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A Comprehensive Review on Heat Release Rate for Fire Modeling in the U.S. Nuclear Power Plant

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1. Introduction

To establish a foundation for Fire Probabilistic Safety Assessment (Fire PSA), methodologies, tools, and data were jointly developed through a collaborative effort between the Electric Power Research Institute (EPRI) and the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES), culminating in the publication of NUREG/CR-6850 Vol.2 in 2005. However, at the time of its release, the lack of essential methods and data required for realistic calculations led to the adoption of simplified and conservative assumptions. Since then, the U.S. NRC and the nuclear industry have conducted continuous fire experiments and research, resulting in the development of more realistic fire data and enhanced methodologies documented in various subsequent reports. Given that these follow-up reports are tailored to specific objectives, their findings remain fragmented, necessitating a comprehensive synthesis. There are several inputs to make fire model and Heat Release Rate (HRR) is one of the most effective parameters. Accordingly, this study conducts a literature survey focusing on HRR and systematically organizes the HRR distributions and profiles provided by NUREG/CR-6850 and its subsequent technical reports.

2. Heat Release Rate Distribution

NUREG/CR-6850 categorizes electrical cabinets into five distinct types based on cable insulation material and loading density. In addition, the peak Heat Release Rates (HRRs) for other fire sources, including pumps, motors, and transient combustibles, are characterized using Gamma distributions, as summarized in Table I [1]. In this context, the values for the 75th and 98th denote the 75th and 98th percentiles of the HRR distribution, respectively.

Table I: Recommended Peak HRR Values for Electrical Fires in NUREG/CR-6850 Vol.2 [1]

Case	Ignition Source	HRR (kW)		Gamma Distribution	
		75th	98th	α	β
1	Vertical cabinets with qualified cable, fire limited to one cable bundle	69	211	0.84	59.3
2	Vertical cabinets with qualified cable, fire in more than one cable bundle	211	702	0.7	216
3	Vertical cabinets with unqualified cable, fire limited to one cable bundle	90	211	1.6	41.5
4	Vertical cabinets with unqualified cable, fire in more than one cable bundle close doors	232	464	2.6	67.8
5	Vertical cabinets with unqualified cable. fire in more than one cable bundle open doors	232	1002	0.46	386
6	Pumps (electrical Fires)	69	211	0.84	59.3
7	Motors	32	69	2.0	11.7
8	Transient Combustibles	142	317	1.8	57.4

Table II: Peak HRR Values for Functionally Based Classification Groups 1-3 Enclosures in NUREG-2178 Vol.1 [2]

Enclosure Class	Fuel Type	HRR (kW)		Gamma Distribution	
		75th	98th	α	β
1 - Switchgear and Load Centers	TS/QTP/SIS	30	170	0.32	79
	TP	60	170	0.99	44
2 - MCCs and Battery Chargers	TS/QTP/SIS	25	130	0.36	57
	TP	50	130	1.21	30
3 - Power Inverters	TS/QTP/SIS	25	200	0.23	111
	TP	50	200	0.52	73

* * TS: Thermoset cable; TP: Thermoplastic cable; QTP: Qualified thermoplastic cable; SIS: Switchboard instrumentation and switchgear wire

Table III: Peak HRR Values for Classification Group 4 Electrical Enclosures in NUREG-2178 Vol.1 [2]

Enclosure Class/ Function Group	Ventilation (Open/Closed)	Fuel Type (TS/QTP/SIS or TP)	Gamma Distribution Characteristics											
			(a) Default				(b) Low Fuel Loading				(c) Very Low Fuel Loading			
			α	β	75th	98th	α	β	75th	98th	α	β	75th	98th
4a - Large Enclosures [>1.42 m^3]	Closed	TS/QTP/SIS	0.23	223	50	400	0.23	111	25	200	0.38	32	15	75
	Closed	TP	0.52	145	100	400	0.52	73	50	200	0.88	21	25	75
	Open	TS/QTP/SIS	0.26	365	100	700	0.26	182	50	350	0.38	32	15	75
	Open	TP	0.38	428	200	1000	0.38	214	100	500	0.88	21	25	75
4b - Medium Enclosures [≤1.42 m^3 and >0.34 m^3]	Closed	TS/QTP/SIS	0.23	111	25	200	0.27	51	15	100	0.88	12	15	45
	Closed	TP	0.52	73	50	200	0.52	36	25	100	0.88	12	15	45
	Open	TS/QTP/SIS	0.23	182	40	325	0.19	92	15	150	0.88	12	15	45
	Open	TP	0.51	119	80	325	0.3	72	25	150	0.88	12	15	45
4c – Small Enclosures [≤0.34 m^3]	N/A	All	0.88	12	15	45	N/A							

NUREG-2178 Vol. 1 provides a more granular classification of electrical enclosures compared to the taxonomy established in NUREG/CR-6850. It categorizes these enclosures into specific groups—including switchgear, load centers, battery chargers, and power inverters—and presents their peak HRR distribution as Gamma distributions, as summarized in Table II [2]. These enclosures were generally assumed to be in a closed configuration.

Furthermore, the report provides peak HRR Gamma distributions that account for variables such as enclosure dimensions (large, medium and small), ventilation status (open and closed), and the type (TS/QTP/SIS or TP) and quantity (default loading, low fuel loading and very low fuel loading) of fuel (cable) loading, as detailed in Table III.

NUREG-2178 Vol. 2 provides peak HRR distributions for motors and dry transformers, categorized by their horsepower (HP) ratings and modeled via Gamma distributions, as detailed in Table IV [3]. Regarding fire propagation between adjacent electrical enclosures, it is postulated that both the exposing and exposed enclosures will reach the 98th percentile peak HRR values specific to their respective enclosure classifications.

In NUREG-2233, transient combustibles are classified into two distinct categories: generic transients and Transient Combustible Control Locations (TCCLs) transient [4]. While the definition of generic transients remains consistent with NUREG/CR-6850, the application of TCCL is contingent upon the following administrative and procedural criteria:

1. Activities must be procedurally controlled under explicit visual markings.
2. There must be no documented trend of violating administrative controls regarding transient ignition sources over a reasonable evaluation period.
3. Long-term storage of transient ignition sources is strictly prohibited without exception.
4. If necessary, temporary storage must be rigorously managed through appropriate compensatory measures.

Table IV: Peak HRR Values for Motor and Dry Transformer in NUREG-2178 Vol.2 [3]

Classification Group	HRR (kW)		Gamma Distribution	
	75th	98th	α	β
Motor A (5-30 hp)	6	15	1.34	3.26
Motor B (30-100 hp)	14	37	1.17	8.69
Motor C (>100 hp)	37	100	1.10	24.19
Transformer A (45-75 kV)	6	30	0.38	12.84
Transformer B (75-750 kV)	15	70	0.41	28.57
Transformer C (>750 kV)	30	130	0.46	50.26

The peak HRR and Total Energy Release (TER) for both generic transients and TCCL transient are characterized using Gamma distributions, as summarized in Table V. These TER values are subsequently utilized in Chapter 3 to derive the HRR profiles for transient ignition sources.

Notably, the peak HRR values prescribed in NUREG-2233 are lower than those in NUREG/CR-6850. Furthermore, within the NUREG-2233 framework, TCCL transients exhibits a lower HRR compared to generic transients.

Table V: Peak HRR Values for Transient Combustible in NUREG-2233 [4]

Type		Percentile		Gamma Distribution	
		75th	98th	α	β
Generic transients	HRR(kW)	41.6	278	0.271	141
	TER(MJ)	11.8	123	0.184	77.1
TCCL transients	HRR(kW)	24.6	143	0.314	67.3
	TER(MJ)	7.0	59.9	0.214	34.5

NUREG/CR-7010 Vol. 1 provides the Heat Release Rate Per Unit Area (HRRPUA) for cable fires, categorized by the specific insulation material [5]. For simplified analytical applications, the report recommends two representative HRRPUA values: 150 kW/m² for thermoset (TS) cables and 250 kW/m² for thermoplastic (TP) cables. In cases where a cable tray contains a combination of both insulation types, a mass-weighted average of these two values is applied to determine the aggregate HRRPUA.

3. Heat Release Rate Profile

Fire development is generally characterized by four distinct stages: incipient, growth, fully developed, and decay [1]. NUREG/CR-6850 provides recommended HRR profiles for electrical fires, where the growth phase is modeled using a t^2 (t-squared) fire growth function [1]. Under this guidance, the fire grows for approximately 12 minutes in proportion to t^2, maintains its peak HRR for 8 minutes, and subsequently undergoes a linear decay for 19 minutes. NUREG-2230 further refines the classification of electrical cabinet fires into interruptible fires and growing fires [6]. Interruptible fire is an event in which plant personnel could detect and perform early suppression activities and growing fire is an event in which the fire may grow in a manner such that plant personnel may not be able to provide suppression prior to fire growth. For interruptible fires, two HRR profile options are proposed: a newly developed curve and the original NUREG/CR-6850 HRR profile augmented with a 4-minute pre-growth time. Regarding growing fires, while specific HRR profile was derived from experimental results, NUREG/CR-6850's profile remains the recommended standard due to the limited representativeness of the five test cases used in the NUREG-2230 study [6]. HRR profiles for motors and transformers had been used these of electrical fires in NUREG/CR-6850. NUREG-2178 Vol. 2 introduces growth curves for motors and dry transformers [3]. Within this framework, fire propagation to an adjacent electrical enclosure is postulated to occur 10 minutes after the onset of the growth period of the exposing enclosure. Finally, NUREG-2262 delineates HRR profile for subsequent electrical fires following a High Energy Arcing Fault (HEAF), which are uniquely characterized by reaching their peak HRR instantaneously upon ignition [7]. These fire growth profiles are summarized in Table VI. Plateau in the Table VI means fully developed which is previously described.

Table VI: Summary of the HRR Profiles

Classifi-cation	Pre-growth (min)	t^2 Growth (min)	Plateau (min)	Decay (min)	Total (min)
NUREG/CR-6850	0	12	8	19	39
Interruptible Fire -1	9	7	5	13	34
Interruptible Fire -2	4	12	8	19	43
Growing Fire	0	12	9	26	47
Post-HEAF	0	0	8	19	27
Motor	0	2	13	2	17
Transformer	0	0	10	10	20
Adjacent Cabinet	10	12	8	19	49

NUREG-2233 characterizes the HRR profiles for transient combustibles through mathematical formulations that incorporate the TER as a key variable, as detailed in Table VII. If plateau time is less than 1 s, set to 1s. Recommended values of growth exponent (n_1) and decay exponent (n_2) are 2.7, 0.32, respectively. If the plateau time is set to 1 s, use Equations (2) and (4) to obtain the growth time and decay time. Otherwise, use Equations (1) and (3).

Table VII: HRR Profile of Transient Combustibles

Time	Recommended Value	Uncertainty Range
Growth Time t_g (s)	$t_g = \frac{690}{q_{peak}} TER^{1.01}$ (1) $t_g = \frac{3700}{q_{peak}}\left(TER - \frac{q_{peak}}{1000}\right) \times \frac{0.186TER^{1.01}}{0.186TER^{1.01} + 0.955TER^{0.940}}$ (2)	300-4090
Plateau Time t_p (s)	$t_p = \frac{1000TER}{q_{peak}} - \frac{t_g}{n_1+1} - \frac{t_d n_2}{n_2+1}$ or 1 s	N/A
Decay Time t_d (s)	$t_d = \frac{3940}{q_{peak}} TER^{0.94}$ (3) $t_d = \frac{1320}{0.32q_{peak}}\left(TER - \frac{q_{peak}}{1000}\right) \times \frac{0.955TER^{0.940}}{0.186TER^{1.01} + 0.955TER^{0.940}}$ (4)	2200-9560

4. Conclusions

This study conducted a literature survey on the HRR, a critical parameter for fire scenarios in nuclear power plants. Through this survey, HRR distributions and profiles were collected and organized. While the foundational NUREG/CR-6850 report adopted a simplified and conservative approach, subsequent technical reports have introduced enhanced methodologies, tools, and experimental data, thereby enabling more realistic fire modeling and analysis. Using updated HRR data can make fire model more realistic and HRR data in NUREG/CR-6850 could be helpful if conservative approach is required.

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