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INTEGRATED PROCESS AND OCCUPATIONAL RISK ASSESSMENT IN A SAHELIAN PETROLEUM DEPOT USING HAZOP–HIRA: THE BINGO DEPOT CASE STUDY

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ABSTRACT

Petroleum depots combine major-accident and occupational hazards that are usually assessed separately. This study proposes an integration step that links the outputs of a Hazard and Operability study (HAZOP) and a Hazard Identification and Risk Assessment (HIRA) through shared root causes and shared safety barriers, and applies it to the Bingo depot (Burkina Faso), which recorded 12 occupational accidents and 9 fire outbreaks in 2022. HAZOP of the largest diesel tank (fixed-roof tank R08) was complemented by screening calculations of boilover propensity, thin-layer boilover onset time, emergency venting and fire protection capacity. HIRA rated 48 hazardous situations at four workstations using a semi-quantitative risk-control index NM = NE × NG × NP. The integration identified six root causes, five of them common to both analyses; the corresponding shared barriers (notably interlocks, ignition control in ATEX zones and remote gauging) address 27 of the 48 workplace situations, including 17 of the 22 uncontrolled ones, while also acting on the major-accident chain. Fire protection analysis showed that water pumping covers a bund fire even under N−1 conditions, whereas the single foam concentrate pump is saturated (99%) in the reference scenario and insufficient (126%) in an envelope scenario. Diesel exceeds the PBO screening threshold (1.20 vs 0.6), but experimental evidence points to a thin-layer boilover with an estimated onset of 21–58 h. Of the 48 situations, 44 (91.7%) do not reach the controlled class of the adopted index. The approach yields a single prioritised action plan transferable to other West African depots.

Keywords: HAZOP; HIRA; Safety barriers; Thin-layer boilover; Fire protection; Petroleum depot

1 INTRODUCTION

Occupational safety and health remains a major global concern. According to the latest International Labour Organization estimates for 2019, about 2.93 million workers died from work-related causes and more than 395 million suffered a non-fatal occupational injury [1]. In Burkina Faso, the Labour Code (Act No. 028-2008/AN, Art. 236) requires

every employer to ensure that workplaces, equipment and processes under its control present no risk to the health and safety of workers [2].

Hydrocarbon storage facilities combine two families of hazards. The first is major accidents: of 242 storage tank accidents reviewed over forty years, 74% occurred in refineries, terminals or oil depots, with fire and explosion as the dominant failure modes [3,4]. The Buncefield fire (United Kingdom, 2005), triggered by the overfilling of a tank whose level gauging and high-level protection had failed, demonstrated the critical role of instrumented barriers [5]. In West Africa, the explosion and fire at the main fuel terminal of Conakry (Guinea) on 18 December 2023 caused more than twenty deaths, several hundred injuries and a disruption of the national fuel supply [6,7]. The second family is everyday occupational risk: manual handling, vehicle traffic, work at height on tank trucks, exposure to vapours and static electricity.

For process hazards, the Hazard and Operability study (HAZOP) is the most widely studied and applied identification technique in the process industries [8–10]. Applied to a fuel storage terminal, it showed that loading and unloading areas are the most sensitive zones, with fuel spillage as the dominant top event [11]. For occupational risks, semi-quantitative Hazard Identification and Risk Assessment (HIRA) methods rely on multi-criteria scoring of exposure, severity and level of protection [12,13]. Both families of methods meet the hazard identification requirements of ISO 45001 [14] within the risk management framework of ISO 31000 [15].

Process safety and personal (occupational) safety are, however, recognised as distinct domains, with different indicators, owners and methods; good personal-safety performance does not guarantee control of major-accident hazards, as shown by the investigation of the 2005 Texas City refinery explosion [16,17]. In practice, HAZOP and workplace risk assessments are therefore conducted by different teams, against different references, and produce separate action lists. Existing combined approaches mostly pair HAZOP with another process-safety technique, such as fault tree analysis, to quantify the same top events [11]; they do not link process deviations to workplace hazardous situations. Yet in a depot the two domains meet physically: a fire at an unloading bay is both an occupational accident and a possible initiating event of a bund fire, and several safety barriers (interlocks, ignition control, detection) act on both. Moreover, published case studies mostly concern European or Asian sites, whereas depots in landlocked Sahelian countries, supplied by road from distant ports and operated with little automated control, remain poorly documented.

The contribution of this study is therefore not the isolated application of HAZOP or HIRA, but an explicit integration step that links their outputs through common root causes and shared safety barriers, so that process-safety and occupational-safety actions can be prioritised within a single hierarchy of controls. The approach is applied to the Bingo depot of the national hydrocarbon company SONABHY, which recorded 12 occupational accidents and 9 controlled fire outbreaks in 2022 [18]. The specific objectives are: (i) to identify the deviations that may lead to fire or explosion of the largest diesel tank (R08) and to screen the associated phenomena (boilover, pressurisation); (ii) to check the adequacy of fire protection capacity for bund fire scenarios; (iii) to rate the level of control of occupational risks at the four most accident-prone workstations; and (iv) to derive, through the integration step, a single prioritised action plan.

2 MATERIALS AND METHODS

2.1 Study site and selected areas

The Bingo depot lies west of Ouagadougou in the Sudano-Sahelian climate zone. At the time of the study it was the largest SONABHY site in area and workforce (209 exposed workers) and supplied 10 of the country's 13 regions [18]; an extension programme was then under way [19]. The depot stores liquid fuels (premium gasoline, diesel, kerosene, distillate diesel oil (DDO), heavy fuel oil) and butane in cylinders. Five process and work areas were selected on the basis of the 2022 accident and fire-outbreak records:

- tank R08, a vertical fixed-roof diesel tank 24 m in diameter and 14.40 m high (6,520 m^3), the largest in the storage area, located in a 60 m × 35 m retention bund (2,100 m^2) with a useful height of 1.85 m (process node analysed by HAZOP);
- the electronic nine-cell palletiser of the 12.5 kg butane cylinder filling line (workstation);
- the filling carousel of the same line (workstation);
- premium gasoline unloading bay No. 1 (workstation);
- premium gasoline loading bay No. 1, operated by top loading (workstation).

Data were collected during a field placement from July to November 2023 through direct observation of tasks, interviews with operators and supervisors, and review of accident registers, drawings and equipment data sheets [18].

2.2 Integrated approach

The approach (Fig. 1) comprises three stages. In the process branch, HAZOP is applied to tank R08 and followed by screening calculations of hazardous phenomena and fire protection capacity. In the workstation branch, HIRA is applied to the four workstations. In the integration stage, each HAZOP cause and each HIRA hazardous situation is coded by (a) its root cause and (b) the safety barrier function that would prevent or mitigate it, following the barrier classification of Sklet [20]. A root cause or barrier that appears in both branches is termed *shared*. Shared engineering barriers are prioritised first, because a single investment then reduces both the frequency of an initiating event of a major accident and the exposure of workers; the remaining actions are ranked according to the ISO 45001 hierarchy of controls [14].

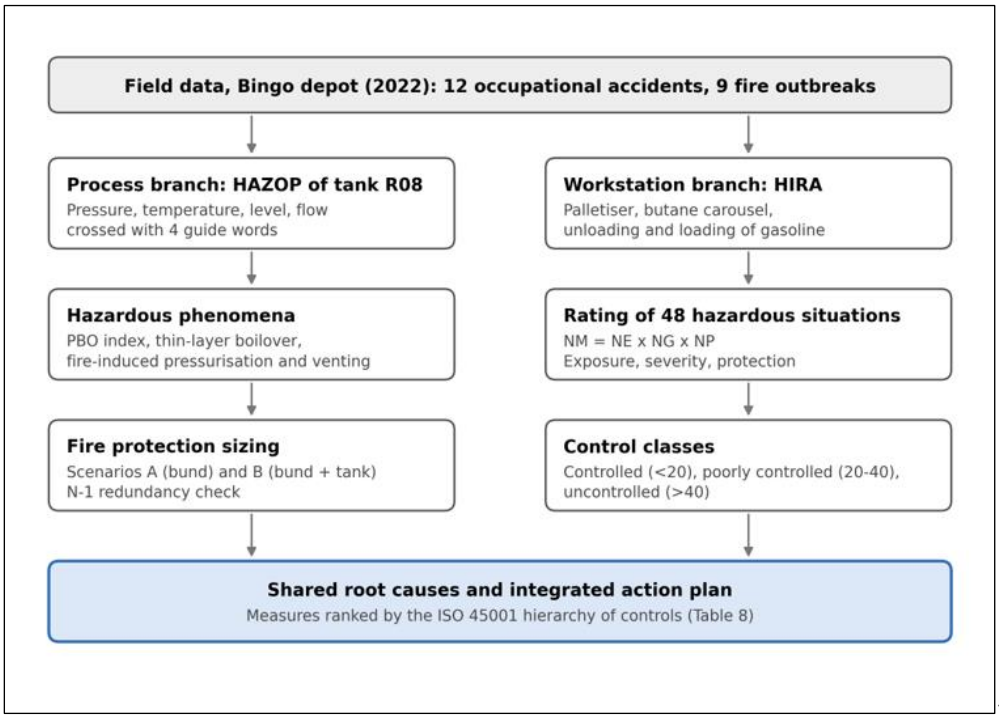


Figure 1: Integrated HAZOP–HIRA approach applied to the Bingo depot. The process branch (left) and the workstation branch (right) start from the same field data; the integration stage links their outputs through shared root causes and barriers.

2.3 HAZOP study of tank R08

The HAZOP study was conducted in accordance with IEC 61882 [9] and methodological guidance reported in the literature [8,10,21]. Tank R08, including its filling and draw-off lines, was considered as a single analysis node. Four process parameters—pressure, temperature, level, and flow—were examined using four guide words (*More*, *Less*, *No*, and *Reverse*), resulting in 16 parameter–guide word combinations.

Each combination was systematically examined to identify relevant deviations. The resulting deviations were classified as developed, merged with another deviation, credible but not further developed, or not physically meaningful for an atmospheric storage tank. For each developed deviation, the analysis considered the potential causes, consequences, detection means, existing safeguards, and recommended additional measures.

The HAZOP analysis was supported by a review of available technical and operational documentation, field observations, and information collected during the assessment of the R08 storage system. This approach enabled the identification and systematic assessment of credible deviations that could contribute to hazardous scenarios associated with the storage and transfer of diesel.

2.4 Boilover propensity and onset time

Boilover results from the sudden vaporisation of water accumulated at the bottom of a burning tank, which ejects the hydrocarbon as a fireball [22,23]. The propensity of a product to boil over was screened with the PBO index (Propensity to Boil Over) proposed by Michaëlis et al. [24] and used by the French working group on flammable liquid depots (GTDLI) [25]:

$$PBO = \sqrt[3]{\left(1 - \frac{393}{T_b}\right) \times \left(\frac{\Delta T_b}{60}\right)^2 \times \frac{\nu}{0.73}} \qquad (1)$$

where T_b is the mean boiling temperature of the product (K), ΔT_b the width of its boiling (distillation) range (K) and ν its kinematic viscosity at 393 K (cSt). Each factor compares a product property with a reference value: a boiling temperature above 393 K, a boiling range of 60 K, needed to form a heat wave, and the viscosity of kerosene (0.73 cSt) [24,26]. A PBO below 0.6 indicates no boilover propensity; above this threshold, boilover is considered possible. The PBO is used here as a screening index of propensity, not as a prediction of the physical boilover mechanism.

Tests conducted in 2006–2007 showed that diesel combustion does not form a heat wave but may produce a less intense *thin-layer* boilover [25,27]. Its onset time t_{BO} was estimated with the GTDLI relation [25]:

$$t_{BO} = \frac{H_0 - \Delta z}{V_r} \qquad (2)$$

where H_0 is the initial liquid height (m), Δz the thickness ejected (a few centimetres, neglected here) and V_r the regression rate of diesel (6.7×10^{-5} m/s) [25]. Because the fill level at the time of a fire is unknown, t_{BO} was computed over the full range of possible levels (0–14.4 m).

2.5 Pressurisation of the fixed-roof tank and vent area

A fixed-roof tank engulfed in a bund fire may pressurise through vaporisation of its contents and rupture if its vents are insufficient; this phenomenon applies to all flammable liquids [25]. The vaporisation rate U_{FB} (Nm^3/h of air equivalent) was estimated with the simplified GTDLI relation derived from API Standard 2000 [28] for tanks higher than 9 m (Eq. 3), and the vent area S_e required to keep the overpressure below the design pressure Δp from Eq. (4):

$$U_{FB} = 6542\, D^{0.82} \qquad (3)$$

$$S_e = \frac{U_{FB}}{C_D \sqrt{\frac{2\Delta p}{\rho_{air}}}} \qquad (4)$$

where D is the tank diameter (m), U_{FB} is expressed in Nm^3/s in Eq. (4), C_D is the vent discharge coefficient and ρ_{air} = 1.3 kg/m^3. The design pressure of tank R08 and the characteristics of its installed vents were not available. Two design pressures usual for atmospheric tanks (5 and 10 mbar) and the range of discharge coefficients given by the GTDLI (0.6–1.0) were therefore used as hypothetical cases. The resulting areas are screening values and do not constitute a compliance assessment of the installed vents.

2.6 Fire protection sizing

Sizing follows the INERIS guidance for flammable liquid storage [29], consistent with the minimum application rate of NFPA 11 [30]: foam solution application rate of 4 $L/min/m^2$, extinguishing time of 20 min, preventive foam blanket of 0.2 $L/min/m^2$ for 60 min after extinction and 3% foam concentrate proportioning. The net bund area S_c is the gross bund area minus the tank footprint; no other equipment occupies the bund:

$$S_c = L \times W - \frac{\pi D^2}{4} = 60 \times 35 - \frac{\pi \times 24^2}{4} = 1647.61\ m^2 \qquad (5)$$

For a burning area S (m^2), the foam solution flow rate Q_m (L/min), the solution volume V_m (L) and the foam concentrate volume V_e and flow rate Q_e are:

$$Q_m = 4\, S \qquad (6)$$

$$V_m = 20\, Q_m + 60 \times 0.2\, S_c \qquad (7)$$

$$V_e = 0.03\, V_m, \quad Q_e = 0.03\, Q_m \qquad (8)$$

Two scenarios were considered. Scenario A, the site's reference scenario, is a fire over the net bund area ($S = S_c$). Scenario B is an envelope scenario representing the escalation sequence: loss of containment (overfill or line rupture) → bund pool fire → engulfment of the tank shell → heating and pressurisation → failure of the roof-to-shell joint → full-surface tank fire concurrent with the bund fire. In scenario B, the extinguishing flow is applied to the gross bund area (S = 2,100 m^2, i.e. bund plus tank surface), while the preventive blanket of Eq. (7) is applied to the net bund area only, since a tank whose roof has failed is not covered by a post-extinction blanket. Applying the blanket to the full 2,100 m^2 would increase the solution volume by 5.4 m^3 (Section 3.4).

Redundancy was checked against an N−1 criterion: with three diesel-driven fire pumps of 450 m^3/h each (N = 3), the capacity available with one pump out of service is 900 m^3/h. This hydraulic check does not by itself demonstrate functional independence, which also depends on pump location, energy supply and suction arrangement (Section 3.9).

2.7 HIRA at the workstations

For each workstation, activities were broken down into operating steps, and each hazardous situation (hazard, risk, harm) was rated on three scales (Tables 1 and 2) taken from the HIRA grid used for the study [13,14,31]. The level of risk control NM is the product of the three ratings:

$$NM = NE \times NG \times NP \quad (9)$$

NM is a semi-quantitative risk-control index that combines exposure, potential severity and the quality of existing protection; it is not a probabilistic measure of risk. Three classes were used: controlled (NM < 20), poorly controlled (20 ≤ NM ≤ 40) and uncontrolled (NM > 40). These class boundaries were set by the authors for this study. Their meaning is shown in Table 2 for daily exposure (NE = 10), which applies to 46 of the 48 rated situations: a situation is uncontrolled when lost-time harm (NG ≥ 7) is possible without structured protection (NP ≥ 0.7), and controlled only when structured protection with periodic verification exists, or structured protection exists for first-aid-level harm. A share of 95% of controlled situations was adopted in this study as the acceptability target. The 48 rated situations, with their ratings and existing controls, are listed in Supplementary Table S1.

Table 1: Exposure level matrix NE (frequency × duration per occurrence).

Frequency	> 4 h	1–4 h	15 min–1 h	< 15 min
Daily (> 150 d/yr)	10	10	7	7
Weekly (50–150 d/yr)	10	7	7	4
Monthly (10–49 d/yr)	7	4	4	1
Yearly (< 10 d/yr)	4	1	1	1

Table 2: Severity (NG) and protection (NP) scales, and resulting NM and control class for daily exposure (NE = 10). C = controlled; P = poorly controlled; U = uncontrolled.

Severity NG	NP = 1 (not protected)	NP = 0.7 (unstructured or insufficient measures)	NP = 0.4 (structured measures)	NP = 0.05 (structured, periodically verified)
10 (> 3 months lost time, disability or death)	100 U	70 U	40 P	5 C
7 (lost-time accident)	70 U	49 U	28 P	3.5 C
4 (first aid, no lost time)	40 P	28 P	16 C	2 C
1 (discomfort, no injury)	10 C	7 C	4 C	0.5 C

3 RESULTS AND DISCUSSION

3.1 HAZOP screening and deviations

Of the 16 parameter/guide-word combinations, seven deviations were developed, two were merged with a developed deviation, three were judged credible but not developed in the workshop, and four were not physically meaningful (Table 3). The three credible combinations not developed (underpressure during draw-off, no flow and reverse flow) are recommended for a follow-up session.

Table 3: Screening of the 16 HAZOP parameter/guide-word combinations for tank R08. D = developed (Table 4); M = merged; ND = credible, not developed; NA = not physically meaningful.

Parameter	More	Less	No	Reverse
Pressure	D	ND: underpressure (vacuum) during draw-off with blocked vents	M (with Less)	NA
Temperature	D	D	NA	NA
Level	D	D	M (empty tank, with Less)	NA
Flow	D	D	ND: blocked line or stopped pump	ND: backflow through failed check valve

All *More* deviations converge on three top events: loss of containment (line rupture, overfill), bund fire and, in a prolonged fire, pressurisation or boilover of the tank (Table 4). Existing safeguards are almost exclusively human (visual checks, manual dipping) and rely on single instruments not relayed to a control room.

Table 4: Developed HAZOP deviations for tank R08 (flow deviations grouped; detailed worksheet in Supplementary Table S2).

Parameter / guide word	Main causes	Consequences	Existing safeguards	Recommendations
Pressure / More	Operator error; failed relief valves; blocked valve or check valve; heating by adjacent fire	Line rupture, spill, fire, tank pressurisation	Single local pressure gauge; relief valves to a secondary line	Duplicate gauges; relay to control room; periodic relief valve calibration; cooling triggered by pressure switch
Temperature / More	Blocked vents; external or internal fire; high ambient temperature	Evaporation, pressure rise, auto-ignition, boilover	Thermostat at tank base; manual water–foam deluge	Dual thermostat (top/bottom); deluge triggered by temperature set point; intermediate cooling ring
Temperature / Less	Climatic conditions (rare in the Sahel)	Waxing, line plugging, pump damage	Visual inspection	Marginal risk; no priority action
Level / More	No automatic shutdown of filling pumps; operator error; faulty gauging	Overfill, pool in bund, bund fire, pollution	Varec gauge and manual dipping from the tank roof	Independent high-high level alarm tripping the pumps; vapour detectors in bund; tested overfill drill
Level / Less	Leak; line rupture; no automatic shutdown of draw-off pumps	Pump cavitation, explosive atmosphere in vapour space, equipment damage	Varec gauge; visual check	Low-level alarm with interlock; emergency drills; designated watch officer
Flow / More and Less	False flowmeter reading; electric pump failure; misaligned valve	Wrong reading, induced overpressure or overfill, longer transfer	Single flowmeter; corrective maintenance	Duplicate flowmeters; relay to control room; valve–pump interlocks

3.2 Boilover screening and onset time

Diesel shows a PBO of 1.20, twice the 0.6 threshold (Table 5). Three products stored on site exceed this threshold: heavy fuel oil, DDO and diesel. The PBO values in Table 5 are screening values reported in the technical literature; product-specific inputs for the stored diesel (distillation curve according to ASTM D86 [32] and viscosity according to ASTM D445 [33]) were not available, so the index could not be recalculated for the actual product.

Table 5: PBO screening values of stored or comparable petroleum products (threshold: 0.6) compared with the behaviour observed in tests.

Product	PBO	Propensity (PBO > 0.6)	Behaviour observed in tests [25]
Heavy fuel oil	6.76	Yes	Classic boilover
DDO (medium crude)	4.24	Yes	Classic boilover (crudes)
Diesel	1.20	Yes	Thin-layer boilover
Kerosene	0.53	No	Thin-layer boilover (Jet A-1)
Naphtha	0.29	No	Not tested
Gasoline	−0.25	No	Neither

The estimated thin-layer boilover onset time increases linearly with the initial liquid height, from 20.7 h at 5 m to 41.5 h at 10 m and 58.0 h at 14 m (Fig. 2). The phenomenon is therefore strongly delayed with respect to the 20 min foam extinction strategy. It occurs earlier when the tank is less full, whereas its effects depend little on the initial level [25].

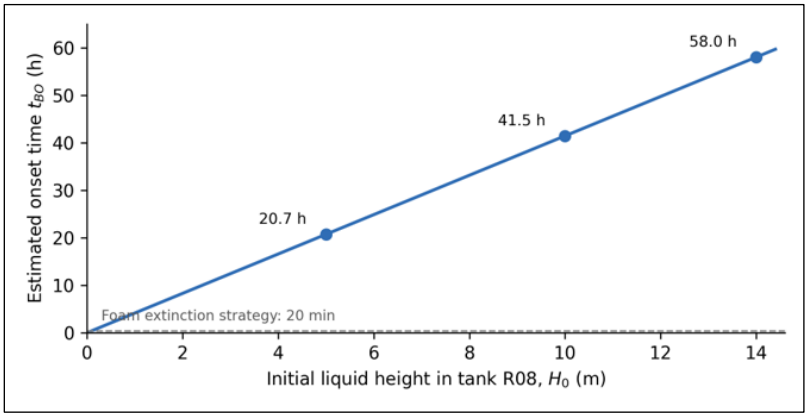


Figure 2: Estimated thin-layer boilover onset time of tank R08 as a function of the initial liquid height (Eq. 2, $V_r = 6.7 \times 10^{-5}$ m/s). The dashed line marks the 20 min foam extinction strategy.

3.3 Pressurisation and vent area

For D = 24 m, Eq. (3) gives a vaporisation rate of U_{FB} = 88,610 Nm^3/h of air, i.e. 24.6 Nm^3/s, for an engulfing bund fire. Depending on the assumed design pressure and discharge coefficient, the required emergency vent area ranges from 0.63 to 1.48 m^2 (Table 6). Because the actual design pressure and installed vent capacity of tank R08 were unavailable, these areas are screening values: the adequacy of the installed vents cannot be established with the available data, and verifying it is a priority action.

Table 6: Required emergency vent area for tank R08 under hypothetical design conditions (U_{FB} = 24.6 Nm^3/s).

Assumed design pressure Δp	C_D = 1.0	C_D = 0.6
5 mbar (500 Pa)	0.89 m^2	1.48 m^2
10 mbar (1,000 Pa)	0.63 m^2	1.05 m^2

3.4 Fire protection requirements

Eq. (5) gives a tank footprint of 452.39 m^2 and a net bund area of 1,647.61 m^2. Scenario A requires 152 m^3 of foam solution, including 4.56 m^3 of concentrate, and a flow rate of 395.4 m^3/h (Table 7). Scenario B requires 504 m^3/h and 187.8 m^3 of solution (168.0 m^3 for extinction plus 19.8 m^3 for the preventive blanket), or 193.2 m^3 if the blanket were applied to the full 2,100 m^2. The site's existing fire-water tank of 2,000 m^3 [19] covers these volumes about ten times.

Table 7: Fire protection requirements and installed capacities.

Quantity	Scenario A: net bund	Scenario B: bund + tank	Installed capacity
Burning area for extinction (m^2)	1,647.61	2,100.00	—
Foam solution flow rate (m^3/h)	395.4	504.0	1,350 (N = 3 × 450); 900 under N−1
Foam solution volume (m^3)	151.6 ≈ 152	187.8	Fire-water tank: 2,000 m^3
of which water, 97% (m^3)	147.44	182.1	—
of which concentrate, 3% (m^3)	4.56	5.63	—
Concentrate flow rate (m^3/h)	11.86	15.12	12 (one electric pump)
Utilisation of concentrate pump	99%	126%	—

Water pumping is therefore not limiting: scenario B uses 56% of the capacity available under N−1 (Fig. 3a). The foam concentrate chain is the bottleneck: it is saturated at 99% in scenario A, with no back-up pump, and insufficient by 26% in scenario B (Fig. 3b).

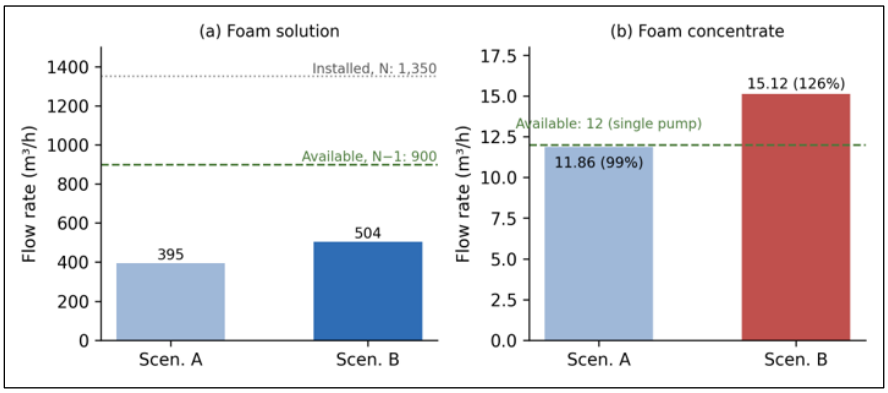


Figure 3: Required versus available capacity for (a) foam solution and (b) foam concentrate in scenarios A (net bund fire) and B (bund + tank fire).

3.5 Level of control of occupational risks

Forty-eight hazardous situations were rated at the four workstations (Table 8, Fig. 4; details in Supplementary Table S1). According to the adopted NM index, 4 situations (8.3%) are controlled, 22 (45.8%) poorly controlled and 22 (45.8%) uncontrolled; 44 situations (91.7%) therefore fall short of the controlled class.

Table 8: Distribution of hazardous situations by workstation and control class.

Workstation	Rated situations	Controlled (< 20)	Poorly controlled (20–40)	Uncontrolled (> 40)	Mean NM	Max NM
Gasoline loading	14	1	5	8	57.6	100
Gasoline unloading	15	1	7	7	50.6	100
Butane carousel	5	0	0	5	70.0	70
Butane palletiser	14	2	10	2	35.7	70
Total	48	4 (8.3%)	22 (45.8%)	22 (45.8%)	50.3	100

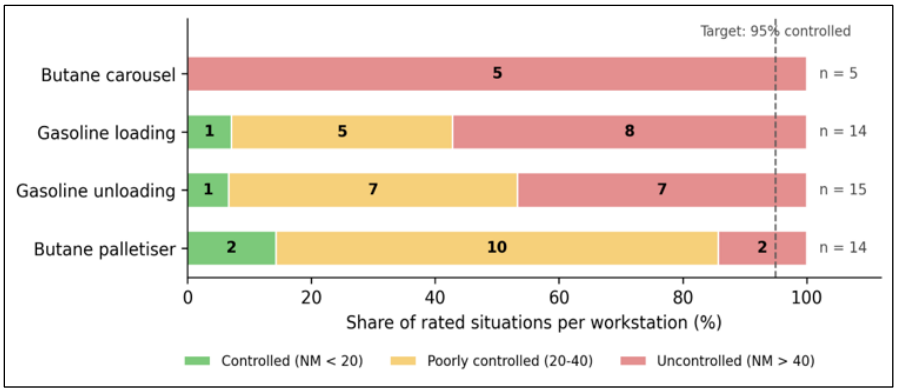


Figure 4: Distribution of hazardous situations by control class and workstation according to the NM index. The dashed line marks the 95% target adopted in this study.

This share expresses insufficient control according to the index, not a probability that these activities will cause an accident. The gap to the 95% target is 87 percentage points.

All five assessed carousel situations were classified as uncontrolled according to the adopted NM index (NM = 70): the operator manually engages and releases pressurised filling clamps on a rotating ring, standing and at production pace, close to butane emissions. At the unloading and loading bays, the maximum score (NM = 100: NE = 10, NG = 10, NP = 1) corresponds to work at height on top of tank trucks without collective fall protection. Next (NM = 70) come failure to earth the truck or to remove the earthing clamp, heavy vapour emissions during top loading, and manual closure of hatches. At the palletiser, the two uncontrolled situations relate to the force and speed of the cylinder transfer ram.

These situations coincide with several 2022 events: a fall of an unloading operator from the top of a tank truck (7 July), a filling ram descending onto a worker (23 June), a finger trapped in the carousel (3 November) and three fire outbreaks on tank trucks [18]. This provides an initial consistency check between the semi-quantitative assessment and the site's historical accident record, although it does not by itself validate the method.

3.6 Integration of HAZOP and HIRA outputs

Table 9: Integration matrix linking HAZOP deviations and HIRA situations (IDs from Supplementary Table S1) through root causes and shared barriers.

Root cause	HAZOP deviations	HIRA situations	Shared barrier
RC1 Missing safety interlocks	Level More/Less; Flow	DEP05, DEP14, CHA03, CHA14 (earthing); CHA08, CHA09 (loading arm, pump start)	Independent high-high level trip of filling pumps; earthing–pump permissive
RC2 Single, uncalibrated instruments	Pressure More; Temperature More; Flow	DEP10, DEP11, CHA09 (transfer pump defects)	Duplicated instruments; planned calibration and pump inspection
RC3 No centralised detection and alarm	All developed deviations (detection by visual check)	CAR01–CAR05 (butane release); DEP02, DEP12, CHA05 (vapour release)	Site-wide gas and fire detection with alarms relayed to a control room
RC4 Ignition sources in ATEX zones	Temperature More, Pressure More (heating by fire)	PAL03, PAL14, DEP03, DEP04, DEP15, CHA01, CHA02, CHA13 (vehicles, electrical equipment)	Battery isolators, spark arresters, earthing control, automatic extinguishing at bays
RC5 Manual work at height or near moving parts	Level More (manual dipping from the tank roof)	DEP02, DEP12, CHA04 (height); PAL06, PAL09, CAR01–CAR05 (rams, rotating ring)	Remote gauging; gangways with guardrails; bottom loading; carousel automation
RC6 Single points of failure in fire protection	Temperature More (manual deluge); fire sizing (§3.4)	— (supports emergency response at all areas)	Duplicated foam concentrate pump; interconnected fire stations; dual energy supply

Coding the HAZOP causes and HIRA situations by root cause and barrier function yielded six root causes (Table 9). Five of them (RC1–RC5) are common to both analyses; RC6 concerns fire protection only. The barriers associated with RC1–

RC5 address 27 of the 48 workplace situations, including 17 of the 22 uncontrolled ones, while acting at the same time on the escalation chain of a bund fire (Fig. 5). The most frequent shared barrier functions are safety interlocks, ignition control in ATEX zones and the removal of manual work at height.

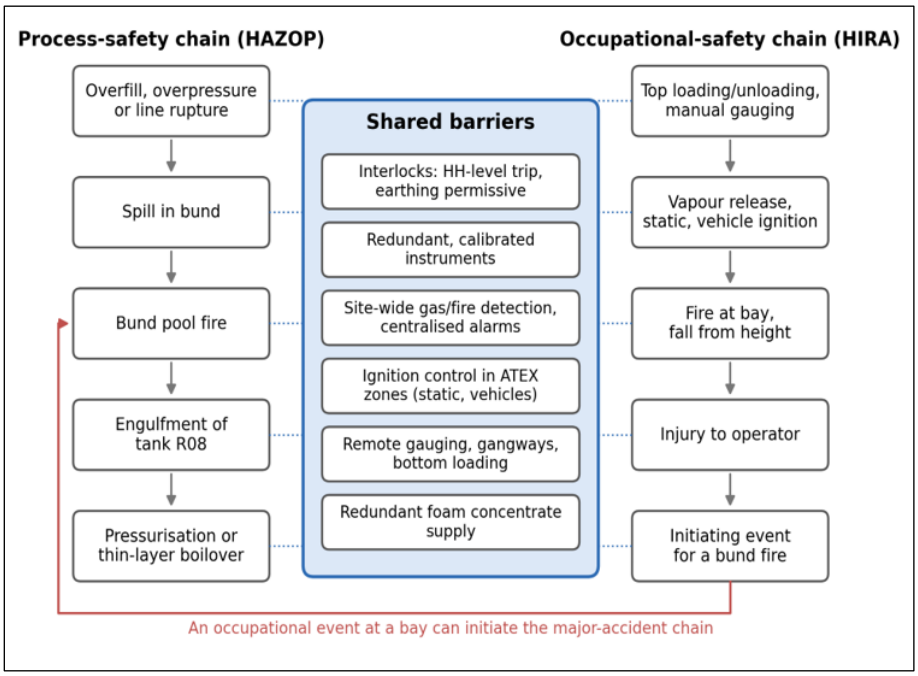


Figure 5: Integrated risk map: the process-safety chain (HAZOP) and the occupational-safety chain (HIRA) are acted upon by the same barriers; an occupational event at a bay can initiate the major-accident chain.

3.7 Contribution of the integration step

Conducted separately, the two analyses would have produced two unrelated lists of recommendations. The integration step shows that most workplace situations with the lowest level of control share their root causes with the process deviations of tank R08 (Table 9). Missing interlocks, for instance, appear both in the shutdown of the R08 filling pumps (HAZOP) and in the absence of a permissive between the earthing clamp and the unloading and loading pumps (HIRA). Likewise, the unloading and loading bays, where the NM = 100 situations and three of the nine 2022 fire outbreaks are concentrated, are also the most likely entry points of a bund fire or spill, in agreement with Fuentes-Bargues et al. [11]. This addresses the separation between process and personal safety discussed in the literature [16,17]: rather than comparing heterogeneous indicators, the integration operates at the level of barriers, which are the objects that management actually funds and maintains [20]. A single engineering measure can thus be justified by its effect on both domains.

3.8 PBO screening versus physical boilover mechanism

A PBO of 1.20 places diesel among products with a boilover propensity, but the index is a screening criterion and not a description of the physical mechanism. The 2006–2007 tests showed that diesel combustion forms no heat wave and therefore produces no classic boilover, but a shorter and less intense thin-layer boilover [22,25,27]. A PBO above 0.6 must therefore not be read as meaning that diesel will produce a classic boilover. The estimated onset time of 21–58 h leaves, in principle, far more time than the 20 min extinction strategy, provided the fire is actually attacked. Acoustic precursors have also been observed before boilover onset [34], offering a monitoring option during intervention.

For a fixed-roof tank such as R08, the main concern in the first hours of a bund fire is rather pressurisation followed by rupture. The 1987 accident at Port Édouard-Herriot (Lyon, France), in which a fixed-roof diesel tank produced a fireball without a prior tank fire, is now interpreted in this way [25,35]. The vent areas in Table 6 indicate the order of magnitude to be checked (0.6–1.5 m^2), but whether the installed vents are adequate remains open. Daily draining of bottom water from diesel, DDO and heavy fuel oil tanks remains relevant but does not remove the risk: a centimetre of water is enough, and firefighting water adds to it during intervention [25].

3.9 Fire protection: sizing driven by foam concentrate

The foam solution flow rate is not limiting in hydraulic terms, but the N−1 check must be qualified. The three diesel fire pumps are grouped at the same location and share the same energy source, and the site action plan itself calls for relocating them and adding electric pumps [18]. A single event (fire, flooding or fuel supply failure) at the pump house

could therefore disable all three, so the hydraulic N−1 margin does not yet correspond to functional redundancy. The weak link remains the foam concentrate chain, saturated in the reference scenario and insufficient in the envelope scenario, with a single pump and a single energy source. The study therefore primarily justifies a duplicated foam concentrate pump of at least 20 m^3/h, the interconnection of the north and south fire stations, the separation of the fire pumps and a dual energy supply. Upgrading the fire pumps from 450 to 650 m^3/h, proposed in connection with the extension programme, is not justified by the R08 scenarios alone and should be reassessed including cooling of adjacent tanks and the future site layout.

3.10 Occupational risks and limits of the NM index

The share of situations below the controlled class is high but largely reflects the structure of the index. With NE = 10 for almost all staffed workstations and NG ≥ 7 for most hazards, the classification depends mainly on NP (Table 2). Moving from NP = 0.7 to NP = 0.05, i.e. structuring a measure and periodically verifying its effectiveness, divides NM by 14 and is enough to move a situation from NM = 70 to the controlled class. The ranking may therefore be dominated by the protection factor rather than by the intrinsic hazard, which is consistent with the management-oriented purpose of the index [14,36] but exposes it to the known limits of multiplied ordinal scales: value compression, sensitivity to class boundaries and subjectivity of the protection score [13,37]. Future applications should use independent double rating by two assessors, comparison of scores and a consensus procedure for discrepancies.

At the carousel, organisational measures will not suffice: only an engineering measure (automatic clamp engagement and release, guarding of the rotating area, accessible emergency stop) addresses the mechanical hazard and butane exposure at source. The latter deserves attention, since an ignited leak near full cylinders may escalate to a boiling liquid expanding vapour explosion (BLEVE) [38]. At the unloading and loading bays, converting top loading to bottom loading removes both work at height and the main vapour emission.

3.11 Integrated action plan

Table 10 ranks the actions according to the hierarchy of controls and links each of them to the root causes of Table 9. Responsibilities and time frames are those of the site action plan drawn up during the study [18]; actions proposed by the authors from the calculations of this study are marked. No cost estimate per action was available; the plan is therefore presented without a global budget.

Table 10: Integrated action plan ranked by the hierarchy of controls.

Level of control	Action	Root cause	Responsible	Time frame	Priority
Engineering	Independent high-high level alarm tripping the filling pumps [5,39]	RC1	DDBI/CSM/CSS/DPP	3 months	1
Engineering	Earthing–pump interlock at unloading and loading bays; mechanical fuse on earthing cable	RC1, RC4	DDBI/CSM/CSS/DPP	3–6 months	1
Engineering	Verify and, if needed, resize the emergency vents of tank R08†	—	DDBI/CSM†	3 months†	1
Engineering	Duplicated foam concentrate pump ≥ 20 m^3/h†; electric fire pumps; separated fire pumps; interconnected fire stations	RC6	DDBI/CSM/CSS/DPP	1 year	1
Engineering	Gangways with guardrails†, then conversion to bottom loading	RC5	DDBI/CSM/DPP	5 years	1–2
Engineering	Automatic clamp handling and guarding of the carousel rotating area†	RC5	DDBI/CSG/CSM†	1 year	2
Engineering	Site-wide gas and fire detection; centralised supervision of process variables and alarms	RC3	DPP/DDBI/CSM/CSS	2 years	2
Engineering	Tank cooling triggered by thermostat and pressure switch; deluge ring around tank R08	RC2, RC6	DPP/DDBI/CSM/CSS	1–2 years	2

Engineering	Automatic fire extinguishing at loading and unloading bays	RC4	DDBI/CSM/CSS/DPP	1 year	2
Engineering	Cathodic protection and coating of buried piping and fire main	—	DDBI/CSM/CSS/DPP	5 years	3
Inspection and maintenance	Duplicated instruments; periodic calibration by an accredited body; inspection schedule	RC2	DDBI/CSM	1 week–3 months	1
Inspection and maintenance	Daily, recorded draining of bottom water (diesel, DDO, heavy fuel oil)	—	DDBI/CSM/CSS	1 week	1
Organisation and training	R08 overfill drill; training in emergency situations	RC1	DDBI/CSS; CRPM	1 month	1
Organisation and training	Targeted training (manual handling, work at height, fire, traffic) and re-qualification after 3 months' absence	RC4, RC5	DQHSE/CRPM/DDBI	1–3 months	2
Organisation and training	Separated, lit and signposted pedestrian and vehicle routes	Traffic	DDBI/CSM/DPP	1 month	2
Protective equipment	Battery isolators, extinguishers and reversing alarms on forklifts; emergency showers at filling centres	RC4	DDBI/CSM/CSS	1–6 months	2

DDBI: Bingo depot management; CSM: maintenance department; CSS: safety department; CSG: gas department; DPP: planning and projects directorate; DQHSE: quality, health, safety and environment directorate; CRPM: petroleum and engine reference training centre. † Proposed by the authors from this study; not in the site action plan.

3.12 Limitations

Several limitations should be noted. The HAZOP study covers a single node, three credible combinations were not developed, and simultaneous failures of several parameters were not addressed, an inherent limitation of the classic method [8]. No frequencies were quantified: coupling with fault tree analysis or layer of protection analysis (LOPA) would allow barriers to be prioritised on a probabilistic basis [11]. The PBO values are literature screening values rather than values computed for the diesel actually stored. The design pressure and installed vent area of the tank could not be obtained, so the vent calculation is a screening exercise. Thermal effect distances and cooling water needs were not modelled. The HIRA rating relies on the judgement of a single team of assessors. Finally, the study does not quantify the uncertainty associated with the input data and with the semi-quantitative scores; a sensitivity analysis of the NM classification to one-step changes in each rating would be a useful extension.

4 CONCLUSION

This study proposed and applied an integration step linking HAZOP and HIRA outputs through shared root causes and barriers at the Bingo petroleum depot (Burkina Faso). The main findings are:

- Five of the six root causes identified are common to the process and occupational analyses; the corresponding shared barriers address 27 of the 48 workplace situations, including 17 of the 22 uncontrolled ones, while acting on the escalation chain of a bund fire.
- The HAZOP study of tank R08 shows that the developed deviations rely on human safeguards and single instruments, without interlocks or centralised alarms.
- Diesel exceeds the PBO screening threshold (1.20), but experimental evidence points to a strongly delayed thin-layer boilover (21–58 h); for this fixed-roof tank, pressurisation during a bund fire and the adequacy of the installed vents, which could not be established, deserve priority attention.
- Water pumping covers demand under hydraulic N−1, but the foam concentrate chain is saturated (99%) in the reference scenario and insufficient (126%) in the envelope scenario, and the fire pumps are not functionally independent.
- According to the adopted NM index, 44 of the 48 rated occupational situations (91.7%) fall short of the controlled class; the carousel and work at height on tank trucks are the most critical, consistent with the 2022 events.

Future work will address probabilistic quantification of scenarios (fault trees, LOPA), uncertainty and sensitivity analysis of the semi-quantitative scores, modelling of thermal effects, recalculation of the PBO with product-specific

data, and extension of the approach to all tanks and workstations of the site and to other depots of the West African sub-region.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

A.A.P. Ouedraogo is affiliated with SONABHY, the operator of the depot studied, which provided access to the site and to internal data [18]. The other authors declare that they have no conflict of interest.

Statement of ethical approval

This non-interventional workplace study did not involve experiments on human participants or animals. Field observations and interviews were conducted during a field placement with the authorisation of SONABHY management.

Statement of informed consent

Informed (oral) consent was obtained from all operators and supervisors interviewed; no personal or identifiable information is reported.

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