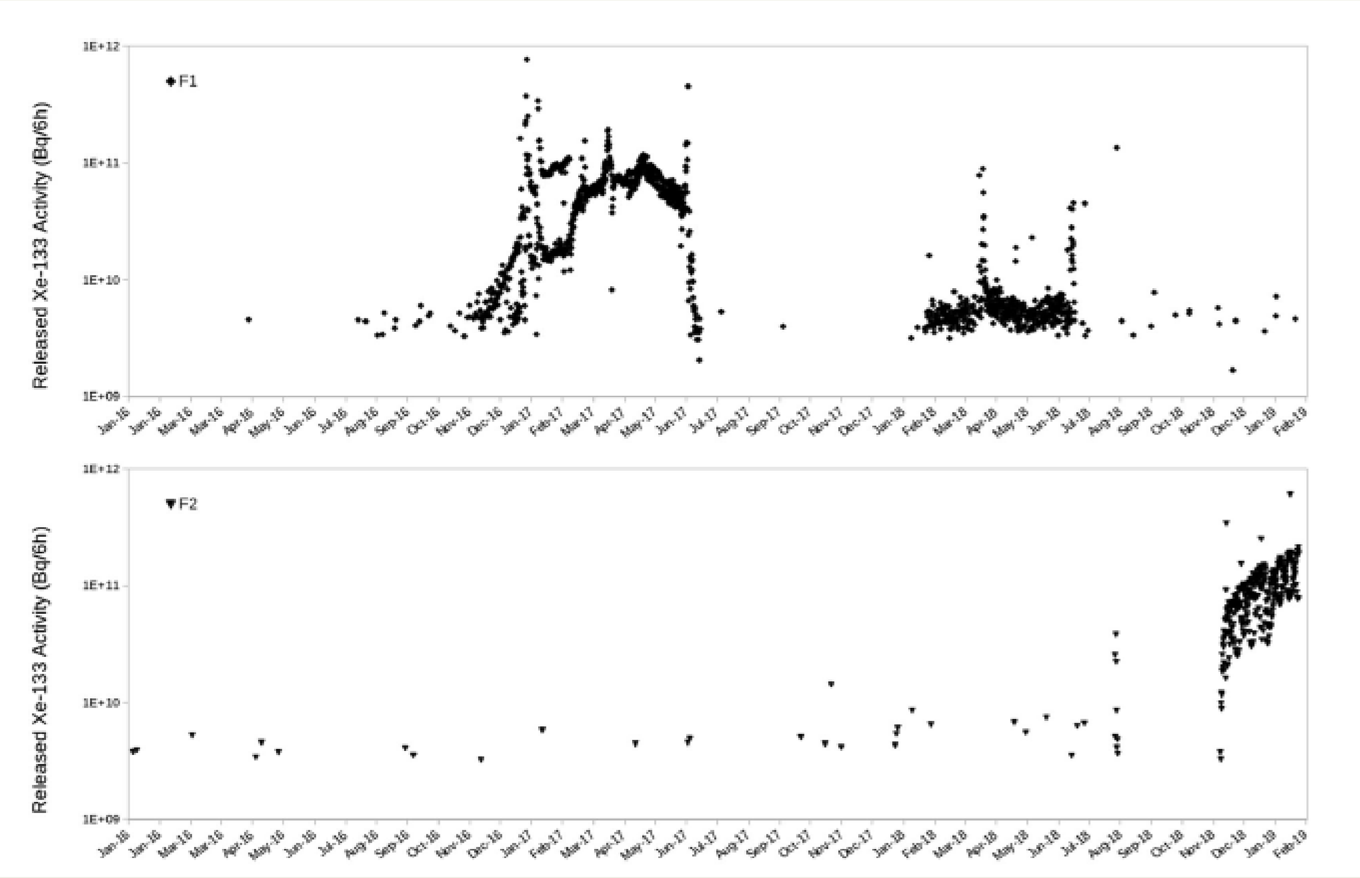
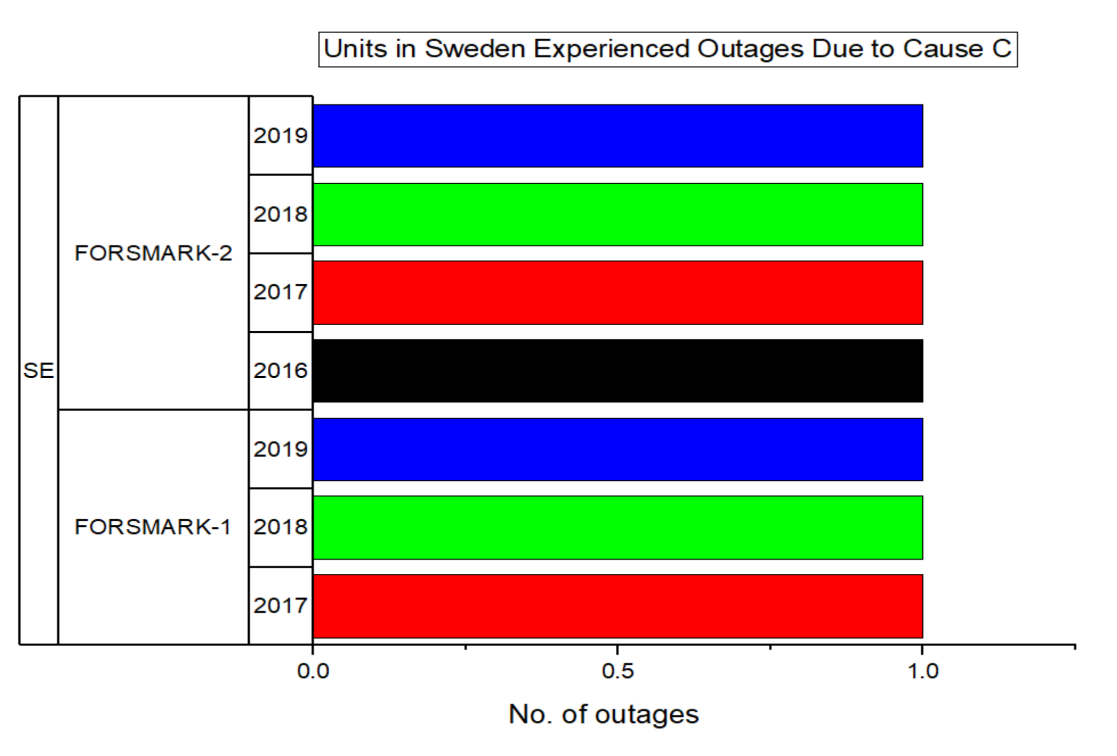
Measured 133Xe activities released from the stacks of the three reactors (F1, and F2) at the Forsmark nuclear power plant





For Forsmark F1, the PRIS data of one outage per year in 2017 and 2018 aligns with the paper's findings of daily xenon releases during those periods due to damaged fuel and a partially functional delay system.

For Forsmark F2, the single 2018 outage recorded in PRIS corresponds with the paper's observation of fuel damage and periodic xenon releases caused by breakthrough in the delay line.

Ringbom, A., Axelsson, A., Björnham, O., Brännström, N., Fritioff, T., Grahn, H., ... & Olsson, M. (2021). Radioxenon releases from a nuclear power plant: Stack data and atmospheric measurements. *Pure and Applied Geophysics*, *178*(7), 2677-2693.

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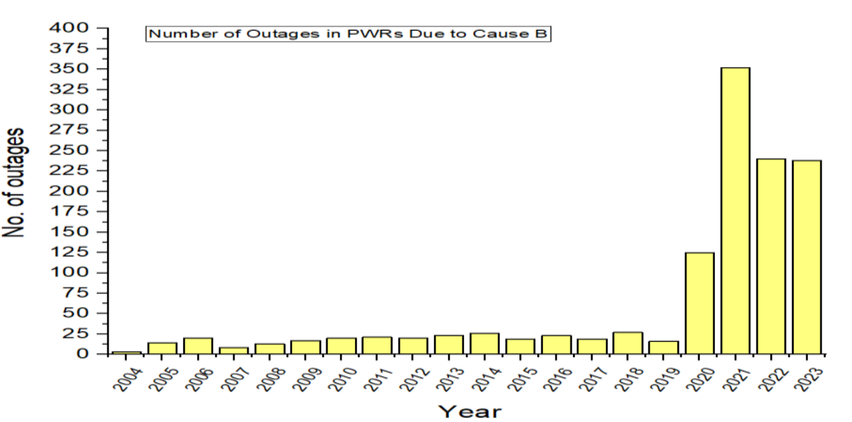
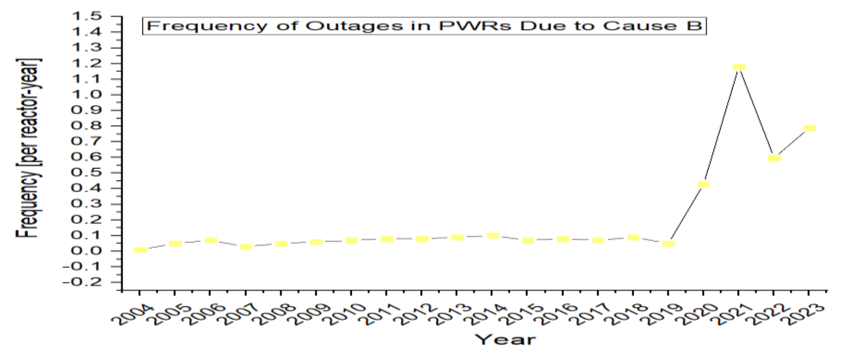
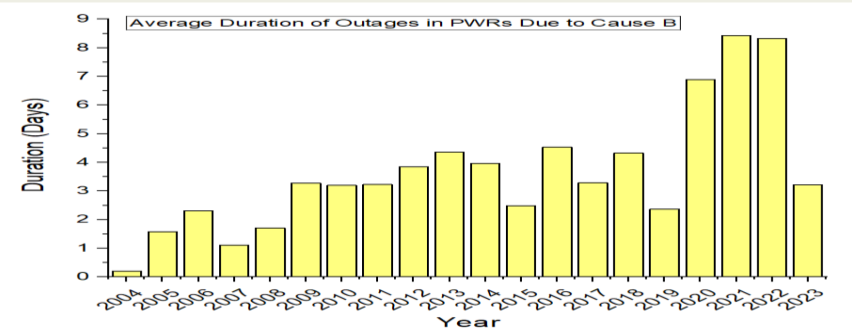
Results for PWR Reactors

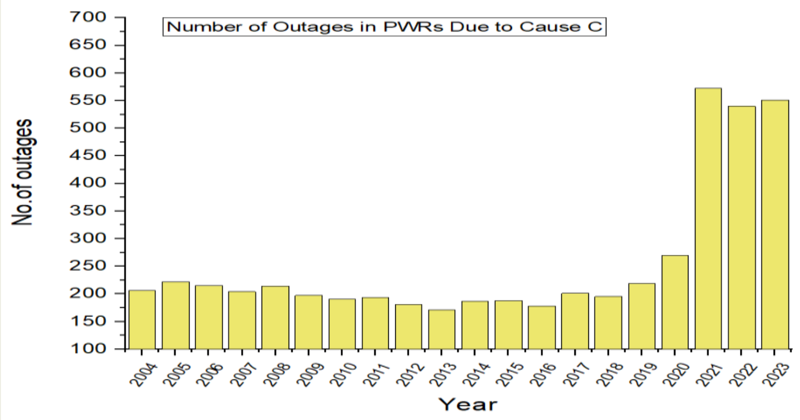
Outage Frequency, Number, and Duration due to Cause B

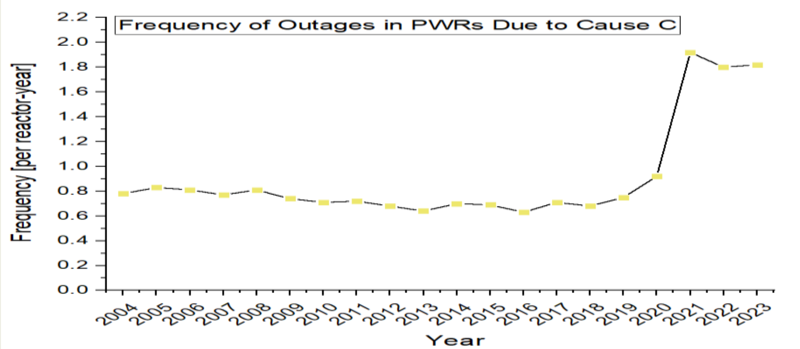


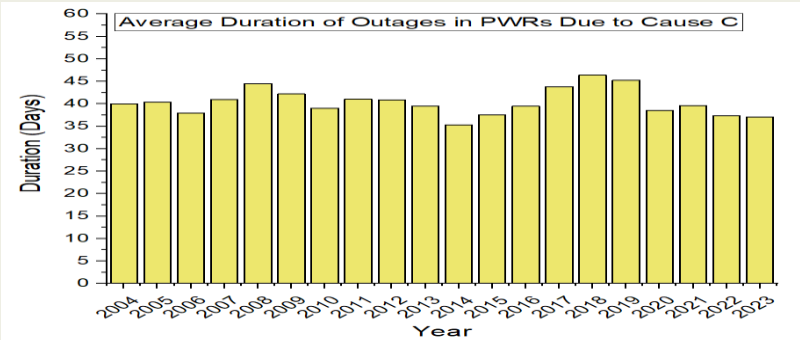




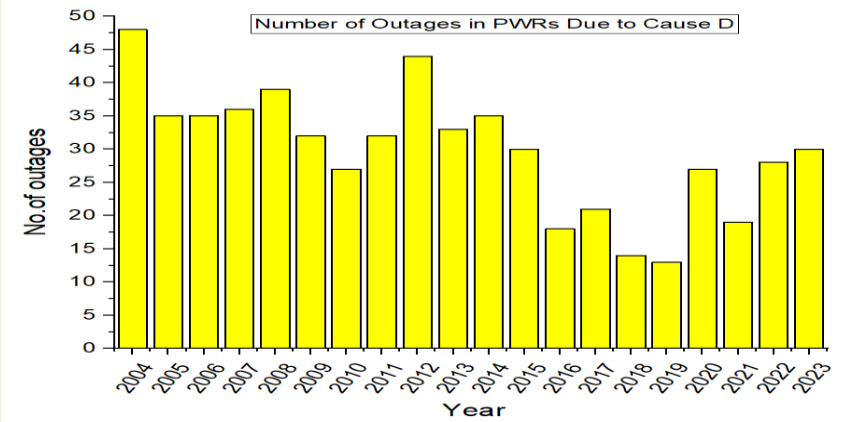
Outage Frequency, Number, and Duration due to Cause C

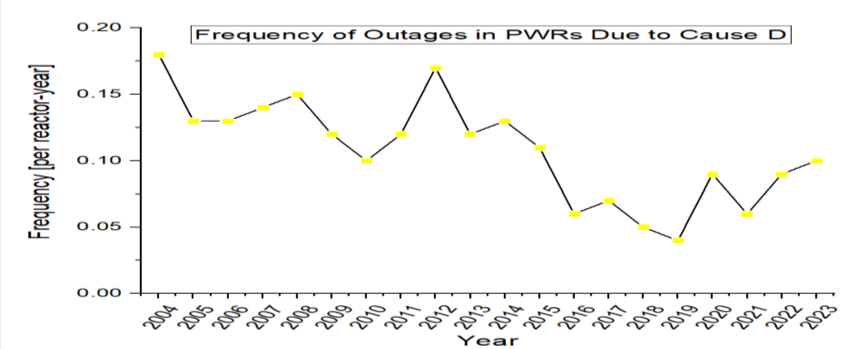


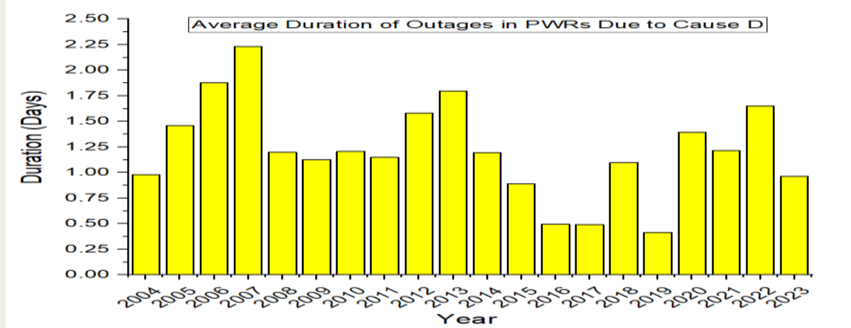




Outage Frequency, Number, and Duration due to Cause D







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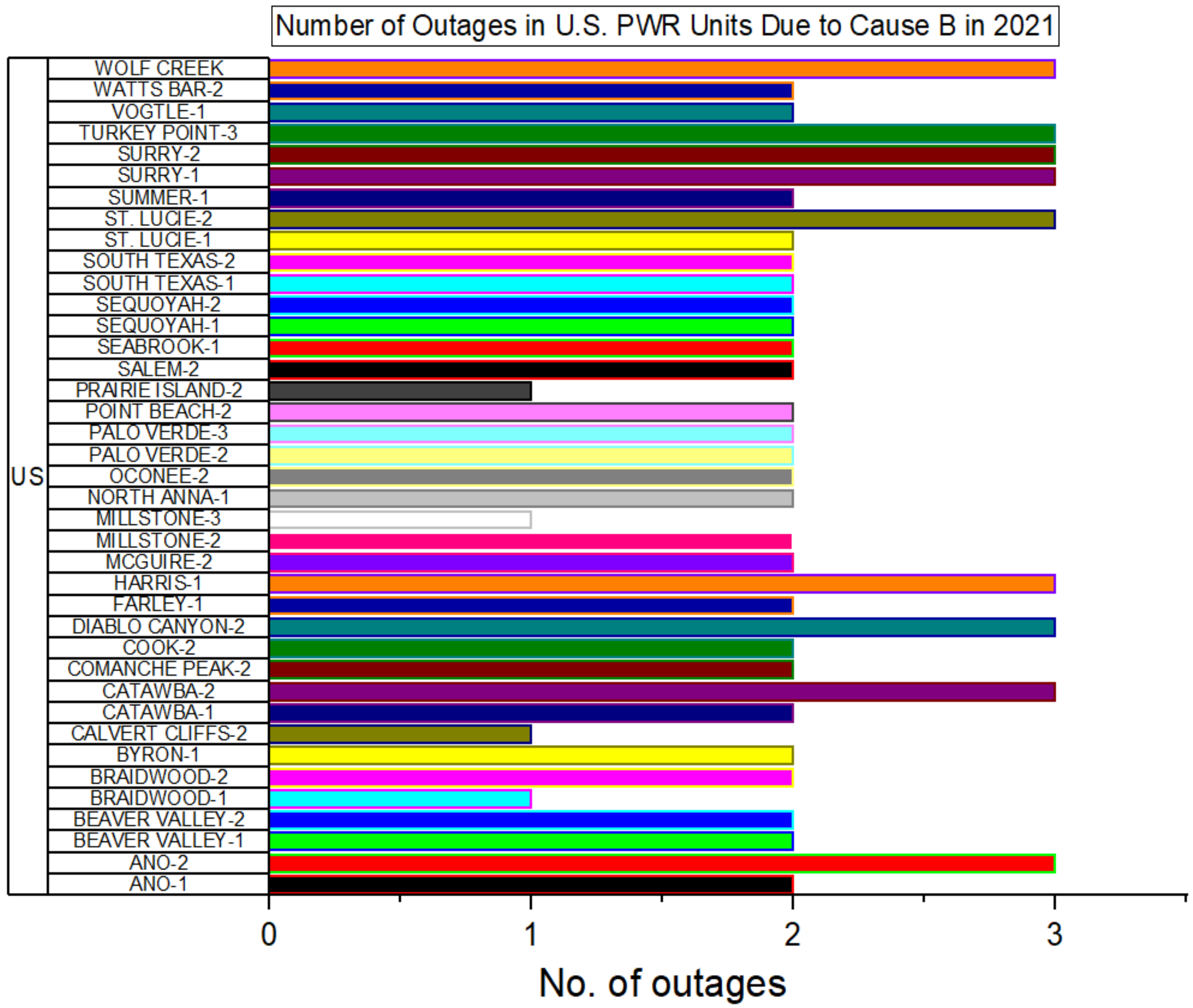
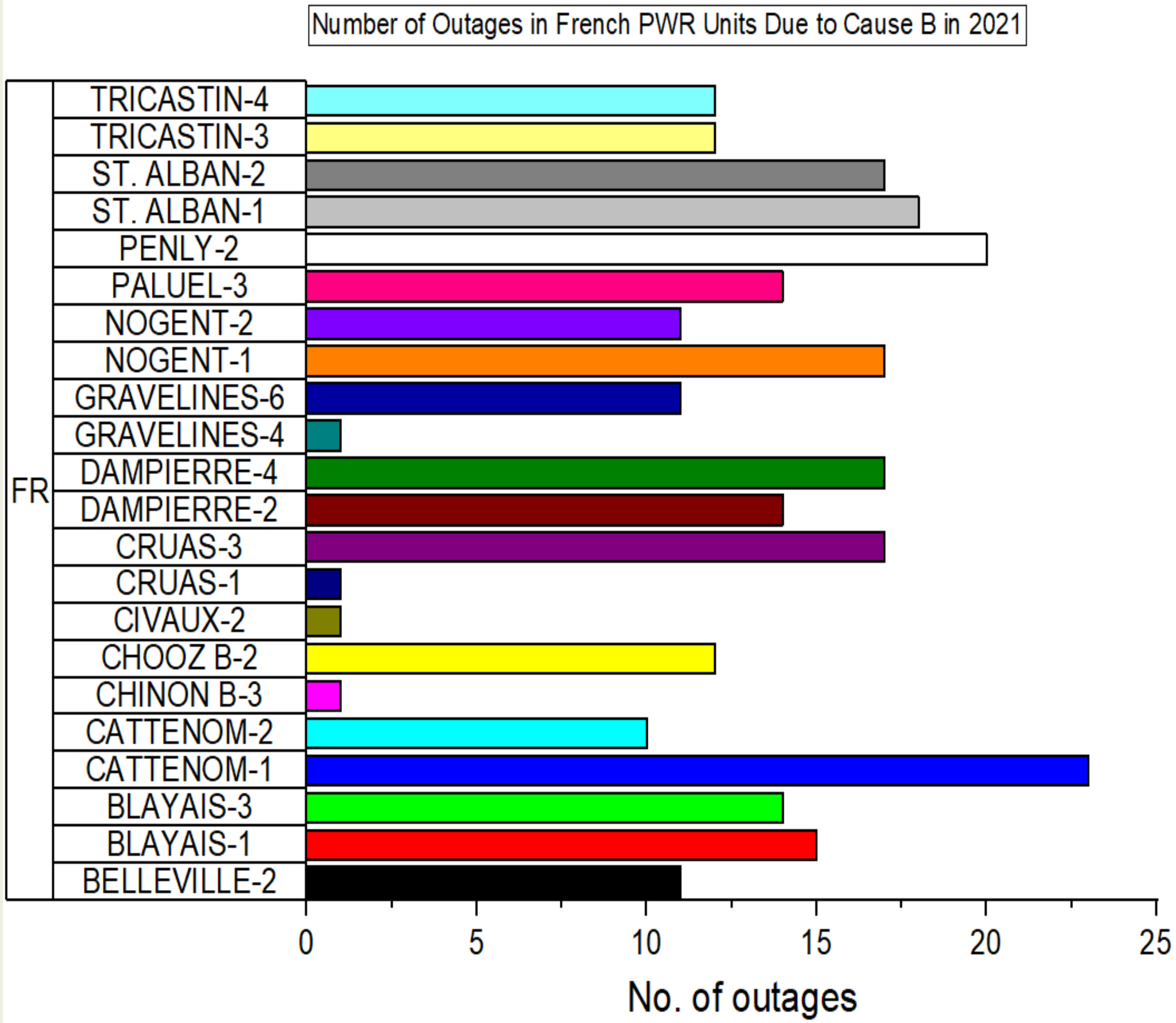
Results for PWR Reactors

Units in the U.S. experienced outages in PWRs due to Cause B in 2021



Units in France experienced outages in PWRs due to Cause B in 2021



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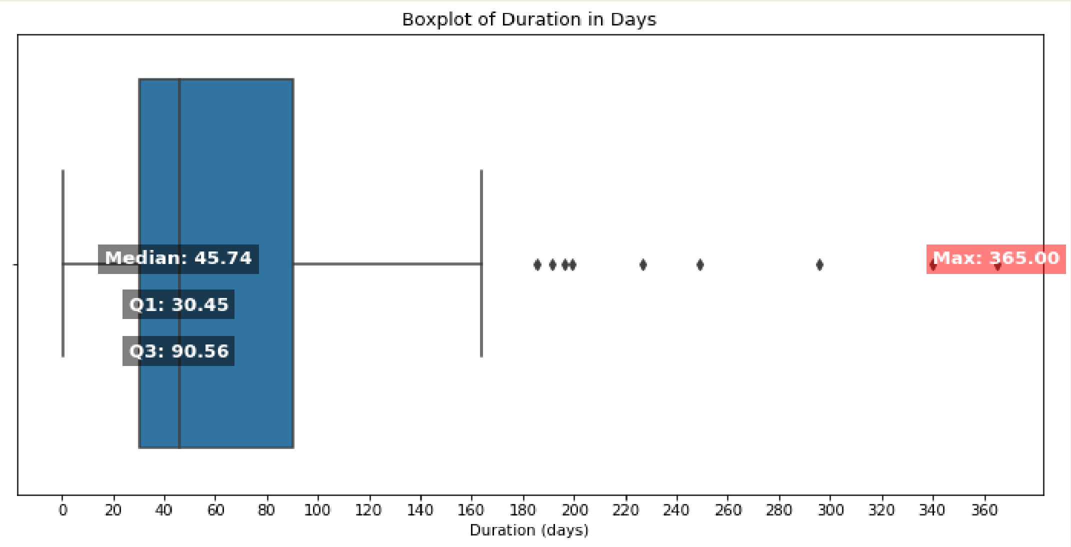
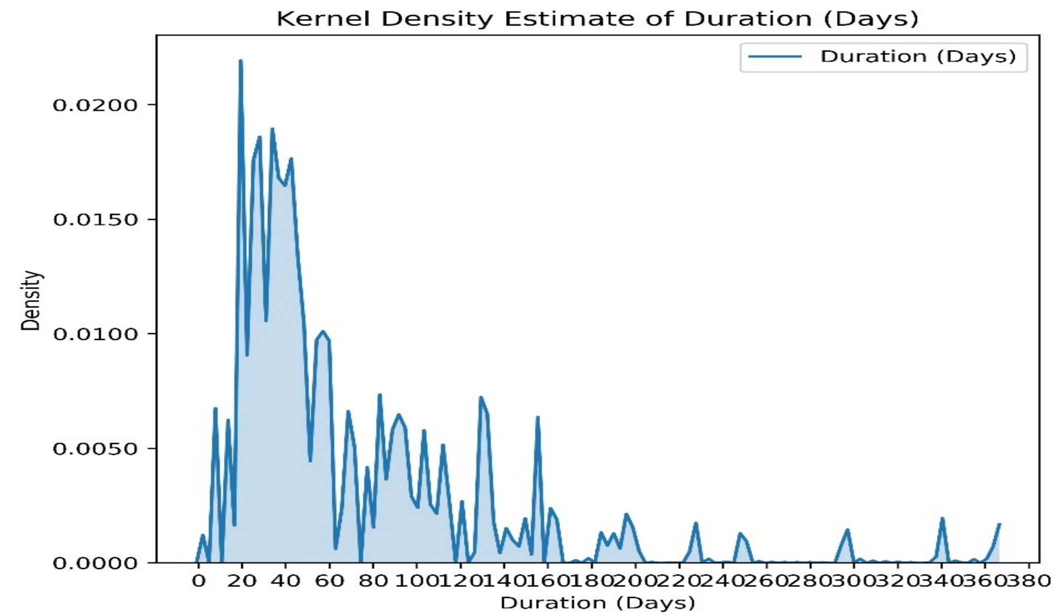
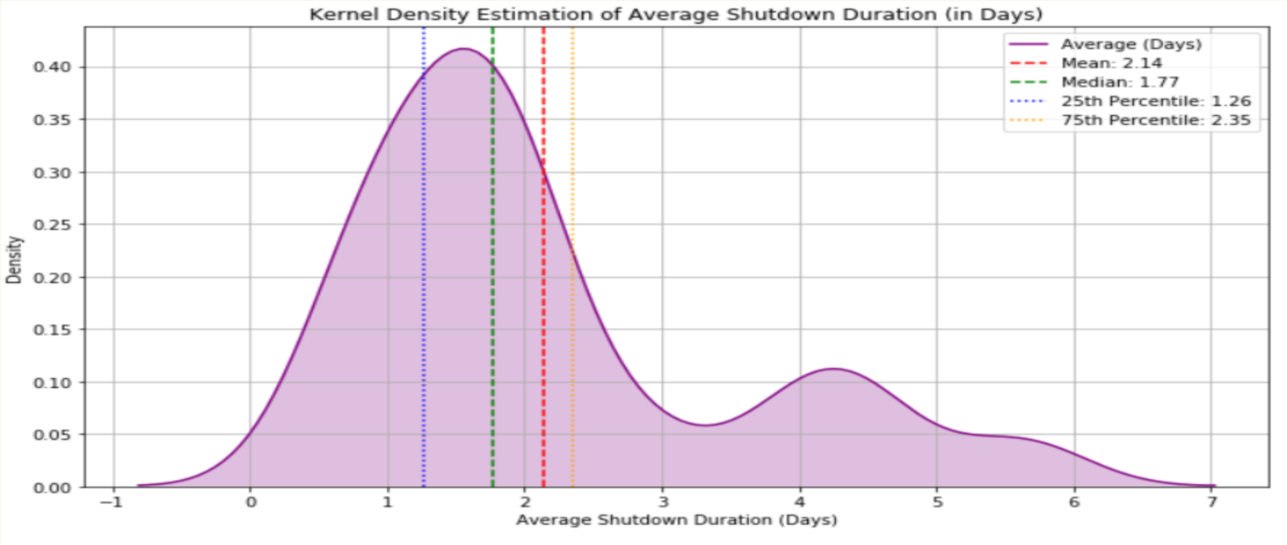
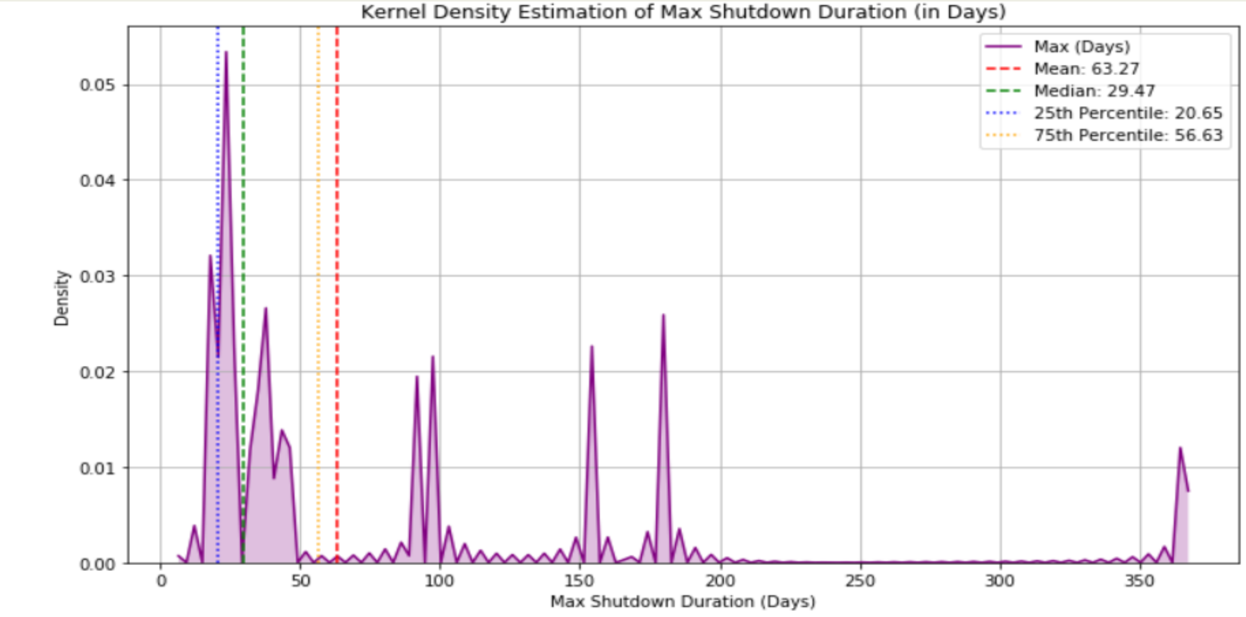
Statistical Analysis of Maximum Durations for PWR Reactors due to Cause C in 2021





Statistical Analysis of Durations for BWR Reactors due to Cause D over 20 Years





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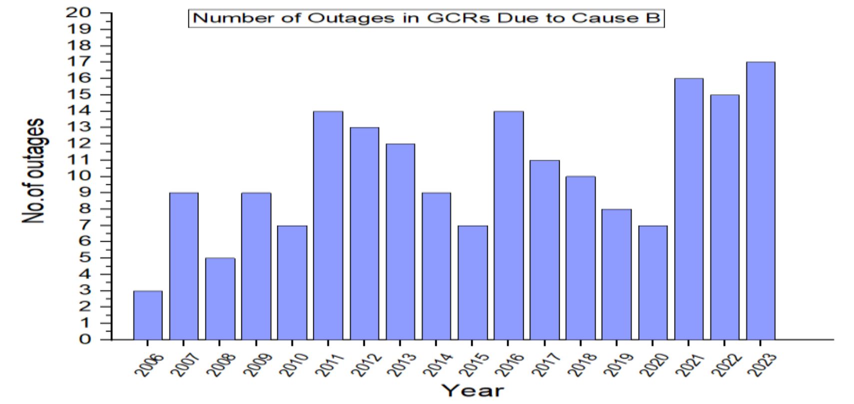
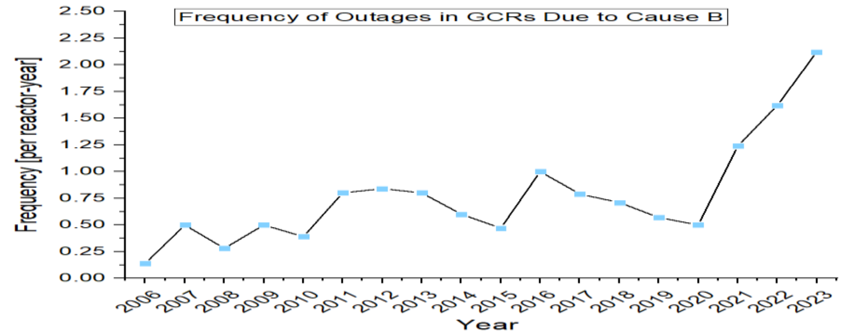
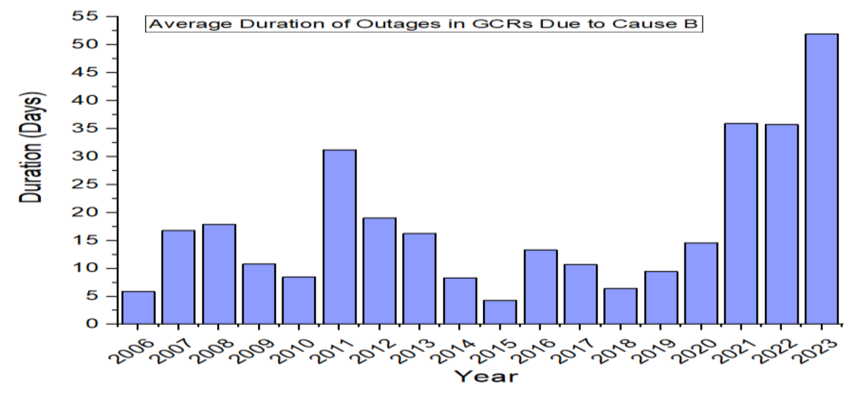
Results for GCR Reactors

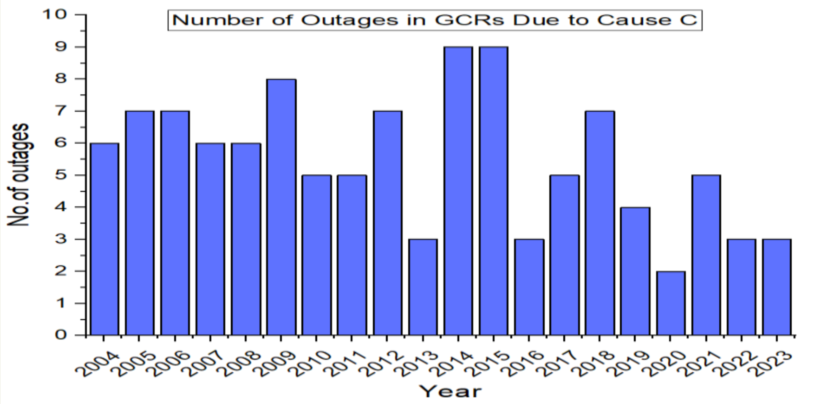
Outage Frequency, Number, and Duration due to Cause B

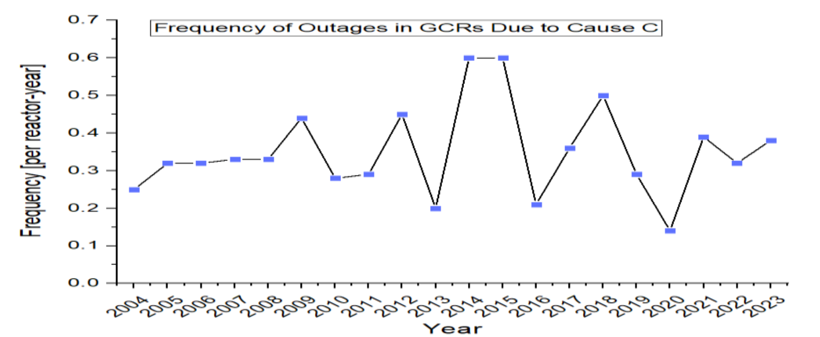


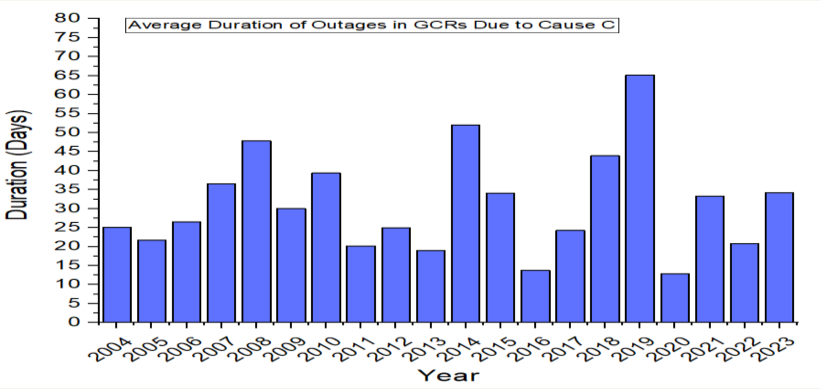




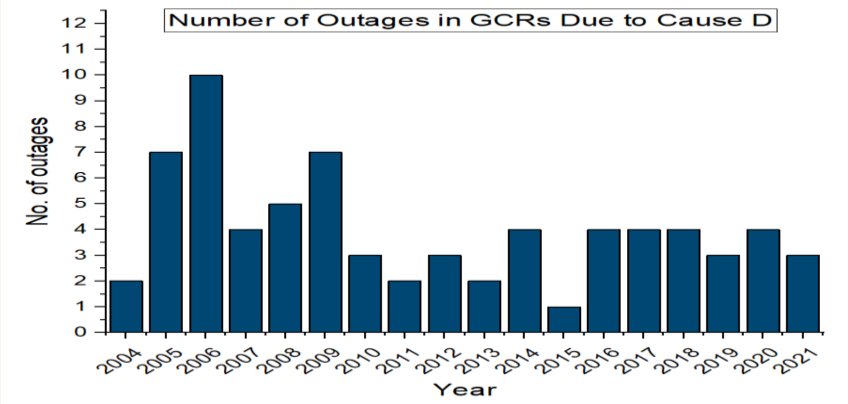
Outage Frequency, Number, and Duration due to Cause C

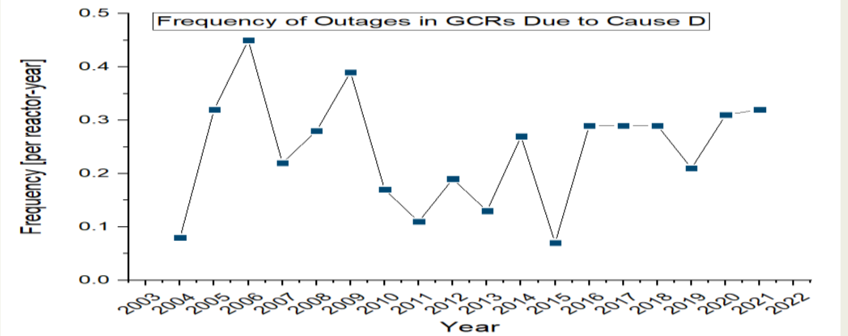


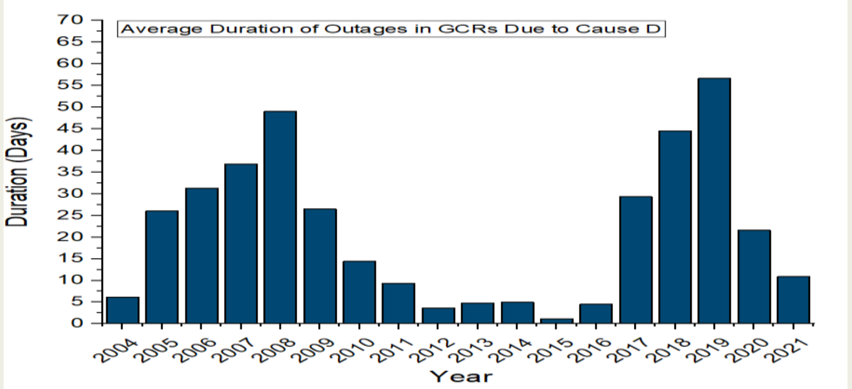




Outage Frequency, Number, and Duration due to Cause D







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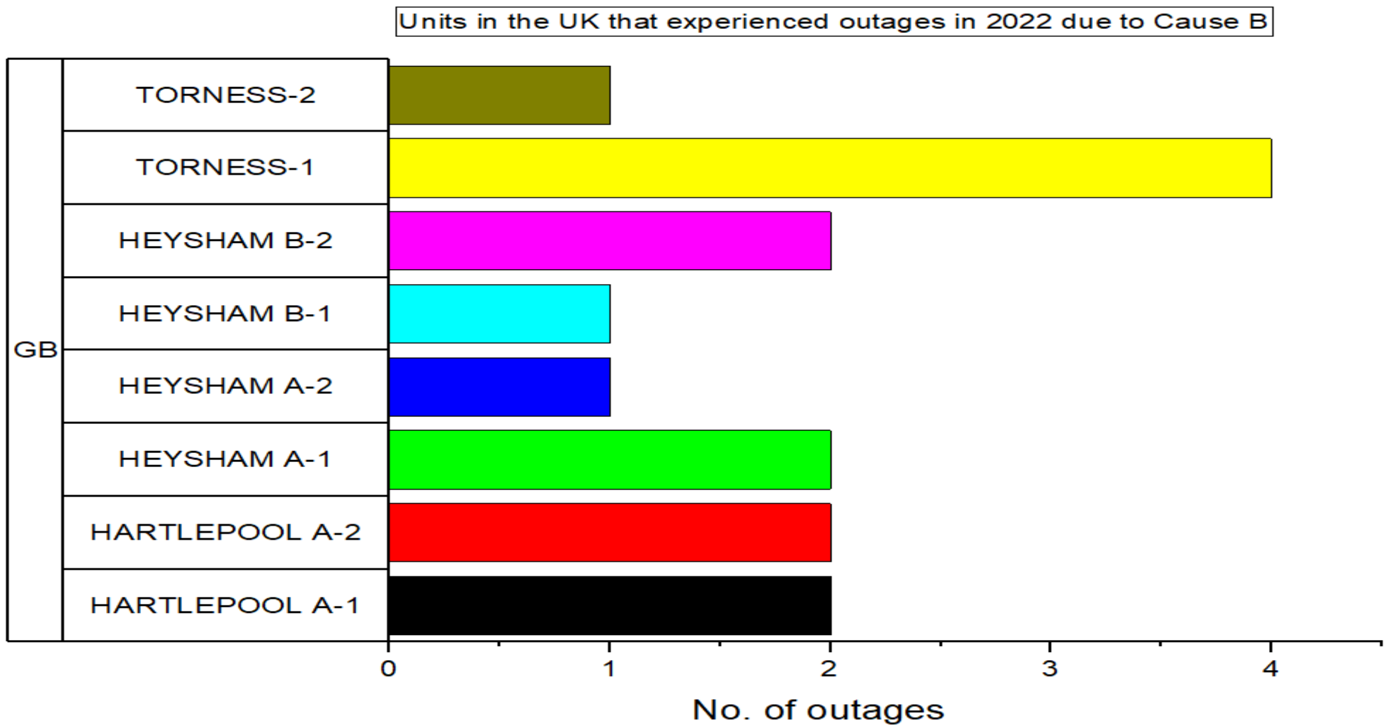
Calculated total discharge activities, in Bq, for the 4 IMS-relevant xenon isotopes

TABLE II. List of the number of measurements taken with the STAX system during each blowdown period and the number of detections of the four key xenon isotopes in each period.

Blowdown period	Number of measurements	^{133}Xe detections	^{135}Xe detections	^{133m}Xe detections	^{131m}Xe detections
R2 March 2022	59	59	59	14	0
R1 June 2022	49	49	49	1	0
R2 September 2022	56	56	56	16	0
R1 November 2022	39	39	39	3	0
R2 February 2023	55	55	55	27	0
R1 April 2023	51	51	51	7	0
Total	309	309	309	68	0

Petts, A., Bowyer, T., Friese, J., Goodwin, M., & Milbrath, B. (2024). Measurements of radioxenon activities during periods of gaseous release from an advanced gas-cooled reactor. *Physical Review Applied*, *22*(4), 044060.



The radioxenon detections across the monitoring array in 2022 are consistent with IAEA PRIS records, which indicate that each UK unit, including Hartlepool 1 and Hartlepool 2, experienced two downtimes during the year.

Statistical analysis of nuclear power reactor outages as sources of elevated radioxenon releases

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Future Work

- **Retrieve from operators webpages dates of outages and apply meteorological data**: link outage-related xenon releases with atmospheric transport modeling for IMS.
  - ✓ Simulating air mass transport from reactors to IMS stations using FLEXPART.
- **Cross-validation with IMS measurements**: compare reactor outage timelines with recorded xenon spikes at nearby stations.
  - ✓ Investigate how the duration and frequency of outages influence xenon emissions detected by IMS.
  - ✓ Assess whether longer outages result in extended emission windows compared to shorter, more frequent outages.
  - ✓ Explore how emission patterns could inform and prioritize IMS monitoring strategies based on reactor outage profiles.
  - ✓ Analyze Xe-133 level fluctuations during outage-related periods.
  - ✓ Map nuclear power plants and nearby IMS stations to study spatial relationships and correlations.

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