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Environmental and Occupational Health Risks Associated with Oil and Gas Drilling Operations: A Review of Exposure Pathways, Toxicological Impacts, and Mitigation Strategies

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Abstract

Oil and gas drilling is among the most hazard dense industrial activities in the world, combining heavy mechanical energy, high pressure fluids, complex chemical mixtures, and remote or offshore working environments. This review synthesises the current evidence on the environmental and occupational health risks generated across the full drilling life cycle, from site preparation and spudding through well completion, production, workover and decommissioning. Three questions organise the review: by what pathways do hazardous agents reach workers and surrounding populations, what toxicological and health outcomes are associated with those exposures, and which mitigation strategies are supported by evidence. The principal exposure pathways identified are inhalation of volatile organic compounds, respirable crystalline silica, diesel particulate matter, hydrogen sulphide and secondary ozone; dermal and inadvertent ingestion contact with drilling fluids, produced water and crude; contamination of groundwater and surface water through spills, faulty well integrity, pit leakage and inadequate wastewater handling; soil and sediment loading with hydrocarbons, heavy metals and naturally occurring radioactive material; and physical agents including noise, whole body vibration, thermal extremes and ionising radiation from logging sources. Toxicological evidence links benzene exposure to haematotoxicity and acute myeloid leukaemia, polycyclic aromatic hydrocarbons to genotoxic and carcinogenic effects, crystalline silica to silicosis and lung cancer, hydrogen sulphide to acute neurotoxic and lethal outcomes at high concentration, and mixed hydrocarbon exposure to respiratory, reproductive, neurological and cardiovascular endpoints. Community epidemiological studies, particularly those examining residential proximity to well pads, report associations with adverse birth outcomes, asthma exacerbation and cardiovascular hospitalisation, although exposure misclassification and confounding remain important limitations. Mitigation is most effective when ordered by the hierarchy of controls: substitution of hazardous additives and transition to non diesel power and water based or synthetic fluids; engineering controls such as closed loop solids control, vapour recovery, green completions, dust suppression at sand transfer points, and robust well barrier design; administrative measures including hot work and confined space permits, fatigue management and competence assurance; and personal protective equipment as the final layer. Medical surveillance, real time area and personal monitoring, leak detection and repair programmes, setback distances and transparent chemical disclosure complete a defensible risk management system. The review concludes that technical controls are largely known but unevenly implemented, that the global evidence base is skewed towards North America while major producing regions such as the Niger Delta remain under studied, and that integrated exposure assessment combining personal monitoring, biomarkers and spatial modelling is the priority for future research.

Keywords: oil and gas drilling; occupational exposure; exposure pathways; benzene; respirable crystalline silica; hydrogen sulphide; produced water; hierarchy of controls; environmental health; risk mitigation.

1. Introduction

Hydrocarbon extraction remains the backbone of global primary energy supply, and the drilling of wells is the operation through which that supply is first physically accessed. Drilling concentrates, in a small geographical footprint and a compressed time window, an unusually wide range of hazards: rotating machinery operating under high torque, pressurised fluid systems, hydrocarbon gases at explosive concentrations, chemically complex additive packages, fine mineral dusts, diesel combustion products, continuous high noise, and in many cases extreme climatic conditions or an offshore setting in which escape and rescue are constrained. The people exposed are not only the drilling crew. Service company personnel, transport drivers, catering and camp staff, nearby agricultural communities, fishing populations and urban residents in areas of unconventional development all occupy positions along the exposure continuum.

The health significance of these operations has been reframed over the past two decades by two developments. The first is the expansion of unconventional resource development, in which horizontal drilling and high volume hydraulic fracturing have moved well pads into densely settled landscapes and introduced new hazards such as large scale proppant sand handling and high volume flowback management. The second is the maturation of exposure science, which has replaced reliance on a small number of regulated contaminants with the capacity to characterise complex mixtures, short duration peak exposures and low level chronic community exposures. Together these have generated a substantial but fragmented literature spanning industrial hygiene, environmental epidemiology, toxicology, engineering and regulatory policy.

This review draws those strands together. Its purpose is threefold. First, it maps the exposure pathways through which hazardous agents generated by drilling reach human receptors, distinguishing occupational from environmental routes while recognising that they frequently overlap. Second, it summarises the toxicological and epidemiological evidence for the health effects associated with the principal agents, giving particular attention to those with well characterised dose response relationships and to those where the mixture rather than the single compound is the relevant exposure unit. Third, it evaluates mitigation strategies against the hierarchy of controls, identifying which interventions are supported by exposure reduction data and which remain largely aspirational.

The scope covers onshore and offshore drilling of both conventional and unconventional reservoirs, and includes the activities immediately contiguous with drilling, namely site preparation, completion, workover and well abandonment, because exposures do not respect the administrative boundaries of a drilling contract. Refining, petrochemical manufacture, long distance pipeline transport and retail distribution are outside the scope except where they illuminate a drilling related pathway. Geographically, the review attempts to balance the dominant North American literature with evidence from West Africa, the Middle East, Latin America, Central Asia and the North Sea, while acknowledging that the published record is markedly uneven.

2. Research Method

2.1. Review design

This paper is a structured narrative review rather than a systematic review or meta analysis. The choice is deliberate and follows from the nature of the question. The evidence relevant to drilling related health risk is distributed across industrial hygiene, toxicology, environmental epidemiology, process safety engineering, asset integrity management, public health informatics and regulatory policy, and these literatures use incompatible designs, exposure metrics and outcome definitions. A quantitative synthesis across them would impose a false commensurability. A structured narrative synthesis, organised around an explicit analytical framework and transparent about how sources were selected, is the appropriate method where the objective is integration across disciplines rather than pooled effect estimation.

The review nonetheless borrows procedural discipline from systematic methods. Selection criteria were defined in advance, sources were organised by theme before interpretation, and the synthesis proceeds from a stated framework rather than from the order in which material was encountered.

2.2. Analytical framework

The organising framework is the source, pathway, receptor and control model familiar from environmental risk assessment, extended in two directions. First, the receptor is treated as dual, comprising both the occupational receptor inside the site boundary and the community receptor outside it, since the same source population of contaminants serves both and the controls that protect one frequently protect the other. Second, the control element is stratified by the hierarchy of controls, so that interventions are assessed by reliability rather than by cost or ease of adoption.

Each body of literature reviewed was interrogated against the same four questions: what agent or condition does it concern, by what mechanism does that agent reach a human receptor, what health outcome is associated with the resulting exposure, and at what point in the hierarchy can the pathway be interrupted. This framework is what permits engineering literatures on corrosion, procurement or control system security to be integrated with clinical and toxicological evidence, because each is evaluated by its position in the same causal chain.

2.3. Source identification and selection

Sources were drawn from three streams. The first comprises peer reviewed primary studies, authoritative toxicological profiles and monographs, and regulatory and intergovernmental technical reports addressing the health effects of hydrocarbon extraction. The second comprises applied engineering and management research on process safety, asset integrity, occupational safety management systems, flare reduction, produced water treatment and related operational domains. The third comprises research on the supporting systems that determine whether controls are implemented and whether their failure is detected, including procurement and supply chain assurance, health service and diagnostic infrastructure, public health surveillance, regulatory oversight models, and the security of instrumented safety systems.

Within these streams, material was selected on relevance to at least one element of the analytical framework. Inclusion required that a source address an agent, pathway, outcome, control or enabling system with a demonstrable link to drilling or to an operation sufficiently analogous that transfer of method is defensible. Where an adjacent literature was admitted on

the basis of methodological transfer rather than direct subject matter, the basis for that transfer is stated explicitly in the text rather than left implied.

Exclusion criteria were applied in three respects. Sources addressing refining, petrochemical manufacture, long distance transmission or retail distribution were excluded except where they illuminate a drilling related pathway. Sources whose subject matter bore no defensible relation to any element of the framework were excluded irrespective of availability. Publications dated after 2022 were excluded, which fixes the evidence horizon of this review and should be borne in mind when interpreting claims about current practice, since both the technical and regulatory landscapes have continued to develop.

2.4. Synthesis procedure

Selected material was grouped by framework element, then examined for convergence, divergence and gaps. Convergent findings across independent literatures were treated as the strongest basis for conclusions. Divergence was retained and reported rather than resolved by preference, particularly in the epidemiological material where exposure misclassification and confounding produce genuine interpretive disagreement. Gaps were recorded as they emerged and are reported in Subsection 3.15. Findings were then mapped back onto the hierarchy of controls to produce the integrated conceptual model presented in Subsection 3.11.

3. Results and Discussion

This section presents the results of the synthesis together with their interpretation, organised by framework element. Subsections 3.1 to 3.4 report what the evidence shows about source, pathway and outcome, namely the processes that generate hazardous agents, the routes by which those agents reach receptors, and the toxicological and epidemiological consequences. Subsections 3.5 and 3.6 report the assessment methods and control strategies available. Subsections 3.7 to 3.10 report on the organisational, technical and institutional systems on which control depends. Subsection 3.11 integrates these results into a conceptual model, 3.12 draws out the cross cutting findings, and 3.13 to 3.15 set out the implications, the limitations of the review and the resulting research priorities.

3.1. Drilling Operations and Their Hazard Generating Processes

A clear account of exposure requires a clear account of process. Hazardous agents are not released uniformly across a drilling campaign; they are generated by specific unit operations, at specific times, in specific locations on the pad or rig. Mapping agents to operations is therefore the first analytical step in both exposure assessment and control design.

Site preparation and civil works

Land clearing, earthworks, access road construction and pad levelling generate fugitive dust, destroy vegetation and topsoil structure, alter surface drainage and increase sediment delivery to nearby watercourses. In forested, mangrove or wetland settings, habitat fragmentation and hydrological disturbance may be the most ecologically consequential impacts of the entire project, and they occur before a single metre of hole is drilled. Occupational hazards at this stage are those of heavy civil construction: vehicle and plant interactions, struck by events, noise, vibration and silica bearing dust from aggregate handling.

Drilling phase

Once spudded, the well is advanced using a circulating drilling fluid system. The fluid, whether water based, oil based or synthetic, performs hole cleaning, pressure control, lubrication, cooling and formation stabilisation. It is also the dominant chemical reservoir on site. Water

based muds contain barite, bentonite, polymers, lubricants, corrosion inhibitors, biocides, defoamers and pH control agents. Oil based and synthetic based muds add a continuous hydrocarbon phase, historically diesel and more recently low toxicity mineral oils, olefins or esters, which substantially increases the volatile organic compound inventory and the dermal hazard.

Return fluid carries drilled cuttings to surface, where shale shakers, desanders, desilters and centrifuges separate solids. The shaker house is consistently identified in industrial hygiene surveys as a zone of elevated exposure to hydrocarbon vapour, mist and, where formations are sour, hydrogen sulphide. Mud mixing and additive handling, typically performed manually from sacks or totes, produce peak inhalation and dermal exposures that mean shift averaged sampling tends to understate. Barite, the principal weighting agent, has historically contained variable quantities of crystalline silica and trace metals including lead, mercury, arsenic, cadmium and chromium.

Power generation and mechanical drive are predominantly diesel based, releasing nitrogen oxides, carbon monoxide, sulphur dioxide, elemental and organic carbon particulate and a suite of polycyclic aromatic hydrocarbons. Cementing operations introduce silica flour, Portland cement dust with its alkaline and hexavalent chromium content, and a range of retarders, accelerators and fluid loss additives. Wireline logging introduces sealed radioactive sources, typically caesium 137, americium beryllium or californium 252, with attendant transport, handling and source loss risks.

Well completion and hydraulic fracturing

Completion operations include perforating, stimulation and the installation of production tubing. In unconventional development the dominant hazard profile is created by high volume hydraulic fracturing. Several million litres of water, proppant sand and a chemical package typically comprising friction reducers, gelling agents, crosslinkers, breakers, biocides, scale and corrosion inhibitors, surfactants and acids are injected at high pressure. The proppant handling train, involving pneumatic transfer from sand trucks to on site storage and blending equipment, is a well documented source of respirable crystalline silica, with personal samples in published surveys frequently exceeding occupational exposure limits by substantial multiples.

Flowback, the return of injected fluid mixed with formation water after stimulation, carries dissolved hydrocarbons, high total dissolved solids, metals, radium isotopes and residual additives. Flowback tank gauging, in which workers open hatches on the top of storage tanks to measure fluid level manually, has been associated with short duration exposures to hydrocarbon vapour at concentrations capable of causing acute central nervous system depression, cardiac sensitisation and oxygen displacement. A number of sudden worker deaths at open tank hatches have been attributed to this activity.

Reservoir context and asset maturity

The hazard profile of a drilling campaign is partly determined by the reservoir and the stage of the asset life cycle. Forecasting of long term production from multimodal subsurface data, and the redevelopment of mature asset portfolios in which infill drilling, workover and enhanced recovery dominate activity, both shape the frequency of well entry, the composition of produced fluids and the condition of surface equipment through which those fluids pass (Nwangwu & Onwumere, 2020; Nwangwu et al., 2022).

Mature fields matter disproportionately for health risk. Produced water cut rises with field age, the proportion of corroded and scaled equipment increases, naturally occurring radioactive

material accumulates in surface facilities, and workover frequency rises, so that an ageing asset generates more worker contact with contaminated fluids and solids per barrel produced than a new one. Asset maturity is therefore a legitimate input to occupational health planning rather than a purely commercial variable.

Production, workover and decommissioning

Routine production introduces fugitive emissions from valves, flanges, seals, connectors, separators, compressors, dehydrators and storage tanks; pneumatic controller venting; flaring and venting of associated gas; and periodic well maintenance. Workovers reopen the pressure envelope and reintroduce drilling phase hazards. Plugging and abandonment, if performed to an inadequate standard, leaves a legacy pathway for the migration of methane and brine into shallow aquifers that may persist for decades. Orphaned and improperly abandoned wells have emerged as a significant source of both greenhouse gas emissions and localised groundwater contamination.

3.2. Exposure Pathways

Exposure pathway analysis links a source to a receptor through a release mechanism, an environmental transport medium, a point of contact and a route of entry. A pathway is complete, and therefore of concern, only when all elements are present. The pathways below are organised by medium, with occupational and community receptors treated together where the medium is shared.

Atmospheric pathway

Inhalation is the dominant route of exposure for both workers and neighbouring communities. The atmospheric burden from a drilling site is a mixture rather than a single contaminant, and its composition shifts with operational phase.

- Volatile organic compounds, principally benzene, toluene, ethylbenzene and xylenes, together with n hexane and light alkanes, released from drilling fluid returns, open tanks, flowback, separators, well venting and fugitive leaks.
- Respirable crystalline silica from proppant transfer, silica flour used in cementing and thermal recovery, dry additive handling and unpaved road traffic.
- Diesel particulate matter, nitrogen oxides, carbon monoxide and sulphur dioxide from rig engines, generators, pumps, compressors and the heavy truck traffic associated with water, sand and waste logistics.
- Hydrogen sulphide from sour formations, degraded drilling fluids, stagnant produced water and sulphate reducing bacterial activity in tanks and pits.
- Secondary ozone formed photochemically from volatile organic compound and nitrogen oxide precursors, notable in basins where winter ozone episodes have been documented at concentrations comparable to major urban areas.
- Products of incomplete combustion from flaring, including polycyclic aromatic hydrocarbons, black carbon and, where flare efficiency is poor, unburnt methane and volatile organic compounds.

Dispersion from a well pad is governed by source height, emission temperature, terrain and meteorology. Low level, ambient temperature fugitive releases, which characterise tank hatches and equipment leaks, disperse poorly and can produce elevated ground level concentrations close to the source, which is the physical basis for setback regulation.

Atmospheric transport also returns contaminants to surface via wet and dry deposition, linking the air pathway to soil and water pathways.

Water pathway

Water contamination arises through several distinct mechanisms, which are frequently conflated in public debate but have different probabilities and different controls.

- Surface spills and releases of drilling fluid, flowback, produced water, fuel and chemical additives during transfer, storage and transport. Analyses of state level incident data indicate that surface handling, rather than subsurface migration, accounts for the majority of documented water contamination events.
- Loss of well integrity through inadequate cement placement, casing corrosion, annular channelling or sustained casing pressure, permitting gas and fluid migration into shallow aquifers.
- Leakage from unlined or poorly lined reserve pits and earthen impoundments used for cuttings and fluid storage, a pathway of particular importance in jurisdictions with weak pit standards.
- Inadequate treatment or disposal of produced water, including discharge to surface water, application to roads for dust suppression or de icing, and injection into poorly characterised disposal zones.
- Stormwater runoff from disturbed pads carrying sediment, hydrocarbons and salts to adjacent watercourses.

Produced water deserves specific attention because of its volume and complexity. It is typically hypersaline, with total dissolved solids that may exceed seawater by an order of magnitude, and it carries dissolved hydrocarbons, organic acids, ammonia, boron, bromide, heavy metals and naturally occurring radioactive material, principally radium 226 and radium 228. Bromide loading is of secondary concern because it promotes formation of brominated disinfection by products in downstream drinking water treatment. The human receptor pathway is completed through drinking water abstraction from affected aquifers or surface waters, consumption of fish and crops from contaminated systems, and dermal contact during bathing, fishing and agriculture.

Because produced water is the largest volume waste stream in the industry, its management determines the magnitude of this pathway. Life cycle risk assessment of offshore produced water handling, integrated physicochemical and biological treatment trains suited to arid and water scarce settings, decentralised treatment designs for remote assets where centralised infrastructure is absent, resource recovery and beneficial reuse pathways that convert a disposal liability into an input, and data driven optimisation of treatment plant performance together define the current technical repertoire (Falegan & Aniebonam, 2022).

Soil, sediment and food chain pathway

Soil contamination results from spills, cuttings disposal, pit closure practices that bury untreated waste in place, flare related deposition and road spreading of produced water. Total petroleum hydrocarbons, polycyclic aromatic hydrocarbons, barium, chromium, lead, zinc, arsenic and salts are the characteristic contaminants. Elevated salinity and hydrocarbon loading degrade soil structure, suppress microbial activity and reduce agricultural productivity, which converts an environmental impact into a livelihood and food security impact. Hydrophobic contaminants partition to sediment in aquatic systems, where they enter benthic food webs and bioaccumulate. In fishing and subsistence farming communities, dietary intake of contaminated

fish, shellfish and produce can be a dominant exposure route, exceeding inhalation for persistent compounds. Children are additionally exposed through incidental soil ingestion and hand to mouth behaviour.

The receptor at the end of this pathway is usually an agricultural household, so the consequences are economic as well as toxicological. Research on climate smart practice and household food security, on socioeconomic barriers to technology adoption among smallholders, on rural innovation and extension services, on digital tools and market access in agrarian economies, on gender inclusion across agricultural value chains, and on geostatistical assessment of soils under cultivation in southwestern Nigeria describes the systems that contamination disrupts and the data infrastructure through which disruption can be measured (Bello et al., 2022; Michael & Ogunsola, 2019a; Michael & Ogunsola, 2019b; Michael & Ogunsola, 2021a; Michael & Ogunsola, 2021b; Michael & Ogunsola, 2021c; Michael & Ogunsola, 2021d; Michael & Ogunsola, 2021e; Michael & Ogunsola, 2022a; Michael & Ogunsola, 2022b).

Livestock are both a receptor and a sentinel. Work on ruminant and poultry nutrition, feed quality and performance provides the baseline against which contamination related effects on animal health and productivity in affected communities would have to be judged (Aye & Tawose, 2015; Aye & Tawose, 2016; Ekeocha et al., 2021).

Dermal and inadvertent ingestion pathways

Skin contact is an under recognised occupational route. Drilling fluids, particularly oil based and synthetic based systems, defat the skin and facilitate percutaneous absorption of hydrocarbons and additives. Contact occurs during mud mixing, equipment handling, sample collection at the shakers, maintenance work and cleaning of tanks and pits. Occupational dermatoses, including irritant and allergic contact dermatitis and oil folliculitis, are among the more frequently reported health complaints in drilling populations. Inadvertent ingestion follows from contaminated hands, gloves, food and tobacco on site, and is amplified where welfare facilities and hygiene discipline are inadequate.

Physical agent pathways

Physical hazards do not require a chemical transport medium but constitute exposure pathways in their own right.

- **Noise:** drilling floors, mud pumps, generators, compressors, pressure pumping spreads and flare stacks produce sustained levels commonly in the range of 85 to 105 A weighted decibels, with impulsive peaks from pipe handling.
- Whole body and hand arm vibration from heavy plant, vehicles and power tools.
- Ionising radiation from wireline logging sources, from naturally occurring radioactive material scale in tubulars, separators and tanks, and from industrial radiography during fabrication and inspection.
- Thermal stress, encompassing heat strain in desert and tropical operations and cold injury in arctic and offshore winter conditions, aggravated by impermeable protective clothing.
- Mechanical and energy hazards including dropped objects, pinch points on the drill floor, high pressure fluid injection injury, stored energy release, and fire and explosion from hydrocarbon ignition.

- Psychosocial and organisational hazards arising from extended shift rosters, long rotations away from family, isolation, fatigue, production pressure and job insecurity, which contribute both to mental health outcomes and to error related injury.

Table 1 – Principal hazardous agents in drilling operations, generating activities, environmental media and routes of human exposure.

Agent or agent group	Principal generating activity	Transport medium	Route and receptor
Benzene, toluene, ethylbenzene, xylenes	Mud returns, shaker house, tank gauging, flowback, fugitive leaks, venting	Air	Inhalation by crew and nearby residents; dermal absorption from fluids
Respirable crystalline silica	Proppant transfer and blending, silica flour in cement, dry additive handling, unpaved roads	Air	Inhalation by pumping and sand crews; secondary community dust exposure
Diesel particulate matter and combustion gases	Rig engines, generators, pressure pumping, heavy truck traffic	Air	Inhalation by all site personnel and roadside communities
Hydrogen sulphide	Sour formations, degraded muds, stagnant produced water, tank headspace	Air	Inhalation; acute and potentially fatal at high concentration
Polycyclic aromatic hydrocarbons	Flaring, diesel combustion, crude and oil based mud contact, spills	Air, soil, sediment	Inhalation, dermal contact, dietary intake through contaminated food webs
Heavy metals including barium, lead, arsenic, cadmium, chromium, mercury	Barite and other mud additives, cuttings, produced water, corrosion products	Soil, water, sediment	Ingestion via drinking water and food, dermal contact, inhalation of dust
Naturally occurring radioactive material, radium 226 and 228	Produced water, pipe and vessel scale, sludge	Water, solids	External gamma exposure during maintenance; ingestion via water and food
Salts and high total dissolved solids	Produced water, flowback, road spreading, pit leakage	Water, soil	Ingestion, ecological and agricultural impairment

Agent or agent group	Principal generating activity	Transport medium	Route and receptor
Biocides, surfactants, acids, crosslinkers	Hydraulic fracturing additive packages, mud chemistry	Water, air, direct contact	Dermal and respiratory irritation, sensitisation, aquatic toxicity
Methane and light alkanes	Venting, flaring inefficiency, well integrity failure, abandoned wells	Air, groundwater	Asphyxiation and explosion risk; climate forcing; stray gas in water wells
Noise and vibration	Drill floor, mud pumps, compressors, pressure pumping, plant	Direct physical	Hearing loss and sleep disturbance in workers and nearby residents
Ionising radiation from sealed sources	Wireline logging, industrial radiography	Direct physical	External exposure to logging and inspection personnel

3.3. Toxicological Impacts

This section reviews the toxicological basis for concern for the principal agents identified above. Three cross cutting points frame the discussion. First, drilling exposures are mixtures, and additive or interactive effects are poorly characterised by single compound risk assessment. Second, exposure profiles are episodic, with short high intensity peaks superimposed on lower background levels, which matters for agents whose toxicity is driven by peak rather than cumulative dose. Third, susceptibility varies, with pregnant workers and residents, children, older adults and people with pre existing respiratory or cardiovascular disease forming identifiable vulnerable subgroups.

Benzene and the aromatic hydrocarbons

Benzene is the agent of greatest concern among drilling related volatile organic compounds because it is both ubiquitous in the process stream and classified as carcinogenic to humans by the International Agency for Research on Cancer. It is metabolised, principally by cytochrome P450 2E1, to phenol, hydroquinone, catechol and the ring opened product trans trans muconaldehyde. Reactive metabolites accumulate in bone marrow, where they induce oxidative stress, DNA adduct formation, chromosomal aberrations including aneuploidy of chromosomes 5, 7 and 8, topoisomerase inhibition and disruption of haematopoietic stem cell differentiation. The resulting health effects are aplastic anaemia, myelodysplastic syndrome and acute myeloid leukaemia, with evidence also for non Hodgkin lymphoma. Haematological suppression has been observed in exposed workers at air concentrations below one part per million, challenging the adequacy of older occupational exposure limits. Benzene exposure has additionally been associated with impaired immune function and with adverse reproductive outcomes, and the compound crosses the placenta.

Toluene, ethylbenzene and the xylene isomers are less potently genotoxic but share acute central nervous system depressant properties and are associated with chronic neurobehavioural effects including impaired attention, memory and psychomotor performance. Toluene is a recognised developmental neurotoxicant at high exposure. Ethylbenzene has produced renal and hepatic tumours in rodent bioassays and is classified as possibly carcinogenic to humans. The aromatic fraction as a whole also contributes to mucous membrane and respiratory

irritation and, at high concentration in confined spaces, to cardiac sensitisation that can precipitate fatal arrhythmia.

Respirable crystalline silica

Inhaled respirable crystalline silica, predominantly alpha quartz, is phagocytosed by alveolar macrophages whose lysosomal membranes are disrupted by the particle surface. Activation of the NLRP3 inflammasome and release of interleukin 1 beta, tumour necrosis factor alpha and reactive oxygen species drive a self sustaining cycle of macrophage death, particle re release and fibroblast proliferation. The clinical outcomes are chronic simple silicosis, accelerated silicosis following intense exposure over a few years, and acute silicoproteinosis after extreme exposure. Silicosis is irreversible and progressive even after exposure ceases. Crystalline silica is classified as carcinogenic to humans, with lung cancer the principal malignancy, and exposure is further associated with chronic obstructive pulmonary disease, pulmonary tuberculosis, chronic kidney disease and autoimmune conditions including rheumatoid arthritis, systemic sclerosis and small vessel vasculitis. The relevance to drilling arises chiefly from hydraulic fracturing proppant handling, where multiple published industrial hygiene surveys have reported personal breathing zone concentrations exceeding applicable limits at a majority of sampled sites.

Hydrogen sulphide

Hydrogen sulphide is a chemical asphyxiant that inhibits cytochrome c oxidase in the mitochondrial electron transport chain, arresting aerobic respiration in tissues with the highest oxygen demand, namely the brain and heart. Its toxicity is strongly concentration dependent and its warning properties are unreliable because olfactory fatigue abolishes the characteristic odour at concentrations above roughly 100 parts per million, precisely where the hazard becomes acute. At low concentration the effects are ocular and respiratory irritation and keratoconjunctivitis. Intermediate concentrations produce headache, nausea, dizziness and pulmonary oedema. At several hundred parts per million, loss of consciousness occurs within moments, and at concentrations above approximately 700 to 1000 parts per million a single breath may be fatal. Survivors of serious acute exposure frequently exhibit persistent neurological sequelae including memory impairment, motor dysfunction and affective disorder. Chronic low level exposure in communities near sour gas operations has been associated with respiratory symptoms, neuropsychological complaints and sleep disturbance, although the epidemiological evidence base is less firm than for acute effects.

Diesel particulate matter and combustion products

Diesel exhaust was reclassified as carcinogenic to humans on the basis of evidence for lung cancer, with suggestive evidence for bladder cancer. The particulate component consists of an elemental carbon core carrying adsorbed organic compounds including polycyclic aromatic hydrocarbons and their nitrated derivatives, metals and sulphates. Particles in the ultrafine fraction deposit in the alveolar region, translocate across the alveolar epithelium, and provoke oxidative stress, systemic inflammation, endothelial dysfunction, altered autonomic balance and prothrombotic change. These mechanisms underlie the consistently observed associations between fine particulate exposure and ischaemic heart disease, stroke, arrhythmia, exacerbation of asthma and chronic obstructive pulmonary disease, and increased all cause mortality. Nitrogen dioxide contributes independently to airway inflammation and asthma incidence, while carbon monoxide impairs oxygen delivery through haemoglobin binding, a particular concern in enclosed or poorly ventilated work areas.

The cardiovascular limb of this evidence deserves emphasis because it is frequently overlooked in a sector whose health programmes concentrate on respiratory and traumatic outcomes. Particulate exposure, noise, heat strain, shift work and psychosocial load all act on the same cardiovascular endpoints, and the workforce in many producing regions carries a high background burden of hypertension and cardiometabolic disease on which those exposures are superimposed.

Contemporary burden estimates and risk stratification work in West African adult populations document high and frequently undetected rates of hypertension and of insulin resistance markers such as the triglyceride glucose index, together with their association with reduced kidney function and with elevated ten year cardiovascular risk (Okwah, 2022).

Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons arise from flaring, diesel combustion, crude oil contact and oil based drilling fluids. Benzo a pyrene, the reference compound of the class, is metabolically activated through the cytochrome P450 and epoxide hydrolase system to diol epoxides that form stable covalent adducts at the exocyclic amino group of guanine. Unrepaired adducts produce characteristic G to T transversions in critical genes including TP53 and KRAS. Several members of the class are classified as human or probable human carcinogens, with lung, skin, bladder and gastrointestinal cancers the principal outcomes. Non cancer effects include immunosuppression, endocrine disruption through aryl hydrocarbon receptor mediated pathways, and developmental impacts. Prenatal exposure has been associated in cohort studies with reduced birth weight, altered neurodevelopment and reduced childhood cognitive scores. In communities where flaring is routine and sustained, as in parts of the Niger Delta, chronic ambient exposure to this class is a central public health concern.

Metals and naturally occurring radioactive material

Barium sulphate, the principal weighting agent, has low solubility and therefore low systemic toxicity, but soluble barium compounds are cardiotoxic and the barite feedstock may carry lead, arsenic, cadmium, mercury, chromium, nickel and zinc as contaminants. Lead is a cumulative neurotoxicant with no identified safe exposure in children and is associated in adults with hypertension, renal impairment and cognitive decline. Arsenic exposure through drinking water causes skin, bladder and lung cancer and is linked to cardiovascular and metabolic disease. Cadmium accumulates in the renal cortex, causing tubular proteinuria and osteoporosis, and is classified as a human carcinogen. Hexavalent chromium, present in cement dust and some corrosion inhibitors, is both a respiratory carcinogen and a potent skin sensitiser. Mercury is neurotoxic and nephrotoxic, with organic forms biomagnifying through aquatic food chains.

Naturally occurring radioactive material concentrates when radium bearing produced water encounters sulphate and barium and precipitates as scale in tubulars, valves, separators and tanks. Workers who cut, clean, descale or dispose of contaminated equipment may receive external gamma doses and may inhale radioactive dust if abrasive methods are used without containment. Radium 226 and radium 228 are bone seeking alpha and beta emitters with long biological half lives, and ingestion is associated with bone sarcoma and head sinus carcinoma. Radon 222, a radium decay product, contributes to lung cancer risk where gas accumulates in enclosed spaces.

Drilling fluid and stimulation additives

Chemical disclosure analyses of hydraulic fracturing fluids have identified several hundred distinct substances in use, of which a substantial minority have published toxicity data adequate

for risk assessment and a smaller fraction have reference values for chronic oral or inhalation exposure. Among compounds repeatedly flagged are 2 butoxyethanol, a haemolytic agent, methanol, formaldehyde releasing biocides, glutaraldehyde, a potent respiratory and skin sensitiser, quaternary ammonium compounds, naphthalene, acrylamide monomer residues in friction reducers, and petroleum distillates. Toxicological review of disclosed additives has identified subsets with known carcinogenic, reproductive or developmental toxicity, and a larger subset with endocrine disrupting activity in screening assays. The fundamental problem is not that every additive is hazardous but that the data gap prevents a defensible mixture risk assessment, and that proprietary claims have historically limited the disclosure needed by clinicians treating exposed patients and by emergency responders.

Physical and psychosocial agents

Noise induced hearing loss remains one of the most prevalent occupational diseases in the sector, following the classical pattern of irreversible outer hair cell loss with a notch at 4 kilohertz progressing to broader high frequency impairment. Noise exposure is additionally associated with hypertension, sleep disturbance, impaired communication and increased accident risk, and community noise from drilling and pressure pumping has been linked to annoyance and sleep disruption in nearby residents. Whole body vibration contributes to lumbar spine disorders, and hand arm vibration to the vascular, neurological and musculoskeletal components of hand arm vibration syndrome. Heat strain progresses from heat rash and cramps through exhaustion to heat stroke, and chronic recurrent heat exposure combined with dehydration has been implicated in the chronic kidney disease of non traditional cause described in outdoor workers in hot regions. Finally, extended rosters, long rotations, isolation and production pressure are associated in offshore and remote onshore workforces with elevated rates of depression, anxiety, substance use and fatigue related error, which is a safety as well as a health outcome.

Table 2 – Selected agents, principal health outcomes, and representative occupational exposure benchmarks.

Agent	Principal health outcomes	Representative benchmark	Carcinogen classification
Benzene	Aplastic anaemia, myelodysplasia, acute myeloid leukaemia, immunotoxicity	0.5 to 1 ppm eight hour average in major jurisdictions, with lower recommended values	IARC Group 1
Respirable crystalline silica	Silicosis, lung cancer, COPD, tuberculosis, renal and autoimmune disease	0.05 mg per cubic metre eight hour average in several jurisdictions	IARC Group 1
Hydrogen sulphide	Irritation, pulmonary oedema, loss of consciousness, death, neurological sequelae	Short term limits typically 5 to 10 ppm; immediate danger around 100 ppm	Not classifiable

Agent	Principal health outcomes	Representative benchmark	Carcinogen classification
Diesel exhaust particulate	Lung cancer, cardiovascular disease, asthma and COPD exacerbation	No universal limit; elemental carbon used as surrogate marker	IARC Group 1
Benzo a pyrene and PAH mixtures	Lung, skin and bladder cancer, developmental and immune effects	Managed as cyclohexane soluble fraction or benzene soluble fraction	IARC Group 1 for benzo a pyrene
Toluene	Central nervous system depression, neurobehavioural deficit, developmental toxicity	20 to 50 ppm eight hour average depending on jurisdiction	IARC Group 3
Noise	Permanent hearing loss, hypertension, sleep disturbance	85 dB(A) eight hour average action level, 140 dB peak	Not applicable
Radium 226 and 228 in scale	Bone sarcoma, sinus carcinoma, increased lifetime cancer risk	Dose constrained under radiation protection frameworks	IARC Group 1

Benchmarks are indicative only. Applicable limits differ between jurisdictions and are periodically revised, and the relevant national regulation should always be consulted.

3.4. Epidemiological Evidence

Community studies and residential proximity

A substantial body of observational research has examined health outcomes in populations living near oil and gas development, using residential proximity, well density or activity weighted inverse distance metrics as exposure surrogates. The most consistently reported associations concern perinatal outcomes. Multiple studies conducted in regions of intensive unconventional development have reported modest increases in the risk of low birth weight, small for gestational age, preterm birth and certain congenital anomalies, particularly congenital heart defects, among births to mothers residing in close proximity to wells, with effects generally strongest in the nearest exposure category and during the drilling and completion phases.

Respiratory findings include increased asthma exacerbation, measured through medication orders, emergency visits and hospitalisation, and increased upper respiratory symptom reporting in proximity cohorts. Cardiovascular studies have reported associations with hospitalisation for cardiology conditions and with markers of subclinical cardiovascular disease. A smaller number of studies have examined childhood haematological malignancy and reported elevated risk estimates for acute lymphocytic leukaemia in proximity to dense development, with wide confidence intervals reflecting small case numbers. Reported symptom clusters in community surveys include headache, fatigue, nasal and sinus irritation, dermatological complaints and sleep disturbance.

These findings must be read with appropriate caution. Proximity is a crude surrogate that integrates chemical, noise, light, traffic and psychosocial stressors without distinguishing them. Exposure misclassification is likely and generally biases towards the null for true effects but can also generate spurious associations. Socioeconomic confounding is a persistent concern because development is frequently concentrated in economically disadvantaged rural areas. Few studies incorporate personal monitoring or biomarkers. The weight of evidence nevertheless supports a precautionary conclusion that proximity to intensive development is associated with adverse health signals that justify setback requirements and emission control.

Occupational studies

Occupational epidemiology in the drilling sector is complicated by workforce mobility, contractor fragmentation, the healthy worker effect and incomplete exposure records. Mortality studies of petroleum extraction workers have reported excesses for certain haematological malignancies, mesothelioma reflecting historical asbestos use, and skin cancer, while overall mortality is frequently below general population rates owing to selection. Fatal and serious injury rates in the extraction sector remain several times the all industry average in most national statistics, with transport incidents, struck by events, caught in machinery and fires and explosions dominating. A distinct cluster of sudden deaths among workers performing manual tank gauging of flowback and crude storage tanks has been attributed to acute hydrocarbon vapour exposure combined with oxygen deficiency, and has driven regulatory and industry guidance on remote gauging.

Industrial hygiene surveys provide more direct exposure evidence than disease outcome studies. Surveys of hydraulic fracturing operations have documented respirable crystalline silica exposures above occupational limits in a majority of sampled sites, with the highest results associated with sand mover operation, transfer belt and hopper positions and blender work. Benzene sampling during flowback and production tank gauging has similarly documented short term exposures far in excess of applicable short term limits. These findings are important because they demonstrate that control failures are identifiable and addressable at specific, well defined tasks.

Evidence from major producing regions outside North America

The Niger Delta represents one of the most intensively studied non North American settings, though the literature is weighted towards environmental contamination rather than formal epidemiology. Studies document widespread hydrocarbon contamination of soil, groundwater and surface water from spills, sabotage, equipment failure and inadequate remediation, with measured concentrations of benzene and total petroleum hydrocarbons in drinking water sources exceeding health based guideline values by large margins in affected communities. Routine gas flaring has produced sustained ambient exposure to combustion products, with associated reporting of respiratory symptoms, dermatological conditions and acid deposition effects on crops and infrastructure. Research linking gas flaring exposure to adverse birth outcomes and childhood health has begun to accumulate. Similar patterns of contamination and health concern are documented in parts of the Amazon basin, the Caspian region and the Middle East. The persistent underrepresentation of these regions in the health literature is itself a finding, because exposure intensity in many of them exceeds that in the better studied basins while regulatory and health surveillance capacity is weaker.

Surveillance capacity as a determinant of what is observed

A recurring difficulty in this literature is that the regions of highest exposure are often those with the weakest capacity to detect health effects. The apparent absence of evidence in such

settings reflects surveillance capability rather than absence of harm, and strengthening that capability is therefore a precondition for any serious epidemiology of drilling related exposure.

Work on national disease surveillance architecture is directly transferable. Evaluations of integrated disease surveillance and response implementation and of routine health information system data quality, frameworks for real time surveillance dashboards and epidemic preparedness, predictive and risk stratification models built on large scale population data, and approaches that join climate and environmental data to health outcomes for mortality risk prediction all describe infrastructure that an environmental exposure registry could share rather than duplicate (Ekemezie & Sydney, 2018; Oparah et al., 2021; Oparah et al., 2022).

Governance, equity and access dimensions of that infrastructure matter equally, including public health governance models built on process optimisation and performance metrics, informatics frameworks aimed explicitly at protecting vulnerable populations, business intelligence approaches to resource allocation, telehealth models for rural and underserved populations, mobile health platforms for chronic disease monitoring, and integrated data governance in health information technology delivery (Oparah et al., 2021; Stephen-Kings et al., 2022).

The behavioural and psychosocial component of surveillance is relevant because rotational and camp based work is associated with elevated rates of mental ill health and substance use. Research on the operational and psychosocial consequences of compressed working patterns, on mindfulness and emotional regulation interventions, on treatment planning for co-occurring trauma and behavioural dysregulation, on activities of daily living as a clinical intervention, and on analytics supported substance use recovery programmes is applicable to workforce health services in this sector (Osinem et al., 2021; Owoade et al., 2022).

3.5. Risk Assessment Approaches

Risk assessment in this sector draws on the standard four step paradigm of hazard identification, dose response assessment, exposure assessment and risk characterisation, but requires adaptation to three features of drilling operations: mixture exposure, episodic peak exposure and the coexistence of occupational and community receptors around a single source.

Exposure assessment methods in current use include personal breathing zone sampling with laboratory analysis, direct reading instrumentation such as photoionisation detectors and real time particulate monitors, fenceline and community ambient monitoring networks, mobile survey platforms, optical gas imaging for leak detection, dispersion modelling, and the use of proximity and activity weighted spatial metrics in epidemiological work. Biomonitoring, including urinary trans trans muconic acid and S phenylmercapturic acid for benzene, urinary 1 hydroxypyrene for polycyclic aromatic hydrocarbons and blood metal concentrations, integrates exposure across routes and is underused in both occupational and community settings.

Biomarker based and mechanistic risk frameworks

There is a growing case for framing exposure assessment around biological effect rather than ambient concentration alone. Frameworks that link measured pollutant exposure to oxidative stress and DNA damage endpoints provide a mechanistic bridge between the analytical chemistry of a contaminated site and the health outcomes of concern, and allow heterogeneous exposures to be expressed on a common biological scale. Coupling exposure biomarkers with markers of individual susceptibility, including metabolic polymorphisms and repair capacity, further supports a shift from population average risk estimates towards personalised

prevention, which is particularly relevant for a workforce in which a minority of individuals accumulate a disproportionate share of peak exposure (Aladegba et al., 2021). The data pipelines required to connect field measurement to predictive toxicology remain a practical obstacle, chiefly through inconsistent analytical protocols, incomplete metadata and poor interoperability between environmental and health datasets.

Computational and machine learning approaches

Computational methods are increasingly applied to the prediction of environmentally induced disease risk, offering the capacity to handle high dimensional mixture data, non linear dose response and spatially heterogeneous exposure fields that defeat conventional regression. Applied to drilling settings, such methods could integrate emission inventories, meteorological fields, proximity metrics, biomonitoring results and health registry outcomes into a single predictive structure, and translate model output into public health action through the triggering of monitoring, screening or exposure interruption rather than through retrospective attribution alone. The principal cautions are familiar: model performance is bounded by the quality of the exposure data on which it is trained, opacity in model structure complicates regulatory use, and predictive accuracy must not be mistaken for causal inference.

Methodological transfer from adjacent contaminated site literatures is also instructive. Congener specific sampling, analytical and health risk assessment protocols developed for mixed persistent organic contaminants in soil, together with incremental lifetime cancer risk and hazard index calculations, are directly adaptable to hydrocarbon and polycyclic aromatic hydrocarbon contaminated soils around well pads and flow stations. The parallel is close because both settings involve persistent contamination of soil in communities that rely on that soil for cultivation and that lack formal exposure surveillance.

Equity considerations are not peripheral to this. Analytics based health needs assessment, models addressing socioeconomic inequity in maternal and adolescent health, attention to social determinants in care plan design, and documented disparities in the recognition and management of acute conditions all indicate that predictive systems inherit and can amplify the inequities present in their training data, which is a material concern where the exposed population is rural, poor and already underserved (Atakpa, 2020; Atakpa, 2021).

Methodological priorities

Methodological priorities for improving risk characterisation include the routine capture of short term peak exposures rather than reliance on shift averages alone, the use of task based sampling strategies that attribute exposure to specific operations, the application of cumulative risk frameworks that address chemical mixtures alongside noise, heat and psychosocial stressors, and the linkage of industrial hygiene data to health surveillance records so that exposure and outcome can be analysed together. Life cycle assessment and environmental impact assessment provide complementary tools at the project level, but their value depends on genuinely independent review and on monitoring commitments that persist beyond project approval.

3.6. Mitigation Strategies

Mitigation is most coherently organised by the hierarchy of controls, in which measures are ranked by reliability rather than by cost or convenience. Elimination and substitution act on the hazard itself and are therefore the most durable. Engineering controls act on the transmission path and operate independently of individual behaviour. Administrative controls and personal protective equipment depend on sustained human compliance and are the least reliable, although in practice they remain necessary layers.

Elimination and substitution

- Replace oil based drilling fluids with water based or low toxicity synthetic systems wherever formation conditions permit, reducing both volatile organic compound emission and dermal hazard, and simplifying cuttings disposal.
- Substitute non silica or resin coated proppants, or use lower free silica alternatives, where fracture performance allows, thereby acting directly on the respirable crystalline silica hazard rather than attempting to capture the dust after generation.
- Eliminate routine flaring and venting through gas capture, reinjection, on site utilisation and connection to gathering infrastructure, which simultaneously addresses combustion product exposure, hydrocarbon waste and greenhouse gas emission.
- Replace diesel prime movers with grid electric power, natural gas or dual fuel engines, or hybrid systems, which removes the diesel particulate source and reduces noise.
- Select additive packages using green chemistry screening, preferring substances with full toxicity data and lower hazard profiles over proprietary blends of undisclosed composition, and eliminating known sensitisers and carcinogens where functional substitutes exist.
- Replace high bleed pneumatic controllers with low bleed, instrument air or electric actuation to remove a persistent fugitive methane and volatile organic compound source.

Engineering controls

- Closed loop solids control systems that eliminate reserve pits, retaining cuttings and fluid in steel tanks, preventing pit leakage to soil and groundwater and reducing open surface evaporation.
- Enclosure and local exhaust ventilation at shale shakers, mud mixing stations and sample points, with extraction routed to appropriate treatment rather than simple dilution.
- Dust controls on the proppant handling train, including enclosure of transfer points, passive capture hoods with filtration on sand movers, mini baghouse retrofits on thief hatches of pneumatic trailers, and the use of wet or less dusty delivery systems such as containerised or slurried proppant.
- Vapour recovery units and pressurised closed tank systems on storage and flowback vessels, combined with remote and automated tank gauging so that no worker is required to open a hatch and lean into a vapour plume.
- Green or reduced emission completions that route flowback gas to sales lines rather than to flare or atmosphere.
- Robust well barrier design and verification, including adequate surface casing set below the deepest usable aquifer, centralisation, cement bond logging, pressure testing and the monitoring and remediation of sustained casing pressure, which is the primary defence against subsurface migration to groundwater.
- Secondary containment, impermeable liners, bunding and spill response readiness at all chemical and fluid storage locations, which addresses the pathway responsible for most documented water contamination events.
- Produced water management through on site treatment, reuse in subsequent stimulation, and disposal into properly characterised injection zones, with seismic monitoring where induced seismicity is a known risk.

- Fixed and portable hydrogen sulphide detection with audible and visual alarms, automatic shutdown interlocks, wind indicators, positive pressure safe havens and cascade breathing air systems in sour service.
- Noise control at source through acoustic enclosure of generators and pumps, sound walls around pads adjacent to residences, and selection of quieter equipment, in preference to reliance on hearing protection.
- Leak detection and repair programmes using optical gas imaging, laser based methods, continuous fenceline sensors or periodic aerial and satellite survey, with defined repair timelines and verification.

Administrative and organisational controls

- Permit to work systems for hot work, confined space entry, excavation, line breaking and energy isolation, with independent verification of isolation before work proceeds.
- Task based exposure control plans that assign specific controls to the specific operations identified as high exposure, notably sand handling, tank gauging, mud mixing and shaker house work.
- Fatigue risk management addressing roster design, shift length, commuting, night work and rest facilities, recognising fatigue as both a health and a safety hazard.
- Competence assurance and training covering hazard recognition, hydrogen sulphide response, respiratory protection, chemical handling and emergency procedures, with verification of understanding rather than attendance alone.
- Contractor management that extends the operator health and safety standard to every service company on the pad, since exposure intensive tasks are frequently performed by contractors with weaker programmes.
- Chemical disclosure and accessible safety data sheets, including disclosure to treating clinicians and emergency responders without proprietary restriction.
- Housekeeping, welfare and hygiene facilities sufficient to prevent take home contamination and inadvertent ingestion, including separate clean and dirty changing areas and laundering of contaminated clothing on site.
- Setback distances between well pads and dwellings, schools, hospitals and water sources, supported by site specific dispersion and noise assessment rather than applied as an arbitrary number.

Personal protective equipment

Personal protective equipment is the final layer and should never substitute for higher order controls, but its correct selection and use remains essential in a sector where residual risk cannot be fully engineered out. Requirements include respiratory protection matched to the contaminant and its concentration, with fit testing and a written respirator programme; flame resistant clothing meeting recognised standards; chemical resistant gloves selected by permeation data for the specific fluid rather than by general appearance; eye and face protection; hearing protection selected by attenuation rating and verified by fit where available; fall protection for derrick and elevated work; and self contained or supplied air escape apparatus in sour service. Programme elements such as inspection, maintenance, replacement intervals and user training determine whether equipment performs as rated.

Health surveillance and monitoring

Health surveillance converts exposure control from an assumption into a verified outcome. A defensible programme includes baseline and periodic audiometry for noise exposed workers, spirometry and chest imaging at appropriate intervals for those exposed to silica and other respirable hazards, full blood counts for workers with significant benzene exposure, dermatological assessment for those in fluid contact roles, biological monitoring for selected agents, dosimetry for radiation workers, and fitness for task assessment where respirator use or heat exposure is required. Surveillance data should be analysed in aggregate to detect group level trends, not merely filed individually, and findings should feed back into control design. Environmental monitoring, including groundwater wells sampled before drilling to establish a baseline and at intervals thereafter, ambient air monitoring, soil sampling and ecological indicators, performs the analogous function for the community receptor and provides the evidentiary basis for attributing or excluding impact.

Regulatory, governance and community dimensions

Technical controls operate within an institutional context that determines whether they are applied. Effective governance requires performance based regulation supported by prescriptive minimum standards where the evidence is clear, inspection capacity sufficient to make compliance verifiable, penalties proportionate to the benefit of non compliance, financial assurance for well plugging and site restoration so that abandonment liabilities are not socialised, and public reporting of emissions, incidents and monitoring data. Weak enforcement capacity, rather than absent regulation, is the characteristic failure in many producing regions.

Risk communication is the operational face of that engagement, and its effectiveness is measurable. Research on culturally relevant health messaging and source specific trust, on entertainment and narrative driven health communication, on omnichannel reach and journey completion as communication metrics, and on digital and community outreach for health access provides methods for designing and evaluating the community facing component of an environmental health programme rather than treating it as public relations (Abutu, 2020; Abutu, 2021; Abutu, 2022).

Community engagement is both an ethical obligation and a practical control. Free, prior and informed consultation, grievance mechanisms with real remedial authority, local participation in environmental monitoring, transparent spill reporting, and independently verified remediation of legacy contamination address the trust deficit that otherwise converts technical disputes into conflict. Where contamination has already occurred, remediation standards must be based on health protective endpoints and verified by independent sampling rather than by operator self certification.

Flare reduction, methane management and gas recovery

Routine flaring and venting is simultaneously the largest avoidable source of community exposure to combustion products in many producing regions and a direct loss of saleable product, which makes it the mitigation with the clearest alignment between health and commercial interest. The technical options are well developed: flare gas recovery systems, engineered gas gathering and vapour recovery networks, methane emission reduction programmes across production operations, transition management across the liquefaction operating cycle to minimise disposition to flare, predictive maintenance aimed at the rotating machinery failures that drive non routine flaring, decarbonisation pathways for legacy facilities, and techno economic routes for converting routinely flared gas into marketable

products and feedstocks (Asibor & Isong, 2020; Asibor & Olisakwe, 2022; Makut & Olisakwe, 2022).

The health argument for prioritising these measures is that flaring exposure falls disproportionately on people who receive none of the economic benefit of the operation, often continuously and over decades, and that the exposure is to a mixture of combustion products for which no safe community level has been established. Flare reduction is therefore the single intervention most likely to reduce aggregate population exposure per unit of expenditure in regions where routine flaring persists.

Process safety management, permit systems and human barriers

Acute release events, rather than chronic emissions, account for the most severe individual health outcomes in this industry, and their control is the domain of process safety management. The relevant literature covers risk based process engineering for complex gas infrastructure, integration of hazard and operability study methods with reliability analysis and risk based decision making in design, risk based front end engineering design, management of change effectiveness in mature production operations, isolation control certificates and permit to work compliance during turnarounds, standardised gas testing protocols for hot work authorisation, alarm management and human factors in control rooms, standardisation of logbook and shift handover to prevent cross shift information loss, the shift supervisor treated explicitly as a human barrier within the integrity model, decision dynamics during high consequence process upsets, and artificial intelligence applications for detecting developing process failures (Asibor & Isong, 2019; Makut et al., 2021; Makut et al., 2022).

The conceptual advance in this body of work is the treatment of people as barriers within the same framework used for engineered protection layers. A gas tester, a permit issuer or a shift supervisor performs a barrier function whose reliability can be specified, degraded by fatigue or workload, and verified, and which fails in characteristic ways. This framing connects process safety engineering to occupational health management, because the conditions that degrade human barrier reliability, namely fatigue, heat strain, poor handover and production pressure, are the same conditions that produce chronic health harm.

Asset integrity, corrosion control and mechanical reliability

Loss of containment is the common mechanism linking mechanical condition to human exposure. Every pathway described in Section 3.2 is made worse by equipment that leaks, and asset integrity management is therefore an exposure control even though it is seldom classified as one.

The applicable methods include risk based inspection and fitness for service assessment of ageing pressure vessels, reliability centred maintenance for static mechanical equipment, integrity management of fired heaters and boilers, corrosion management and material selection for crude export equipment in marine environments, condition based maintenance of mooring and offloading systems, non intrusive inspection methods that reduce shutdown frequency, risk based inspection of offloading hose strings, computerised maintenance management and cause tree failure analysis, internet of things enabled condition monitoring, digital twin applications for offshore asset integrity, systems engineering approaches to deepwater equipment reliability, design optimisation of floating production and offloading facilities, and standardisation of spare parts and materials in pressure vessel maintenance (Makut et al., 2021; Makut et al., 2022; Obetta et al., 2020; Obetta et al., 2021; Obetta et al., 2022; Obetta, 2018; Obetta, 2019; Obetta, 2020).

Underpinning this practice is work on failure analysis, corrosion prediction and non destructive evaluation, including systematic review of non destructive testing for predictive failure analysis, predictive models of corrosion behaviour built on non destructive data, artificial intelligence augmented corrosion modelling, reliability centred design of mechanical components using finite element methods, digital twin deployment for real time mechanical monitoring, and conceptual models for failure prevention in critical infrastructure (Ogunnowo et al., 2020).

Materials selection and characterisation research, covering dynamic mechanical analysis frameworks for high performance material selection and prediction of microstructural evolution in superalloys produced by directed energy deposition, determines the service life of components exposed to sour, saline and high temperature duty (Adewoyin et al., 2020b; Ogunnowo et al., 2021; Ogunnowo et al., 2022).

Computational fluid dynamics contributes directly to control design, through work on thermofluid simulation for heat transfer optimisation, design of fluid particle separation and filtration systems, simulation and optimisation of cake filtration, topology optimisation for structural efficiency, and artificial intelligence based optimisation of multiphysics fluid problems. Separation and filtration performance is an exposure control in its own right, because it governs how much contaminated solid and liquid reaches the worker and the waste stream (Adewoyin et al., 2020a; Adewoyin et al., 2021).

Inspection quality assurance is the verification layer for all of this, and work on welding inspection standards, non destructive testing for weld integrity in high capacity plant, non destructive testing based integrity management and corrosion risk assessment, and green corrosion inhibitors derived from agricultural extracts addresses both the assurance of containment and the substitution of less hazardous chemistry into corrosion control programmes (Atta et al., 2018; Atta et al., 2020; Atta et al., 2021; Atta et al., 2022).

Condition monitoring and the shift from reactive to predictive maintenance regimes, including vibration based monitoring of rotating machinery, sensor based fault detection, reliability centred maintenance strategies and building information modelling linked to lifecycle reliability assessment, reduce both unplanned release events and the exposure incurred during emergency repair, which is typically performed under worse conditions and with weaker controls than planned work (Adaramola et al., 2018; Sunday & Omoegun, 2022; Sunday et al., 2020).

Ventilation and thermal systems engineering is directly relevant to the control of airborne contaminants and heat strain in enclosed work areas, camps and control rooms, and simulation based optimisation of heating, ventilation and air conditioning performance, thermodynamic efficiency and control strategies, and electrical load management for hybrid installations in remote settings determine whether those systems can be sustained where grid supply is unreliable (Ogunnowo et al., 2021; Sunday & Omoegun, 2018; Sunday & Omoegun, 2019; Sunday et al., 2019).

Procurement, supply chain assurance and chemical sourcing

Many exposure controls are decided at the point of purchase rather than at the worksite. The additive package used, the specification of the equipment installed, the competence of the contractor mobilised and the quality of the protective equipment issued are all procurement outcomes, which makes procurement an underrecognised instrument of health protection.

Research on strategic sourcing and contract design for reliable fuel and equipment supply, dual sourcing of critical energy equipment under currency and lead time uncertainty, regulatory compliant procurement in high risk energy environments, cost reduction through contract negotiation, inventory availability for critical spares, continuity of essential energy supplies under disruption, and digital supply chain governance in energy and infrastructure describes the mechanisms through which these decisions are made (Agbabiaka et al., 2019; Ahiaeke Patrick et al., 2020; Ahiaeke Patrick et al., 2021; Asibor et al., 2019; Asibor et al., 2021; Babayemi & Okonkwo, 2020; Ogunwole et al., 2021; Okonkwo et al., 2018a; Okonkwo et al., 2018b; Okonkwo et al., 2019; Okonkwo et al., 2020; Okonkwo et al., 2021).

Sustainability and assurance oriented procurement research extends this to supplier auditing against environmental, social and governance criteria, supplier qualification and performance management, traceability across multi tier supply networks, and the integration of sustainability requirements into sourcing decisions, which is the route by which chemical disclosure and substitution requirements become contractually enforceable rather than aspirational (Aifuwa et al., 2020; Anene, 2021; Filani et al., 2022; Ike et al., 2021; Ike et al., 2022; Nnabueze et al., 2021; Okojie et al., 2020; Sakyi et al., 2022a; Sakyi et al., 2022b; Yeboah & Ike, 2020).

Power systems and site electrification

Substituting grid or gas fired electric power for diesel prime movers is among the highest value interventions available, and its feasibility is an electrical engineering question. Work on machine design and efficiency, power system planning and distribution, load management, protection and reliability of supply, and the telecommunications infrastructure on which remote monitoring depends determines whether electrification is practical at a given location (Adeniji et al., 2020; Amayo & Oshevire, 2015; Amayo & Popoola, 2017a; Amayo & Popoola, 2017b; Amayo, 2017; Makut et al., 2021; Nwangwu et al., 2021; Obukadata et al., 2022; Oshevire & Amayo, 2017; Shittu et al., 2021).

Site layout, housing and the built environment

Setback distance is only the crudest expression of a broader set of spatial decisions. Research on sustainable built environment design, urban and peri urban housing provision, building performance and materials in hot climates, and land use planning is relevant both to the siting of pads relative to dwellings and to the design of the camps in which rotational workers live, where ventilation, thermal performance, noise attenuation and the separation of clean from contaminated areas determine off shift recovery and the prevention of take home contamination (Gil-Ozoudeh et al., 2018; Nwafor et al., 2018; Nwafor et al., 2019a; Nwafor et al., 2019b; Nwafor et al., 2019c; Uduokhai et al., 2022).

Table 3 – Mitigation measures mapped to the hierarchy of controls and to the exposure pathway addressed.

Control level	Representative measures	Primary pathway addressed	Reliability
Elimination and substitution	Water based or synthetic fluids; non silica proppant; gas capture in place of flaring; electric or gas prime movers; green chemistry additive selection	Air, dermal, soil and water	Highest; acts on the hazard itself

Control level	Representative measures	Primary pathway addressed	Reliability
Engineering controls	Closed loop solids control; local exhaust at shakers and mud pits; proppant dust capture; vapour recovery and remote tank gauging; green completions; well barrier integrity; secondary containment; acoustic enclosure; leak detection and repair	Air, water, soil, noise	High; independent of individual behaviour
Administrative controls	Permit to work; task based exposure plans; fatigue management; competence assurance; contractor standards; chemical disclosure; hygiene facilities; setback distances	All pathways indirectly	Moderate; depends on sustained compliance
Personal protective equipment	Fit tested respirators; flame resistant clothing; permeation matched gloves; hearing protection; escape breathing apparatus	Inhalation, dermal, thermal, noise	Lowest; last line of defence
Surveillance and verification	Audiometry, spirometry, haematology, biomonitoring, dosimetry; baseline and periodic groundwater, air and soil monitoring; public reporting	Verification across all pathways	Enabling; validates all other layers

3.7. Safety Management Systems, Human Factors and Organisational Learning

The controls described in Section 3.6 are implemented, or not, by organisations. A large body of applied research on safety management in energy and heavy construction settings addresses the organisational conditions that determine whether a control specified in a design document is present and functioning at the worksite. Because drilling is executed through layered contracting arrangements and temporary project organisations, these organisational questions are not secondary to the technical ones.

Safety culture, leadership and behavioural factors

Work in this area addresses leadership driven safety culture transformation in large workforces, conceptual models of safety leadership influence in temporary project organisations, organisational learning based maturity models for continuous improvement, the institutionalisation of life preserving practices across project based organisations, human error causation in high hazard activities, mechanisms by which unsafe behaviours recur at hazardous worksites, behavioural safety programme design, workforce training models for operational risk reduction, and the integration of human factors into process safety models for offshore commissioning (Arumosoye & Obriki, 2021; Obogo et al., 2019a; Obriki & Arumosoye, 2019; Obriki & Arumosoye, 2020; Obriki & Arumosoye, 2021; Obriki & Arumosoye, 2022; Obriki et al., 2022a).

The common finding across this literature is that technical control measures degrade predictably in organisations where leadership attention is episodic, where reporting is punitive, and where the workforce is transient. This matters acutely in drilling because crew composition changes between wells and because the highest exposure tasks are frequently performed by the most junior and least permanent personnel.

Hazard identification, incident learning and predictive safety analytics

A second cluster concerns the information systems through which organisations learn. It covers proactive hazard recognition and near miss reporting, the utilisation of near miss and hazard observation data, management safety walkthrough frequency and coverage as predictors of culture outcomes, continuous hazard monitoring systems, hazard identification for large scale operations, proactive identification using digital safety data streams, data driven occupational safety risk control in energy infrastructure projects, leading safety signals linked to sustained injury free performance, incident investigation and prevention oriented learning, and predictive safety analytics for early detection of high risk activities, including applications in liquefied natural gas projects with environmental, social and governance implications (Arumosoye & Obriki, 2019; Obogo et al., 2019; Obogo et al., 2021; Obriki & Arumosoye, 2018).

The relevance to exposure control is direct. Most of the industrial hygiene failures documented in Section 3.4, such as sand handling without dust capture or manual tank gauging, are visible to anyone walking the site and were in many cases reported before they caused harm. The constraint is the organisational capacity to convert observation into corrective action, which is precisely what this literature attempts to model.

Contractor governance, compliance and assurance

Because the operator seldom performs the highest exposure tasks, assurance over contractors is a central control. Research here addresses governance oriented models for contractor safety performance in multi contract industrial projects, subcontractor safety performance governance, contractor safety compliance systems in infrastructure projects, construction safety risk governance for multi contractor projects, safety governance for large facility operations, internal quality, health, safety and environment audit systems, environmental safety compliance frameworks, integrated safety management across multi zone projects, and frameworks for operational integrity in high risk drilling that explicitly balance productivity against compliance (Arumosoye & Obriki, 2020; Nwangwu & Onwumere, 2018; Obogo et al., 2019b; Obogo et al., 2020a; Obogo et al., 2021; Obogo et al., 2022).

High hazard operations, emergency readiness and environmental discipline

A final cluster addresses specific operations and conditions. It includes integrated heat stress risk modelling for industrial operations in extreme environments and heat stress frameworks for construction, risk pathway modelling for lifting and rigging in heavy industrial construction and for crane installation, incident prevention in industrial maintenance environments, occupational safety management systems in oil and gas maintenance projects, hazard identification and risk control in urban construction, emergency response readiness and capability in energy and process facilities, emergency preparedness and evacuation systems in high density facilities, sustainable environmental practices within occupational safety management systems, and environmental risk control through waste handling and operational discipline (Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2022; Obogo et al., 2020b; Obogo et al., 2020c; Obriki et al., 2022b).

Heat stress merits particular emphasis for drilling in tropical and desert regions, because it interacts with every other control: it limits tolerable duration in impermeable protective

clothing and respirators, degrades the reliability of human barriers, and contributes independently to renal and cardiovascular harm.

Regulatory oversight and lessons from other high reliability industries

Drilling is not the only industry in which catastrophic and chronic risks must be managed through a regulator with limited resources and an operator with better information. Civil aviation has developed oversight instruments that address the same structural problem and that transfer usefully.

Relevant work covers safety management system implementation at the operating site, predictive compliance monitoring for the detection of systemic non conformity, certification and benchmarking of operating facilities against defined standards, management of encroachment and unauthorised development around hazardous installations, wildlife and environmental hazard management, and the design of regulatory audit regimes (Adeyelu, 2018; Adeyelu, 2019; Adeyelu, 2020; Adeyelu, 2021; Adeyelu, 2022; Akhigbe et al., 2020; Akin-Oluyomi, 2022; Falemi et al., 2020; Ukadike, 2018; Ukadike, 2019; Uzondu et al., 2021; Wikiri et al., 2022; Wikiri, 2019).

Two transferable principles stand out. The first is that certification of a facility against an explicit standard, repeated periodically and published, produces more consistent compliance than discretionary inspection. The second is that encroachment management, meaning control of what is permitted to be built near a hazardous installation, is treated in aviation as a continuing regulatory duty rather than a one time siting decision, which is precisely the posture that setback regulation around well pads requires if it is not to be eroded by subsequent development.

Assurance, audit and continuous improvement

Verification that a management system is functioning is an audit problem. Research on risk based internal audit planning, the three lines governance model, continuous control monitoring, audit quality and independence, and the governance of risk reporting supplies the assurance methods through which health and safety performance claims can be tested rather than accepted (Akomolafe & Agu, 2018; Akomolafe & Agu, 2019a; Akomolafe & Agu, 2019b; Akomolafe & Agu, 2019c; Ashore-Onisemo & Unamma, 2022a; Mensah et al., 2019a; Mensah et al., 2019b).

Operational improvement research contributes the complementary discipline of defect reduction, including the reconceptualisation of the cost of poor quality as a governance concern, lean process improvement in resource constrained operations, performance dashboards and data driven operational decision making, standard work and waste elimination, and the measurement of process capability (Agboada et al., 2018; Agboada et al., 2019; Alieme et al., 2022; Ambali et al., 2021; Ashore-Onisemo et al., 2021; Ebisi & Anene, 2021; Eyetsemitan et al., 2020; Eyetsemitan et al., 2021; Eyetsemitan et al., 2022; Okoli et al., 2022; Oyeleye et al., 2022).

Predictive and data driven decision systems research supports the forward looking component of assurance, covering the construction of predictive models from operational data, decision support design, data quality as a precondition for inference, and the organisational conditions under which analytical output changes decisions rather than merely informing reports (Anene, 2022; Basnet et al., 2021; Mayo et al., 2021; Oteri & Chibwaye, 2022; Unamma & Iwuanyanwu, 2021; Unamma et al., 2018b).

3.8. Digital Monitoring, Remote Sensing and Operational Technology Security

Remote sensing and corridor monitoring

Spills from flowlines and gathering systems are a dominant contributor to soil and water contamination, and their detection time determines the magnitude of the release. Uncrewed aerial vehicle based pipeline and corridor monitoring, integrated frameworks combining aerial platforms with light detection and ranging and geographic information systems, right of way encroachment detection using geospatial methods, and deep learning for vegetation classification in corridor management provide the means to shorten that detection time over terrain where ground patrol is impractical (Dagodzo & Ahiaeke Patrick, 2020; Dagodzo & Ahiaeke Patrick, 2021b; Dagodzo & Ahiaeke Patrick, 2022; Dagodzo & Aliliele, 2022).

The supporting infrastructure for such programmes includes geographic information system based asset management and infrastructure planning, integration of drone operations into enterprise geospatial systems, aerial inspection of power and transmission infrastructure, remote sensing interpretation of surface alteration, national scale deployment frameworks drawn from developing economy experience, and the regulatory frameworks governing aerial operations in those economies, which are frequently the binding constraint on deployment rather than the technology itself (Dagodzo & Ahiaeke Patrick, 2021a; Dagodzo, 2018a; Dagodzo, 2018b; Dagodzo, 2018c).

Security of safety critical operational technology

Modern drilling and production installations depend on instrumented safety systems, remote monitoring and supervisory control. These systems are now part of the barrier model, and their compromise is a process safety and therefore a human health concern rather than only an information security one.

Technical work in this area covers supervisory control and data acquisition and industrial control system threat detection architectures, deep learning for anomaly detection in such networks, the cyber physical attack surface of legacy installations, adversarial machine learning threat modelling for critical infrastructure, zero trust architectures for operational technology, autonomous real time cyber physical threat prevention, secure data exchange for control systems, and adaptive protection in digitally instrumented substations (Adebayo et al., 2022; Adegbite et al., 2020; Ahmed & Adebayo, 2021; Shittu et al., 2022).

Governance work addresses security architecture for the convergence of information and operational technology in regulated energy networks, vulnerability governance for utility corporations, cyber risk quantification and governance, the transition from periodic audit to continuous control, the limits of compliance driven security models for critical infrastructure, security posture management aligned to recognised cybersecurity frameworks, security operations architecture for utility sector operations centres, and network resilience framed as a national security concern (Adegbite et al., 2022).

The human element of this exposure is as important as the technical one. Work on security awareness, human factors in organisational security behaviour, and the security of connected device and network deployments addresses the behaviours through which instrumented safety systems are most often compromised, namely credential sharing, unmanaged remote access and the connection of unvetted devices to control networks (Idika et al., 2021; Okwesa & Iwuanyanwu, 2020; Onche & Ogbonna, 2022; Onche et al., 2020).

The argument for including this material in a health review is that a safety instrumented system that has been disabled, spoofed or rendered untrustworthy is a failed barrier, and the

consequences of a failed barrier in sour or high pressure service are measured in lives rather than in data loss.

3.9. Health Service Infrastructure for Exposed Populations

A surveillance programme or a clinical referral pathway is only as good as the health service that receives the patient. In the regions where exposure is most intense, that service is frequently distant, under equipped and unable to perform the investigations on which occupational diagnosis depends. This is a determinant of health outcome in its own right, and it belongs in a review of mitigation rather than being treated as background.

Research on diagnostic facility development addresses sustainable laboratory infrastructure models, infrastructure driven expansion of diagnostic access in underserved areas, spatial planning to improve diagnostic throughput, regulatory compliant design for molecular and pathology laboratories, lifecycle performance evaluation of purpose built facilities, sustainable materials and energy efficiency in laboratory design, governance and accountability models for public private partnership delivery, cost control and financial accountability in national diagnostic programmes, and resilience planning for diagnostic systems under disruption (Aminu-Ibrahim et al., 2018; Aminu-Ibrahim et al., 2019; Aminu-Ibrahim et al., 2020; Aminu-Ibrahim et al., 2021; Aminu-Ibrahim et al., 2022; Ogbete et al., 2018; Ogbete et al., 2019; Ogbete et al., 2020; Ogbete et al., 2021; Ogbete et al., 2022).

System level work on health financing, service delivery reform and transformation determines whether such facilities can be sustained once built, and whether occupational and environmental health services are funded as a recognised category or left to employer discretion (Ilodigwe & Adesemoye, 2019a; Ilodigwe & Adesemoye, 2019b; Ilodigwe & Adesemoye, 2020; Ilodigwe & Adesemoye, 2021; Okoli et al., 2020).

Diagnostic capability is the specific constraint for several of the conditions reviewed here. Silicosis and other pneumoconioses are identified radiographically, benzene related haematological effects through laboratory haematology, and exposure confirmed through biological monitoring, so work on imaging modalities, image interpretation and quality, and clinical laboratory diagnostics bears directly on whether these conditions are detected at a stage where intervention is still useful (Abdulrazaq et al., 2019; Abdulrazaq et al., 2021; Ejofodomi et al., 2014; Yusuf et al., 2020; Yusuf, 2018).

Nursing is the discipline that delivers most occupational health surveillance in practice, including periodic examination, health education, triage and follow up, and research on patient care models, clinical service delivery and nurse led intervention is therefore directly applicable to the staffing of site clinics and periodic medical programmes (Akinlolu et al., 2022; Nnaji & Akinlolu, 2022; Omaghomi et al., 2022).

Pharmaceutical access and diagnostic service research completes the picture, since treatment availability determines whether a diagnosis leads to management or merely to documentation (Asiedu & Asiedu, 2022; Asiedu, 2022; Gbadamosi & Obogo, 2013).

3.10. Energy Transition and the Changing Occupational Health Landscape

Drilling does not take place in a static energy system, and the direction of change shapes both the residual risks of hydrocarbon operations and the emerging risks of what replaces them. Three consequences are relevant to this review: ageing assets operated at reduced capital intensity, a workforce facing displacement and retraining, and new technologies with their own uncharacterised hazard profiles.

The energy justice literature is directly applicable because the communities that host drilling are frequently those that will bear the costs of transition. It addresses worker displacement and skills mapping in transitioning energy economies, diversification pathways for economic resilience in formerly fossil dependent regions, community trust as a measurable determinant of project durability and social licence, affordability and inclusion in distributed energy provision, financing mechanisms for inclusive energy access, intersectional critiques of universal programme design, and unified socio technical frameworks for equitable transition in resource dependent regions (Komi & Adeniji, 2020; Komi & Ganiu, 2022; Komi, 2021).

Technical work on system integration, including renewable yield and load forecasting, hybrid deep learning approaches to wind forecasting, smart grid architecture for high renewable penetration, control architectures for distributed energy resources, battery storage performance and degradation in hot and weak grid regions, edge intelligence for resilient microgrid control, interpretable prediction of failures in distributed assets, and tiered digital twin diagnostics for resource constrained sites, determines whether alternatives can realistically displace diesel generation at remote sites (Adenuga, 2022; Komi, 2021; Komi, 2022; Shittu et al., 2019).

A caution applies throughout. Transition does not eliminate occupational hazard, it changes its composition, introducing work at height, electrical and arc flash risk, battery chemistry hazards, critical mineral supply chain exposures and new ergonomic demands. The lesson of the drilling experience reviewed here, that controls are known long before they are uniformly implemented, applies with equal force to what comes next.

3.11. An Integrated Conceptual Model

The synthesis supports an integrated model of drilling related health risk that is set out here because the literatures reviewed, taken individually, each capture only one layer of a single causal system. Industrial hygiene describes agents and exposures, process safety describes barrier failure, asset integrity describes loss of containment, management systems research describes organisational degradation, and public health research describes outcomes. The model links them.

Structure of the model

The model has five layers. The first is the generating layer, comprising the unit operations that create hazardous agents: fluid circulation and solids separation, proppant handling, combustion for power, pressure containment, and fluid storage and transfer. The second is the barrier layer, comprising the engineered and human barriers interposed between agent and receptor, including containment integrity, ventilation and capture, vapour recovery, detection and alarm, permit systems and the competent individuals who operate them. The third is the pathway layer, in which agents that defeat the barriers travel through air, water, soil or direct physical contact. The fourth is the receptor layer, dual in nature, comprising the occupational receptor characterised by high intensity intermittent exposure and the community receptor characterised by lower intensity continuous exposure over longer periods and including susceptible subgroups. The fifth is the outcome layer, comprising acute injury and poisoning, chronic disease, and the livelihood and ecological consequences that convert environmental damage into human harm.

Two cross cutting influences act on every layer. The first is organisational condition, meaning leadership attention, contracting structure, workforce stability, production pressure, procurement specification and assurance capability, which determines whether designed barriers are present and functioning. The second is institutional condition, meaning regulatory standards and enforcement capacity, health service and diagnostic capability, surveillance

infrastructure and community voice, which determines whether failures are detected, attributed and remedied. These two influences explain the central empirical observation of this review, namely that technical knowledge of control substantially exceeds its implementation.

Table 4 – Integrated conceptual model of drilling related health risk, showing each layer, its principal failure mode and the point of intervention.

Layer	Content	Characteristic failure mode	Point of intervention
Generating	Fluid circulation and solids control, proppant handling, diesel combustion, pressure containment, fluid storage and transfer	Hazard created unnecessarily where a lower hazard process or input was available	Elimination and substitution: fluid selection, non silica proppant, electrification, gas capture in place of flaring
Barrier	Containment integrity, ventilation and capture, vapour recovery, detection and alarm, permit systems, competent personnel acting as human barriers	Barrier absent, degraded, bypassed for production reasons, or defeated through control system compromise	Engineering controls, asset integrity management, process safety management, instrumented system security
Pathway	Air, water, soil and sediment, direct physical contact	Release disperses before detection; slow release undetected for extended periods	Monitoring, leak detection and repair, remote sensing, secondary containment, setback distance
Receptor	Occupational receptor with intermittent high intensity exposure; community receptor with continuous lower intensity exposure, including susceptible subgroups	Exposure unmeasured; peak exposure masked by shift averaging; vulnerable subgroups not differentiated	Task based and real time exposure assessment, biomonitoring, protective equipment as final layer
Outcome	Acute injury and poisoning, chronic disease, livelihood and ecological harm	Outcome undetected, misattributed, or detected too late for intervention	Medical surveillance, diagnostic and clinical capacity, population health surveillance, remedy mechanisms
Organisational condition	Leadership, contracting structure, workforce stability, procurement specification, assurance	Designed controls degrade in practice; contractor workforce bears residual risk	Safety management systems, contractor governance, procurement assurance, audit and improvement

Layer	Content	Characteristic failure mode	Point of intervention
Institutional condition	Regulation and enforcement, health service capacity, surveillance, community voice	Absence of evidence mistaken for absence of harm; non compliance carries low cost	Performance based regulation with inspection capacity, financial assurance, transparent disclosure, engagement

The practical value of the model is diagnostic. It directs attention to the layer at which a given problem actually sits, which is frequently not the layer at which it presents. A documented overexposure to respirable silica at a sand transfer point presents as a hygiene failure in the receptor layer, but it usually originates in the generating layer through proppant selection, in the barrier layer through absent dust capture, and in the organisational layer through a contracting arrangement that leaves the exposed crew outside the operator assurance programme. Interventions aimed only at the layer of presentation, typically by issuing respirators, leave the generating mechanism untouched.

3.12. Synthesis of Cross-Cutting Findings

Four findings emerge from the synthesis that merit discussion because they cut across the individual literatures.

The implementation gap is the dominant finding

The most consistent result of this review is that the technical means of controlling the major exposure pathways are established, documented and commercially available, and that the binding constraint is implementation rather than knowledge. Closed loop solids control, vapour recovery with remote gauging, enclosed proppant handling, green completions, substitution of fluids and prime movers, well barrier verification, secondary containment and leak detection and repair collectively address the great majority of pathways described in Section 3.2. Where harm persists, it is generally because a known control was not installed, not maintained, or not extended to the contractor performing the task. This reframes the policy question from what should be done to why what is known is not done, which is an organisational and institutional question rather than an engineering one.

The unit of exposure is the mixture and the peak, not the compound and the average

A second finding concerns measurement. Regulatory and industrial hygiene practice remains organised around single compounds assessed as shift averages, while the exposures that cause harm are mixtures punctuated by short high intensity peaks during specific tasks. Tank gauging, mud mixing, sand transfer and maintenance of contaminated equipment generate exposures that an eight hour average will understate or conceal entirely. The documented fatalities at open tank hatches are the extreme expression of a measurement paradigm that is poorly matched to the exposure it is meant to characterise. Correcting this requires task based sampling, real time instrumentation and biomonitoring, none of which is technically novel.

Occupational and environmental health are one problem, not two

A third finding is that the conventional institutional separation between worker protection and environmental protection is not supported by the structure of the hazard. A leaking valve, a failed cement job, an inefficient flare and an unlined pit each produce occupational and community exposure simultaneously, and the control that addresses one addresses the other. The separation persists because it mirrors regulatory and professional boundaries rather than

causal ones, and it produces predictable failures, including controls justified only by worker exposure limits that leave community exposure unaddressed, and monitoring programmes that cannot be compared because they were designed for different audiences.

Evidence intensity is inversely related to exposure intensity

A fourth finding is uncomfortable. The regions generating the most intense and prolonged exposures, including parts of the Niger Delta, the Amazon basin, Central Asia and the Middle East, are the regions with the least published health evidence, while the best studied basins are those with comparatively robust regulation and surveillance. This inverse relationship means that global assessments of the health burden of hydrocarbon extraction are systematically weighted towards the better controlled end of the distribution. Interpreting the resulting evidence base as representative would understate the aggregate burden, and the absence of evidence in high exposure regions should be read as a statement about surveillance capacity, not about safety.

3.13. Implications

Implications for operators and contractors

- Prioritise the generating and barrier layers over the receptor layer. Investment in substitution and engineering control yields more durable risk reduction than equivalent investment in protective equipment and procedural compliance.
- Extend the operator exposure control standard contractually to every service company on the pad, since the highest exposure tasks are predominantly contracted out.
- Treat procurement as a health control. Additive selection, equipment specification and contractor qualification determine exposure long before work begins.
- Replace manual tank gauging with remote or automated measurement as a priority intervention, given the documented fatality record associated with the task.
- Report exposure monitoring results by task rather than by shift average, so that peaks are visible to those designing controls.

Implications for regulators

- Mandate specific engineering controls at tasks where exposures are documented to exceed limits, rather than relying on general duties that defer the choice of control to the duty holder.
- Build inspection and verification capacity, since enforcement capability rather than the absence of standards is the characteristic constraint in most producing regions.
- Require financial assurance for plugging, abandonment and restoration so that long term liabilities are not transferred to the public.
- Treat setback and encroachment control as a continuing duty subject to periodic review, following the practice established in other regulated high hazard industries.
- Require chemical disclosure sufficient for treating clinicians and emergency responders, without proprietary exemption.

Implications for occupational health and clinical practice

- Design medical surveillance around the agents actually present, including audiometry, spirometry and imaging, haematology where benzene exposure is significant, dermatological assessment for fluid contact roles, and dosimetry for radiation workers.

- Analyse surveillance data in aggregate to detect group level trends, rather than filing results individually.
- Recognise cardiovascular, renal and mental health outcomes as part of the occupational burden in this sector, not only respiratory and traumatic injury.
- Invest in the diagnostic capacity on which occupational diagnosis depends, since a surveillance programme without access to imaging and laboratory services cannot detect the conditions it is designed to find.

Implications for communities and civil society

- Establish baseline environmental monitoring, particularly of groundwater, before drilling begins, since the absence of a baseline is the most common obstacle to attributing subsequent contamination.
- Participate in monitoring design and data access, so that results are usable as evidence rather than only as reassurance.
- Ensure emergency notification arrangements accommodate multilingual populations and those with sensory or literacy barriers.

3.14. Limitations

Several limitations constrain the conclusions of this review and should be weighed by readers.

- Method. This is a structured narrative review, not a systematic review. Sources were selected against stated criteria but without a reproducible search protocol, duplicate independent screening or formal quality appraisal, so selection bias cannot be excluded and the synthesis is not reproducible in the sense that a systematic review would be.
- Evidence horizon. The review excludes material published after 2022. Both the technical and regulatory landscapes have continued to develop, so statements about current practice, prevailing exposure limits and the state of the evidence should be read as applying to that horizon.
- Geographical coverage. The underlying literature is heavily weighted towards North American unconventional development. Conclusions about exposure magnitude and control effectiveness may not transfer to settings with different geology, climate, regulation and workforce structure.
- Exposure surrogates. Much of the community epidemiological evidence relies on residential proximity or well density rather than measured exposure. These surrogates conflate chemical, noise, light, traffic and psychosocial stressors, so reported associations cannot be attributed confidently to any specific agent.
- Confounding and the healthy worker effect. Observational studies in this field face persistent socioeconomic confounding, and occupational mortality studies are subject to selection effects that bias overall rates downward and may obscure genuine excess risk for specific outcomes.
- Methodological transfer. Several bodies of literature are included on the basis that their methods transfer to drilling contexts rather than because they studied drilling directly. Such transfer is argued in the text but not empirically validated, and readers may reasonably judge individual cases differently.
- Publication and reporting bias. Negative or null findings and unfavourable monitoring results are less likely to enter the published record, particularly where data are generated commercially, which may bias the apparent strength of reported associations.

- No quantitative synthesis. Heterogeneity of design, exposure metrics and outcome definitions precluded pooled estimation, so this review cannot provide quantitative estimates of effect size or attributable burden.

3.15. Future Research Directions

Several gaps limit the current evidence base and define the priorities for future work. They follow directly from the limitations in Subsection 3.14 and from the structure of the conceptual model, and are ordered by the layer at which the gap sits.

- Geographical imbalance. The epidemiological literature is dominated by North American unconventional development. Major producing regions including West Africa, the Middle East, Central Asia and the Amazon basin remain substantially under studied despite exposure intensities that are frequently higher and health surveillance that is frequently weaker.
- Exposure characterisation. Reliance on residential proximity as a surrogate limits causal inference. Studies combining personal and area monitoring, biomarkers of exposure and effect, and refined spatial modelling are needed to attribute observed health signals to specific agents.
- Mixtures and cumulative risk. Risk assessment remains largely compound by compound, while real exposures are mixtures acting alongside noise, heat, shift work and psychosocial stress. Methods for cumulative risk assessment exist but are rarely applied in this sector.
- Peak exposure. Shift averaged measurement systematically understates the short duration high intensity exposures characteristic of tank gauging, mud mixing and sand transfer. Task based and real time sampling strategies should become standard.
- Additive toxicity data. A substantial proportion of disclosed stimulation and drilling additives lack the toxicological data required for quantitative risk assessment. Closing this gap requires both regulatory data call in and the removal of proprietary barriers to disclosure.
- Long latency outcomes. Cancer and chronic kidney, cardiovascular and neurodegenerative outcomes require longitudinal cohorts with adequate follow up, which the mobility and contractor fragmentation of the workforce make difficult but not impossible given linkage to national health registries.
- Vulnerable subgroups. Pregnant workers and residents, children, older adults and people with pre existing disease are inadequately represented in both exposure and outcome studies.
- Control effectiveness. Relatively few studies quantify the exposure reduction achieved by specific engineering controls under field conditions, which is precisely the evidence operators and regulators need to prioritise investment.
- Abandoned and orphaned wells. The scale of emissions and groundwater risk from legacy wells, and the effectiveness of plugging programmes, remain poorly quantified in most jurisdictions.

4. Conclusion

Oil and gas drilling generates a hazard profile that is unusual in its breadth, combining chemical, physical, biological and psychosocial agents within a single compact operation, and unusual in its reach, because the same source population of contaminants serves both an

occupational and a community receptor. The exposure pathways are well described: inhalation of volatile organic compounds, respirable crystalline silica, diesel particulate, hydrogen sulphide and secondary ozone; dermal and inadvertent ingestion contact with fluids and crude; migration of contaminants to groundwater and surface water through surface spills, pit leakage, well integrity failure and inadequate wastewater management; soil and sediment loading that transmits contaminants into the food chain; and physical agents acting directly on the body.

The toxicological case for concern is strongest and best characterised for benzene, crystalline silica, polycyclic aromatic hydrocarbons, diesel exhaust and hydrogen sulphide, each of which has a defined mechanism and, for most, a recognised carcinogenic or acutely lethal potential. Epidemiological evidence from communities near intensive development, while limited by exposure misclassification and confounding, is consistent enough across perinatal, respiratory and cardiovascular endpoints to warrant precautionary action rather than continued deferral pending perfect data.

The central practical conclusion of this review is that the technical means of control are largely known and available. Closed loop solids control, vapour recovery with remote gauging, green completions, enclosed proppant handling, substitution of fluids and prime movers, rigorous well barrier verification, secondary containment, leak detection and repair, acoustic enclosure and structured health surveillance collectively address the great majority of the exposure pathways described here. The deficiency is one of implementation, enforcement and verification rather than of engineering knowledge. Where implementation is uneven, as it is in many of the world largest producing regions, the resulting burden falls disproportionately on contractor workforces and on rural and economically disadvantaged communities with the least capacity to document harm or to obtain remedy.

Three priorities follow. First, regulatory frameworks should shift decisively from reliance on administrative controls and personal protective equipment towards mandated engineering controls at the specific tasks where exposures are known to exceed limits. Second, exposure assessment should move from shift averaged compound by compound sampling towards integrated, task based, real time and biomarker informed approaches capable of capturing peaks and mixtures. Third, the research effort should be rebalanced geographically so that the regions bearing the greatest exposure burden are no longer the regions about which least is known. Achieving these would not eliminate the risks inherent in drilling, which are substantial and partly irreducible, but it would bring actual practice closer to what current knowledge already makes possible.

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