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Construction Safety Management in High-Voltage Electrical Engineering Projects: Challenges and Practical Solutions

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ABSTRACT

Background: High-voltage transmission, distribution and substation construction combines lethal electrical energy with lifting, mobile plant, work at height, excavation, traffic and rapidly changing system configurations. Although standards describe individual precautions, serious incidents continue to occur when critical controls are not positively established or verified at the point of work.

Objective: To identify recurrent severe-incident pathways in power-line construction and convert them into a practical project-level safety-management framework for high-voltage electrical engineering projects.

Methods: A retrospective archival study coded 31 publicly available U.S. Occupational Safety and Health Administration (OSHA) accident investigations from 2019–2024 involving NAICS 237130 power and communication line construction and closely related high-voltage line activities. Cases were purposively selected for sufficient narrative detail and severe outcomes. Event mechanism, fatality status and the primary critical-control family implicated by the documented pathway were coded using an a priori hierarchy informed by OSHA, IEEE, NFPA and construction-safety literature. Descriptive analysis was used; no incidence rates or causal risk estimates were calculated because the sample was not denominator-based.

Results: Twenty-two of 31 investigations (71.0%) were fatal. Electrical-exposure pathways accounted for 21 cases (67.7%) and 16 fatalities; direct electrical contact/arc was the most frequent narrow mechanism (14 cases). The two most frequent critical-control families were isolation/de-energization/test-before-touch (8 cases; 7 fatal) and minimum-approach-distance (MAD), insulating cover-up and conductive-object clearance (8 cases; 6 fatal). Mechanical-energy/rigging/equipment-integrity failures accounted for 6 cases, while mobile-plant/traffic exclusion, grounding/bonding, energized-work/arc-flash, and fall/excavation controls accounted for the remainder.

Conclusion: Severe high-voltage construction events were not confined to PPE failures or individual rule violations. They repeatedly involved breakdowns in energy-state control, approach-path control, work-interface management and field verification. The study proposes a High-Voltage Construction Critical-Control Framework (HV-CCF) that links engineering design, switching and permit-to-work governance, point-of-work proof, active supervision, and an independent energization-readiness gate. This provides owners and contractors with a practical mechanism for managing serious-injury-and-fatality risk across the project lifecycle.

Keywords: high-voltage construction; electrical safety; transmission lines; power distribution; electrocution; minimum approach distance; lockout/tagout; grounding; critical controls; construction safety management

1. INTRODUCTION

Expansion and modernization of electrical grids require construction work in environments where the consequences of control failure can be immediate and catastrophic. New transmission corridors, reconductoring, substation extensions, overhead distribution, underground feeders, tower and pole replacement, and protection/control upgrades often proceed beside energized assets that must remain in service. The work therefore combines construction uncertainty with operational electrical-system constraints. Crews can face direct contact, arc flash, induced or backfeed voltage, step-and-touch potential, suspended loads, conductor tension, mobile equipment, traffic, excavation, work at height and commissioning hazards during a single shift. The safety challenge is not simply to identify these hazards; it is to ensure that the small number of controls capable of preventing a fatal exposure are correctly designed, authorized, installed, verified and maintained as the system configuration changes.

Electrical injury is disproportionately severe. Historical U.S. analyses found that construction accounted for a large share of occupational electrical fatalities and that overhead power-line contact was a dominant pathway [1-5]. A 2013 study focused specifically on transmission and distribution line construction highlighted the elevated electrocution risk faced by electrical contractors and the need to connect hazard recognition to systematic risk controls [1]. Contemporary construction-safety evidence likewise identifies overhead-line contact, live equipment, damaged equipment and arc-flash exposure as recurring electrical hazards requiring strong engineering and organizational controls [2]. Contemporary surveillance remains relevant: Electrical Safety Foundation International statistics available in 2025, compiled from U.S. Bureau of Labor Statistics and OSHA sources for 2011–2023, reported 1,940 workplace electrical fatalities, with construction contributing 855, the largest industry count [30].

The engineering context makes high-voltage projects different from conventional building electrical work. Minimum approach distance (MAD) changes with system voltage, exposure type and altitude; the electrical state of a line can change through switching; induction can energize a nominally de-energized conductor; temporary grounds may create or remove equipotential zones; and mobile booms, cranes, stringing equipment, guy wires, conductive materials and suspended conductors can bridge safe distances even when workers themselves do not. OSHA Subpart V and 1910.269 therefore require controls around qualified employees, minimum approach distances, job briefings, de-energization, grounding and energized work [23,24]. IEEE 516 provides engineering guidance for energized-line maintenance methods, while the National Electrical Safety Code addresses practical safeguarding for supply stations and overhead and underground lines [25,65]. NFPA 70E and IEEE 1584 provide complementary frameworks for electrically safe work conditions and arc-flash hazard analysis [26,27].

Yet standards do not automatically become effective field barriers. Construction projects are temporary multi-employer organizations. The asset owner controls network state and outage authority; the engineer controls design and technical acceptance; principal contractors control sequence and resources; specialist subcontractors may execute line work; and system operators may retain switching authority. A permit-to-work can therefore be procedurally correct but operationally weak if the work limits are misunderstood, the one-line diagram is stale, temporary grounds are absent, a third party changes the configuration, or a mobile equipment operator crosses an unmarked approach boundary. Serious-incident prevention requires alignment of technical and organizational controls.

Safety-management research supports this systems view. Construction leading-indicator studies emphasize proactive verification of safety processes rather than dependence on lagging injury rates [8-11,62]. Meta-analytic work links management commitment, supervisor safety role, safety rules and procedures, training, individual responsibility, safety knowledge and motivation with safer performance [12-15]. Construction-specific research has also shown that effective programs combine multiple mutually reinforcing practices rather than relying on a single intervention [16,17]. These findings are consistent with systems-safety theories that interpret accidents as the product of interacting defenses, controls and organizational conditions rather than as a linear chain ending with worker error [18-20].

The gap is operational. Published electrical-safety research describes epidemiology and risk factors; standards define technical requirements; and general construction literature describes safety-management practices. Fewer studies translate severe high-voltage construction incident pathways into a project-level set of critical controls that can be independently verified at design, pre-job, point-of-work and energization stages. The term critical control is used here for a control whose absence or failure could permit a serious-injury-or-fatality (SIF) exposure and whose presence can be directly verified in the field. This approach intentionally shifts attention from the volume of safety documentation to whether the barriers that must work are demonstrably in place.

The study had three objectives. First, it sought to characterize recurrent severe-incident mechanisms in a contemporary archival sample of power-line construction investigations. Second, it mapped each case to the primary critical-control family that, based on the documented incident pathway, would have interrupted the exposure. Third, it translated the cross-case patterns into a High-Voltage Construction Critical-Control Framework (HV-CCF) and practical verification dashboard for owners, engineers and contractors. The research questions were: RQ1, which severe-event mechanisms recur in high-voltage line construction? RQ2, which critical-control families are most frequently implicated by those pathways? RQ3, what project-level safety-management practices can make those controls verifiable rather than merely procedural?

2. METHODS

2.1 Study design

This research used a retrospective archival multiple-case design with directed qualitative content analysis. The unit of analysis was a severe construction incident investigation rather than an individual worker or contractor. Public regulatory narratives were selected because they provide event-specific descriptions of the work activity, energy source, equipment and immediate exposure pathway without requiring retrospective interviews. The design supports mechanism-oriented inference—identifying recurrent pathways and control opportunities—but does not estimate population incidence, relative risk or the effectiveness of any one intervention.

The empirical evidence base comprised OSHA Integrated Management Information System (IMIS) Accident Report Detail records for severe incidents associated with power and communication line construction (NAICS 237130) and directly related power-line/transmission-line work. The analytic period was 1 January 2019 through 31 December 2024. Records were retrieved and checked through 10 December 2025. The period was selected to provide a contemporary multi-year sample while avoiding records not fully available by the evidence cutoff. OSHA records are enforcement and inspection data; they are not a complete census of all U.S. incidents, and coverage varies across federal and state-plan jurisdictions.

A purposive case strategy was used because the research objective required narratives detailed enough to reconstruct the hazard path. Cases were included when they: (1) concerned construction, alteration, repair, inspection or installation of electric power-line or closely related high-voltage infrastructure; (2) involved a fatality or serious non-fatal injury/hospitalization; (3) contained sufficient narrative evidence to identify the initiating mechanism and a primary control family; and (4) occurred during 2019–2024. Records were excluded when the death was natural/medical rather than traumatic, the activity was unrelated telecommunications work, the project was generic construction with only incidental electrical exposure, or the narrative was too sparse for defensible coding. Thirty-one cases met the analytic criteria [31-61].

2.2 Coding framework and operational definitions

An a priori hierarchy of seven critical-control families was developed from OSHA electric-power standards, ISO 45001 and ISO 31000 management-system principles, IEEE/NFPA electrical-safety guidance, and construction risk-control literature [21-28]. The families were: (1) isolation, de-energization and test-before-touch; (2) MAD, insulating cover-up and conductive-object clearance; (3) grounding, bonding and induced-voltage control; (4) energized-work/arc-flash planning and PPE; (5) mechanical energy, rigging and equipment integrity; (6) mobile plant, traffic and exclusion zones; and (7) fall, excavation and civil-work critical controls. A single primary family was assigned to each event to avoid double-counting. This does not imply that only one barrier failed; serious incidents usually involve multiple contributing conditions.

Coding prioritized the physical exposure pathway over behavioral labels. For example, a conductive steel member contacting an overhead line was coded to MAD/conductive-object clearance rather than to “worker awareness”; a conductor being assumed safe without positive energy-state control was coded to isolation/de-energization; and a trench collapse was coded to excavation protective systems. PPE was treated as a control within energized-work planning, not as a substitute for elimination, de-energization, engineered distance or isolation. This hierarchy reflects the principle that higher-order engineering and energy-control barriers should be considered before reliance on individual behavior or personal protective equipment.

Because coding was conducted by one researcher using public narratives, no inter-rater reliability statistic was calculated. To improve auditability, Table 3 reports every case identifier, year, mechanism, severity and primary assigned control family. The appendix also describes decision rules so that future researchers can independently recode the sample. Ambiguous facts were not inferred beyond the narrative. The study does not make legal determinations about regulatory violations and does not infer the motives, competence or culpability of named persons or organizations.

2.3 Analysis

Descriptive counts and proportions summarized event mechanisms, fatality status and critical-control families. Year-specific counts were reported only to show sample composition; they were not interpreted as trends because case retrieval was purposive and no denominator was available. Electrical-exposure events were defined as direct electrical contact/arc, mobile-equipment contact with energized lines, conductive-material contact with energized lines, arc flash, or arc/equipment failure. The remaining cases were treated as non-electrical high-energy construction mechanisms.

Cross-case synthesis then examined how events could propagate through four control layers: engineering/design, authorization and work planning, point-of-work physical proof, and active field verification. Practical solutions were retained when they were (a) directly responsive to one or more observed pathways, (b) supported by a current standard or high-quality safety-management literature, and (c) capable of being expressed as observable evidence rather than a generic instruction to "work safely." The resulting HV-CCF is an author-developed analytic framework, not an OSHA, NFPA, IEEE or ISO standard.

2.4 Ethics and research integrity

The study used publicly available regulatory records and published literature, did not interact with human participants, and did not access confidential personal data. Institutional review board approval was therefore not sought. Case details were limited to information necessary to analyze the occupational exposure pathway. The analysis intentionally avoids invented interviews, reconstructed witness testimony, and unsupported root-cause claims. All incident classifications should be understood as research coding based on public narratives rather than official OSHA causal determinations.

3. RESULTS

3.1 Sample characteristics

Thirty-one severe incident investigations were included. Twenty-two were fatal (71.0%) and nine were serious non-fatal events. Electrical-exposure pathways accounted for 21 cases (67.7%) and 16 fatalities. The remaining 10 cases involved mechanical, vehicle, fall, excavation or other high-energy construction mechanisms, of which 6 were fatal. These percentages describe the purposive sample only and must not be interpreted as industry incidence or fatality risk.

3.2 Severe-event mechanisms

Direct electrical contact or arc was the most frequent narrow mechanism, occurring in 14 of 31 cases (45.2%) and accounting for 11 fatalities. When direct contact was combined with energized-line contact by mobile equipment (three cases), conductive materials (two cases), and arc/equipment-failure events (two cases), electrical exposure represented 21 of 31 cases. The remaining ten incidents demonstrate an important management point: a high-voltage construction project remains a construction project even when electrical risk dominates the safety narrative. Workers were also exposed to suspended and shifting loads, conductor tension, equipment crush points, road traffic, falls and excavation collapse.

The event narratives repeatedly involved bridging of a physical boundary. That bridge could be a body part entering an energized zone, a bucket/boom moving into a conductor, a guy wire or steel truss becoming conductive, a ground wire creating a current path, or a mechanical component entering an exclusion zone. The relevant safety question was therefore not only whether a hazard had been discussed, but whether a physical barrier or verified work state made the hazardous energy inaccessible.

3.3 Critical-control families

Two families jointly accounted for more than half of the case assignments. Isolation, de-energization and test-before-touch was the primary family in eight cases, seven of which were fatal. MAD, insulating cover-up and conductive-object clearance was also assigned to eight cases, six fatal. The distinction is operationally important. The first family concerns proving and maintaining the electrical state of the equipment or conductor; the second concerns preventing workers, mobile equipment or conductive objects from entering a hazardous approach path when energized parts remain present. Treating both as generic "electrical safety" can conceal different assurance requirements.

Mechanical energy, rigging and equipment integrity was the primary family in six cases. These included a falling pole, shifting loads, boring/pipe-handling equipment and a personnel-basket/crane control failure. Three cases were assigned to mobile plant, traffic and exclusion-zone control where the primary harmful energy was vehicle or plant movement rather than electrical current. Grounding/bonding and induced-voltage control, energized-work/arc-flash planning, and fall/excavation controls each appeared in two cases. The distribution supports a multi-hazard critical-control model rather than an electrocution-only safety program.

3.4 Cross-case pathways: where safety management loses control

Four recurrent loss-of-control pathways emerged. The first was energy-state ambiguity. Severe events occurred where the work interface involved existing energized circuits, reconductoring, disconnection or new construction close to live lines. Paper isolation is insufficient unless the point of work is proved safe. A robust system therefore needs a traceable chain from network configuration and switching instruction to field identification, test-before-touch, grounding where required, and controlled release for re-energization. This chain should have one accountable authority for each transition. A change in system state invalidates the preceding verification.

The second pathway was approach-path failure. Several cases did not require a worker to intentionally reach toward a live conductor. Instead, a bucket, boom, guy wire, tracer material, steel truss or other conductive object entered the electrical boundary. Conventional training that focuses on body position can therefore miss the geometry of the task. Work planning should model the maximum envelope of plant and materials, not just the worker position. Where a long conductive object can rotate, flex or be lifted into a conductor, its entire swept path should be controlled.

The third pathway was interface drift. High-voltage projects often change crews, switching states, weather conditions, equipment, access arrangements and construction sequence during the day. A job briefing conducted hours earlier cannot guarantee that the critical controls still match the work. The practical response is trigger-based revalidation: if system state, crew composition, work limits, equipment, lift path, weather, or adjacent-party activity changes, the job pauses and the critical-control check is repeated. The stop-work trigger must be defined before production pressure is encountered.

The fourth pathway was hazard displacement. Electrical work can be made electrically safer while simultaneously increasing other high-energy hazards—for example, using heavy mechanical equipment to avoid direct manual handling, excavating to underground a conductor, or using aerial devices to maintain electrical clearance. The case sample included crush, traffic, load, fall and trench events for this reason. A credible high-voltage safety system therefore treats SIF controls as a portfolio; it does not allow an electrical permit to eclipse lifting, vehicle, excavation or fall-protection requirements.

3.5 From compliance to critical-control verification

The cross-case synthesis suggests that the most useful assurance question is not "Was the procedure completed?" but "What evidence proves that the fatal-energy pathway is blocked right now?" The proposed HV-CCF therefore uses a verification ladder (Figure 4). At design/method stage, hazards should be eliminated or engineered out where practicable. Before work, switching, permits, competency and configuration are authorized. At the point of work, the crew proves the actual condition through testing, grounding, cover-up, boundaries, equipment condition and exclusion zones. During execution, supervisors verify the small number of controls that must remain effective. Before energization or turnover, an independent readiness gate confirms that temporary protective measures are removed in the correct sequence and the permanent system matches the accepted configuration.

4. DISCUSSION

4.1 Principal findings

This study found that severe high-voltage construction incidents clustered around failures of energy-state control and approach-path control. Isolation/de-energization/test-before-touch and MAD/cover-up/conductive-object clearance together represented 16 of the 31 primary assignments. This is consistent with decades of electrical-injury literature identifying energized-source contact and overhead-line contact as dominant fatal mechanisms [1-7]. It is also consistent with OSHA requirements that distinguish the electrical state of equipment from the minimum distance that qualified employees and conductive objects must maintain around exposed energized parts [23,24]. The practical implication is that project safety systems should treat these as separate critical controls with separate verification evidence.

The findings also reinforce the limitation of a PPE-centered electrical safety program. PPE is necessary for specific energized tasks, but many event pathways are better interrupted upstream: remove voltage, establish a clearance, install protective grounds, increase distance, cover exposed parts, redesign the material path, or physically segregate mobile equipment. Hierarchy-of-control logic is embedded in modern occupational health and safety systems [21,28]. NFPA 70E similarly prioritizes establishment of an electrically safe work condition where feasible, while IEEE guidance supports engineering-based energized-line work methods [25,26]. PPE becomes one layer of defense rather than the primary strategy.

Non-electrical SIF hazards were not peripheral. Ten cases in the sample involved mechanical, traffic, fall, excavation or related pathways without electrical energy as the immediate mechanism. This aligns with general construction-safety research showing that effective performance depends on broad risk-control systems, management commitment, supervision, training, planning and leading indicators rather than a narrow compliance checklist [8-17,62]. In line projects, mechanical and electrical hazards are especially coupled: stringing tensions, poles, cranes, aerial devices and conductive materials are the means by which the electrical work is physically performed.

4.2 Challenge 1: outage constraints and energized-work normalization

Owners face pressure to maintain network reliability, avoid customer interruptions and meet commissioning milestones. These constraints can normalize work near energized assets. The safety-management failure occurs when “cannot de-energize” becomes an assumption rather than a documented engineering and operational decision. A practical control is an energized-work challenge process: the project team must document the operational reason that de-energization is infeasible, compare alternative sequences or temporary supplies, identify the exact energized boundaries, and specify the work method, qualifications, cover-up, tools and PPE. The authorization should expire when the configuration or task changes. For transmission and distribution work, outage strategy should be part of constructability planning, not a same-day safety decision.

4.3 Challenge 2: configuration control, switching and test-before-touch

High-voltage construction creates temporary configurations: jumpers are removed, new conductors are installed adjacent to existing circuits, bus sections are extended, protection schemes are altered, and temporary grounds are added and removed. A single stale drawing or misunderstood clearance can defeat multiple downstream controls. The recommended project solution is a configuration-controlled switching package that links the current single-line diagram, equipment identifiers, switching order, isolation points, lock/tag or clearance status, voltage test method, temporary protective grounds and release authority. The crew should identify the equipment in the field against that package and independently verify absence of voltage at the point of work. “Test before touch” should be observed as a critical control, not inferred from paperwork.

4.4 Challenge 3: minimum approach distance and conductive-object geometry

OSHA requires employers to establish voltage-appropriate MADs, with adjustments for voltage range and, where relevant, altitude and transient overvoltage [23,24]. The engineering challenge is that projects routinely introduce objects whose movement envelope is larger than the worker: cranes, bucket booms, pulling equipment, tag lines, guy wires, reinforcement, steel supports, ladders and long tools. The case sample demonstrates the importance of planning the swept volume of those objects. Practical solutions include physical goalposts or boundary markers, dedicated line-clearance spotters, insulating cover-up installed by qualified employees, nonconductive alternatives where technically appropriate, equipment movement limits, and pre-job simulation of the worst credible boom/material position. Proximity alarms may provide supplementary warning, and experimental evidence supports their potential utility, but they should not replace isolation, distance or engineered barriers [7].

4.5 Challenge 4: grounding, bonding and induced voltage

A conductor may be de-energized at its normal source yet remain hazardous through induction, accidental contact, backfeed or stored energy. This is particularly important during parallel-line construction and reconductoring. The grounding system should therefore be engineered to create a predictable equipotential zone and to withstand available fault current. Ground location, conductor size, connection sequence, visibility and removal control matter. Project records should allow a supervisor to answer four questions immediately: where are the grounds, who authorized them, are they adequate for the exposure, and who controls their removal? Grounding is not a generic housekeeping item; it is part of the electrical state of the work zone.

4.6 Challenge 5: contractor interfaces and supervision

Electrical infrastructure is frequently delivered through layered subcontracting. The system operator may issue the clearance, a civil contractor may control access, a line contractor may perform the work, an OEM may support commissioning, and an owner’s engineer may verify quality. Responsibilities can therefore be distributed precisely when risk is greatest. Safety climate and leading-indicator literature consistently identifies management commitment, supervisor role, competence and stakeholder engagement as important determinants of safety performance [8-15]. The owner should establish a single interface matrix identifying who has authority to energize, isolate, ground, issue permits, control plant movement, approve lifting/stringing plans, stop work and release the system. The field supervisor must have both technical competence and organizational authority to exercise those controls without schedule penalty.

4.7 Challenge 6: energization and commissioning

Commissioning changes the risk profile because equipment that was construction work becomes an operating electrical system. Temporary wiring, incomplete labels, open protection settings, test jumpers, provisional grounds and unfinished punch items can become hazardous when energy is introduced. The final control should therefore be an energization-readiness gate separate from routine construction progress reporting. Minimum evidence should include approved as-built/marked-up diagrams, resolved safety-critical non-conformances, protection and interlock test records, equipment identification, temporary-ground reconciliation, access-control arrangements, communications with affected crews, emergency response readiness and formal transfer of operational authority. Energization should be treated as a configuration change that invalidates previous assumptions about what is safe to touch.

4.8 A practical owner-contractor critical-control system

Table 6 translates the HV-CCF into leading indicators suitable for weekly project assurance. The proposed measures deliberately avoid generic counts such as total toolbox talks. A large number of meetings can coexist with an absent ground or incorrect system state. Higher-value indicators test whether the control was present where exposure existed: percentage of planned high-voltage tasks with verified isolation packages, percentage of point-of-work observations with correct MAD and cover-up, closure time for safety-critical defects, or the number of energization packages rejected before release. The aim is not to reward low rejection rates; early detection of a missing control is a successful prevention event.

4.9 Safety technology: useful supplement, poor substitute

Digital permit-to-work systems, electronic switching logs, geofenced plant, RFID tool/ground tracking, wearable proximity alarms, camera analytics and connected inspection records can strengthen assurance when they reduce ambiguity and create timely feedback. Worker-worn electric-field sensing has shown technical feasibility for detecting proximity and contact conditions [7]. However, technology can create false confidence when it becomes a substitute for primary barriers. Sensors may be affected by voltage, geometry, calibration, shielding or environmental conditions; digital forms can reproduce poor logic faster; and geofences can drift from the actual conductor position. Technology should therefore be assigned a defined role in the barrier model, tested under site conditions, and treated as supplementary unless validated as the primary engineered control.

4.10 Relationship to contemporary standards and practice

The framework is compatible with, but does not replace, current standards. ISO 45001 remained current at the 10 December 2025 evidence cutoff and provides the management-system structure for hazard identification, operational control, competence, worker participation, performance evaluation and improvement [21]. ISO 31000 supports integrated risk identification, treatment, monitoring and communication [22]. OSHA Subpart V and 1910.269 provide enforceable U.S. requirements for electric power work, including approach distances and energized/de-energized work controls [23,24]. IEEE 516 and the NESC provide line-work engineering and safeguarding guidance [25,65], while NFPA 70E and IEEE 1584 support electrical safe-work and arc-flash practices [26,27]. OSHA construction guidance on work near overhead power lines reinforces de-energization, safe clearances and controlled equipment movement near energized lines [64]. The HV-CCF contributes by connecting these technical requirements to project governance and verification cadence.

4.11 Implications for project leadership and procurement

Safety performance is partly designed before mobilization. Owners can require bidders to demonstrate high-voltage work methods, switching/clearance governance, qualified-person systems, grounding engineering, live-line capability, rescue arrangements, supervision ratios and evidence from leading indicators. Contracts can define hold points for first-of-kind work, critical lifts, stringing, work inside approach zones and energization. Safety-critical method statements should not be treated as generic submittals approved once for an entire project; they should be configuration-specific and linked to the actual system state. Procurement should also discourage business models in which specialist line work is passed through multiple subcontracting layers without preserved technical authority and competence.

4.12 Limitations

This study has important limitations. First, the 31 cases are a purposive sample of severe OSHA investigations selected for relevance and narrative sufficiency; they are not a complete set of U.S. high-voltage construction incidents. Federal and state-plan reporting and enforcement systems differ, and serious events may be absent from the searchable database. Consequently, the observed percentages cannot be interpreted as incidence, prevalence or comparative fatality risk.

Second, public regulatory narratives are concise and primarily written for enforcement/inspection purposes. They may omit upstream design, commercial, supervision, fatigue, weather, organizational or communication factors. The primary critical-control assignment identifies a plausible barrier that directly interrupts the documented pathway; it is not a formal root-cause analysis and should not be interpreted as a legal conclusion.

Third, a single researcher performed coding, so inter-rater reliability was not available. The event-level table and explicit decision rules were included to support replication. Future work should use blinded dual coding, larger datasets, denominator-based exposure measures and prospective field observation to test the reliability and predictive value of the framework.

Fourth, the empirical sample is U.S.-based. The physics of electrical contact and many engineering controls are transferable, but legal duties, qualification systems, grid practices, climate, contractor structures and resource constraints differ internationally. The framework should therefore be adapted to the applicable national code, system operator rules and project context rather than copied mechanically.

4.13 Research agenda

Future research should evaluate critical-control verification prospectively across transmission, distribution and substation projects. A useful design would record exposure opportunities—such as energized-adjacent work hours, plant movements near lines, switching operations, grounding installations and critical lifts—along with verified control presence, near misses and high-potential events. This would permit denominator-based rates and multilevel analysis across crews and projects. Digital records could support this work if data definitions are standardized. Particular research priorities include induced-voltage control during parallel-line construction, effectiveness and human factors of proximity-warning technologies, interface risk during energization, subcontractor-tier effects, and the relationship between field-verified leading indicators and SIF potential rather than total recordable injury rates.

5. CONCLUSIONS

The archival evidence in this study supports a simple but consequential conclusion: high-voltage construction safety is primarily a problem of controlling fatal energy pathways, not of producing more safety paperwork. In the 31 investigated severe cases, electrical exposure was prominent, and the two most frequent critical-control families were positive energy-state control and control of approach paths around energized systems. Mechanical, traffic, fall and excavation events remained material, confirming that line and substation projects require an integrated SIF-control portfolio.

For practice, the recommended model has five linked stages. Plan the work so energized exposure is eliminated or minimized; establish and prove the electrical state; control approach distance and the movement of conductive objects and plant; execute with qualified crews, suitable equipment and active supervision; and apply an independent energization/turnover gate. At every stage, assurance should ask for observable evidence that the critical control exists and is functioning. Configuration changes, crew changes, equipment changes, weather changes or altered work limits should trigger revalidation.

This approach places responsibility at the project-system level. Owners create outage and contractual conditions, engineers shape constructability and system interfaces, operators control switching, contractors control execution, and supervisors verify the point of work. When these roles are connected through explicit critical controls and stop-work authority, compliance requirements become an operational barrier system. That is the practical direction suggested by the severe-incident pathways analyzed in this study.

DECLARATIONS

Ethics approval and consent to participate

Not applicable. The study analyzed publicly available regulatory records and published literature and involved no interaction with human participants.

Consent for publication

Not applicable.

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Data availability

The case identifiers and source links used in the analysis are reported in Table 3 and the reference list. The analytical coding rules are described in the Methods and Appendix A.

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APPENDIX A. REPRODUCIBILITY AND CODING AUDIT TRAIL

Case identification: Search the OSHA Accident Report Detail/IMIS interface for NAICS 237130 and the study years 2019–2024; screen severe/fatal records for power-line/transmission/distribution construction relevance. The final analytic case identifiers are listed in Table 3. Because search interfaces and indexing can change, the case numbers—not search-result ranking—should be used for replication.

Primary control assignment rule: Assign the earliest verifiable barrier in the exposure pathway that could prevent the serious/fatal energy transfer without relying solely on worker reaction. Use isolation/de-energization when the work should be rendered electrically safe and the event involves contact with a conductor/equipment state; use MAD/cover-up/clearance when energized parts remain and a worker, plant or conductive object crosses the approach path; use grounding/bonding for induction/backfeed/current-path cases; use energized-work/arc-flash when the task is intentionally energized and shock/arc protection is the dominant pathway; use mechanical/rigging/equipment integrity for stored mechanical energy or equipment failure; use mobile plant/traffic for vehicle movement; and use fall/excavation/civil controls for those dominant hazards.

Multiple-control rule: Serious incidents generally involve several defenses. For descriptive counting, record only one primary family. Secondary contributors can be recorded narratively but should not be used to inflate frequency counts. If two controls are equally plausible and the narrative cannot distinguish them, flag the case as ambiguous rather than forcing a score. No such ambiguity was retained in the present final dataset.

Interpretation rule: Do not calculate incidence or compare fatality probabilities between control families using this sample. The database is not a denominator-based cohort and the inclusion process intentionally selects severe incidents with sufficient narrative detail. Counts are used to reveal recurrent pathways and to construct management controls, not to estimate population risk.

Framework validation: Future replication should employ at least two independent coders, prespecified inclusion criteria, blinded control-family assignment, agreement statistics, and prospective testing of whether field-verified critical-control indicators predict high-potential near misses or SIF events.

Table 1. Data extraction and coding framework.

Variable	Definition	Coding rule
Year / severity	Calendar year of event; fatal versus serious non-fatal	Directly transcribed from OSHA narrative/record.
Mechanism	Immediate physical event producing or nearly producing the injury	Coded as direct electrical contact/arc, mobile-equipment contact, conductive-material contact, arc/equipment failure, mechanical/rigging, vehicle/mobile plant, fall, excavation or related category.
Electrical-exposure pathway	Whether energized electrical energy or an electrical arc was integral to the event	Yes for direct contact/arc, line contact by mobile equipment or conductive material, and arc/equipment-failure events.
Primary critical-control family	Single control family most directly capable of interrupting the documented pathway before exposure	Assigned conservatively from narrative facts; not intended as a legal conclusion or attribution of personal blame.
Secondary contributors	Context such as supervision, PPE, traffic, equipment condition or work-interface issues	Used qualitatively in discussion; not numerically scored when the regulatory narrative did not support a reliable determination.
Project-level implication	Owner/contractor governance practice needed to make the critical control verifiable	Derived during cross-case synthesis and compared with standards and safety-management literature.

Table 2. Sample composition by year and outcome.

Year	Cases	Fatal	Serious non-fatal	Fatal share*
2019	10	4	6	40.0%
2020	5	3	2	60.0%
2021	5	4	1	80.0%
2022	2	2	0	100.0%
2023	5	5	0	100.0%
2024	4	4	0	100.0%
Total	31	22	9	71.0%

**Descriptive of the purposive severe-incident sample; not an annual industry fatality rate.*

Table 3. Incident-level archival coding matrix (31 OSHA investigations).

OSHA summary	Year	Outcome	Mechanism	Documented event pathway (condensed)	Primary critical-control family	Source
112598.015	2019	Serious non-fatal	Electrical contact/arc	Worker contact/exposure to energized high-voltage circuit	Isolation, de-energization & test-before-touch	[31]
113188.015	2019	Serious non-fatal	Struck-by conductor	Conductor twisted/released and struck worker during line work	Mechanical energy, rigging & equipment integrity	[32]
116866.015	2019	Fatal	Falling pole/load	Utility pole came off loader forks during handling	Mechanical energy, rigging & equipment integrity	[33]
117695.015	2019	Serious non-fatal	Electrical contact/arc	Guy wire contacted energized 14.4-kV equipment during placement	MAD, cover-up & conductive-object clearance	[34]
118062.015	2019	Fatal	Electrical contact/arc	Electrocution during work on utility-pole electrical equipment	Isolation, de-energization & test-before-touch	[35]
118136.015	2019	Fatal	Electrical contact/arc	Contact with 144-kV energized transmission conductor	Isolation, de-energization & test-before-touch	[36]
119728.015	2019	Serious non-fatal	Electrical contact/arc	Shock/burn during line-pulling activity with grounding/induction pathway	Grounding, bonding & induced-voltage control	[37]
121594.015	2019	Serious non-fatal	Arc flash	Arc-flash exposure during 7.2-kV underground connection work	Energized-work/arc-flash planning & PPE	[38]
121881.015	2019	Fatal	Electrical contact/arc	Contact with live high-powered wiring while preparing jumper	Isolation, de-energization & test-before-touch	[39]
122735.015	2019	Serious non-fatal	Mobile equipment contact	Bucket truck contacted 14.4-kV overhead line	MAD, cover-up & conductive-object clearance	[40]
123235.015	2020	Fatal	Arc/equipment failure	Insulator/equipment failure produced electrical arc during pole work	Mechanical energy, rigging & equipment integrity	[41]
125016.015	2020	Fatal	Caught/struck by equipment	Worker struck by boring/pipe-handling equipment	Mechanical energy, rigging & equipment integrity	[42]
127319.015	2020	Fatal	Vehicle struck-by	Worker conducting utility-pole inspection struck by road vehicle	Mobile plant, traffic & exclusion zones	[43]
127611.015	2020	Serious non-fatal	Falling/shifted load	Pipe/load shifted during handling and injured worker	Mechanical energy, rigging & equipment integrity	[44]
134216.015	2020	Serious non-fatal	Fall from height	Worker fell through roof during utility-pole related work	Fall, excavation & civil-work critical controls	[45]
132686.015	2021	Fatal	Caught-between equipment	Personnel-basket/crane control malfunction crushed worker against structure	Mechanical energy, rigging & equipment integrity	[46]
133641.015	2021	Serious non-fatal	Vehicle caught-between	Worker caught between boom-truck components during backing/movement	Mobile plant, traffic & exclusion zones	[47]
136491.015	2021	Fatal	Electrical contact/arc	New transmission-line work contacted existing energized line	Isolation, de-energization & test-before-touch	[48]
136983.015	2021	Fatal	Electrical contact/arc	Contact while transferring existing energized transmission conductors	Isolation, de-energization & test-before-touch	[49]
137781.015	2021	Fatal	Electrical contact/arc	Contact during disconnection/work on 23-kV overhead line	Isolation, de-energization & test-before-touch	[50]
145638.015	2022	Fatal	Trench collapse	Worker killed in trench collapse during underground utility work	Fall, excavation & civil-work critical controls	[51]
145779.015	2022	Fatal	Electrical contact/arc	Guy wire contacted energized line during tensioning/structure movement	MAD, cover-up & conductive-object clearance	[52]
157346.015	2023	Fatal	Mobile equipment contact	Aerial-lift basket contacted energized power line during repositioning	MAD, cover-up & conductive-object clearance	[53]
158252.015	2023	Fatal	Electrical contact/arc	Lineman contacted energized 7.2-kV phase from bucket; PPE absent	Energized-work/arc-flash planning & PPE	[54]
158302.015	2023	Fatal	Electrical contact/arc	Ground wire contact created phase-to-ground current path through worker	Grounding, bonding & induced-voltage control	[55]
159708.015	2023	Fatal	Conductive material contact	Conductive tracer/material contacted 7.2-kV overhead line	MAD, cover-up & conductive-object clearance	[56]
160027.015	2023	Fatal	Electrical contact/arc	Energized pole work during cutout/riser activity resulted in electrocution	Isolation, de-energization & test-before-touch	[57]
165589.015	2024	Fatal	Conductive material contact	Steel support truss carried vertically contacted live overhead line	MAD, cover-up & conductive-object clearance	[58]
166277.015	2024	Fatal	Mobile equipment contact	Bucket-truck boom contacted energized overhead conductors	MAD, cover-up & conductive-object clearance	[59]
168353.015	2024	Fatal	Electrical contact/arc	Reconductoring near energized conductor without insulating hose/cover	MAD, cover-up & conductive-object clearance	[60]
172445.015	2024	Fatal	Vehicle struck-by	Worker run over by haulage truck during underground power-line work	Mobile plant, traffic & exclusion zones	[61]

Note: Event pathways are concise paraphrases of public OSHA Accident Report Detail narratives. Primary control families are researcher-coded analytical constructs, not OSHA findings.

Table 4. Aggregated mechanism distribution.

Mechanism group	Cases	Fatal	Serious non-fatal	Share of sample
Direct electrical contact / arc	14	11	3	45.2%
Mobile equipment to line	3	2	1	9.7%
Conductive material to line	2	2	0	6.5%
Arc/equipment failure or arc flash	2	1	1	6.5%
Mechanical / rigging / caught-struck	5	3	2	16.1%
Road vehicle / mobile plant struck-caught	3	2	1	9.7%
Fall / excavation	2	1	1	6.5%

Table 5. Critical-control families, recurrent challenges and practical verification evidence.

Critical-control family	Cases	Fatal	Recurrent challenge	Practical solution	Observable verification evidence
Isolation, de-energization & test-before-touch	8	7	Uncertain or changing system state; work close to existing energized circuits; assumptions based on switching paperwork alone.	Plan outages early; establish switching/clearance authority; identify every source including backfeed; lock/tag where applicable; prove absence of voltage with correctly rated test equipment; define re-energization authority.	Current one-line; approved switching order; clearance/permit ID; test-before-touch record or observed verification; controlled cancellation/release.
MAD, cover-up & conductive-object clearance	8	6	Workers, booms, guy wires, steel, ropes or other conductive objects can bridge the approach distance.	Calculate voltage-specific MAD; physically mark boundaries where practicable; install insulating cover-up by qualified personnel; use dedicated spotters for plant; control material orientation and handling path.	MAD documented for system voltage/altitude; boundary visible; cover-up inspected; spotter assigned; lift/material path reviewed at point of work.
Mechanical energy, rigging & equipment integrity	6	4	Pole/conductor tension, suspended loads, pinch points and equipment failures coexist with electrical work.	Engineered lift/stringing plan; rated rigging; exclusion zones; stored-energy release plan; pre-use mechanical inspection; fail-safe/emergency controls tested.	Lift/stringing plan approved; rigging certificates; exclusion-zone check; equipment inspection; emergency-stop/control function check.
Mobile plant, traffic & exclusion zones	3	2	Vehicle reversing, road traffic and plant movement create SIF exposure independent of electricity.	Traffic management plan; physical segregation; banksman/spotter; reversing controls; defined pedestrian routes; high-visibility work zones and lighting.	Traffic plan current; barriers/cones installed; spotter in position; reversing alarm/camera check; pre-start exclusion-zone verification.
Grounding, bonding & induced-voltage control	2	1	Nominally de-energized conductors can become energized through induction, backfeed or contact.	Engineering study where induction is credible; equipotential work zone; visible temporary protective grounds; bonding sequence; test before grounds are applied/removed.	Grounding plan; ground locations and ratings; visible ground count; continuity/bonding verification; controlled ground-removal register.
Energized-work/arc-flash planning & PPE	2	1	Energized work may be undertaken without a sufficiently specific justification, boundary or protection system.	Document why energized work is necessary; task-specific energized-work permit where required; shock and arc-flash assessment; insulated tools, rubber goods and arc-rated PPE; rescue plan.	Authorized permit; task/voltage match; PPE and rubber-goods test dates; tool inspection; rescue equipment and trained standby personnel.
Fall, excavation & civil-work critical controls	2	1	Line work includes roofs, poles, trenches, foundations and access works that can generate non-electrical fatal hazards.	Fall-protection plan and compatible anchorage; excavation protective system; competent-person inspection; underground-service locating; safe access/egress.	Harness/anchor compatibility verified; excavation inspection; shoring/shielding/sloping evidence; access ladder; service locate/permit.

Table 6. Proposed high-voltage construction critical-control assurance dashboard.

Control	Leading indicator / evidence	Expected criterion	Verification method	Escalation if absent
Energy-state control	% of high-voltage work packages with current one-line, approved switching/clearance, identified sources and point-of-work test method	100% before release	Work-package audit + field observation	Immediate stop; re-establish system state and authorization
Test-before-touch	Observed confirmation that correctly rated test equipment was proved, used and re-proved where required	100% of applicable tasks	Supervisor critical-control observation	Stop work; repeat verification and investigate why proof was absent
Grounding/bonding	Temporary grounds installed at approved locations, visible/accounted for, and controlled through removal register	100% when required	Grounding register + field count	Stop work/energization; reconcile grounds
MAD / cover-up	Correct MAD documented and physically maintained; insulating cover-up and barriers match task	100% of energized-exposure tasks	Point-of-work check	Withdraw from boundary; reconfigure work zone
Plant / material clearance	Boom/material swept path reviewed; spotter and exclusion controls in place	100% of applicable movements	Pre-move check + observation	Freeze movement; redesign path/boundary
Mechanical / rigging integrity	Lift/stringing plan current; rigging and critical equipment inspection valid	100% of critical lifts/stringing operations	Plan review + pre-use inspection	Remove equipment/rigging from service; re-plan
Contractor competence	Qualified-person/authorized-person requirements matched to task and voltage	100%	Competency matrix / authorization list	Replace or directly supervise worker; suspend task if competence unavailable
Safety-critical NCRs	Age and closure status of defects that can affect SIF controls or energization safety	Zero overdue before energization	NCR register	Escalate to project director; block energization
Change-trigger revalidation	Jobs re-briefed/re-authorized after configuration, crew, equipment, weather or work-limit change	100% of triggered changes	Field change log / permit revalidation	Pause work; re-brief and re-verify controls
Energization readiness	Formal gate passed with drawings, protection tests, temporary-ground reconciliation and operational handover	100%	Independent energization checklist	No energization until evidence complete

APPENDIX B. SUGGESTED HIGH-VOLTAGE PRE-TASK CRITICAL-CONTROL CHECK

Table B1. Field-ready critical-control check for high-voltage construction tasks.

Question area	Critical question	Minimum evidence
System state	Is the exact equipment/conductor identified and does the current field condition match the controlled one-line and switching package?	Current drawing + equipment ID + responsible switching authority
Isolation / clearance	Are all sources, including backfeed and induced sources, addressed and is the clearance/permit valid for this crew and work limit?	Isolation points + permit/clearance + lock/tag where applicable
Absence of voltage	Has an appropriately rated tester been proved, used at the point of work, and re-proved in accordance with the method?	Observed test-before-touch
Grounding / equipotential zone	Are temporary protective grounds/bonds installed at the engineered locations and accounted for?	Ground plan + visible ground count
Approach distance	What is the applicable MAD and how is it physically maintained for workers, tools, materials and plant?	Calculated distance + marked boundary/spotter
Cover-up / insulation	Are exposed energized parts that could be contacted protected with suitable inspected cover-up?	Installed and inspected insulating protective equipment
Plant / material movement	Can any boom, load, wire, pole, truss, rope or tool enter the energized zone through rotation, sag, swing or failure?	Swept-path review + exclusion zone + spotter
Mechanical energy	Are conductor tension, suspended loads, pinch points and equipment failure modes controlled?	Rigging/stringing plan + inspection + exclusion
Competence / roles	Are qualified persons, spotters, switching authority and emergency/rescue roles named and present?	Competency/authorization + role assignment
Change triggers	What conditions require immediate stop and revalidation?	Predefined triggers: system/crew/equipment/weather/work-limit change
Energization	Who alone can release the system for energization, and how are temporary grounds, permits and personnel reconciled first?	Energization gate + sign-off + ground/permit reconciliation

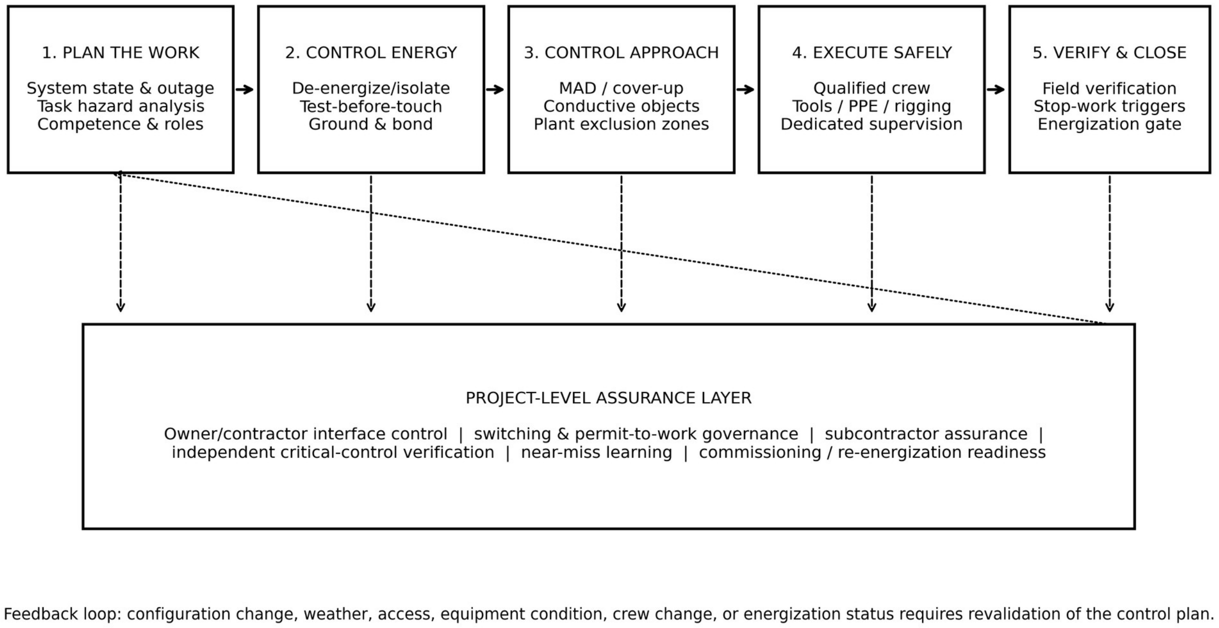

Figure 1. High-Voltage Construction Critical-Control Framework (HV-CCF). The model treats electrical and non-electrical SIF controls as an integrated barrier system, with project-level governance supporting point-of-work verification.

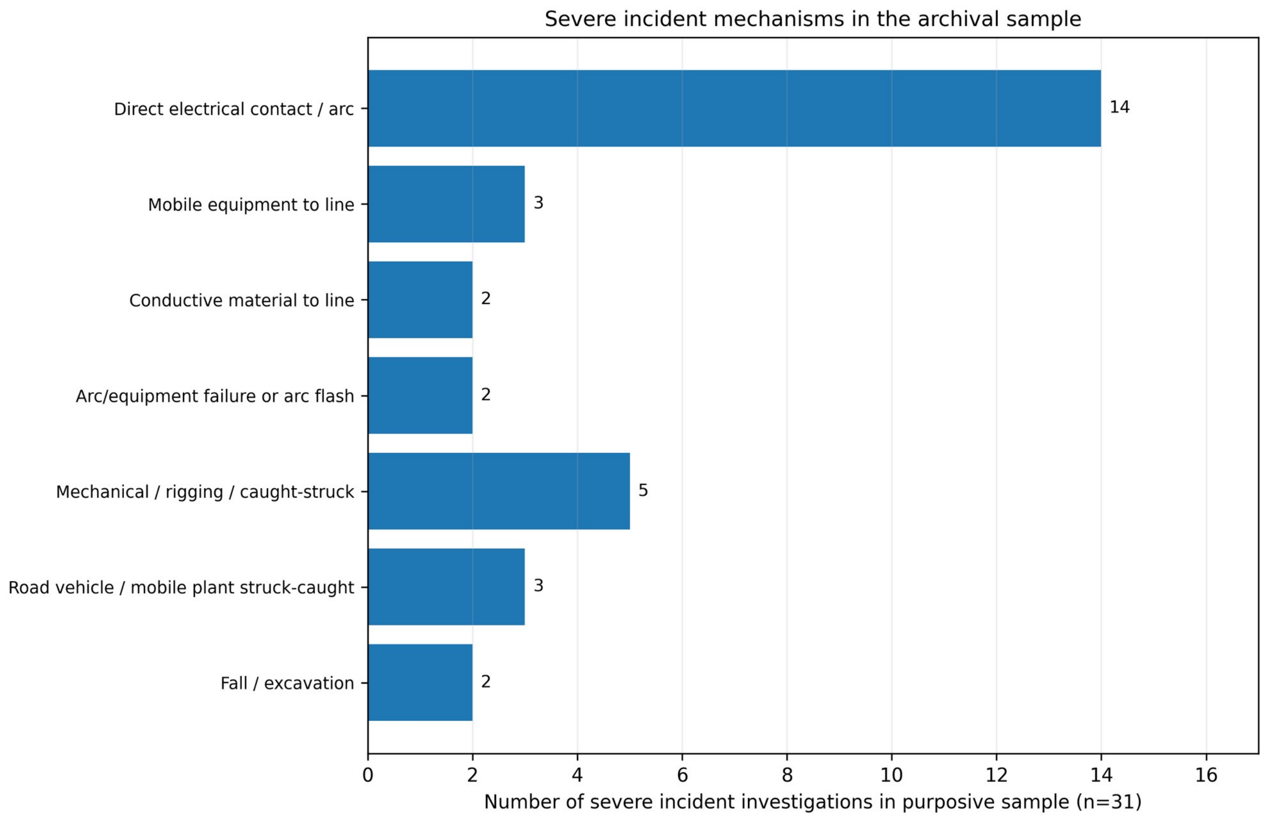

Figure 2. Distribution of severe incident mechanisms in the purposive 31-case archival sample. Categories were aggregated for readability; counts are descriptive and are not incidence rates.

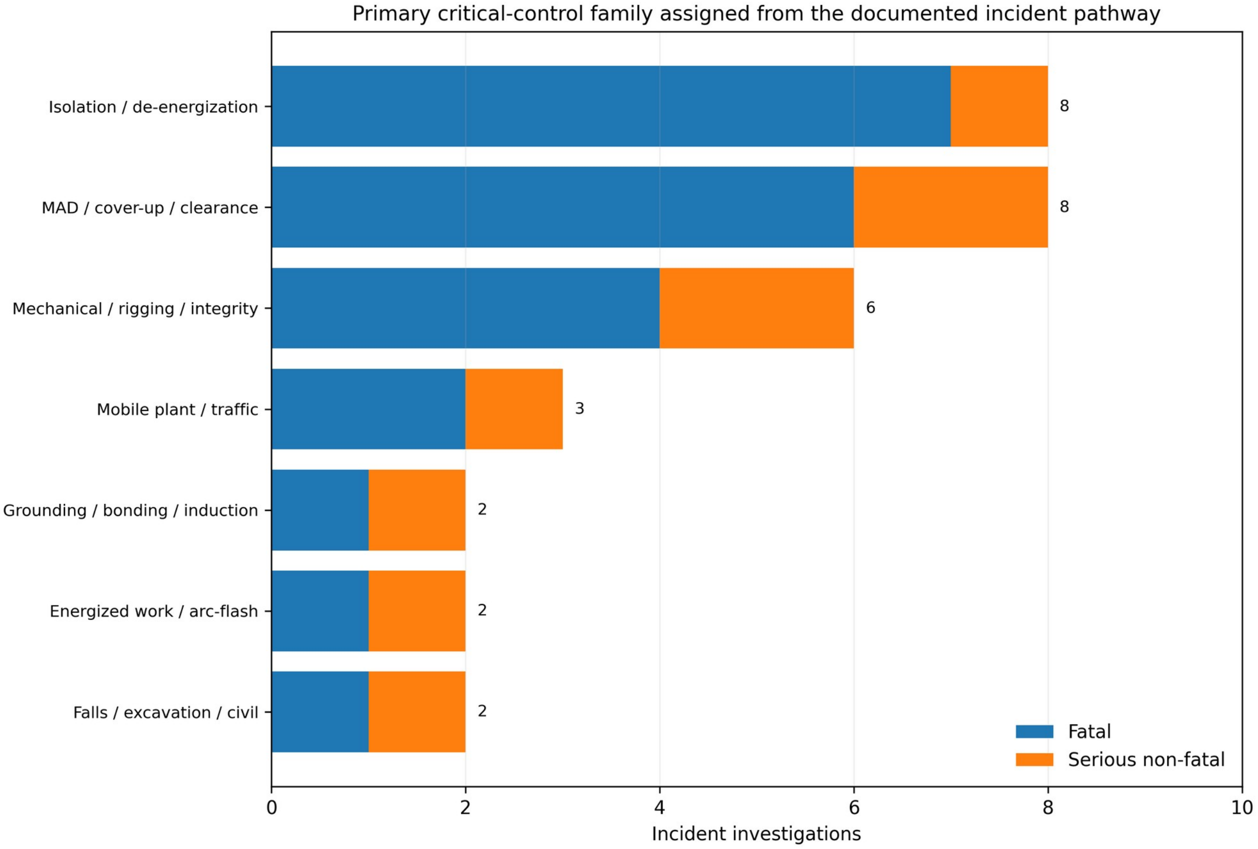

Figure 3. Primary critical-control family by outcome. A single primary family was assigned per case to prevent double counting. Fatal/non-fatal proportions must not be interpreted as comparative risk because the sample was purposively selected.

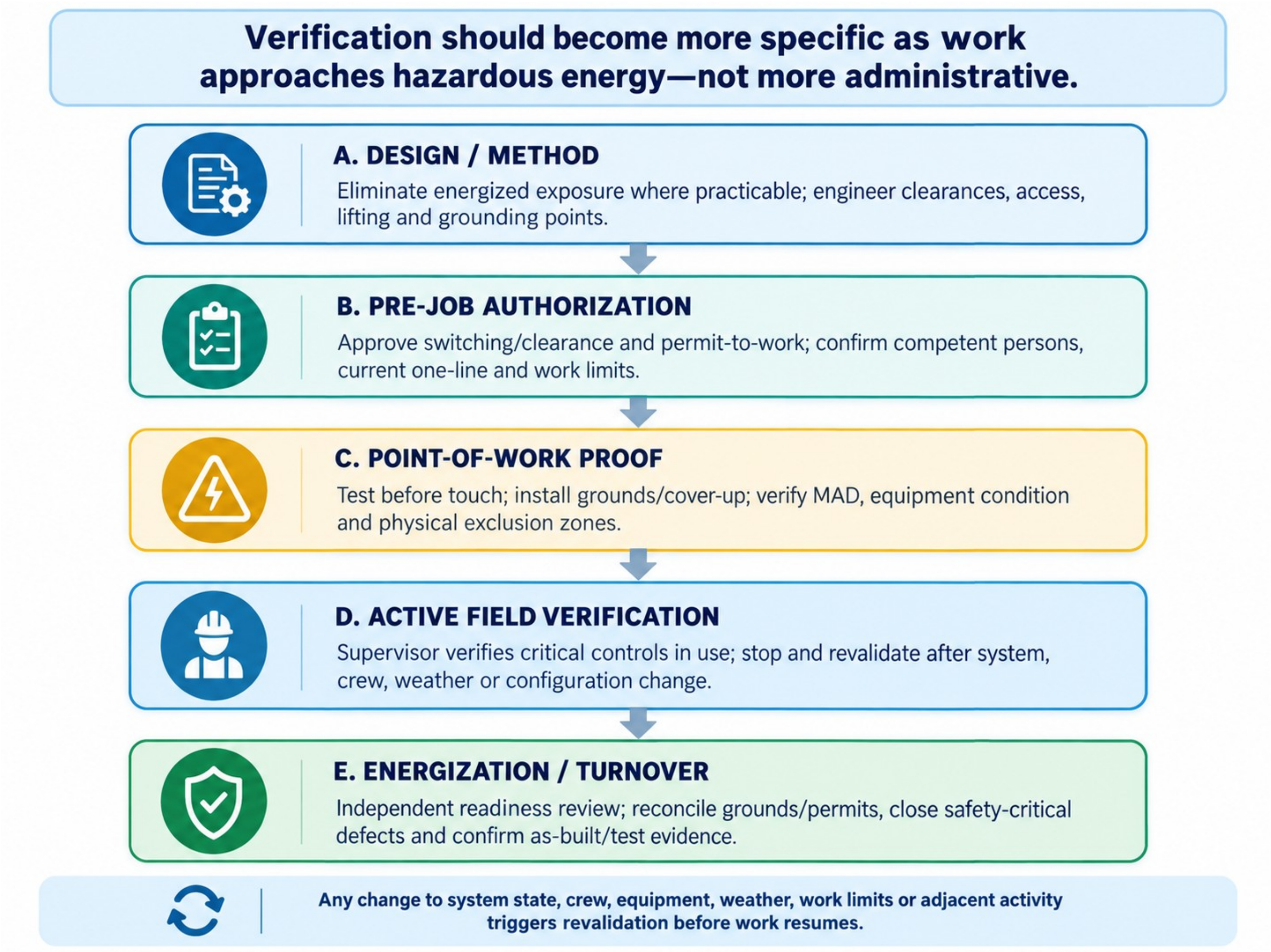

Figure 4. Critical-control verification ladder. Evidence becomes more specific as work approaches hazardous energy; changes in configuration or work conditions trigger revalidation.

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