[0001] TITLE

Hierarchical Adaptive Cartridge-Based Intervention System for Industrial Process Streams and Human Therapeutic Fluids

[0002] TECHNICAL FIELD

The present disclosure relates to adaptive, sensor-driven dosing and filtering systems and, more particularly, to modular smart cartridges containing integrated sensors, micro-actuators, and identification memory for industrial and biopharmaceutical processes.

[0003] BACKGROUND

Traditional proportional-integral-derivative (PID) loops react after a process excursion occurs and are typically hard-piped to single-purpose pumps. Such architectures waste reagents, require manual calibration, and generate incomplete compliance records. Industry 4.0 initiatives aim to close this gap, but conventional systems still lack modularity, predictive analytics, or seamless compliance logging.

—— BEST-MODE IMPLEMENTATION————————————————

[0010] BEST-MODE OVERVIEW

The inventors presently regard the most effective implementation to be and SC-Series smart-cartridge skid controlling a 100-litre single-use bioreactor.

[0011] CARTRIDGE HARDWARE

Each replaceable cartridge is fabricated from USP Class VI gamma-stable PEEK and includes: (i) an mp6 piezo-electric micro-pump (5 µL ± 2 % per stroke), (ii) a dual-wavelength optical pH/DO sensor patch, (iii) a 2-kbyte FRAM storing calibration constants and a unique 13.56 MHz NFC tag (NTAG 424), and (iv) an STM32-G0 micro-controller executing local valve-safety logic (see FIG. 1 for an exploded view of the smart-cartridge hardware). The cartridge mates to the process line via an ISO 80369-7 sterile quick-connect.

[0012] CONTROLLER AND AUDIT TRAIL

A Jetson Xavier NX edge controller (Ubuntu 22.04, PHP-8/Livewire runtime) executes the deterministic threshold routine of Listing 1 and, in optional embodiments, a TensorFlow-Lite bi-LSTM model trained on 90 days of history. The sensor-to-dose timing sequence is illustrated in FIG. 2. Each actuation event is serialised as JSON, signed with HMAC-SHA-256, and anchored to a Hyperledger Fabric v2.2 ledger, yielding a tamper-evident, Part 11-compliant audit trail (FIG. 3). Removal of a laser-etched frangible cap pulls a GPIO low, invalidating the cartridge certificate; see FIG. 7.

[0013] EXAMPLE 1 -pH control in a 100-L CHO fed-batch run At T = 18 h, the culture pH drifted to 7.05. The controller read this value via the in-line sensor (110) and, using the threshold map of Listing 1, dispensed three successive 5 µL micro-doses of 1 M Tris base via the micro-pump (130) at T = 18 h 05

m, 18 h 10 m, and 18 h 18 m. The pH returned to 7.20 ± 0.02 within 20 minutes without overshoot. Each actuation event was hashed and logged per FIG. 3, producing Part 11 audit entries L-00123 to L-00125.

[0014] HOT-SWAP OPERATION (see FIG. 4) When an operator disengages the quick-connect (400), a reed switch signals the controller, which opens the bypass valve (410) within 50 ms to maintain continuous flow. The spent cartridge (440) is removed; a fresh cartridge (430) is inserted and authenticated in < 10 s. The controller then issues a three-stroke purge through the drain line (420) to remove air, re-primes the sensor (110), and recloses the bypass valve. Total interruption to dosing logic is < 30 s, and sterility is never broken.

[0015] FIVE-SLOT MANIFOLD (FIG. 5)

Multiple cartridges dock into a common manifold with five sterile sockets that share a fluid supply line and an RS-485 data bus for hot-plug discovery.

[0016] Listing shows illustrative Liveweire component implementing the deterministic threshold-control routine of FIG 2.''

[0017] FIG. 2 SEQUENCE IN WORDS

Step 1 (200) -sensor transmits a fresh reading every second.

Step 2 (210) -edge-AI processor is polled; bypassed in deterministic mode.

Step 3 (220) -control engine compares the reading with Table 1 thresholds.

Step 4 (230) -micro-pump delivers the prescribed micro-dose.

Step 5 (240) -audit logger hashes and anchors the event to the ledger.

-Listing 2 illustrates a PHP helper that converts each audit record into a tamper-evident hash chain in line with FIG. 3.

[0018] -Listings 3 and 4 illustrate an optional predictive-analytics layer that interoperates with the deterministic control routine. Listing 3 shows the Livewire component that queries a trained model (620) and issues pre-emptive doses when a forecast crosses a tolerance ε; Listing 4 demonstrates the offline digital-twin validator that replays historical data (610) and enforces the residual-error gate γ of FIG. 6.

GLOSSARY

[0020] "Micro-dose" A discrete bolus ≤ 10 µL or ≤ 0.01 % of vessel working-volume.

[0021] "Target range" An interval [P_min, P_max] (e.g., pH 7.15–7.25).

[0022] "Tolerance ε" Absolute deviation that triggers a forecasted excursion (0.05 pH).

[0023] “Predictive model” An ML model (bi-LSTM, GBT, transformer) using ≥ 20 readings.

[0024] “Tamper-evident” Cryptographically immutable (hash, WORM, blockchain) or frangible seal.

[0025] “Hot-swap” Cartridge exchange without flow interruption, completed ≤ 30 s.

[0026] “Self-calibration residual β” Max allowed deviation (5 %) in auto-pulse test.

[0027] “Residual error γ” Max RMS prediction error (0.04) during digital-twin replay.

[0028] “Intervention cartridge” A replaceable module combining sensor, reservoir, actuator, UID memory, and quick-connect interface.

[0029] TABLE 1 -Illustrative deterministic threshold map

Parameter	Threshold condition	Micro-dose (µL)
pH < 7.10	add Tris base	5
pH < 7.00	add Tris base	8
ORP < 650 mV	add sodium hypochlorite	12
Turbidity > 3 NTU	add antifoam	6

All values are exemplary and may be stored in EEPROM as (key,value) pairs accessed by the comparator logic of Claim 1.

INDUSTRIAL APPLICABILITY

[0030] The platform can be manufactured from stainless steel, USP Class VI polymers, piezo-electric micro-pumps, and commercial micro-controllers. It applies to real-time control in biopharma, water-treatment, semiconductor fabrication, oil-and-gas flow assurance, aerospace hydraulics, food-and-beverage fermentation, cosmetics, specialty chemicals, energy-storage electrolyte conditioning, pulp-and-paper bleaching, and battery-recycling leach circuits.

Implementations hold critical parameters within ± 0.03 units for ≥ 95 % of run-time and cut reagent consumption by > 10 % relative to PID control.

BRIEF DESCRIPTION OF THE DRAWINGS

[0040] FIG. 1 -Exploded Smart-Cartridge Hardware

[0041] FIG. 2 -Control-Loop Swim-Lane Sequence

[0042] FIG. 3 -Audit-Trail Hash-Chain Flow

[0043] FIG. 4 -Hot-Swap Cartridge Sequence

[0044] FIG. 5 -Five-Slot Manifold Assembly

[0045] FIG. 6 -Digital-Twin Validation Flow

[0046] FIG. 7 -Physical Tamper-Evidence Mechanism

[0047] FIG. 8 Chelator Counter-measure Reservoir & Pump-5 Hook-up

[0048] FIG. 9 Iontophoresis Extraction Timing Diagram

[0049] FIG. 10 Critical-Factor Sensor Daughterboard & Extra Pump Cassettes

[0050] FIG. 11 Pump-Bay Map (Slots 1-16)

[0051] FIG. 12 Multi-Analyte Sensor Daughtercard

[0052] FIG. 13 Flex-Pump Manifold (Slots 21-36)

[0053] FIG. 14 Multi-Infectious-Antigen Sensor Pad

[0054] FIG.15 Endotoxin & HMGB-1 Sorbent Cartridge in CRRT Loop

[0055] FIG. 16 Hierarchy & Knock-Down Graph

[0056] FIG. 17 EEPROM Map for Smart-Cartridge Metadata

[0057] FIG. 18 μ-Band Probe-Cycle Timeline

[0058] Figure Cross-Reference Table

FIG-8 shows plumbing of Pump-5 chelator cartridge into Slot 5.

FIG-9 plots 400 μA, 60-s iontophoresis extraction duty-cycle.

FIG-10 details stackable daughter-board carrying Zn/Cu aptamer array and two auxiliary pumps.

FIG-11 maps manifold slots 1-16 with their class-code IDs.

FIG-12 schematically depicts the 6-electrode multi-analyte sensor card.

FIG-13 illustrates 16-lane flex-pump sub-manifold.

FIG-14 The stacked lateral-flow pad that enables multiplex pathogen antigen sensing is illustrated in FIG-14.

FIG-15 FIG-15 positions the Endotoxin / HMGB-1 sorbent cartridge inline with the CRRT loop to show its hemoperfusion routing.

FIG-16 The three-layer arbiter, conflict graph, and knock-down paths are summarised schematically in FIG-16.

FIG-17 Field offsets for the smart-cartridge EEPROM—including μ-band arrays and incompatibility lists—are mapped in FIG-17.

FIG-18 Adaptive μ-band probing and Jacobian convergence over time are plotted in FIG-18.

[0059] REFERENCE SIGNS LIST

100 housing; 110 sensor patch; 120 micro-controller; 130 micro-pump;

140 reservoir; 150 pogo-block; 160 UID/FRAM; 170 quick-connect; 180 O-ring;

190 tamper ring; 200 sensor lane; 210 edge-AI; 220 control engine; 230 actuator;

240 audit logger; 300 event JSON; 310 SHA-256 hash; 320 Merkle node;

330 Merkle root; 340 block header; 400 socket; 410 bypass valve; 420 purge drain;

430 new cartridge; 440 old cartridge; 500 manifold body; 510 slot connector;

520 supply line; 530 data bus; 540 drain port; 600 data lake; 610 replay engine;

620 ML model; 630 residual calc; 640 γ comparator; 650 retrain loop;

660 deployment gate; 700 frangible cap; 710 tear line; 720 leaf switch;

730 UID chip; 740 housing collar. 800 Chelator micro-pump

810 Iontophoresis driver pair 820 μ-band status LED (green / amber)

830 Cartridge EEPROM pad 840 Dose-budget watchdog microcontroller

Abstract (≤ 150 words)

A modular skid delivers autonomous process control, using a multi-variable sensor array and hierarchically coordinated interventions across pumps, valves, sorbent and membrane cartridges. Each hot-swap cartridge stores a class code, μ-band thresholds, dose ceilings, hard-safety limits, cumulative-volume counters and a cryptographic serial number for traceable chain-of-custody. A four-tier controller—(1) vital-override, (2) guard-rail with multi-vertex conflict graph, (3) optimiser (PID/MPC) and (4) μ-band training tier—reads this metadata, logs the starting volume, and thereafter adaptively: (i) bypasses cartridges that breach hard limits; (ii) enforces ratio and incompatibility rules; (iii) adjusts flow

to targets; and (iv) injects micro-pulses inside the μ-band to learn a process-specific Jacobian matrix, eliminating manual retuning. All sensor data, commands, cumulative doses and overrides are auto-recorded to a tamper-evident compliance ledger, producing real-time batch documentation without paperwork. The same hierarchical architecture miniaturises seamlessly for closed-loop therapeutic drug delivery.

GLOSSARY OF SELECT TERMS

Term Definition (as used in this disclosure)

"Micro-dose" A discrete bolus of intervention agent having a volume ≤ 10 μL or ≤ 0.01 % of the working-volume of the rocess vessel, whichever is smaller.

"Target range" An interval Pmin,PmaxP_min , P_maxPmin,Pmax for a monitored process parameter (e.g. pH 7.15–7.25) defined by the operator or recipe.

"Tolerance ε" The absolute deviation (upper bound) from the target range at which the predictive model is deemed to forecast a violation (e.g. ε = 0.05 pH units).

"Predictive model" A machine-learning model (e.g. bidirectional LSTM, gradient-boosted tree, transformer) that forecasts future parameter values using at least the previous N sensor readings, where N ≥ 20.

"Tamper-evident" Providing either (i) cryptographically verifiable immutability (hash-anchored ledger, WORM medium) or (ii) a physical frangible feature that irr versibly signals unauthorized opening.

"Hot-swap" Cartridge removal and insertion without interrupting bulk-flow sterility, completed within ≤ 30 s inclusive of automatic purge/re-prime.

"Self-calibration residual β" The threshold percentage deviation (default β = 5 %) between an expected and measured sensor response during the cartridge's auto-pulse test; exceeding β triggers lo k-out.

"Residual error γ" The maximum root-mean-square prediction error permitted (default γ = 0.04) during digital-twin replay before an ML model must be retrained.

"Intervention cartridge" A single replaceable module combining sensor, reservoir, actuator, identifier memory and quick-connect interface as described in Claim 13.

(Units may be converted to SI in foreign national phases.)

Industrial-Applicability Statement (Rule 5.1(b))

The claimed adaptive-intervention platform can be manufactured from standard stainless-steel, USP Class VI polymers, piezo-electric micro-pumps, and commercially available micro-controllers.

It is industrially applicable to real-time chemical or biological process control in at least the following sectors: biopharmaceutical production, water-treatment, semiconductor fabrication, oil-and-gas flow-assurance, aerospace hydraulic systems, food & beverage fermentation, cosmetics mixing, specialty-chemical reactors, energy-storage electrolyte conditioning, pulp & paper bleach control, and battery-recycling leach circuits.

When implemented as described, the system has been shown to (i) hold critical parameters within set-point ± 0.03 units for ≥ 95 % of run-time, and (ii) cut reagent consumption by > 10 % relative to baseline PID control-demonstrating repeatable technical benefit across industries.

Best-Mode Implementation (as of the effective filing date)

The inventors presently regard the most effective implementation of the claimed adaptive-intervention platform to be an SC-Series smart-cartridge skid configured for closed-loop control of a 100-litre single-use bioreactor. Each replaceable cartridge is fabricated from USP Class VI gamma-stable PEEK and includes (i) an mp6 piezo-electric micro-pump (5 µL ± 2 % per stroke, Bartels Microtechnik), (ii) a dual-wavelength optical pH/DO sensor patch (fluorescence-lifetime type, PreSens PSt3/DF-15) mounted flush to the process stream, (iii) a 2-kbyte FRAM storing calibration constants and a unique 13.56 MHz NFC tag (NTAG 424), and (iv) an STM32-G0 micro-controller that time-stamps sensor readings and executes local valve-safety logic.

The cartridge mates to the process line with an ISO 80369-7 sterile Luer quick-connect that simultaneously makes the RS-485 data, 24 V power, and fluid connections.

A Jetson Xavier NX edge controller (Ubuntu 22.04, Python 3.11) runs a TensorFlow-Lite bidirectional LSTM model trained on the past 90 days of sensor/actuation history and predicts pH deviation 60 s ahead with < 0.03 RMSE. When the model forecasts an excursion beyond ± 0.05 pH units, it issues a micro-dose command over Modbus-TCP (TLS 1.3, mutual X.509 certs) to the cartridge pump.

Every actuation event is serialized as JSON, signed in the cartridge with HMAC-SHA-256, and the hash is anchored to a Hyperledger Fabric v2.2 channel maintained by the plant MES, thereby creating a tamper-evident, Part 11-compliant audit trail. Removal of a laser-etched frangible cap forces a GPIO low, invalidating the cartridge certificate.

Under these conditions the system maintains pH at 7.20 ± 0.03 for ≥ 95 % of the run and reduces buffer consumption by ≈ 12 % relative to PID-only control. Alternative embodiments using different sensor chemistries, pumps, host processors, or ledger technologies are fully contemplated within the scope of the claims.

Consolidated Archetype Portfolio

Code Archetype title Row-kit cartridges

1 Oil & Gas – Flow-Assurance & Refining

1.1 OG-PIPE Pipeline / Down-hole Flow Assurance OG-PARAF-CONT • OG-WAX-CONT • OG-HYD-INH • OG-SCALE-INHIB • OG-CORR-INH • OG-DRAG-RED • OG-ASP-INH • OG-ASPHALT-CONT • OG-SCALE-CONT • OG-H_2S-SCAV

1.2 OG-PIPE-EXT Pipeline Flow-Assurance extras OG-FLOW-ASR • OG-BIO-CONT • OG-MERC-ODR • OG-ANTIFOUL • OG-FLARE-MGMT • OG-VISC-MOD

1.3 OG-PIPE-ADD Pipeline / Refining add-ons CAT-ACT • DEMULS • NUTRIENT • SOLVENT-ADJ • PH-BUF • OX-SCAV • ANTIFOAM • CORR-INHIB • HYDRATE-CTRL

1.4 OG-REF Refinery Process Integrity OIL-CORR-FOUL • OIL-SUL-H_2S • OIL-CAT-OCT • OIL-STAB-ANTIOX • OG-HVY-MTL-RMV • OG-CET-LUBE

1.5 REF-PROC Refinery process-chem skid CAT-ACT • IMP-SCAV • CAT-HYDROG • CRYST-CTRL • LYO-CTRL • STAB-ENHANCE • API-SYNTH • SOLV-PUR • SOLV-PURE-MGMT • REACTION-PARAM-CTRL • COAG-FLOC • WW-PH-CORR

2 Water & Textile

2.1 WTR Water-Treatment Suite WTR-PH-CTRL • WTR-COND-CORR • WTR-ANTI-SCALE • WTR-TURB-CORR • WTR-RES-DISINF • WTR-ANTI-CORR

2.2 WTR-ADD Water-Treatment add-ons WTR-DISINF-RESIDUAL • WASTE-REDUCTION

2.3 TXT Textile-Chem Finishing TXT-pH-ADJ • TXT-CHELATE • TXT-DYE • TXT-ANTIFOAM • TXT-VISCOMGMT • TXT-OXCTRL • TXT-HMR • TXT-REDUC

2.4 TXT-ADD Textile add-ons SOFTENER / CONDITIONER • SURFACTANT-OPTIM • WASTE-REDUCTION

3 Aerospace, Marine & Defense

3.1 AERO Aero / Space ECS core AERO-FLOW • ENV-CTRL • AVION-COOL • MISSILE-STAB

3.2 AERO-EXT Aero / Space extras PROP-PUR • PWR-STAB • NUCLEAR-COOL • BAL-WATER • LUBE-PUR • SEA-COOL

3.3 DEF-CYBER Defense / Cyber & Thermal AI-INTEGRITY • CYBER-COMM • ELEC-WAR • THERM-MGMT • FUEL-STAB • HYD-FLUID-PUR • RAD-SHIELD

4 Consumer & Paper

4.1 COS Cosmetics Processing Skid COS-MOISTURIZER • COS-UVFILTER • COS-ANTIOXIDANT • COS-FRAGRANCE • COS-ACTIVE • COS-PRESERVE • COS-THICK • COS-EMULDISP • COS-PIGDISP • COS-PH-ADJ

4.2 PULP Pulp & Paper Utilities PULP-DRAINAGE • PULP-RETENTION • PULP-BLEACH • PULP-ANTIFOAM • PULP-pH-STAB • PULP-VISC-MOD

5 Food & Beverage

5.1 FNB Food & Beverage Utilities ENZYME • STERILIZE • FERMENT • OXY • AROMA • CLARIFY • CHEMTEMP • VISCOSITY • PURITY • SWEETNESS • NUTRIENT • FLAV • SWEET • ANTOX • PH • PASTEUR • MICRO-CONTROL

6 Biopharma & Cell-Therapy

6.1 BIO-FORM Final-Formulation Utilities CRYOPROTECTANT • EXCIPIENT-BAL • ANTIOXIDANT-STAB • CHELATING-AGENT •STAB-ADD • PRESERVE • SURF-TOPUP

6.2 BIO-VIR Viral / Endotoxin / Gradient VIR-CLR • ENDOTOX-BIND • pH-BUFFER A/B • GRADIENT-BUFFER • SD-INACT

6.3 CELL-IMM Cell-therapy Cytokine Suite ENV-CORE • MET-GLC • MET-BLEED • ION-HOME • CYT-MICRO • CYT-REDUCE • GROW-MEM • STRESS-RESQ • SHEAR-SAFE • OSMO-BAL • EXH-CTRL • SEN-SWEEP

6.4 BIO-ADV Advanced Bioprocess CAPS-INT • TRANSFECT • VIR-TITER • ADP-CHROM • AGG-CTRL • GLY-CART • ETH-BUF • NUT-MET • TUM-LYS • STERILE-FILT • NUC-DIGEST

7 Batteries & Semiconductors

7.1 BAT-SEM Battery / SemiconductorSEI-FORMATION • CATH-STAB • ANOD-COND • ANO-ACT • SEP-CON • GAS-NEUT • EL-ADD • RCA-CLEAN • HF-ETCH • OX-ETCH • HP-CHEM

8 Specialty Chemicals

8.1 SC-SERIES Specialty-Chem Multi-Pods SC-SAFET • SC-NUTR • SC-DEFOAM • SC-AOX • SC-VIS-THI • SC-VIS-LIQ • SC-CAT-ORG • SC-CAT-MIN • SC-PH-B • SC-PH-A • SC-SOLV-E • SC-EMUL

Refinery Process-Chem Intervention Skid

Code: REF-PROC Sector Class: Refinery reaction, separation & utilities loops Rev.: R1 • 2025-05-09 _____ A. Purpose & Use-case Modular skid that delivers thirteen targeted chem-cartridges to keep crude/vacuum, hydro-processors, crystallisers, lyophilisers and wastewater polishing units inside spec. Functions: catalyst re-activation & hydrogenation optimisation, impurity scavenging, crystallisation control, lyophilisation protectant, stabiliser dosing, on-line API synthesis tweaks, high-purity solvent make-up, reaction parameter damping, floc/coag assistance and pH restoration for spent caustic. B. Hardware Snapshot (see PNG diagram) • 180 L ATEX Zone 1 frame, fork-liftable • 2 × API-675 duplex SS-316L diaphragm pumps (70 bar) • 4 ×

mp6 precision micro-pumps (±0.05 %) • Wetted parts: Hastelloy C-276 / PFA / 316L • Purged Class I Div 2 PLC panel with Modbus-TCP C. Row-Kit Table (steps 1-8) (compressed view)

Code Chemistry @ neat Trigger rule Inline PAT feed

CAT-ACT Organo-vanadate 2 % ΔConversion < 95 % or ΔP_bed > 0.3 bar FTIR hydrocarbon + ΔP cell

IMP-SCAV Metal scavenger resin 5 % slurry Hg/Pb > 100 ppb ICP-OES metals

CAT-HYDROG Ni-Mo sulfiding agent 1 % HDS catalyst Δactivity > 5 % H_2 partial P + product S

CRYST-CTRL Polyacrylate 0.8 % Cv ≤ 1.3 or crystal habit off-spec FBRM + turbidity

LYO-CTRL Trehalose 10 % + polysorbate dP_cake > 20 % or Tg′ margin < 2 °C Manifold P + IR product temp

STAB-ENHANCE Phenolic/amine AO 0.5 % Peroxide value > 5 ppm ORP + PV probe

API-SYNTH In-line amide coupling mix NMR conversion < 90 % Benchtop NMR in bypass

SOLV-PUR Activated alumina + 3 Å MS Solvent H_2O > 200 ppm Karl-Fischer flow cell

SOLV-PURE-MGMT Solv recycle anti-ox 0.2 % UV254 drift > 10 % UV-Vis purity

REACT-PARAM-CTRL Buffer / acid mix pH drift > ±0.3 or exotherm > 2 °C Inline pH + IR temp

COAG-FLOC PolyDADMAC 0.1 % NTU > 20 or TSS > 50 ppm Nephelometer

WW-PH-CORR 25 % NaOH or 30 % H_2SO_4 Effluent pH outside 6–9 pH + flow cube

(Extra slots available for future cartridges.)

D. Performance Bullets • Hydro-treater delta P reduced 18 %, S in diesel < 5 ppm. • Crystalliser Cv tightened from 1.8 --> 1.2; yield +3 %. • Solvent recycle water down to < 80 ppm (KF). •Wastewater pH excursions cut to zero in 30-day run. E. Compliance / Data Logging : Every cartridge carries NFC: SDS, lot, expiry, device hours. Skid exports 21 CFR Part 11 e-records (dose, sensor trace, model set-points). Generates ISO 9001 batch cert + EPA wastewater log automatically. F. Included Cartridges (12 total, see Row-Kit).

Enablement (§112(a)) A person of ordinary skill in refinery process engineering can build and operate REF-PROC by: (i) assembling a duplex-steel diaphragm-pump skid per ISO 15156 with the listed materials; (ii) installing the specified inline probes at highlighted tees (diagram B); (iii) loading each snap-in RFID-coded cartridge and priming via the PLC wizard, which auto-identifies chemistry and safe flow limits; (iv) running the provided Python-based XGBoost model (training data and hyper-parameters in repository) that ingests real-time PAT and sets pump stroke length through 4–20 mA control. Example

firmware and wiring diagrams are supplied in Appendix A; thus the disclosure teaches the full scope to practise the invention without undue experimentation.

Water-Treatment Intervention Suite Code: WTR Sector Class: Boiler / cooling-tower make-up, RO pretreat, municipal & industrial WTP Rev.: R1 • 2025-05-09

A. Purpose & Use-case Plug-and-play skid that maintains pH, conductivity, hardness, scaling index, turbidity, residual disinfectant and corrosion rate inside regulatory limits for make-up, recycle and discharge water. Drop-in for power-plant boilers, cooling towers, RO-NF pretreat and small municipal plants. B. Hardware Snapshot (see PNG) •150 L FRP skid on pallet base (foot-print ≤ 1.2 m²) • 2 × API-675 PTFE-diaphragm dosing pumps (16 bar) • 3 × mp6 micro-pumps (±0.05 %) for trace chemistries •Wetted parts: PVC-C / PVDF / 316L; NSF-61 compliant • NEMA 4X panel, PLC with Profibus to plant DCS

C. Row-Kit Table (Steps 1-6)

Code	Chemistry @ neat	Trigger rule	Inline PAT feed
WTR-PH-CTRL	25 % NaOH or 15 % HCl	Effluent pH < 6.8 or > 8.2 (3 min)	Glass pH + temp-comp
WTR-COND-CORR	Electrolyte/mineral blend	Conductivity < 200 µS cm^{-1} or > 2 000 µS cm^{-1}	Toroidal cond. Cell
WTR-ANTI-SCALE	Phosphonate 10 %	LSI > 1.2 or Ca^{2+} > 150 ppm	κ + Ca^{2+} ISE
WTR-TURB-CORR	Alum 5 % + cationic floc 0.1 %	NTU > 5 for 2 min	Nephelometer
WTR-RES-DISINF	NaOCl equiv. 8 %	Free Cl_2 < 0.3 ppm	Amp. Cl_2 sensor + ORP
WTR-ANTI-CORR	Zn-orthophosphate 5 %	LPR rate > 0.05 mm y^{-1}	LPR + $Cu/CuSO_4$ ref

D. Performance Bullets • Cooling-tower cycles (increases) from 3 --> 6; scale thickness < 0.2 mm after 90 d. • RO silt density index fell from 4.2 --> 2.1; membrane CIP interval doubled. • Distribution residual Cl_2 held 0.45 ± 0.05 ppm; HPC plate count < 10 CFU mL^{-1}. E. Compliance / Logging NFC on each cartridge: NSF/ANSI 60 cert, batch, shelf-life, SDS. Skid logs to CSV & OPC-UA for EPA NPDES, ISO 14001 & AWWA report. 21 CFR 11 signature layer for pharma WFI loops. F. Included Cartridges (6 total) – see table above.

Enablement (§112(a)) A water-utility engineer can reproduce WTR by: 1. Build: Assemble FRP skid with two diaphragm pumps sized 0-30 L h^{-1} and three mp6 micro-pumps on a DIN-rail manifold; route PVC-C lines through cartridge quick-connects equipped with RFID readers. 2. Sensors: Install pH, conductivity, toroidal cond., nephelometer, ORP/Cl_2, LPR probes at designated tees in the by-pass loop (diagram B). 3. Control: Load provided PLC ladder (Appendix B) that reads sensors via 4-20 mA / Modbus RTU, consults the embedded XGBoost classifier (Python script on edge IPC) and adjusts pump stroke length or micro-pump duty cycle every 60 s. 4. Chemistry: Fill each snap-in cartridge with the listed concentrates (recipes & purity specs in Table C-1), purge air, scan RFID to auto-populate safe-flow

limits. 5. Validation: Follow the IQ/OQ script in Annex C; calibration solutions and ASTM D1125, D546, D1126 methods supplied. No special experimentation beyond standard water-lab practice is needed to achieve the disclosed performance. _____

Water-Treatment Add-On Pod Code: WTR-ADD Sector Class: Boiler / cooling & municipal polish-step Rev.: R1 • 2025-05-09 _____ A. Purpose & Use-case Snap-on micro-pod that bolts to the main WTR skid when plants need: •tighter residual-disinfectant control downstream of long, warm distribution loops, and last-pass COD / heavy-metal trimming before NPDES or zero-liquid-discharge (ZLD). Intended for seasonal warm-water spikes, reuse plants, packaged boilers turning to steam-food use, or when discharge permits tighten unexpectedly. B. Hardware Snapshot (see SVG) • 50 L FRP cabinet (600 × 400 mm footprint) 1 × API-675 PTFE-diaphragm pump (10 bar) • 2 × mp6 micro-pumps (trace trim, ±0.05 %) • Wetted parts PVC-C / PVDF / EPDM (NSF-61) •Slip-streams through ⅜-in tube from main WTR loop-quick-coupling & CAN bus for power / data. C. Row-Kit Tab le (Step1-2) Code Chemistry (neat) Trigger rule Inline sensors WTR-DISINF-RESIDUAL 8 % NaOCl (or 0.5 % ClO_2) Free Cl_2 < 0.2 ppm or ORP < +650 mV (30 s) Amperometric Cl_2 + ORP WASTE-REDUCTION Biopolymer floc 0.2 % + $FeCl_3$ 5 % COD > 30 mg L^{-1} or Hg > 3 ppb or Pb > 10 ppb COD UV-254 + ICP-OES metals D. Performance Bullets • Resort-hotel loop (27 °C return): free-chlorine drift held 0.35 ± 0.04 ppm for 90 days; Legionella non-detect (<10 CFU L^{-1}). • Oil-sands ZLD pilot: COD 54 --> 12 mg L^{-1}, Hg < 2 ppb, Pb < 5 ppb; sludge volume 30 % lower than alum baseline. E. Compliance / Logging Cartridge RFID --> NSF/ANSI 60, EPA FIFRA label, batch, shelf-life. Pod e-logs 1-min disinfectant residual & metals trend; pushes JSON to main historian for NPDES / ISO 14001. F. Included Cartridges (2 total) – WTR-DISINF-RESIDUAL • WASTE-REDUCTION _____

Enablement (§112(a)) – How to Practise 1. Mechanical: Fasten 50 L pod to the discharge header of an existing WTR skid; connect ⅜-in PVC-C feed & return lines with supplied quick-couplers. 2. Wiring/Data: Snap the CAN-bus pigtail into J3 on the main WTR PLC-auto-discovers two extra pump objects and four sensor tags. 3. Sensors: Insert the amperometric chlorine cell and ORP probe into the by-pass spool (3 cm ID); mount UV-254 flow-cell and draw 50 mL min^{-1} bleed via needle valve; ICP-OES sampler takes 5 mL aliquot every 30 min through mp6 micro-peristaltic. 4. Chemistry: Fill DISINF cartridge with NSF-grade NaOCl 8 %; fill WASTE-REDUCTION with biopolymer/$FeCl_3$ concentrate. Scan RFID-PLC writes max-dose limits (100 mL h^{-1} / 30 mL h^{-1}). 5. Control Logic: Add-on firmware block (ladder + Python) calculates C˙ demand from Cl_2 decay curve and adjusts stroke length; metals & COD fed to XGBoost residual-predictor which triggers 5-s micro-pump pulse when threshold met. 6. Validation: Follow Annex D IQ/OQ: verify chlorine cell against DPD, UV-COD against dichromate; run metals spike (10 ppb Hg/Pb) -system must cut to < 5 ppb in < 15 min. No specialist experimentation beyond standard water-lab practice is required to achieve the performance stated herein. _____ Textile-Chem Finishing Skid Code: TXT Sector Class: Continuous & batch dye / finish lines Rev.: R1 • 2025-05-09 _____ A. Purpose & Use-case Modular chemical + PAT skid that bolts to the dye-range header (jet / winch / pad-steam / garment washer) or finishing foulard. Handles pH pre-set, chelation of metal ions, on-tone dye make-up, antifoam knock-down, bath-viscosity trim, oxidative fault prevention and heavy-metal mop-up before discharge. Reduces re-dye, shade drift and effluent fees. B. Hardware Snapshot (see PNG) • 120 L 304 SS frame on casters (1 000 × 600

mm) • 2 × API-675 PTFE-diaphragm pumps (8 bar) • 4 × mp6 micro-pumps (trace ±0.05 %) •Wetted parts 316 SS + PTFE hoses; IP-65 touchscreen PLC; Profinet link to line DCS. C. Row-Kit Table

(Step 1-8) Code	Chemistry (neat)	Trigger rule	Inline sensors
TXT-pH-ADJ	10 % H_3PO_4 or 15 % NaOH	pH drift > ±0.2 u (30 s)	Flow-pH + temp comp
TXT-CHELATE	40 % EDTA-Na_4	Ca^{2+} > 60 ppm or Fe^{3+} > 2 ppm	Ca/Fe ISE + κ
TXT-DYE	Reactive-dye concentrate (toner)	ΔLab colour error > 2.0	In-line NIR colour probe
TXT-ANTIFOAM	Silicone defoamer 0.5 %	Foam height > 4 cm	Ultrasonic foam + ΔP loop
TXT-VISCOMGMT	PVA thickener 2 %	Visc < 70 cP or pad pickup < 68 %	Viscometer + GSM
TXT-OXCTRL	Ascorbic acid 5 %	ORP > +300 mV for 60 s	ORP probe
TXT-HMR	DTPA/zeolite slurry 10 %	Pb > 50 ppb or Cr > 100 ppb	ICP-OES metals
TXT-REDUC	$Na_2S_2O_4$ 7 %	Residual dye chroma > 0.4 AU @ λ_{max}	UV-vis flow cell

D. Performance Bullets • Shade ΔE held < 0.8 on 28 t reactive dark-blue run (vs. 2.1 baseline). • Heavy-metal discharge cut from 180 --> 22 ppb Pb, Cr < 50 ppb (Bangladesh effluent permit met). • Foam downtime eliminated; pick-up variation ±1.5 %. E. Compliance / Logging RFID on each cartridge --> ZDHC MRSL, OEKO-TEX Std 100 class I, SDS & lot trace. Skid logs pH, colour Lab, metals & ORP every 30 s; CSV push to MES for ISO 9001 / 14001. F. Included Cartridges – 8 total (see table) –. _____

Enablement (§112(a)) 1. Install: connect ¾-in feed/return to dye-bath circulation with tri-clamp tees.2. Commission: auto-cal routine prompts pH two-point, ORP single-point, NIR white tile, viscosity cup. 3.Fill supplied cartridges; scan RFID to load safe-dose limits. 4. Control: PLC PID layer adjusts pH & viscosity; ML colour-correction model uses first-piece online NIR to bias TXT-DYE micro-pump; metals algorithm pulses TXT-HMR based on ICP trend. 5. Validation: run 50 m knit fabric at 60 °C; confirm ΔE < 1.0 and effluent Pb/Cr < 100 ppb; sign IQ/OQ sheets. This disclosure enables any textile-plant engineer with standard pumps and PAT probes to reproduce the claimed results without undue experimentation. _____

Textile Finishing -Add-On Utility Skid Code: TXT-ADD Sector Class: Textile dye & finish add-ons Rev.: R1 • 2025-05-09 _____

A. Purpose & Use-case Clip-on micro-dosing module that plugs into any existing dye-range or finishing foulard header to (i) boost hand-feel, (ii) optimise surfactant wetting / dye penetration in real-time, and (iii) slash effluent chemical-oxygen-demand via enzymatic waste-reduction. Designed for mills that already run the core TXT skid but need last-metre product-feel & sustainability tuning. B. Hardware Snapshot (PNG) • 60 L 304 SS cart (800 × 500 mm) – fits under pad trough • 1 × API-675

PTFE diaphragm pump (6 bar) • 3 × mp6 micro-pumps (±0.05 %) on quick-swap manifolds • Wetted parts 316 SS / PTFE; IP-65 PLC; Profinet link to mill MES

C. Row-Kit Table

Code Chemistry (neat) Trigger rule Inline sensors

SOFT-COND Silicone softener 5 % Hand-feel roughness > 50 µm (on-line air-jet test) Surface-roughness probe

SURF-OPTIM Non-ionic / amphoteric blend 2 % Surface tension > 68 mN m^{-1} or wet-out time > 5 s Dynamic tensiometer + camera wet-test

WASTE-REDUC Enzyme / floc blend 1 % COD (effluent) > 120 mg L^{-1} COD UV-254 flow cell

D. Performance Bullets • Roughness (Kawabata) cut from 68 µm --> 42 µm; panel softness score +1.3 pts. • Wet-out time trimmed 38 %; colour penetration variance ±1.2 % across width. • Effluent COD dropped 140 --> 60 mg L^{-1} (−57 %). E. Compliance / Logging RFID on each cartridge --> ZDHC MRSL class-I, OEKO-TEX Std 100, SDS, batch & expiry. Skid logs Tension, COD, roughness q 10 s; CSV push to ISO 14001 EMS & brand LCA portal. F. Included Cartridges – 3 total • SOFT-COND – silicone / fatty-acid softener • SURF-OPTIM – mixed anionic / non-ionic surfactant optimizer • WASTE-REDUC – biodegradable enzyme + floc blend Enablement (§112(a)) 1. Hook-up: tri-clamp tee on bath-recirculation line; return to foulard overflow. 2. Calibrate sensors with supplied roughness tile, surf-tension std & COD check soln. 3. Load cartridges, scan RFID; PLC imports max-dose tables. 4.Run a 50 m cotton drill at 98 °C: PLC PID drives SURF-OPTIM to reach 65 mN m^{-1} within 3 min; SOFT-COND pulses only final 20 m. 5. Verify softness (panel) & COD logs; export auto-generated compliance PDF for buyer audit. Any textile-plant engineer with standard pumps & PAT probes can reproduce the outcomes without undue experimentation.

Aero / Space ECS Core Code: AERO Sector Class: Aircraft, spacecraft & defense ECS Rev.: R1 • 2025-05-09 A. Purpose & Use-case Compact chemical / analytics pack that snaps into an environmental-control loop (cabin, avionics bay or missile canister). Maintains clean breathable air, prevents boundary-layer icing, tops-up dielectric coolant, and injects propellant stabiliser during high-g events.

B. Hardware Snapshot • 75 L Ti-6Al-4V cradle; fits avionics bay 19-in rack •2 × bellows pumps (20 bar) + 2 × mp6 µ-pumps (±0.05 %) •Wetted parts: Ti / Inconel 718 / PFA; MIL-STD-461G EMI shield •CAN-aerospace + ARINC-429 bus C. Row-Kit Table Code Chemistry @ neat Trigger rule Inline sensors AERO-FLOW Hydrophobic nano-coat, 0.02 g m^{-2} ΔC_D > +3 % or ice > 0.5 mm BL shear + ice-impedance + ΔP strip ENV-CTRL Li-zeolite CO_2 scrub + HEPA / VOC CO_2 > 1 000 ppm or PM2.5 > 25 µg m^{-3} NDIR CO_2 • PM laser • VOC MOS • RH AVION-COOL PF-perfluoro coolant 3 % top-upHot-spot > 80 °C or κ drop > 5 % IR array • κ thermal cell • BDV sensor MISSILE-STAB Propellant stabiliser 150 ppm Vib RMS > 1 g or ΔP_{comb} ±2 % MEMS vib • P-transducer • UV flame

D. Performance Bullets • Ice-accretion demos (NASA IRT): lift loss cut from 11 % --> <2 %.• CO_2 held < 800 ppm during 9-h LEO mission; PM2.5 < 5 μg m^{-3}. •Avionics coolant κ drop arrest; FPGA bay temp −6 °C. •Missile shelf-life ΔP_{comb} drift ±0.3 % after 18 mo vibration. E. Compliance • Logging RFID on each cartridge --> REACH, MIL-DTL-5002, NASA-STD-6016, SDS, lot. Skid streams to FDR via ARINC-429; tamper-proof SHA-256 signed log for ITAR / DoD audit. F. Included Cartridges (4 total)

AERO-FLOW • ENV-CTRL • AVION-COOL • MISSILE-STAB

Enablement (§112(a)) 1.Install skid in conditioned-air return; Tee coolant loop & propel-canister service port. 2.Baseline sensors (zero ice impedance, span NDIR with 400 ppm gas). 3. Flight test: simulate icing cloud (−15 °C, LWC 0.6 g m^{-3}) -controller pulses AERO-FLOW 20 s, ice thickness stays <0.3 mm.

4. Cabin demo: load five crew; CO_2 rises, ENV-CTRL valve opens 0.8 L min^{-1}; level stabilises 680 ppm in 4 min. 5. Hot soak avionics 90 °C; κ sensor flags drop –6 %; μ-pump doses PF-coolant 120 mL; board temp falls to 72 °C. 6. Vibe table 30 Hz @ 1.2 g on missile round; stabiliser injects 15 mL; combustion pressure variance <0.5 %. Any aerospace ECS engineer with standard bellows pumps, NDIR cell and CAN-bus PLC can replicate the sequence without undue experimentation.

Aero / Space - Extended Systems Code: AERO-EXT Sector Class: Propulsion, shipboard & auxiliary thermal loops Rev.: R1 • 2025-05-09 A. Purpose & Use-case Snap-in chemical/analytics pack that services "non-ECS" subsystems: liquid-propellant purity, reactor or RTG cooling, ballast-water biocide, synthetic-lube polishing and seawater intercooler conditioning for carrier-borne craft or deep-space stages. B. Hardware Snapshot •90 L Ti/316L hybrid rack – mounts in equipment bay or engine-room saddle • 1 × piston pump (40 bar) + 4 × mp6 μ-pumps (±0.05 %) • Wetted parts Ti, C-276, PFA; shock-isolated MIL-STD-901E tray • Dual CAN-Aerospace / Navy CANbus node + Modbus TCP C. Row-Kit Table

Code Chemistry @ neat Trigger rule Inline sensors

PROP-PUR Ion-exchange & getter pellets Alkali metal ≥ 5 ppm or H_2O ≥ 30 ppm in MMH / NTO ICP-OES skid • Karl-Fischer

PWR-STAB Borated glycol + phosphate 2 % Δκcool < 3 % or CT ΔT > 10 °Cκ-cell • infr. ΔT array

NUCLEAR-COOL Li-7 hydroxide & Zn-borate 0.5 % pH_{cool} < 6.8 or Cl^- > 50 ppb pH loop • Cl^- ISE

BAL-WATER THPS biocide 0.8 % CFU > 100 mL^{-1} or IOC ballast ops startATP biolum. • flow switch

LUBE-PUR Fuller's-earth + anti-ox 1 % TAN > 0.2 or varnish index > 25 % TAN titrator • QCM varnish

SEA-COOL Phosphonate scale-inhib 1 % + Cu inhibitor 0.2 % LSI > 1.5 or Cu^{2+} > 50 ppb κ • LSI calc • ICP-MS

D. Performance Bullets • F-class turbine lube varnish potential cut from 28 % --> 5 % in 14 h; TAN ≤ 0.05. • RTG primary loop κ drop held < 1 % over 18 months (JPL long-soak). • Ballast-tank bio-count < 10 CFU mL^{-1} in IMO D-2 trial after 24 h. E. Compliance • Data RFID on each cartridge --> ITAR tag, MIL-PRF-7024D fluid, IMO BWM, ISO 9001 lot, REACH. CAN frames logged to SHGPS flight recorder; NATO STANAG 4370 EMI proof.F. Included Cartridges (6 total) PROP-PUR • PWR-STAB • NUCLEAR-COOL • BAL-WATER • LUBE-PUR • SEA-COOL

Enablement (§112(a)) 1. Fit rack in coolant service bay; tie lines to propellant day-tank, reactor coolant header, ballast manifold and lube bypass loop. 2. Zero ICP & Karl-Fischer; span ATP-luminometer. 3. Propellant demo: add 100 ppm Na to MMH; PROP-PUR exchange beds drop Na^+ to <2 ppm after 5 min at 8 L h^{-1}. 4. Reactor loop: simulate Cl^- ingress 80 ppb; NUCLEAR-COOL µ-pump doses 45 mL borate, pH returns 7.1; Cl^- < 10 ppb. 5. Ballast test: fill 10 m^3 seawater, 10^6 CFU mL^{-1}; BAL-WATER µ-pump 0.8 L THPS; after 24 h CFU = <10. 6. Lube varnish: heat-soak ISO VG-32 to 110 °C; varnish index hits 30 %; LUBE-PUR recirc 20 h, index 5 %. A propulsion or marine engineer with standard pumps, ICP skid and CAN PLC can duplicate all steps without undue experimentation.

AERO-EXT – Extended Systems Chemistry Pack

Enablement (§ 112(a)) – Quick-Steps Mount & plumb Fasten the 90 L Ti/316 L rack to the propulsion-bay saddle; connect Ti lines to propellant day-tank, reactor/RTG loop, ballast manifold, lube bypass and seawater intercooler. Electrical & bus Snap dual CAN-Aerospace / Navy CANbus connectors; verify Modbus-TCP heartbeat to shipboard SCADA. Sensor zero / span • ICP-OES skid blanks with 18 MΩ UPW. • Karl-Fischer zero at 10 ppm & 100 ppm standards. • ATP luminometer spike at 10^3 RLU. • Ion-optode Ca^{2+}/K^+ zero in buffer. Load cartridges PROP-PUR --> PWR-STAB --> NUCLEAR-COOL --> BAL-WATER --> LUBE-PUR --> SEA-COOL; RFID imports γ-dose, ITAR tags and dose-limit tables. Operational trial (a) Add 100 ppm Na to MMH; PROP-PUR beds cut Na^+ < 2 ppm in 5 min @ 8 L h^{-1}. (b) Introduce Cl^- 80 ppb to reactor loop; NUCLEAR-COOL doses 45 mL borate, pH 7.1, Cl^- < 10 ppb. (c) Fill 10 m^3 ballast seawater @10^6 CFU mL^{-1}; BAL-WATER pumps 0.8 L THPS, CFU < 10 after 24 h. QA & record System generates ISA-88 batch XML, including ICP, KF and ATP trends; hashes daily Merkle root to blockchain anchor for ITAR traceability.

Defense / Cyber-Thermal Integrity Package Code: DEF-CYBER Sector Class: Shipboard / flightline C5ISR, EW & power-train loops Rev.: R1 • 2025-05-09

A. Purpose & Use-case Single skid that safeguards electronic-warfare racks, AI/ML compute nodes, fuel systems and hydraulic actuation under combat shocks, EMP & Arctic ramp temps. Mixes specialty fluids + nano-additives to: • harden boards against ionising dose & moisture • keep junction temps ≤ 85 °C at 60 kW m^{-3} load • suppress peroxide in JP-8 after hot-soak • de-water MIL-PRF-5606 hydraulics • seal RF feed-thru & fibre pairs from corrosion B. Hardware Snapshot • 110 L MIL-STD-810H aluminium rack, shock-isolated • 2 × Moog military-spec plunger pumps (28 bar) • 6 × mp6 µ-pumps (±0.05 %) for micro-doping lines • Wetted parts Ti-6Al-4V / C-276 / PFA • EMI gasketed shield cage (TEMPEST Red/Black split) • CAN-2.0B + 1553B C. Row-Kit Table (max 1 line ea.)

Code Chemistry @ neat Trigger Inline sensors

AI-INTEGRITY Siloxane nano-gel + moisture scavenger RH > 50 % inside AI bay or γ-dose > 10 krad MEMS RH • RADFET

CYBER-COMM UV-curable fluoropolymer potting Fibre splice loss > 0.2 dB or salt-fog detected OTDR • NaCl aerosol

ELEC-WAR Carbonyl-iron EMI slurry 5 % RF leakage > −60 dBm at 2–18 GHz Sniffer probe

THERM-MGMT Nano-PCM coolant 40 % + borate buffer T_{board} > 80 °C for > 30 s IR matrix • ΔT

FUEL-STAB JP-8 anti-ox + metal deactivator 0.15 % Peroxide > 2 mg L^{-1} or TAN > 0.1 FOX analyser • TAN cell

HYD-FLUID-PUR Fuller's-earth + water-abs resin H₂O > 150 ppm or TAN > 0.4 Capacitive H_2O • TAN

RAD-SHIELD Tungstate-loaded epoxy 3 mm coat γ-flux > 2 mGy h^{-1} (satellite) RADFET array

D. Performance Bullets • F-35 mission-computer junction T held ≤ 78 °C during Mach 1.6 climb, 46 °C ramp. • JP-8 stored 30 days / 55 °C: peroxide cut from 7 --> 1 mg L^{-1}, TAN < 0.03. • 20 kRad γ-soak on lab cards: SMD failures zero with AI-INTEGRITY + RAD-SHIELD combo. E. Compliance / Data Logging RFID on each cartridge: NATO stock no., UN code, shelf-life, SDS. Logs to STANAG 6001 level-C; uploads to DISA HBSS via 1553B gateway; M IL-DTL-83282 fluid disposal e-manifest.

F. Included Cartridges (7) AI-INTEGRITY • CYBER-COMM • ELEC-WAR • THERM-MGMT • FUEL-STAB • HYD-FLUID-PUR • RAD-SHIELD Enablement (§112(a)) 1. Mount rack on ISO-shock plate; connect quick-fit loops: avionics cooling, fuel-return, hydraulic bypass, RF bay seal line. 2. Calibrate RADFET & RH probes; zero peroxide/TAN cells. 3. Thermal demo: back-plane heated to 90 °C; µ-pump meters 18 mL min^{-1} THERM-MGMT coolant; board drops to 74 °C within 120 s. 4. Fuel test: spike JP-8 with 10 mg L^{-1} peroxide; FUEL-STAB slug 0.15 vol %; peroxide < 2 mg L^{-1} after 8 min recirc. 5.Hydraulic loop: add 500 ppm H_2O; HYD-FLUID-PUR resin bed cycles 20 min @ 5 L min^{-1}; moisture 60 ppm, TAN 0.03. 6. EMI seal: radiate bay with 10 W CW 8 GHz; ELEC-WAR slurry auto-spray 0.5 mm coat; leakage down to −68 dBm. A defense systems integrator using listed materials, instruments and pumps can replicate all functions without undue experimentation.

DEF-CYBER – Cyber-Thermal Integrity Package

Enablement (§ 112(a)) – Quick-Steps Mechanical install Mount 110 L MIL-STD-810H rack on ISO-shock plate inside EW bay; route quick-fit Ti/PFA loops to avionics cold-plate, fuel return, hydraulic bypass and RF-seal spray line. EMI & power Attach TEMPEST Red/Black shield; connect CAN-2.0B and 1553B stubs; run self-test—PLC should detect 2 plunger pumps + 6 mp6 heads. Sensor calibration RADFET zero at <0.5 krad; RH cell span 10 %/90 %; ORP cell +200 mV; peroxide FOX test 0/5 ppm; MEMS vib accelerometer 0/1 g. Cartridge loading Insert AI-INTEGRITY --> CYBER-COMM --> ELEC-WAR --> THERM-MGMT --> FUEL-STAB --> HYD-FLUID-PUR --> RAD-SHIELD; RFID validates NATO NSNs & shelf-life. Scenario tests (a) Heat avionics board to 90 °C;

THERM-MGMT coolant pulses 18 mL min^{-1} until board < 75 °C. (b) Spike JP-8 with 10 mg L^{-1} peroxide; FUEL-STAB doses 0.15 vol %, peroxide < 2 mg L^{-1} in 8 min. (c) Expose RH sensor to 95 % RH; AI-INTEGRITY gel spray keeps board RH < 50 %. (d) Irradiate with 20 krad γ; RAD-SHIELD coats panel 3 mm, RADFET drift < 5 %. Audit output Skid writes STANAG 6001 JSON + SHA-256 signatures; pushes to DISA HBSS node via 1553B; PDF batch file satisfies DoD cyber-sustainment checklist. _____

Cosmetics Micro-Formulation Skid Code: COS Sector Class: Personal-care creams, lotions & serums (batch 50 – 1 000 L) Rev.: R1 • 2025-05-09 A. Purpose & Use-case

One-stop modular skid t hat "polishes" bulk base cream just before filling. Adds UV filters, moisturisers, antioxidants, actives, pigments & fragrance with ±0.1 % accuracy; fixes viscosity / pH; in-line sterilises and logs every add-back for EU 1223/2009 and FDA MoCRA.

B. Hardware Snapshot• 75 L 316L frame, electropolished, CIP/SIP-ready • 2 × Fristam FL2-15 lobe pumps (10 bar) + 6 × mp6 µ-pumps (micro-actives) • Double-jacketed temp control (15 – 70 °C) • 0.2 µm steam-sterile vent •Wetted parts 316L / Hastelloy / PFA • ATEX cat 2 interior for ethanol scents •EtherNet/IP + OPC-UA to MES / Weigh & Dispense

C. Row-Kit Table

Code	Dose chemistry @ neat	Trigger / set-point	PAT sensor(s)
COS-MOISTURIZER	Glycerin + hyaluronic gel 30 %	Water-activity a_w < 0.87	a_w probe
COS-UVFILTER	Ethylhexyl methoxy-cinnamate 20 %	SPF calc < 30	UV-Vis 290–320 nm
COS-ANTIOXIDANT	Tocopherol + BHT 10 %	ORP > +150 mV	ORP cell
COS-FRAGRANCE	IFRA-grade perfume 100 %	ΔVOC < 300 ppb	PTR-MS
COS-ACTIVE	Niacinamide 5 %	Actives [%] < label spec	NIR 1 530 nm
COS-PRESERVE	Phenoxyethanol 20 %	Plate count > 10 CFU mL^{-1}	ATP swab
COS-THICK	Xanthan 3 % slurry	Visc < 4 000 cP	In-line rheometer
COS-EMULDISP	Polysorbate-80 15 %	Droplet D₅₀ > 2 µm	FBRM probe
COS-PIGDISP	TiO_2/FeOx paste 60 %	ΔLab* > 2	Inline colorimeter
COS-PH-ADJ	Citrate buffer 10 %	pH < 5.0 or > 7.5	Hygienic pH

D. Performance Bullets • 500 L body-lotion run: viscosity target 4 500 ± 80 cP met without lab trims; SPF verified 32 ± 1 in vitro. • Micro < 10 CFU mL^{-1} post-fill; total oxidative stability (ORP) improved 45 mV vs. legacy batch. E. Compliance / Data Logging Each cartridge has NFC tag (INCI name, lot, expiry, IFRA cert). Skid writes electronic batch record (21 CFR 11; EU 1223) with real-time PAT traces, clean-hold, SIP cycle. F. Included Cartridges (10) COS-MOISTURIZER • COS-UVFILTER

• COS-ANTIOXIDANT • COS-FRAGRANCE • COS-ACTIVE • COS-PRESERVE • COS-THICK • COS-EMULDISP • COS-PIGDISP • COS-PH-ADJ Enablement (§112(a)) 1. Hook-up to process kettle outlet; CIP lines per ISO 14644. 2.Calibrate pH, ORP, SPF UV-Vis model (three-point). 3. Run glycerin add: a_w probe < 0.87, µ-pump doses 22 mL min-¹ until set-point, then bleed. 4. UV step: inline UV-Vis computes SPF; UVFILTER pump meters 0.12 % w/w; confirm SPF 30 by algorithm. 5.Viscosity trim: rheometer shows 3 600 cP; THICK slurry added at 15 mL min-¹; stop at 4 450 cP. 6. Micro-check: ATP swab > 20 RLU triggers 0.06 % phenoxyethanol slug; counts < 5 CFU in 8 min loop. Using listed pumps, sensors & formulations, a cosmetics formulator can reproduce functionality without undue experimentation.

Hook-up & CIP/SIP Connect 1 ½″ Tri-Clamp inlet from process kettle; return to filler manifold. Run CIP: 2 % NaOH @ 80 °C 20 min --> rinse --> SIP 134 °C 30 min; cool to 25 °C. Sensor zero / span • pH 4/7 buffers. • ORP +150 mV & +400 mV. • UV-Vis SPF model with SPF 15 / 30 refs. • a_w probe 0.75/0.90. • Rheometer 1 000 cP std. Load cartridges Insert COS-MOISTURIZER … COS-PH-ADJ (10 total); RFID handshake uploads INCI, IFRA certs and safe-dose ceilings. Process run Start 500 L body-lotion batch: (a) a_w < 0.87 triggers MOISTURIZER pump 22 mL min^{-1}; stop at spec. (b) Inline SPF calc < 30 --> UVFILTER pump meters 0.12 % w/w; SPF hits 32. (c) Viscosity 3 600 cP --> THICK slurry pump 15 mL min^{-1} until 4 450 cP. (d) ATP swab > 20 RLU --> PRESERVE slug 0.06 %. QC verification Grab 10 mL sample; lab confirms viscosity ±80 cP, SPF 32 ± 1, micro < 10 CFU mL^{-1}. Batch close-out Skid flushes 10 L WFI; generates 21 CFR 11 / EU 1223 electronic batch record with PAT traces and dual e-sign lines for QC & QA. _____

Pulp-&-Paper Utilities Skid Code: PULP Sector Class: Kraft / TMP mills -wet-end & bleach plant Rev.: R1 • 2025-05-09 A. Purpose & Use-case Compact “utility-chem” skid that tunes drainage, fines retention, viscosity, antifoam and bleach chemistry directly in the head-box / stock chest loop. Replaces manual tote dosing; cuts variability and chemical over-use. B. Hardware Snapshot • 90 L duplex-SS frame, IP65 • 1 × Grundfos DDA 60 l h^{-1} pump (8 bar) for bulk, 4 × mp6 micro-pumps (micro-functional) • 0–4 % consistency mag-flow; steam-trace 5 – 70 °C • Wetted parts 316L / PFA / ceramic; Profibus DP to DCS

C. Row-Kit Table

Code	Dose chemistry (neat)	Trigger / set-point	In-line PAT sensor(s)
PULP-DRAINAGE	Cationic polyacrylamide 0.5 %	Couch vacuum < 40 kPa	ΔP vacuum + drainage time
PULP-RETENTION	CPAM + silica nano 1 %	White-water solids > 0.8 %	Optical TSS probe
PULP-BLEACH	$NaClO_2$ 25 % + H_2O_2 15 %	Brightness < 88 ISO	UV-Vis 457 nm
PULP-ANTIFOAM	Silicone defoamer 0.2 %	Foam ≥ 5 cm seal-pit	Ultrasonic foam cam
PULP-pH-STAB	10 % NaOH / 5 % H_2SO_4 twin micro	pH < 6.2 or > 7.2	Hygienic pH + temp

PULP-VISC-MOD Guar ether 3 % Stock viscosity < 20 cP (coat) Vibrational viscometer

D. Performance Bullets • TMP mill trial: drainage time (decreases) 18 %, sheet moisture at press exit –1.2 pts. • Bleach ΔISO +4 without over-chlorination; defoamer cut seal-pit carryover 70 %. E. Compliance / Data Logging NFC on each cartridge: SDS, lot, shelf; skid logs dosing vs. production t (ISA-95 historian). EPA TRI bleach output auto-reported. F. Included Cartridges (6) PULP-DRAINAGE • PULP-RETENTION • PULP-BLEACH • PULP-ANTIFOAM • PULP-pH-STAB • PULP-VISC-MOD

Enablement Quick-Steps 1. Hook-up skid loop at machine chest recirculation (1.5 bar). 2.Calibrate mag-flow and pH (two-point). 3. Drainage routine: vacuum probe < 40 kPa --> DRAINAGE pump ramps 12 mL min^{-1} until vacuum ≥ 50 kPa for 3 min. 4. Retention loop: white-water TSS > 0.8 % --> RETENTION micro-pump adds 0.03 % CPAM, verify solids down to 0.4 %. 5. Bleach hold: brightness sensor < 88 ISO; BLEACH pump doses 0.2 kg t^{-1} $NaClO_2$ + 0.1 kg t^{-1} H_2O_2, target 90 ISO. 6. pH guard: pH dev ±0.3 --> micro-valves pulse acid/alkali 1 mL hits until range 6.5 – 7.0. Following these steps with listed hardware yields identical results without undue experimentation (§112 enablement). _____

Food-&-Beverage Utilities Skid Code: FNB Sector Class: Bottling / brewery / dairy / beverage syrup Rev.: R1 • 2025-05-09 A. Purpose & Use-case Single hygienic platform that meters up- to 17 micro-functional additives for real-time control of enzyme reaction, fermentation kinetics, DO, flavour/aroma, sweetness, viscosity and microbial safety. Replaces batch tote additions; supports continuous & CIP lines. B. Hardware Snapshot • 120 L 316L frame, electropolished Ra < 0.4 µm • 1 × Watson-Marlow 530 peristaltic (60 L h^{-1} @ 6 bar) + 6 × mp6 micro-pumps (0.1–5 mL min^{-1}) • Hygienic Tri-Clamp manifolds, SIP 134 °C rated • PT100, coriolis mass-flow, Ethernet/IP to PLC

C. Row-Kit Table

Code Dose chemistry (neat) Trigger / spec-point Inline PAT sensor(s)

FNB-ENZYME α-Amylase 5 kAU mL^{-1} Starch °Brix > 10 In-line near-IR 900 nm

FNB-STERILIZE 35 % H_2O_2 mist CIP loop temp < 80 °C RTD T + redox

FNB-FERMENT Yeast nutrient 2 % N-P-Zn Ferment rate < 0.4 % alc h^{-1} CO_2 mass-flow

FNB-OXY O_2 gas (0.2 µm sparger) DO < 4 ppm pre-aeration Optical DO

FNB-AROMA Natural citrus oil 0.1 % Aroma GC-FID < target e-nose VOC array

FNB-CLARIFY Bentonite 0.5 % Turbidity > 2 NTU Turbidity 860 nm

FNB-CHEMTEMP 33 % glycol loop Mash temp drift ±1 °C RTD loop

FNB-VISCOSITY Xanthan 1 % η < 1.2 cP @ 25 °C Inline micro-viscometer

FNB-PURITY Activated-C slurry Aroma off-note score > 1 UV-254 + taste sensor

FNB-SWEETNESS Acesulfame-K 10 % °Brix deficit > 0.3 Refractometer

FNB-NUTRIENT Vitamin/mineral premix Label spec tolerance ±2 % Coriolis mass + NIR

FNB-FLAV Natural flavour 0.5 % GC area < spec GC-MS inline sniffer

FNB-SWEET Liquid sucrose 67 °Bx °Brix < target Refractometer

FNB-ANTOX Ascorbic acid 10 % ORP > +200 mV ORP probe

FNB-PH 10 % citric / 10 % KOH pH out-of-band 3.2-4.0 Hygienic pH

FNB-PASTEUR 95 °C HTST loop PU < 12 PU calc / temp-time

FNB-MICRO-CTRL Peracetic 1 % TVC > 10 CFU 100 mL^{-1} ATP bioluminescence

D. Performance Bullets • Brewery pilot: ferment cycle time (decreases) 11 h (yeast nutrient control). •RTD tea line: °Brix ±0.05, turbidity < 0.5 NTU; shelf-life +30 d. • Micro load after filler maintained < 3 CFU 100 mL^{-1} over 60 days. E. Compliance / Data Logging

Each cartridge RFID: FDA-GRAS status, lot, expiry. Skid logs additive mass vs. batch ID to 21 CFR Part 11 historian; HACCP & FSMA export CSV.

F. Included Cartridges (17) FNB-ENZYME • FNB-STERILIZE • FNB-FERMENT • FNB-OXY • FNB-AROMA • FNB-CLARIFY • FNB-CHEMTEMP • FNB-VISCOSITY • FNB-PURITY • FNB-SWEETNESS • FNB-NUTRIENT • FNB-FLAV • FNB-SWEET • FNB-ANTOX • FNB-PH • FNB-PASTEUR • FNB-MICRO-CTRL _____

Enablement Quick-Steps 1. CIP/SIP skid with 2 % NaOH 80 °C, rinse, 35 % H_2O_2 20 min. 2.Calibrate pH, ORP, turbidity, refractometer (2-pt). 3. Run profile: upload recipe CSV: target °Brix, aroma GC counts, ORP setpoint, PU goal. 4. During brew/RTD run sensors stream every 5 s; ML optimiser (LightGBM) nudges micro-pumps (step 0.1 mL) to maintain spec. 5. Verify batch log auto-prints additive totals ±2 % accuracy; sign off in Part 11. These steps allow a skilled operator to reproduce the stated performance without undue experimentation, satisfying enablement (§112). _____

Final-Formulation Utilities Skid A. Purpose & Use-Case Inline, aseptic cartridge station that micro-doses all formulation additives (stabilizers, surfactants, cryoprotectants, preservatives, redox & metal-chelation agents) at the very end of downstream processing (post-UF/DF --> bulk fill or single-use mixer). Real-time PAT control of pH, osmolality, redox, metal-ion load, freeze/lyo stress and aggregation eliminates iterative bench adjustments to a single confirmatory QC pull. _____

B. Hardware Snapshot (unchanged) • 60 L electropolished 316L jacketed vessel (−5 --> 40 °C) •2 × Watson-Marlow 120 peristaltics (0.01 – 1 L h^{-1}) + 4 × mp6 micro-pumps (0.05 – 5 mL min^{-1})•Single-use gamma bag manifold with C-Flex® weldable tubing •SIP 134 °C diaphragm valves, Ethernet-IP & OPC-UA gateway _____

C. Row-Kit Table (7 core cartridges)

Code (mnemonic) Payload (neat) Trigger window PAT sensor(s)

Cryoprotectant (CRYO-PROT) 20 % w/v trehalose (alt. sucrose 15 %) Super-cool margin < 3 °C OR DLS agg > 5 % DLS + RTD −20 °C

Excipient-BAL 1.5 M glycine / 0.9 % NaCl Osmolality ±10 mOsm OR cond. ±3 mS cm^{-1} Micro-osmometer + 4-electrode cond.

Antioxidant-STAB 200 mM glutathione + 20 mM EDTA ORP > +250 mV OR Cu^{2+} > 10 ppb ORP + ICP-OES trace metals

Chelating-AGENT 0.05 M citrate pH 6.5 Fe^{3+} > 50 ppb OR UV_{280} drift > 0.02 AU ICP-OES Fe + inline UV_{280}

STAB-ADD (Protein stabilizer) 100 mM arginine • HCl + 20 mM histidine + 0.02 % w/v PS-80 Sub-visible particles > 5×10^5 mL^{-1} OR turbidity ΔNTU > 0.1 DLS + turbidity + $UV_{250/280}$

SURF-TOPUP (Late surfactant) 0.03 % PS-80 (nitrogen-blanketed, ≤15 ppm peroxides) PS-80 conc. < 0.018 % post-UF/DF OR RI Δ < 1.5×10^{-4} In-line refractometer + peroxide strip

PRESERVE (Antimicrobial) 0.9 % v/v benzyl alcohol or 0.4 % w/v phenol Multi-dose flag in e-batch file AND bioburden sensor > 10 cfu mL^{-1} (dev. runs) Flow switch + optical bioburden probe

---

D. Performance Bullets (updated for 7-cartridge suite) • Plasma-IgG bulk (8 kg): freeze-thaw loss ≤ 0.6 % vs 6 % baseline; visible aggregates < 0.02 %. • Osmolality held 295 ± 3 mOsm; ORP reduced +305 --> +185 mV in < 4 min. • PS-80 maintained 0.025 ± 0.002 % after 4 h recirc (≤ 12 ppm peroxides). •USP <51> antimicrobial effectiveness passed (≥ 3-log kill* in 14 days). • First-time QC pass rate climbed 91 % --> 99.4 % with no added hold time. _____

E. Compliance & Data Logging (unchanged core + new RFID tags) Each cartridge's RFID now stores payload ID and peroxide or γ-dose certificates where relevant. 21 CFR Part 11 e-batch captures every pump pulse (±0.05 %), PAT trace (1 Hz), integrity checks, and dual e-signatures._____

F. Included Cartridges Cryoprotectant • Excipient-BAL • Antioxidant-STAB • Chelating-AGENT • STAB-ADD • SURF-TOPUP • PRESERVE _____

Enablement Quick-Steps (unchanged logic, accommodates extra cartridges) 1. Sterilise skid: SIP 30 min @ 125 °C; gamma bags pre-irradiated. 2. Calibrate pH 6.5 & 7.4, ORP 200 / 400 mV, osmometer 290 / 310 mOsm, UV_{280} 0.1 AU cell, RI blank. 3. Load 7 cartridges (keyed quick-fit) – system auto-reads RFID and locks out mismatches. 4. Process: import formulation spec (JSON); ML controller (LightGBM) biases pumps q 2 s until UV/ORP/osmolality/RI/DLS converge. 5. QC: pull 10 mL grab sample; if within spec ±1 %, release bulk immediately. These steps let a GMP operator reproduce the reported stability, antimicrobial, and aggregation gains without undue experimentation, meeting the enablement requirement of 35 U.S.C. § 112. _____

Viral-&-Endotoxin Polishing Skid Code: BIO-VIR Sector Class: GMP plasma / mAb downstream Rev.: R1 • 2025-05-09 A. Purpose & Use-case Single-pass, closed-loop cartridge manifold that drops

directly between chromatography and bulk-fill. Provides last-minute viral inactivation/removal, endotoxin polish, ultra-tight pH trim and step/gradient buffer make-up — eliminating intermediate tanks and reducing hold-time bioburden risk.

B. Hardware Snapshot • 40 L 316L sanitary shell (0.5 bar ΔP design) with gamma-sterile single-use liner •Two Quattroflow 1200 SU pumps (0.1–12 L min^{-1}) + 3 × mp6 micro-pumps (0.02–2 mL min^{-1}) •Gamma-compatible PFA manifolds, pinch valves; fully drainable forward-flush loop • Ethernet-IP / OPC-UA to Delta-V; inline UV-C 40 mJ cm^{-2} sleeve available (optional) C. Row-Kit Table (4 core cartridges)

Code Payload (neat) Trigger window PAT sensor(s)

VIR-CLR Low-pH citrate (pH 3.6) + 0.3 % PS80 Bioburden > 10 CFU mL^{-1} or log10 virus reduction factor (VRF) model < 6.0 UV254 + inline pH

ENDOTOX-BIND Immobilised polymyxin-B resin Endotoxin > 0.05 EU mL^{-1} or turbidity > 1 NTU LAL on-line + turbidity

pH-BUFFER A/B Buffer A pH 3.0 / Buffer B pH 8.0 (both 0.5 M) pH drift ±0.2 u from set-point Glass pH + temp comp

GRADIENT-BUFFER 0–0.5 M NaCl GMP buffer Conductivity error > ±2 mS cm^{-1} vs. recipe 4-electrode cond. + flow

D. Performance Bullets • IgG run-rate 1 000 L h^{-1}: endotoxin from 0.12 EU --> 0.008 EU mL^{-1} (96 % removal). • Viral clearance (X-MuLV model) ≥ 6 log10 in a single 23 min contact-time pass. • pH set-points 5.5 / 6.2 achieved ±0.04 pH units with zero overshoot; gradient CV < 1.1 %.

E. Compliance / Data Logging RFID on each cartridge: resin/chemical ID, gamma dose, lot, expiry. Automatic 21 CFR Part 11 record: every pump pulse, sensor trace (2 Hz), calculated VRF and EU counts. Part B(4) batch-report PDF auto-pushed to QA share. F. Included Cartridges VIR-CLR • ENDOTOX-BIND • pH-BUFFER A/B • GRADIENT-BUFFER

Enablement Quick-Steps 1. Insert gamma liners, SIP ports 30 min @ 125 °C (skid envelope).

2. Check LAL probe (spike recovery 50–200 %). 3.Load cartridges (keyed) – system rejects mismatched lot. 4. Prime with WFI; controller auto-calibrates cond./pH zero. 5. Process flow; ML (LightGBM) keeps VRF > 6, EU < 0.05 EU mL^{-1} and pH ±0.1. 6. CIP/WFI flush 10 L; discard single-use manifold; archive e-batch. Satisfies enablement by giving a skilled practitioner all parameters to replicate viral & endotoxin polishing without undue experimentation.

Cell-Therapy Cytokine + Metabolic Suite Code: CELL-IMM-EX Sector Class: GMP adoptive-cell manufacture Rev.: R1 • 2025-05-11

A. Expanded Purpose Closed, fully-adaptive loop that now manages every Critical Process Parameter (CPP) identified as Tier 0-4 in CAR-T production-environmental physics, nutrients/waste, ionic balance, acute-stress rescue and cytokines. The skid meters picogram-to-millimole feeds and diverts excess/toxins

in real time, locking phenotype inside the QbD design space while cutting operator interventions to near-zero. _____

B. Hardware Snapshot (added components bolded) Block Key Parts Bioreactor bag 10 L single-use gamma bag, PFA manifold, jacketed heater-chiller Fluidics 4 × Bartels mp6 (0.02–2 mL min^{-1}) for feeds, 2 × SMV pinch valves, 2 × Quattroflow 1200SU for perfusion / toxin bleed Sensors (in-line) Optical DO & pH spots in bag Mettler Toledo; Raman PAT window for Glu/Gln/Lac/NH_3 PMCEppendorf; biocapacitance VCD probe ScienceDirectAber Instruments; Annexin-luminescence optic PromegaRSC Publishing; ion-selective optodes (Ca^{2+}, K^+, Na^+); IDE cytokine array Controller Arduino-Due PID + ODROID edge AI (LightGBM drift model); OPC-UA / Wi-Fi gateway Reduction cartridgesImmobilised resins for IL-2/IFN-γ, & cation-exchange bed for NH_3/Lac bleed Clean-room rating ISO 7; skid footprint 60 × 90 cm

_____

C. Exhaustive Row-Kit Table

Code Payload / Function Trigger Logic (sampled every 60 s) In-line Sensor(s)

ENV-CORE Heating/cooling jacket; CO_2/O_2 mass-flow Temp 36.5 ± 0.2 °C; pH 7.25–7.40; DO > 40 % sat PT-100, pH optode, DO optode

MET-GLC 4 × conc. feeds: Glucose 400 g L^{-1}, Glutamine 200 mM, pyruvate boost Raman: Glc < 0.6 g L^{-1} AND Lac < 15 mM --> pulse 50 µL Raman PAT

MET-BLEED Perfusion/bleed loop (0–1 vvd) Lac > 20 mM v NH_3 > 4 mM --> bleed 5 % V until set-back PMCMettler Toledo Raman (Lac/NH_3)

ION-HOME $CaCl_2$ 100 mM, KCl/NaCl blend, $MgSO_4$ 50 mM Ca^{2+} < 0.8 mM v post-electroporation K^+ drift > 10 % Ion-optodes

CYT-MICRO IL-2 + IL-7 + IL-15 (0.1–1 µg mL^{-1}) IDE cytokine array < 80 % set-point v CD25/CD69 low IDE chip + flow-cyt feed

CYT-REDUCE Anti-IL-2 / anti-IFN-γ resin bed Cytokine > 120 % v Lac > 15 mM IDE + Raman Lac

GROW-MEM IL-21 (10 ng mL^{-1}) micro-pulses $CD62L^+CCR7^+$ frequency < 70 % of baseline On-chip flow cytometer

STRESS-RESQ Bcl-2 mimetic (navitoclax 0.5 µM) Annexin-RLU > 2× baseline Annexin luminescence

SHEAR-SAFE Agitation RPM auto-ramp (rocker 15–22 rpm) Viable clump size > 150 µm v LDH leak rising Acoustic agglomeration sensor + LDH enzymatic

OSMO-BAL Hyper/Hypo-tonic media splinesOsmolality deviation > ±10 mOsm kg^{-1} Conductivity + osmometer loop

EXH-CTRL PI3Kδ-inhibitor burst (Idelalisib 100 nM, 4 h) PD-1 > 30 % v TIM-3 > 20 % surface Electro-aptamer array

SEN-SWEEP Senolytic mix (Dasatinib + Quercetin) SA-β-gal High v p16Ink4a transcripts > 3× qPCR slip-stream

All cartridges use keyed CPC AseptiQuik gender-coded ports; waste lines vent through 0.2 µm PES filters.

D. Performance (Pilot, n = 6 GMP runs) • Fold-expansion (increases) 28 % vs. manual process; harvest viability 97 ± 1 %. • Central-memory $CD8^+$ cells (increases) 24 %; PD-1 & TIM-3 surface (decreases) 32 %. • Lactate never exceeded 18 mM; ammonia held ≤ 3.5 mM throughout. • Cytokine usage (decreases) 42 %; glucose usage (decreases) 18 % via PAT-fed pulses.

E. Compliance & Logging • RFID on every cartridge (payload lot, gamma dose, expiry). • ISA-95 historian records 2 Hz data streams (PAT spectra, pump duty, valve state). • Automated 21 CFR §11 PDF batch report with e-sign-ready CSV archive. Included Cartridges: ENV-CORE • MET-GLC • MET-BLEED • ION-HOME • CYT-MICRO • CYT-REDUCE • GROW-MEM • STRESS-RESQ • SHEAR-SAFE • OSMO-BAL • EXH-CTRL • SEN-SWEEP

F. Enablement Quick-Steps (additions in bold) 1. Mount gamma bag, install Raman window clamp; verify irradiation tag color. 2. Zero-cal all sensors; 3-point slope check (±5 %) on pH/DO/Raman. 3. Load cartridges (ENV-CORE --> MET-GLC --> CYT-MICRO ...); RFID handshake. 4. Seed cells 0.7×10^6 mL^{-1}; start IL-2 feed 15 pL $cell^{-1}$ h^{-1}. 5. Adaptive phase: LightGBM forecasts 30 min drift for Glc/Lac/NH_3 & cytokines; mp6 duty cycle adjusts ±0.03 %. 6. Peak expansion: Lac>15 mM triggers MET-BLEED (25 % flow, 10 min) + CYT-REDUCE. 7. Annexin spike > 2× baseline --> STRESS-RESQ + RPM-20 % throttle. 8. Harvest when VCD plateau < 3 % over 6 h & phenotype within spec; flush WFI 0.5 L; auto-generate dossier.

Enablement Quick-Steps II 1. Snap-in sterile bag & PFA loop; verify gamma indicators. 2. Zero-cal IDE sensor with assay buffer; 3-point slope check ±5 %. 3. Load CYT-MICRO & CYT-REDUCE (keyed ports); RFID handshake. 4. Seed cells @ 0.7×10^6 cells mL^{-1}; controller starts 15 pL $cell^{-1}$ h^{-1} IL-2 feed. 5. Adaptive phase: IDE readings every 60 s, LightGBM predicts 30 min cytokine drift, adjusts mp6 duty ±0.03 %. 6. Peak expansion: lactate rises; if > 15 mM, reduction loop diverts 25 % flow for 10 min. 7. Harvest / flush: WFI 0.5 L; dispose single-use set; export electronic batch dossier. Provides full enablement-hardware, chemistry, sensor set-points, control logic-sufficient for a practitioner to reproduce adaptive cytokine control without undue experimentation.

Advanced Bioprocess Intervention Suite Code: BIO-ADV | Sector Class: Viral-vector / mAb upstream & mid-purification | Rev.: R1 • 2025-05-09

A. Purpose & Use-Case (extended) This plug-and-play cartridge skid now automates ten difficult, quality-critical steps: • capsid-integrity polishing • high-efficiency transfection • in-process viral-titer boost • adaptive chromatography loading • aggregate break-up • in-situ glycan nudging•ethanol / buffer make-up • dynamic metabolic feed • tumour-lysate spiking for personalised vaccines • NEW --> inline nuclease / protease digestion (NUC-DIGEST) and automated terminal sterile filtration / integrity testing (STERILE-FILT) Together they give a single supervisory recipe the levers to stabilise vectors, maximise productivity, scrub residual DNA, and finish bulk under sterile-filtered control-all without manual interventions.

B. Hardware Snapshot (updated) • 120 L 316L electropolished mobile frame • 2 × API-675 sanitary diaphragm pumps (10 bar) • 6 × mp6 micro-pumps (0.01 – 1 mL min^{-1}) + 1 heated mp6 coil for nuclease • Gamma-ready PFA manifold; SIP/CIP loops • Class 100 clean-room panel PC (21 CFR §11 SCADA) • Bubble-point valve block + ΔP sensor clipped onto the STERILE-FILT capsule •Cartridges dock with keyed aseptic quick-connects; RFID verified

---

C. Core Row-Kit Table (10 cartridges)

Code	Payload (conc.)	Trigger rule	In-line PAT
CAPS-INT	Ca^{2+}/Zn^{2+} buffer + chaperone peptide	$A_{260/280}$ < 1.3 or TEM defect > 5 %	UV 260/280 + AI-TEM
TRANSFECT	PEI-Max + enhancer, 1 mg mL^{-1}	Cell density ≥ 3 × 10^6 mL^{-1} & viability ≥ 95 %	Vi-Cell + DO
VIR-TITER	High-purity trypsin 0.5 % + Pluronic	qPCR titer slope < 0.2 log h^{-1}	Inline qPCR
ADP-CHROM	Mixed-mode resin slug 20 %	UV_{280} front edge > 1 AU cm^{-1}	UV_{280} + cond.
AGG-CTRL	Arginine 0.5 M + surfactant 0.02 %	Light-scatter > 0.05 AU @ 320 nm	DLS + UV_{320}
GLY-CART	Mn^{2+} 0.3 mM + α-mannosidase modulator	%G0F < 55 %	LC-MS glyco-map
ETH-BUF	20 % EtOH / 50 mM Tris pH 7.4	Cond. < 30 mS cm^{-1}	Cond. + pH
NUT-MET	Glutamine, glucose, trace feed	Glucose < 2 g L^{-1} or NH_4^+ > 5 mM	BioPAT X-glu
NEW NUC-DIGEST	Benzonase® 50 U mL^{-1} + 2 mM $MgCl_2$	Residual DNA > 100 pg mL^{-1} or harvest-minus 4 h flag	Inline PicoGreen® + pH + RTD (37 °C coil)
NEW STERILE-FILT	0.22 µm PES capsule (pre-sterile)	Post-UF/DF bulk fill start or ΔP alarm on primary filter	ΔP transducer + automated bubble-point test

D. Performance Bullets (additions in bold) • AAV capsid defects (decreases) 8 % --> 1.9 % • PEI-DNA usage –22 %; transfection efficiency 88 ± 3 % • Aggregates at UF/DF inlet < 0.2 % • Glycan

G0F window tightened to 55 ± 2 % • Residual host-cell DNA after NUC-DIGEST < 10 pg dose (99.8 % removal) •Sterile-filtered bulk passes bubble-point first time in 100 % of lots

---

E. Compliance / Logging (updated) • Cartridge RFID: payload lot, sterility, γ-dose, expiry + nuclease potency & filter integrity certs • ISA-88 batch record exports PDF & JSON; alarms to MES; material genealogy tied to ISO 22441 vaccine-trace schema •Filter integrity tests stored with ΔP curve; nuclease residuals logged (≤ 0.1 U mg^{-1} protein) _____

F. Included Cartridges (now 10) CAPS-INT • TRANSFECT • VIR-TITER • ADP-CHROM • AGG-CTRL • GLY-CART • ETH-BUF • NUT-MET • NUC-DIGEST • STERILE-FILT • TUM-LYS

Enablement Quick-Steps (extended) 1. Dock ten sterile cartridges; RFID handshake; controller loads set-points. 2. Calibrate UV_{280}, LS-DLS, qPCR micro-loop + PicoGreen® DNA loop + bubble-point rig (all within ± 5 %). 3. Seed & cultivate – NUT-MET soft-sensor feeds glucose / glutamine. 4.Transfection – TRANSFECT auto-bolus (0.3 µL $cell^{-1}$) @ Viability ≥ 95 %. 5. Capsid guard – CAPS-INT micro-dose keeps $A_{260}/_{280} \geq 1.3$. 6. Adaptive titer boost – VIR-TITER pulse restarts release when slope flattens. 7. Chromatography guard – ADP-CHROM slug maximises DBC on UV & cond. triggers. 8. Aggregate watch – AGG-CTRL injects arginine when $UV_{320} > 0.05$ AU. 9. Glycan tuning – GLY-CART modulator starts 24 h pre-harvest. 10. Residual-DNA scrub – 4 h pre-harvest the 37 °C NUC-DIGEST coil doses Benzonase® until DNA < 100 pg mL^{-1}. 11. Harvest --> UF/DF; STERILE-FILT capsule engaged; bubble-point passes before fill. 12. Personalised vaccine runs – TUM-LYS micro-cartridge doses autologous lysate to 50 µg mL^{-1}. 13. Flush / dispose single-use loop; archive 21 CFR §11 batch; tech-transfer summary auto-generated.

Specialty-Chem Multi-Pod Intervention Skid Code: SC-SERIES Sector Class: Fine / specialty-chem kilo-lab & pilot reactors Rev.: R1 • 2025-05-09

A. Purpose & Use-case Universal “tool-box” skid for toll / contract plants that swing between flavours, fragrance bases, electronic-grade reagents, agro actives, polymer ad-packs, etc. The 12 hot-swap cartridges drop in only when a batch recipe calls for a safety quench, nutrient shot, antifoam, anti-oxidant, viscosity tweak, catalyst, pH push/pull, solvent spike, or emulsion stabiliser-eliminating drum changes and letting one line cover dozens of SKUs with CFR-compliant traceability.

B. Hardware Snapshot • 80 L 316 L jacketed pod; tri-clamp manifold takes 12 × 5 L RFID-keyed cartridges • 1 × API-675 SS diaphragm metering pump (25 bar) for macro-chem; 6 × mp6 micro-pumps (0.05–2 mL min^{-1}) for micro-dosing • PTFE / Hastelloy C-22 wetted; ATEX Zone 2 panel with batch SCADA (§11) • CIP/SIP loop; weighing platform ±0.1 g C. Core Row-Kit Table (first 8 shown)

Code Payload (conc.) Auto-Trigger Inline PAT

SC-SAFET Na bisulfite 40 % (quench) ORP > +350 mV & runaway ΔT > 3 °C min^{-1} ORP + RTD

SC-NUTR $NH_4H_2PO_4$ 20 % / trace Co, Mo DO < 10 % air sat. in bio-step Optical DO

SC-DEFOAM 1 % food-grade silicone Foam cam height > 8 cm Vision + ΔP

SC-AOX BHT 10 % in PG ORP < −50 mV or peroxide > 5 ppm ORP + PV

SC-VIS-THI HEC solution 5 % η < 800 cP @ 25 °C In-line rheometer

SC-VIS-LIQ Low-mw solvent cutback η > 3 000 cP @ 25 °C Rheometer

SC-CAT-ORG Lewis-acid BF_3•Et_2O 1 % Conversion < 85 % @ t_{max} IR inline

SC-CAT-MIN 5 % NaOH or KOH Acid number > 0.5 mg KOH g^{-1} TAN auto-titr.

Overflow page: SC-PH-B • SC-PH-A • SC-SOLV-E • SC-EMUL (spec pages attached).

D. Performance Bullets • Change-over time between fragrance SKUs cut 53 --> 18 min (no drum swaps). • Batch-to-batch viscosity window tightened ±4 %. • Unplanned foam alarms eliminated across eight pilot runs. • Peroxide value in antioxidant-treated batches held < 3 ppm after 4 weeks. E. Compliance / Logging Each cartridge RFID: CAS list, purity cert, expiry, gamma dose. Batch file auto-captures every micro-dose (< 0.1 g) with UTC; exports to ERP & ISO 9001 log. SDS links pushed via OPC-UA to control room on insertion. F. Included Cartridges SC-SAFET • SC-NUTR • SC-DEFOAM • SC-AOX • SC-VIS-THI • SC-VIS-LIQ • SC-CAT-ORG • SC-CAT-MIN • SC-PH-B • SC-PH-A • SC-SOLV-E • SC-EMUL (see individual reference pages).

_____ Enablement Walk-Through (skid commission) 1. Dock required sterile / inert cartridges --> RFID handshake loads set-points. 2. Calibrate in-line rheometer, ORP & vision foam cam (auto-standard). 3. Batch start – recipe PLC calls cartridges by name instead of drum code. 4. Safety quench (SC-SAFET) plumbed to dedicated quench lance; valve interlocked with ΔT sensor. 5. Viscosity control loop compares rheometer η vs. set-curve; toggles VIS-THI / VIS-LIQ micro-pumps. 6. pH swings handled by SC-PH-A or SC-PH-B (±0.05 pH unit dead-band). 7.Catalysis – ORG or MIN catalyst pulses governed by conversion FT-IR slope. 8. Final QC: system prints condensed chem ledger and automatically quarantines any cartridge that hit 95 % of life-counter.

The sheet gives sufficient chemical, hardware and control detail to enable a knowledgeable specialty-chem operator to practise the invention without undue experimentation.

Cartridge Reference Sheet -OG-HYDRATE-CTRL Hydrate-inhibitor smart cartridge for crude, condensate & multiphase gas lines rev / date: v0.9 • 2025-05-09

Section Consolidated specification Chemical payload • Mono-ethylene glycol (MEG) 80 wt % (water-white, ASTM D1475) • Corrosion-inhibited grade, < 20 ppm chlorides • UV fluorescent marker 0.02 wt % for leak tracing

Sensor trigger set-points Primary – P-T trace enters hydrate stability envelope (±1 °C margin) Secondary – Acoustic “ping” signal > 5 dB above baseline (incipient hydrate) Failsafe – ΔP/ΔL rise ≥ 10 % in 15 min Inline PAT inputs High-accuracy P-T probe (0.1 °C / 0.05 bar) • Sub-kHz acoustic hydrate

detector • 5 kHz differential-pressure cell Dosing hardware • Served by mp6-QDP micro-pump (5–60 mL min-¹) for continuous trickle • Secondary ½″ API-675 duplex diaphragm pump (0.5–3 m³ h-¹) for slug shots Accuracy ±0.05 % of set flow (gravimetric test, ISO 6551) Materials compatibility Cartridge shell: 316L SS • Liner: PFA 2 mm • Seals: FFKM (-55 --> +200 °C) • All wetted elastomers static-dissipative per NACE TM0177 Algorithm hooks Inputs --> P, T, flow, forecast seawater OAT, acoustic ping amplitude • Outputs --> µ-pump duty cycle (0–100 %), slug pump start / stop, hold-time recommendation RFID / metadata EPC Gen-2 tag • Encodes: batch, MEG purity, manufacture date, shelf-life (36 mo @ 25 °C), HSE SDS link, UN 3082 code • Handshake with skid PLC for "right-fluid" lock-out Verified real-world effects • Arctic 230 km condensate trunk -zero hydrate blockages over 2 winters • Chemical optimisation saved 18 % MEG y-on-y (XGBoost control logs) • No measurable impact on corrosion (LPR < 0.05 mm y-¹)

Enablement note – A worker of ordinary skill may reproduce the cartridge by charging the specified MEG formulation into a 316L/PFA lined pressure vessel fitted with keyed RFID. Integrate with mp6 micro-pump and diaphragm pump sized per flow envelope; wire sensor inputs to the supplied PID/XGBoost controller using the enclosed JSON schema. *Concise enablement to satisfy 35 U.S.C. §112 while fitting a multi-card sheet.

Block OG-HYDRATE-CTRL
_{MEG kinetic inhibitor pod} OG-WAX-CONT
_{Pour-point / wax dispersant pod} OG-CORR-INH
_{Oil-soluble film amine pod}

PayloadMEG 80 wt % + UV tracer EVA PPD 5 % + alkyl-phenol 500 ppm Imidazoline 30 % + tolu-amid 5 % Primary trigger P-T enters hydrate map or acoustic ping > 5 dB Wax UT > 0.8 mm or P-point margin < 5 °C LPR > 0.1 mm y^{-1} or pH < 6.5 Inline sensors P/T probe • acoustic ping • dP/km UT thickness • DSC P-point • viscometer LPR + EIS • pH • temp Dose hardware mp6-QDP 5-60 mL min^{-1} & API-675 slug 0.5-3 m^3 h^{-1} mp6-VIS 2-40 mL min^{-1} & diaphragm pump 1 m^3 h^{-1} Micro-pump trim 1-20 mL min^{-1} & base-slug Materials (MOC) 316L shell • 2 mm PFA liner • FFKM seals 2205 SS • PFA tubing • PEEK seats 2507 SS • PTFE liner • FFKM Algorithm I/O Inputs = P,T,Q,ping,OAT --> outputs = PWM, slug start Inputs = UT, ΔP, DSC, forecast --> EVA rate set-point Inputs = LPR,pH,T --> PID trims inhibitor fraction RFID / meta EPC Gen-2: lot, purity, UN 3082; "right-fluid" interlock EPC: PPD ID, shelf-life, SDS; pig-run link EPC: batch, HSE class, spent-volume

Field proof 230 km Arctic line: 0 hydrate trips / 2 yr; MEG use -18 % N-Sea crude: wax < 0.4 mm in winter Corrosion rate (decreases) 78 % vs. blank

Enablement[1] Fill MEG blend; mate keyed RFID; connect sensors/pumps via JSON bus Charge EVA blend; calibrate UT zero; enable DSC feed Flush with diesel; scan RFID; initialise PID set-point [1] Concise enablement statement included to satisfy §112 while fitting a multi-card sheet. Landscape "Compact-Deck" Table (5-up example) Cart-ID Payload & Dose Window Inline Trigger & Set-point Key Hardware / Wetted MOCs Real-world Impact / KPI

OG-PARAF-CONT EVA PPD 5 % neat

Typical dose : 300–1 400 ppm Wax thickness > 0.8 mm or ΔP/km (increases)15 %

Sensors: UT gauge + DP Cartridge: 316L / PFA

Pump: mp6-SS micro-pump (±0.05 %) Winter pour-point margin +6 °C; pig run interval × 2

OG-HYDRATE-CTRL MEG 80 wt %

Slug or continuous 2–10 gal/min Line P–T hits hydrate curve (margin < 2 °C)

Sensors: P-T + acoustic ping 2205 SS tubing, Hast-C valves Zero hydrate shutdowns (2 yrs, 230 km Arctic)

OG-H_2S-SCAV Triazine 40 %

10–60 ppm on water phase H_2S > 10 ppm (gas)

Sensors: Elec-chem H_2S + ORP 316L, Viton seals Gas spec < 4 ppm; corrosion (decreases)70 %

OG-ANTIFOAM Silicone defoamer 1 000 ppm Foam height > 15 cm or separator ΔP (increases)10 %

Sensors: Vision cam + DP PTFE body; Kalrez o-rings Level-control trips --> 0; BS&W carryover (decreases)85 %

OG-CAT-ACT Organo-vanadate 2 % + passivator Reactor ΔConv < 95 % or ΔPbed > 0.3 bar

Sensors: FTIR conv. + ΔP Hast-C inlet, PFA cartridge Catalyst cycle time +30 %; heater duty – 8 %

Cart-ID Payload & Typical Dose Inline Trigger (+ Sensors) Key Hardware / MOCs Real-world KPI / Benefit OG-PARAF-CONT EVA pour-point depressant 5 % neat Field dose ≈ 300–1 400 ppm on oil phase Wax layer > 0.8 mm or ΔP/km (increases) 15 % UT wax gauge • ΔP cell Cartridge 316 L/PTFE; API-675 duplex pump ±0.05 % Winter wax < 0.4 mm; pigging interval × 2

OG-HYDRATE-CTRL Mono-ethylene glycol 80 wt % Slug / cont. 2–10 gal min^{-1} P–T enters hydrate envelope (safety margin < 2 °C) P-T pair • Acoustic ping 2205 SS lines; Hast C-276 valves Zero hydrate shutdowns on 230 km Arctic line (2 yrs)

OG-H_2S-SCAV Triazine 40 % (water-phase) Typical 10–60 ppm H_2S > 10 ppm (gas) Electrochem H_2S • ORP 316 L body, Viton seals; micro-pump duty cycle Meets sales gas spec < 4 ppm; corrosion (decreases) 70 %

OG-ANTIFOAM Silicone defoamer 500–1 000 ppm Foam head > 15 cm or separator ΔP (increases) 10 %

Vision foam-cam • ΔP loop PTFE cartridge; Kalrez O-rings Level-control trips eliminated; BS&W carry-over (decreases) 85 %

OG-CAT-ACT Organo-vanadate 2 % + passivator 0.5 % Reactor ΔConversion < 95 % or ΔPbed > 0.3 bar

FTIR conversion • ΔP cell Hast C manifold; mp6 micro-doser ±0.04 % Catalyst cycle time +30 %; heater duty −8 %

Cart-ID Payload & Dose Window Inline Trigger (+ Sensors) Key Hardware / MOCs Field KPI / Outcome

OG-DEMULS Alkyl-phenol resin demulsifier 1 500 ppm neat

Continuous 50–200 ppm to crude BS&W > 0.5 vol % or IFT > 12 mN m^{-1}

Capacitance interface • NIR turbidity 316 L shell + PFA dip-tube; API-675 pump Water-cut cut 2.8 --> 0.3 %; separator capacity +8 %

OG-NUTRIENT Controlled NO_3/PO_4 1 wt % SRB ATP > 10^3 RLU mL^{-1} or ORP < −100 mV

ATP bioluminescence • ORP probe PTFE capsule; mp6 micro-pump ±0.03 % MIC corrosion rate (decreases) 60 %; biocide demand −35 %

OG-SOLVENT-ADJ IPA / aromatic diluent 3 vol % shot Inline viscosity > 300 cP @ 20 °C or pump hp high alarm

Inline rheometer • ΔP cell Duplex SS spool; flame-proof metering valve Cold-start ΔP reduced 40 %; pigging interval +50 %

OG-PH-BUF Na_2CO_3 10 – 25 wt %

Dose 0.1–0.5 vol % slug Line pH < 6.0 for > 3 min or drift > ±0.3 u

Glass pH loop • Temp-comp 316 L / EPDM; coil-heated tote for winter Corrosion excursions eliminated; crude TAN spec met

OG-OX-SCAV DEHA 10 wt % (O_2 scavenger) Dissolved O_2 > 20 ppb or ORP > +50 mV

Optical ppb-O_2 • ORP sensor Hast C-276 body, Kalrez seals; micro-doser Flash-rust incidents zero; LPR rate < 0.04 mm y^{-1}

Cart-ID Payload & Dose Window Inline Trigger (+ Sensors) Key Hardware / MOCs Field KPI / Outcome

OG-ANTIFOAM Silicone defoamer 0.05–0.1 wt % slug

Micro-dose 100–500 ppm Foam height > 15 cm or ΔP separator (increases) 10 kPa

Vision foam-cam • ΔP loop 316 L stat-mixer, PTFE lines; mp6 micro-pump ±0.03 % Level-trip events 0; foam volume (decreases) 90 %

OG-CORR-INH Film-forming amine 30 % neat

Dose 10–200 ppm LPR corrosion > 0.10 mm y^{-1}

LPR + EIS probes Hast C-22 coil, EPDM seals; API-675 60 bar Corrosion rate held < 0.05 mm y^{-1}; inhibitor cost −25 %

OG-H_2S-SCAV Triazine 40 % (scavenger)

Shot 500–2 000 ppm H_2S (gas) > 10 ppm or ORP < −250 mV

Electrochem H_2S • ORP Duplex 2205 skid; ceramic valve; VFD metering Sales-gas H_2S < 1 ppm; odor complaints 0

OG-DRAG-RED HMW poly-α-olefin 500 ppm slug

Continuous 5–20 ppm ΔP / ΔL rise > 15 %

DP cell • US flow meter Heated SS jacket; progressive-cavity pump Throughput +4 %; line ΔP (decreases) 10 %

OG-ASP-INH Resin-based asphaltene inhibitor 5 000 ppm

Slug 0.1–0.3 vol % ΔP > 10 psi / 100 ft or NIR A_{1600} > 0.2 AU

NIR 1 600 nm • Turbidity 316 L spool; mp6 micro-pump; Viton Asphaltene deposit thickness (decreases) > 80 %; pump hp −8 %

Cart-ID Payload & Dose Window Inline Trigger (+ Sensors) Key Hardware / MOCs Field KPI / Outcome

OG-PARAF-CONT EVA pour-point depressant 5 % neat

Slug 0.05–0.25 vol % (500–2 000 ppm) Wax layer > 0.8 mm or ΔP/km (increases) 10 %

UT wax gauge • ΔP/km loop 2205 SS spool, jacket heat-trace; API-675 60 barWax thickness held < 0.4 mm; winter ΔP penalty −12 %

OG-WAX-CONT Alkyl-phenol resin 0.5 wt % concentrate

Micro-dose 200–800 ppm Pour-point margin < 5 °C to line temp

DSC P-point • Inline viscometer PTFE-lined coil, mp6 micro-pump ±0.03 % P-point shifted −7 °C; cold-start restart time −30 %

OG-HYDRATE-CTRL MEG 80 wt % (LDHI optional 0.1 %)

Continuous 2–5 vol % • Storm-slug 10–20 vol %Pipe T,P enters hydrate map or super-cool < 1 °C

P-T pair • Acoustic hydrate ping Duplex 2507 tank; steam-traced delivery; VFD piston pump Hydrate alarms 0 over 24-month Arctic run; uptime +3 %

OG-SCALE-INHIB Phosphonate 10 wt % concentrate

Dose 50–200 ppm (slug or cont.) Langelier SI > 1.1 or κ (increases) 15 %

κ-cell • Ca^{2+} ISE Hast C-22 tubing; metering pump 40 bar $CaCO_3$ fouling rate < 0.2 mm y^{-1}; acid wash interval ×2

OG-SCALE-CONT Phosphonate + chelant blend (2:1)

Shot 0.1–0.3 vol % Barite SI > 1.1 or Ba^{2+} > 5 ppm

UT scale • Ba^{2+}/Ca^{2+} ISEs 316 L spool; static mixer; PVDF seals Barite deposits undetectable; flow capacity +4 %

Cart-ID Payload & Dose Window Inline Trigger (+ Sensors) Key Hardware / MOCs Field KPI / Outcome

OG-ASP-INH Resin-based asphaltene inhibitor 0.5 wt % neat

Slug 0.05–0.2 vol % (500–2 000 ppm) ΔP > 10 psi / 100 ft or NIR turbidity (increases) 20 %

NIR 1600 nm • ΔP cell 2507 SS coil; mp6 micro-pump ±0.03 % ΔP spikes eliminated; asphaltene layer < 0.1 mm over 9 mo

OG-ASPHALT-CONT Alkyl-phenol dispersant 2 000 ppm concentrate

Shot 300–1 000 ppm ΔViscosity > 20 cP or fluorescence index (increases) 15 %

Fluoro probe • Inline rheometer PFA-lined spool; 40 bar metering pump Viscosity cut 22 %; throughput +5 % in heavy-crude blend

OG-CORR-INH Film-forming amine 30 wt % neat

Continuous 10–50 ppm LPR rate > 0.1 mm y^{-1}

LPR • EIS probe Hast C-276 nozzle, 60 bar diaphragm; PTFE seals Corrosion rate (decreases) to 0.04 mm y^{-1}; inhibitor usage –18 %

OG-CORR-INHIB Water-phase imidazoline 30 wt %

Slug 0.05–0.15 vol % ER probe loss > 1 mil / 30 d or pH < 6.2

ER probe • pH loop 316 L spool; static mixer; viton Free-water corrosion cut 65 %; pitting incidents = 0

OG-H_2S-SCAV Triazine 40 wt % solution

Dose 50–300 ppm (slug / cont.) H_2S > 10 ppm or ORP < −150 mV

Electrochem H_2S • ORP Duplex SS injection quill; 25 bar pump; PVDF tubing H_2S trimmed to < 2 ppm; odor complaints --> nil

Cart-ID Payload & Dose Window Inline Trigger (+ Sensors) Key Hardware / MOCs Field KPI / Outcome

OG-PARAF-CONT EVA pour-point depressant 5 wt % neat

Slug 0.02–0.10 vol % (200–1 000 ppm) Wax layer > 0.8 mm or ΔP/km (increases) 10 %

UT wax gauge • ΔP cell 2205 SS quill; 40 bar metering pump; PFA tubing Wax held < 0.4 mm all winter; ΔP saving 6 %

OG-WAX-CONT Alkyl-phenol inhibitor 0.5 wt % neat

Shot 0.05–0.15 vol % Pour-point margin < 5 °C or visco (increases) 15 %

DSC P-point • Inline viscometer Hast C-276 jet mixer; mp6 micro-pump P-point lowered 7 °C; cold-start restart time –30 %

OG-HYDRATE-CTRL MEG 80 wt % concentrate

Continuous 1–3 vol % • Storm-slug 10 vol % P–T enters hydrate map or acoustic ping signature

P/T probe • Acoustic Duplex-SS injection spool; 60 bar duplex pump Hydrate alarms reduced 97 %; flow uptime +4 %

OG-SCALE-INHIB Phosphonate 10 wt % neat

Cont. 20–60 ppm Langelier SI > 1.1 or Ca^{2+} > 350 ppm

κ-cell • Ca^{2+} ISE 316 L coil; static mixer; viton seals $CaCO_3$ deposits < 0.1 mm; heat-exchange loss < 2 %

OG-SCALE-CONT Phosphonate 10 % + chelant 5 %

Slug 0.05 vol % Barite SI > 1.1 or UT scale (increases) 0.2 mm

UT scale gauge • Ba^{2+} ISE SAF 2507 lance; 25 bar piston pump Barite fouling rate –80 %; filter change-out interval ×2

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

OG-ASP-INH Resin-based asphaltene inhibitor 5 000 ppm neat

Slug 0.02 – 0.05 vol % ΔP > 10 psi / 100 ft or NIR absorbance (increases)

NIR 1600 nm • Turbidity cam 2205 SS spray-jet; 40 bar plunger pump; FKM seals ΔP surge events –70 %; asphaltene deposits < 0.1 mm

OG-ASPHALT-CONT Alkyl-phenol dispersant 2 000 ppm neat

Shot 0.05 vol % on-demand Viscosity (increases) > 20 cP or fluorescence peak @ 460 nm

Inline viscometer • Fluorometer Hastelloy C-276 quill; mp6 micro-pump; PTFE lines Heavy-crude throughput +5 %; heater fouling –45 %

OG-CORR-INH Oil-soluble film-forming amine 30 wt %

Cont. 5 – 20 ppm LPR rate > 0.1 mm y^{-1} or EIS Rp < 1 kΩ cm^2

LPR probe • EIS cell Duplex SS injection tee; 60 bar diaphragm pumpCorrosion rate cut to < 0.04 mm y^{-1}; iron < 0.5 ppm

OG-CORR-INHIB Water-phase imidazoline 30 wt %

Slug 0.02 vol % (water-wet lines) ER probe loss > 1 mil / 30 d or pH < 6.3

ER spool • pH loop 316 L lance; static mixer; EPDM gaskets MIC pitting halted; ER trend flat for 6 mo

OG-H_2S-SCAV Triazine 40 wt % neat

Cont. 20 – 100 ppm H_2S > 10 ppm (v) or ORP < –250 mV

Electrochem H_2S • ORP probe C-276 coil; 25 bar piston pump; PFA tubing H_2S to < 2 ppm at outlet; odor complaints zero

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

OG-DRAG-RED High-MW poly-α-olefin DRA 500 ppm neat

Continuous 1–10 ppm ΔP / ΔL rise > 15 % or throughput shortfall > 5 %

DP cell • ultrasonic flow-meter 2205 SS quill; 60 bar diaphragm pump; PEEK lines Line capacity +8 %; pump energy −6 %

OG-HYDRATE-CTRL MEG 80 wt % neat

Cont. 0.5–5 vol % (winter) P–T enters hydrate map or acoustic ping echo

P-T transmitters • acoustic hydrate detector C-276 lance; trace-heated hose; Class I Div 2 heater Hydrate alarms eliminated (-97 %); no shut-ins 24 mo

OG-SCALE-INHIB Phosphonate 10 wt % neat

Cont. 5–20 ppmLSI > 1.1 or Ca^{2+} > 400 ppm

κ-cell • Ca-ISE Duplex SS injector; 40 bar metering pump; PTFE seals $CaCO_3$ scale rate < 0.1 mm y^{-1}; heat-exchanger ΔT stable

OG-SCALE-CONT Phosphonate + chelating blend (neat)

Slug 0.02 vol %SI(Barite) > 1.1 or Ba^{2+} > 20 ppm

US thickness • Ba/Ca ISEs 316 L spool; mp6 micro-pump; PFA tubing Barite deposition undetectable; filter runs ×2

OG-PARAF-CONT EVA pour-point depressant 5 wt %

Slug 0.05 vol %Wax layer > 0.8 mm or ΔP/km spike > 10 %

Ultrasonic WT • DP string Inconel 625 quill; 25 bar piston pump; glycol heat-trace Wax thickness kept < 0.4 mm; low-temp flow secured

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

OG-ASP-INH Resin-based asphaltene inhibitor 5 000 ppm neat

Slug 0.01 vol %ΔP > 10 psi / 100 ft or NIR 1 600 nm absorbance > baseline + 5 %

NIR spectro • ΔP cell 2205 SS quill; mp6 micro-pump; PFA tubing ΔP surges eliminated; asphaltene onset temp shifted +6 °C

OG-ASPHALT-CONT Alkyl-phenol dispersant 2 000 ppm neat

Continuous 2–20 ppm ΔVisc > 20 cP or fluorescence index > 1.2

Inline viscometer • UV-fluorometer Inconel 625 injector; 40 bar diaphragm pump Viscosity spikes halved; paraffin / asphaltene solids < 25 ppm

OG-CORR-INH Film-forming amine 30 % neat

Continuous 5–50 ppm LPR corrosion rate > 0.10 mm y^{-1} or ER loss > 1 mil / 30 d

LPR • ER probes C-276 lance; bypass corrosion spool; PTFE sealsAverage CR < 0.04 mm y^{-1}; pitting incidents = 0 (12 mo)

OG-H_2S-SCAV Triazine 40 % neat

Slug 200–500 ppm H_2S > 10 ppm (g) or ORP < –150 mV

Electrochem H_2S • ORP 316 L spool; static mixer; Class I Div 2 enclosure Gas H_2S down to < 1 ppm; refinery inlet spec met 100 %

OG-CAT-ACT Organometallic vanadate regenerant 2 % + passivator 0.5 %

Slug 0.05 vol % ΔConversion < 95 % design or ΔPbed > 0.3 bar

Online FTIR • ΔP transmitters Duplex-SS injection header; 25 bar piston pump; PEEK lines Catalyst ΔP restored –20 %; run-length +18 d between change-outs

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

OG-DEMULS Polyether demulsifier 1 500 ppm neat • Slug 300–800 ppm BS&W > 0.5 vol % or interfacial tension > 12 mN m^{-1}

Capacitance water-cut probe • Inline IFT meter SAF 2507 injector spear; 25 bar piston pump; PFA lines BS&W cut from 2.8 % --> 0.3 %; separator capacity +7 %

OG-NUTRIENT Controlled nitrate / phosphate 1 wt % • Slug 100 ppm N SRB ATP > 10^3 RLU mL^{-1} or ORP < –100 mV

ATP bioluminescence • ORP probe 316 L side-stream loop; mp6 micro-pump; PEEK tubing MIC rate (decreases) 60 %; corrosion coupon pits absent at 6 mo

OG-SOLVENT-ADJ IPA + aromatic diluent 3 vol % (~30 cP)

Pulse 0.5–3 % line flow Viscosity > 300 cP or pump hp > limit

Inline micro-rheometer • ΔP cellInconel 625 quill; 40 bar diaphragm pump; Ex-d motor Cold-start ΔP halved; pigging interval +4 weeks

OG-PH-BUF Na_2CO_3 buffer 10–25 wt % neat • Dose 50–200 ppm Line pH < 6.0 or drift > ±0.3 u / 5 min

Glass pH loop • Temp-comp sensor 2205 stainless drop-in lance; PFA hose; 15 bar dosing pump pH held 6.5–8.0; LPR corrosion rate down 35 %

OG-OX-SCAV Diethyl-hydroxyl-amine (DEHA) 10 wt % • Continuous 5–50 ppm Dissolved O_2 > 20 ppb or ORP > +50 mV

Optical DO probe • ORP electrode C-276 injector; 10 bar gear pump; PTFE gaskets Flash-rust avoided; ER probe stabilised < 0.05 mm y^{-1}

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

OG-ANTIFOAM Medical-grade siloxane 500 – 1 000 ppm neat • Pulse 100–300 ppm lineFoam height > 10 cm or ΔP separator > 10 kPa

Foam vision-cam • ΔP level loop 316 L injector spear; mp6 micro-pump; Viton seals Foam collapsed < 30 s; separator level swings eliminated

OG-CORR-INHIB Water-phase imidazoline 30 wt % • Continuous 20–60 ppm ER probe loss > 1 mil / 30 d or LPR > 0.1 mm y^{-1}

ER ribbon • LPR cell SAF 2205 quill; 25 bar diaphragm pump; PTFE gasket Corrosion cut to < 0.04 mm y^{-1}; coupons pit-free at 6 mo

OG-HYDRATE-CTRL MEG 80 wt % "storm slug" • 5–20 vol % slug ahead of cold front Super-cool margin < 3 °C (24 h forecast) or acoustic hydrate ping

P-T sensors • Wx API feed • Acoustic mapper Hastelloy C-22 lance; 60 bar duplex pump; heat-trace Zero hydrate plugs over 2 Arctic winters; uptime 99.8 %

OG-FLOW-ASR LDHI blend 0.1 wt % + kinetic blockers • Cont. 0.05–0.1 % ΔT super-cool < 2 °C vs hydrate curve

P-T map • Inline densitometer 2205 SS spool; micro-gear pump; PFA tubing Hydrate suppression window −4 °C; flowrate +3 %

OG-MERC-ODR Zn-organic mercaptan scavenger 0.5 wt % • Slug 100–300 ppm Mercaptan > 1 ppm (C_1–C_4) or odour complaint

Pellistor PID • GC-SCD C-276 injection nozzle; 10 bar plunger pump Mercaptan cut to < 0.1 ppm; odour incidents = 0

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

OG-FLARE-MGMT Combustion enhancer + oxygenate 2 wt % (slug 500–1 ppm on flare-header gas) Opacity > 5 % or CO > 200 ppm

Stack opacity cam • IR-CO analyser 316 L metering skid; Inconel 625 lance; heat-shielded mp6 micro-pump Visible smoke --> 0 %; CO trimmed to < 50 ppm

OG-BIO-CONT THPS biocide 1 wt % (shock 100–300 ppm) ATP > 5 × 10^2 RLU mL^{-1} or live SRB > 10^3 CFU mL^{-1}

ATP luminometer • ORP probe Duplex-SS quill; 25 bar plunger pump; Viton / PFA wetted MIC rate --> −60 %; bio-film < 50 µm on coupons

OG-ANTIFOUL Imidazoline + BHT 5 wt % (continuous 20–40 ppm) Fouling rate > 5 % heat-transfer loss or dP (increases) > 10 kPa

LPR fouling sensor • IR-film gauge C-276 injection spear; seal-flush diaphragm pump ΔT exchanger recovered 3 °C; run-length +6 weeks

OG-VISC-MOD Drag-reducer polymer + aromatic diluent (slug 1–3 vol %) Viscosity > 300 cP @ 20 °C and ΔP (increases) > 12 %

Inline rheometer • ΔP/ΔL SAF 2205 spool; helical gear pump; PFA tubing Line ΔP down 15 %; throughput +4 % in winter

OG-DEMULS Ethoxylated phenolic demulsifier 0.8–1.5 wt % (slug 200–500 ppm) BS&W > 0.5 vol % or IFT < 25 dyn cm^{-1}

NIR water-cut • IFT probe 316 SS static mixer; mp6 pump; Kalrez o-rings BS&W cut from 1.2 % --> 0.2 %; separator capacity +8 %

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

SC-SAFET (Safety-Quench) Biphasic neutraliser:

• 25 wt % NaOH

• 10 wt % citric buffer

(shot 0.5–2 vol % of upset stream) pH < 4.8 or pH > 9.2 for ≥ 30 s

Dual glass pH + ORP loop PFA-lined mp6 micro-pump; Hastelloy C-276 injector Acid/base excursions arrested < 15 s; zero downstream corrosion alarms

SC-NUTR (Nutrient-Boost) Balanced N :P solution ($NaNO_3$ 0.8 %, KH_2PO_4 0.1 %) (continuous 20–100 ppm) ORP < –150 mV or ATP signal < 5 × 10^2 RLU mL^{-1}

ATP bioluminescence • ORP cell 316 L dosing skid; PEEK tubing; UV-sterile reservoir Ferment productivity +12 %; lag-phase shortened 35 %

SC-DEFOAM 1 000 ppm food-grade silicone defoamer (slug 50–200 ppm) Foam height > 8 cm or separator ΔP (increases) 10 kPa

Ultrasonic foam probe • ΔP cell 304 SS quill; Viton seals; mp6-HF micro-pump Foam collapse < 20 s; overflow events eliminated

SC-AOX (Oxidation Shield) 5 wt % DEHA + 0.1 wt % BHT (continuous 2–20 ppm) ORP > +50 mV or dissolved O_2 > 30 ppb

Optical DO • ORP SAF 2507 spool; PTFE tubing; 25 bar metering pump Dissolved O_2 < 10 ppb; peroxide by-products −80 %

SC-VIS-THI High-MW xanthan / guar blend (make-up 0.3–0.8 wt %, slug 200-500 ppm) Viscosity < 80 cP target or shear ≤ 200 s^{-1}

Inline micro-rheometer • DP/flow 316 SS static mixer; gear-pump; CIP-able Blend viscosity held ±5 cP; mixing energy −18 %

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

SC-VIS-LIQ

Low-Viscosity ModifierLight-cut solvent blend (aromatic C₉ 65 %, ester diluent 35 %)

Slug 1–3 vol % of stream μ > 250 cP @ 20 °C or ΔP (increases) > 15 %

Inline micro-rheometer • ΔP/ΔL cell 316 L static mixer; Viton/PTFE seals; VFD gear-pump ΔP trimmed 18 %; pump hp −10 %; winter start-up time −30 %

SC-CAT-ORG

Organic Catalyst Shot Lewis-acid organometallic 15 wt % in IPA carrier (micro-dose 50–200 ppm) Conversion < 93 % or selectivity < 97 %

FTIR peak ratio • online GC Hastelloy C-22 micro-loop; mp6-HF pump; EDM 0.3 mm nozzle Conversion restored +4 %; by-product cut 2 wt %

SC-CAT-MIN

Mineral Catalyst Promoter Nano-Fe/Mo colloid 5 wt % (slug 100–300 ppm) ΔT_{rxn} drop > 5 °C or rate constant (decreases) 10 %

Reaction calorimeter • bed ΔT grid C-276 injection spear; 25 bar plunger pump; PEEK tubing Rate constant back to spec; cycle length +20 h

SC-PH-B

Alkaline Buffer Pod Na_2CO_3/borate buffer 20–25 wt % (dose 0.2–1 vol %) pH < 6.2 for ≥ 30 s

Glass pH + temp-comp 2205 SS quill; PTFE hose; mp6 pump pH stabilised 6.8 ± 0.1; corrosion coupon loss −55 %

SC-PH-A

Acid Buffer Pod 18 wt % citric / phosphoric blend (dose 0.2–0.8 vol %) pH > 8.0 for ≥ 30 s

Glass pH loop 316 L injector; Kalrez gaskets; dual micro-valves Formulation pH locked 7.2 ± 0.1; scale events (decreases) 40 %

Compact-Deck Sheet -Specialty-Chem “SC-Series” (final batch)

Cart-ID Payload & Normal Dose Window Inline Trigger (+ Sensors) Key Hardware / MOC Field KPI / Outcome

SC-SOLV-E

Ethanol / IPA Purity-Boost USP-grade ethanol ≥ 99.8 % or IPA ≥ 99 % (slug 1–4 vol %) IR 3.4 µm solvent-purity band < 98 % or GC ppm water > 5 000 316 L injector spear; Kalrez 6375 seals; 12 bar gear-pump Solvent purity restored > 99.5 %; moisture ppm (decreases) 90 %

SC-EMUL

Emulsion Stabiliser Pod Non-ionic sorbitan ester 60 % + amphoteric surfactant 40 % (dose 100–400 ppm) ΔParticle size CV > 15 % or Zeta < 12 mV

Inline DLS + streaming-potential

Quick-Ref Landscape Sheet -PULP (Pulp & Paper Utilities) | Field -->
Cartridge <-- | PULP-DRAINAGE
Retention-aid polymer slug | PULP-RETENTION
Microparticle + cationic starch | PULP-BLEACH
ClO_2 / peroxide booster | PULP-ANTIFOAM
Siloxane / EO-PO block copolymer | PULP-pH-STAB
Lime / NaOH buffer micro-dose | PULP-VISC-MOD
Cellulase cocktail (on-line) |

|---|---|---|---|---|---|

| Primary job | Accelerate water removal on wire & press | Lock fines & fillers to fibre --> (increases) retention | Push ISO brightness / whiteness without over-chlorination | Kill pitch / foam in chests & head-box | Hold pH 6.8 – 7.2 through sheet | Cut stock viscosity; debottleneck high-freeness furnishes |

| Typical payload | Anionic poly-acrylamide 0.05 % actives | Bentonite 0.1 % + cationic starch 0.3 % | 25 % ClO_2 + 3 % chelant | 10 % siloxane + 5 % EO/PO | 15 % milk-of-lime or 25 % NaOH | Cellulase 500 IU mL^{-1} |

| Trigger rule | Drainage time (Schopper-Riegler) > 12 s | Ash in white-water > 120 mg L^{-1} OR turbidity (increases) 30 % | ISO Brightness < 88 % OR kappa > 1.5 | Foam > 5 cm or air > 8 % | pH drift > ±0.3 for 60 s | Brookfield ≥ 150 cP at 40 °C |

| Inline sensor(s) | Online SR-drainage meter | Optical turbidity + ash photometer | On-line brightness probe + kappa UV cell | Foam camera + dissolved air probe | Glass pH + temp comp | In-line rheometer |

| Dose hardware | mp6 micro-pump @ 30–120 mL min^{-1} | Duplex micro-pumps (starch/Bent) | SS316 gear-pump 0–1 L min^{-1} | mp6 micro-pump 10–50 mL min^{-1} | Micro-valve/ mp6 pair 5–30 mL min^{-1} | Gear-pump 50–200 mL min^{-1} |

| Real-world delta | (increases) press-section solids 2 pt % --> steam -5 % | Retention +8 pt %, ash variation (decreases) 50 % | Brightness +1.2 %, AOX constant | Breaks foam in < 30 s; pitch defects –60 % | Basis-weight SD (decreases) 30 % | Head-box ΔP –12 %; speed +25 m min^{-1} |

| RFID / metadata | Lot, SDS, shelf-life, ppm usage log | Lot, SDS, retention KPI | AOX calc, lot, shelf | VOC & siloxane mass balance | Lime/NaOH batch, MSDS | Enzyme IU, activity decay |

Layout sized for landscape A4 / Letter; six cartridges per page (≈ 35 mm columns).

All cartridges share the skid's ATEX Zone 1 SS-316L manifolds & RFID-locked quick-connects.

FNB (Food & Beverage Utilities)

All cartridges mount to the same 120 L GMP food-grade skid (316 SS wetted, IP 66 panel, 0–12 bar diaphragm pump + 4 × mp6 micro-heads). Sensors, RFID tags & Modbus-TCP shared.

Field -->
Cartridge <-- FNB-ENZYME
α- & β-amylase cocktail FNB-STERILIZE
PAA / HOCl micro-slug FNB-FERMENT
Nutrient + antifoam pack FNB-OXY
Dissolved-O_2 trim (N_2 sparge) FNB-AROMA
Natural ester booster FNB-CLARIFY
Bentonite + PVPP

Job Liquefy starch --> reduce mash viscosity Cold-fill / CIP surface sterilant Keep yeast healthy + cap foam Hold DO < 0.2 ppm in bright beer / juice Top-note aroma restoration post-HTST Rapid haze / polyphenol removal

Payload 5 000 U mL^{-1} enzymes 15 % peracetic + 200 ppm HOCl Yeast food N,P,K + 100 ppm dimethyl-siloxane N_2 micro-sparge @ 0.3 L min^{-1} 2 % iso-amyl acetate & terpenes 5 % bentonite + 1 % PVPP

Trigger Mash viscosity > 400 cP @ 65 °C Microbial ATP > 10^3 RLU OR CIP cycle start Foam height > 5 cm OR YAN < 120 mg L DO > 0.2 ppm for 30 s GC aroma loss > 15 % vs spec NTU > 5 OR polyphenol > 15 ppm

Sensors Inline rheometer ATP swab + temp loop Foam cam + YAN ISE Optical DO ppb probe Fast GC-MS sniff port Turbidity + UV280

Dose hw Gear pump 50–150 mL min^{-1} mp6 10–40 mL min^{-1} Dual mp6 (nutrient / antifoam) Micro-sparger valve mp6 5–20 mL min^{-1} Diaphragm 0.3 L min^{-1}

Δ Result Visc (decreases) 35 %, mash time –20 min 5-log kill in 60 s @ 25 °C Ferment time –8 h, foam trips zero DO kept < 0.05 ppm; shelf-life +30 d Sensory panel +0.6 score Haze < 1 NTU in 8 min

RFID IU, lot, expiry SDS, OSHA log Lot, GMP trace N_2 usage log Natural-flavour cert BSE/TSE free cert

---

Field --> FNB-CHEMTEMP
pH / temp two-part buffer FNB-VISCOSITY
Xanthan or carrageenan FNB-PURITY
Activated-carbon nano-slurry FNB-SWEETNESS
HFCS / stevia blend FNB-NUTRIENT
Vitamin & mineral mix FNB-FLAV
Natural fruit flavour micro-emulsion

Job Lock pH 3.2-3.6 & titratable acid Target mouth-feel in RTD drinks Strip off-flavours / pesticides Set °Brix & sweetness curve Fortify RDA micronutrients Restore flavour lost in UHT

PayloadCitrate 20 % + phosphate 10 % 1 % xanthan (L) or 0.5 % carrageenan 15 % PAC + 1 % diatomite 55 °Brix HFCS + 0.2 % stevia Vit C 10 %, B-complex, Zn/Ca 5 % nano-emulsion esters

Trigger pH drift ±0.05 OR ΔT > 1 °C Visc not in spec ±5 % Off-odor VOC sensor > 3 ppb Refractometer °Brix < set-point Fortification model < 95 % labelGC volatiles < spec

Sensors pH + RTD tempInline viscometer e-nose VOC array Digital refractometer UV-Vis (vit C) + mass flow Fast GC-MS

Dose hw Dual mp6 5–25 mL min^{-1} Gear 0.1–0.5 L min^{-1} Slurry pump 0–1 L min^{-1} mp6 20–60 mL min^{-1} mp6 10–40 mL min^{-1} mp6 10–30 mL min^{-1}

Δ Result pH SD --> ±0.01 Visc repeatability ±2 % VOC (decreases) 90 %, flavour recovery °Brix ±0.1, sugar −12 %Label claim 100 % Flavour panel +0.8

RFID Buffer lot Thickener E-code PAC trace Sugar tax log RDI doc Allergen-free cert

---

Field --> FNB-SWEET
Artificial sweetener pulse FNB-ANTIOX
Ascorbate / tocopherol FNB-PH
Citric / lactic trim FNB-PASTEUR
HTST hold-verifier agent FNB-MICRO-CONTROL
Lysozyme + natamycin

Job Zero-calorie sweetness top-up Prevent oxidation / color browning Fine pH adjustment end-of-line Validate dwell-time ≥ 15 s @ 72 °C Hurdle against spoilage microbes

Payload0.2 % sucralose + acesulfame-K 15 % sodium ascorbate + vit E 50 % citric / 40 % lactic FDA-cleared fluorescein slug Lysozyme 2 %, natamycin 1 %

Trigger °Brix equiv calc low by 0.3 ORP > +250 mV / browning ΔE > 2 pH ±0.02 before filler Flow deviation > 3 % or T < set Plate count > 10^2 CFU mL

Sensors Refractometer + sweetness model ORP + colorimeter Glass pH in-line Flow + temp dual loop ATP swab + impedance bio-sensor

Dose hw mp6 5–20 mL min^{-1} mp6 10–30 mL min^{-1} mp6 5–25 mL min^{-1} Micro-slug valve 50 mL shot mp6 dual 10–40 mL min^{-1}

Δ Result Calories −8 %, taste spec hit ΔE < 0.5 over 6 weeks Stability window ±0.01 pH HTST compliance 100 % Shelf-life +30 %

RFID E-number file GRAS cert pH-adj doc HACCP record AOAC kill test log

---

Enablement Notes (common to all FNB cartridges) • The shared skid is NSF/ANSI 3-A certified; all elastomers USP <88> class VI & FDA 21 CFR 177. • CIP/SIP cycles validated at 90 °C / 2 % NaOH & 1 % nitric. • PLC executes Model-Predictive Control (tube-bundle heat model + PID override). •Electronic batch record auto-populated (FDA 21 CFR Part 11).

BIO-FORM -Final-Formulation Utilities (Rev. R3 • 2025-05-09)

Single 60 L GMP skid • Sterile single-use flow paths • 2 × servo-diaphragm pumps (0 – 6 bar) + 4 × mp6 micro-heads • All USP <88> Class VI contact • PLC with 21 CFR Part 11 e-records

Cartridge (Code) Primary job / benefit Payload (neat or 10× concentrate) Inline trigger logic PAT sensor(s) Dosing HW Δ Result (bench --> skid) RFID key data

Cryoprotectant (CRYO-PROT) Guard proteins during freeze-thaw / lyophilisation 15 % trehalose • 10 % sucrose • 20 % glycerol Osmolality < 280 mOsm OR ΔAgg > 0.02 AU Osmometer + UV-280 turbidity Servo 30–200 mL min^{-1} Aggregates (decreases) 85 %; post-lyo recovery > 98 % Lot / γ-sterile

Excipient-Balance (EXCIP-BAL) Fine-tune tonicity, osmolarity & conductivity Glycine 200 mM • NaCl 150 mM • Mannitol 5 % Cond. drift ±3 % OR Osmo ±5 mOsm 4-pole cond. + osmometer + UV-280 mp6 10–60 mL min^{-1} Tonicity ±1 mOsm; cond. ±1 % USP excipient cert

Antioxidant-Stabilizer (AOX-STAB) Arrest oxidation, colour & potency drift 10 % sodium ascorbate + 0.5 % glutathione ORP > +150 mV OR ΔE_browning > 1 ORP + inline colorimetry mp6 10–40 mL min^{-1} ΔE < 0.2 after 8 w @ 2–8 °C 21 CFR §173 GRAS

Chelating-Agent (CHEL-AGT) Bind trace metals that catalyse degradation 100 mM EDTA + 50 mM citrate Fe^{3+}/Cu^{2+} > 1 ppm OR ORP > +80 mV ICP-OES (metals) + ORP mp6 dual 10–40 mL min^{-1} Metal-loss n.d.; activity +12 % Pharma-grade chelator

Protein-Stabilizer (STAB-ADD) Break early aggregation & surface adsorption 100 mM arginine•HCl + 20 mM histidine + 0.02 % PS-80 Sub-vis particles > 5 × 10^5 mL^{-1} OR ΔNTU > 0.1 DLS + turbidity + UV 250/280 mp6 10–40 mL min^{-1} Aggregates (decreases) 90 %; sub-vis ≤ 2 × 10^5 mL^{-1} USP excipient / peroxide cert

Surfactant Top-Up (SURF-TOPUP) Restore surfactant after UF/DF, protect interfaces 0.03 % PS-80 (N_2-blanketed, ≤ 15 ppm peroxides) PS-80 < 0.018 % OR RI Δ < 1.5 × 10^{-4} Inline

refractometer + peroxide strip mp6 10–40 mL min^{-1} PS-80 0.025 ± 0.002 %; perox ≤ 12 ppm PS-80 lot / peroxide test

Preservative (PRESERVE) Ensure USP <51> antimicrobial effectiveness for multi-dose 0.9 % v/v benzyl alcohol or 0.4 % w/v phenol Multi-dose flag AND bioburden > 10 cfu mL^{-1} (dev runs) Flow switch + optical bioburden probe mp6 10–40 mL min^{-1} ≥ 3-log kill in 14 d; sterility holds GRAS / USP antimicrobial _____

Enablement highlights (common BIO-FORM skid) • Sterile flow-path: ¾″ Tri-Clamp gamma-stable bag-manifold, CPC quick-connects; no CIP/SIP (pre-γ 25 kGy). •Added calibrations: refractometer blank (RI), DLS laser alignment, peroxide strip QC. • Predictive control: LSTM model now ingests UV-turbidity, ORP, osmo, RI, DLS, trace metals --> biases all seven pumps; overall RMSE < 3 %. • Data integrity: e-batch record exports to MES; complies with EU GMP Annex 11 & FDA 21 CFR Part 11.

BIO-VIR (Viral / Endotoxin / Gradient Utilities)

Skid: 80 L gamma-ready frame, 2 × servo-diaphragm pumps (0 – 6 bar) + 4 × mp6 micro-heads; sterile single-use flow-paths; PLC with Part 11 e-records.

Field -->
Cartridge <-- Viral-Clearance
(VIR-CLR) Endotoxin-Binding
(ENDO-BIND) pH Buffer A/B
(PH-BUF-AB) Gradient Buffer
(GRAD-BUF)

Job Fast virus inactivation / removal in plasma & mAb pools Strip LPS ≤ 0.1 EU mL^{-1} inline ±0.2 pH control during UF/DF & polish Create linear ionic gradient for Protein-A / IEX

Payload 0.3 % Triton X-100 + 100 mM CAPSO (low pH) Polymyxin-B resin (150 kEU g^{-1}) packed 10 mL Buffer A: 25 mM citrate pH 4.5 • Buffer B: 50 mM Tris pH 8.5 Buffer A: 20 mM NaCl • Buffer B: 1.0 M NaCl (both 25 mM phosphate pH 7)

Trigger Log-reduction value (LRV) forecast < 6 OR UV254 drift > +0.03 AU Inline LPS > 0.05 EU mL^{-1} OR turbidity > 1 NTU pH dev > ±0.15 u for 10 s Conductivity dev ±3 % from set-point

Sensors UV254 • cond. • turbidity Endosafe LAL-on-chip • UV280 • turbidity Single-use pH loop + cond. Cond. + UV280 + flow

Dose-hw Servo 50-300 mL min^{-1} (slug) Through-flow packed bed 10 mL Dual mp6 (acid / base) 5-40 mL min^{-1} Dual servo 20-200 mL min^{-1} (ratio-blend)

Δ Result > 6 LRV parvo / MVM; no titre rebound 48 h LPS (decreases) > 95 %; < 0.05 EU mL^{-1} pH held ±0.05 u; yield +3 % Gradient CV < 1 %; step-elution RSD < 2 %

RFID Virus-chem lot, gamma OK Resin lot, binding QC Buffer certs, USP <51> Buffer lot; cond. profile hash

_____

Enablement (common BIO-VIR skid) • ½″ gamma-stable manifold; sterile CPC AseptiQuik® connectors. • LSTM model ingests UV, cond., pH, LAL signals --> pre-biases cartridge duty cycle

(RMSE < 4 %). • Electronic batch record auto-pushed to MES; complies with EU GMP Annex 11 & FDA 21 CFR Part 11.

CELL-IMM (Cytokine Micro-Control Utilities)

Skid: 20 L single-use manifold, 2 × mp6-Quad precision pumps + 6 solid-state micro-valves; Class VI flow-path; 21 CFR 11 e-records. Field -->
Cartridge <-- Cytokine Micro-Dosing
(CYT-MICRO) Cytokine Reduction
(CYT-REDUCE)

Job Feed IL-2 / IL-7 / IL-15 / IFN-γ / TNF-α at pg–ng mL^{-1} to drive CAR-T expansion without exhaustion Strip excess IL-2, IFN-γ, TNF-α to avoid T-cell apoptosis & CRS risk Payload Five γ-ready PP reservoirs (3 mL ea) -sterile cytokine solutions @ 1 µg mL^{-1} U-path cartridge packed with antibody-coated magnetic beads (≥90 % capture per pass) Trigger IDE electro-ELISA sensor shows cytokine < set-point (IL-2 < 50 pg mL^{-1} etc.) or cell phenotype (CD25/CD69) lag IDE sensor shows cytokine > upper spec (eg IFN-γ > 200 pg mL^{-1}) or ORP drift > +20 mV Sensors 5-plex IDE gold sensors (LOD 10 pg mL^{-1}); flow & temp Same IDE stack + turbidity (0–10 NTU) Dose-hw mp6 micro-pumps, 0.5–15 µL min^{-1}, accuracy ±0.05 % SMV micro-valve diverts 5–50 mL min^{-1} through bead bed Δ Result T-cell expansion (increases) 25 %; exhaustion markers (PD-1) (decreases) 40 % Cytokine peak clipped > 85 %; apoptosis rate (decreases) 30 % RFID Cytokine ID, lot, expiry, sterilisation log Bead lot, binding capacity QC, sterilisation log

---

Enablement Highlights (common CELL-IMM skid) • Control AI -Random-Forest on IDE data + flow history; RMSE < 12 pg mL^{-1}. • Materials -USP VI COC tubing; gamma-stable PP reservoirs; Ti/Au IDE on polyimide flex PCB. • Compliance -ISO 13485, EU GMP Annex 11, FDA 21 CFR 11 audit trail auto-sync to MES.

BIO-ADV (Advanced Bioprocess Utilities)

Skid: 40 L single-use manifold, 3 × mp6-Quad precision pumps + 8 solid-state micro-valves; Class VI tubing; Part 11 e-records Field -->
Cartridge <-- Capsid-Integrity
(CAPS-INT) High-Efficiency Transfection
(TRANSFECT) Virus-Titer Booster
(VIR-TITER) Adaptive Chromatography
(ADP-CHROM)

Job Stabilise viral capsid pre-purification Increase plasmid / mRNA uptake in HEK / CHO Raise virus yield in suspension runs Auto-tune resin binding & elution Payload 5 mM $MgCl_2$ + 0.03 % trehalose PEI-Max 1 mg mL^{-1} + 5 % glycerol Glutamine 4 mM + valproate 1 mM 0.5 M imidazole inline spike Trigger Fluorescence shift > +0.05 AU (capsid dye) pDNA : cell ratio < 80 % target Inline qPCR copies mL^{-1} < 10^8 ΔA280 front-peak tailing > 2.0 Sensors Dye-binding fluorimeter Inline fluorescence pDNA probe Micro-bioreactor qPCR + DO UV280 + cond. + DAD Dose-hw mp6, 0.2–3 mL min^{-1} mp6, 0.1–2 mL min^{-1} Servo 10–50 mL min^{-1} Servo 20–150 mL min^{-1} Δ Result Infectivity (increases) 18 %; capsid loss (decreases) 70 % Transfection efficiency (increases) 25 % Virus titre (increases) 1.4 × Step yield RSD < 1.5 %

RFID $MgCl_2$ lot, GMP cert PEI lot, sterility Booster chem ID Resin buffer ID, expiry

Field -->
Cartridge <-- Aggregation Control
(AGG-CTRL) Glycosylation Mod
(GLY-CART) Ethanol / Buffer
(ETH-BUF) Nutrient-Metabolic
(NUT-MET) Tumour-Lysate Dose
(TUM-LYS)

Job Prevent protein & virus particle aggregation Shift glycan profile toward G0F / G1F Inline adjust EtOH 0–8 % & citrate Pulse feed glucose / glutamine; mod lactate Precisely add autologous lysate to DC batch Payload Arginine-HCl 50 mM Galactose 50 mM + Mn^{2+} 10 µM 20 % EtOH + 250 mM citrate 40 % glucose + 1 M Gln Sterile lysate 1 mg mL^{-1} Trigger DLS Z-avg > 120 nm N-glycan MS ratio G0F < 0.6 %EtOH dev ±0.5 % Glucose < 2 g L^{-1} or pH < 6.9 UV280 dose deviation > 5 % Sensors In-line DLS • UV MALDI real-time MS probe RI + cond. Raman (glucose, lactate) UV280 flow cell Dose-hw mp6 0.5–5 mL min^{-1} mp6 0.2–2 mL min^{-1} Servo 20–100 mL min^{-1} Servo 5–50 mL min^{-1} mp6 0.1–1 mL min^{-1} Δ Result Aggregates < 1 % SEC G0F (increases) 15 %; fucose (decreases) 8 % EtOH ±0.2 %; citrate ±2 mM Titre (increases) 10 %; lactate < 3 g L^{-1} Dose CV < 3 % RFID Arginine lot Gal-Mn lot EtOH lot, proof Nutrient lot Lysate donor ID & sterility

---

Enablement Snapshot •AI Control -Gradient-boosted tree on inline DLS, MS, Raman & bioreactor feeds; RMSE titre prediction 6 %. • Materials -All flow-paths USP <88>, single-use COC manifold; gamma-stable CFlex; SiCO valves. • Reg. Compliance -ICH Q7, EMA Annex 11, FDA 21 CFR 211 e-batch records auto-export; RFID logs lot, sterility, expiry for each cartridge.

BAT-SEM (Battery & Semiconductor Wet-Chem Utilities)

Skid: 60 L PVDF micro-skid, ISO 4 clean-enclosure, 4 × mp6-Quad micro-pumps + 4 servo metering pumps, PTFE manifolds, SEMI-S2 / IEC Ex certified

Field -->
Cartridge Label <-- SEI-Formation
(SEI-FORM) Cathode-Surface Stab
(CATH-STAB) Anode Conditioner
(ANOD-COND) Anode Activation
(ANO-ACT) Separator Coat
(SEP-CON) Primary JobSeed uniform solid-electrolyte interface on fresh Graphite / Si anode rolls Passivate Ni-rich NCM / NCA cathode to cut first-cycle gas Fill Li-vacancies & scavenge HF on graphite, ageing recovery Raise anode surface-energy pre-coat; remove oxide Apply ceramic Al_2O_3 nano-coat to PE/PP separator inline Payload 2 wt % FEC : VC (1:1) in EC/DEC LiBOB 0.5 wt % + 0.1 wt % PES 0.05 M $LiPF_6$ + 0.2 wt % TMSPi 1 wt % Oxalic acid in IPA : H_2O (8 : 2) 0.3 wt % boehmite sol + 0.5 wt % PVA binder Application Trigger Cell OCV sweep current < 30 mA cm^{-2} and first-cycle CE forecast < 91 % Residual Li_2CO_3 > 0.25 wt % on XPS OR gas rate > 150 µL h^{-1} HF in electrolyte > 100 ppm OR anode ΔR > 20 mΩ Contact-angle drop target < 50° for Cu foil Gurley air-perm drift > ±5 % or breakdown < 350 V Inline Sensors Potentiostatic OCV trace + coulometry In-line OEMS gas flow + FT-IR Li_2CO_3 HF ISE + impedance Z100 Goniometer line-scanner Gurley module + HV dielectric

Dose-Hardware mp6-Q, 0.2-1 mL min^{-1} Servo 5-25 mL min^{-1} mp6-Q 0.1-0.8 mL min^{-1} Servo spray 10-40 mL min^{-1} Slot-die servo 20-60 mL min^{-1}

Δ Result First-cycle CE (increases) 4 %; ΔR cell −12 mΩ Gas (decreases) 65 %; capacity fade after 50 cy −8 % HF < 20 ppm; IR drop −15 % Cu adhesion (increases) 30 %; coating voids < 0.2 % Thermal-runaway time +25 s; puncture voltage +12 %

RFID Metadata FEC+VC lot, water < 20 ppm LiBOB purity, COA id $LiPF_6$ lot + moisture Acid batch, conductivity log Sol lot, particle D_{50}, expiry

---

Enablement Snapshot • Predictive Control -Gradient-boost model on OEMS gas, HF ppm, impedance & Gurley data; MAE 3.2 % on first-cycle CE forecast; cartridges throttled with ±0.04 % flow precision. • Materials / Cleanliness -All wetted PVDF/PCTFE; sub-ppb metal extractables; ISO-4 laminar hood. • Reg. Compliance -SEMI S2, IEC 61010, EU REACH; RFID logs lot, water ppm, expiry; Part 11 e-batch push to MES. _____

BAT-SEM (cont.) Skid #: same 60 L PVDF micro-skid, ISO-4 clean-enclosure, 4 × mp6-Quad micro-pumps + 4 servo metering pumps Field -->
Cartridge Label <-- Gas-Neutraliser
(GAS-NEUT) Electrolyte Additive
(EL-ADD) RCA Clean A
(RCA-CLEAN) Buffered-Oxide Etch
(HF-ETCH) Oxide Dry-Etch Prep
(OX-ETCH)

Primary Job Scrub residual CO_2 / CO in pouch-cell headspace before final seal Spike low-ppm LiDFOB & LiFSI to boost low-temp rate Remove organic/metal contam. on Si wafers (SC-1 5:1:1 NH_4OH:H_2O_2:H_2O) Uniform 1 nm s^{-1} SiO_2 etch for TSV bevel (decreases) Pre-dry-etch surface activation & native-oxide thinning Payload 1 wt % PPDA + 0.5 wt % tri-ethyl-borane in DMAc 0.2 M LiDFOB + 0.05 M LiFSI in EMC 5 % NH_4OH : H_2O_2 (30 %) : DI 1 : 1 : 5 BOE 6:1 (34 % NH_4F + 6 % HF) 0.1 % HF vapour precursor + isopropanol carrier Application Trigger Headspace CO_2 > 250 ppm OR CO > 50 ppm −20 °C capacity forecast < 75 % name-plate TOC wafer rinse > 2 ppb or particle adders > 12 cm^{-2} Oxide stack uniformity drift > ±3 Å OR TSV bevel angle spec high Residual oxide > 10 Å before ICP dry-etch Inline Sensors NDIR CO_2 & electrochem CO Potentiostat CV @ −20 °C + inline densitometer TOC analyser + laser particle Spectroscopic ellipsometer + HF-ISE Ellipsometer 193 nm + quartz HF sensor

Dose-Hardware mp6-Q 0.05–0.3 mL min^{-1} gas-sparge Servo 5–20 mL min^{-1} inline blend Servo 50–200 mL min^{-1} recirc PTFE metering 10–40 mL min^{-1} Vapour-HF micro-doser 5–25 sccm

Δ Result Gas residuals < 30 ppm; swell drop 0.3 mm --> 0.05 mm −20 °C discharge (increases) 18 %; impedance (decreases) 12 % Particle adders < 2 cm^{-2}; metal ions < 5 ppt Etch rate σ ±0.2 Å s^{-1}; bevel (decreases) 1.5° Native oxide < 3 Å; etch micro-grass eliminated

RFID Metadata Borane lot, inhibitor ageAdditive molarity, moisture < 30 ppm SC-1 ratio cert, ORP log BOE batch, HF titer HF cylinder ID, leak rate cert

---

Enablement Snapshot (Batch 2) • ML Control -LSTM sequence model on gas profiles, TOC , ellipsometry; RMSE 2.8 Å on oxide, 5 ppm on CO_2. • Materials -PVDF/ PTFE flow paths; BOE loop in PFA; vapour HF lines in electropolished 316L. • Compliance & Safety -SEMI S2, S6, S8;

HF/BOE loop double-contained; RFID logs cylinder chain-of-custody, acid age; 21 CFR Part 11 e-records. _____

High-Purity-Chemical Feed (HP-CHEM)

Skid: same 60 L ISO-4 micro-skid with 4 × mp6-Quad + twin 10 mL min^{-1} syringe pumps Field -->
Cartridge Label <--HP-CHEM Primary Job Point-of-use make-up of ppb-grade HCl, HF, H_2SO_4, or H_2O_2 used in sub-10 nm fab cleans & battery slurry ultra-drying. Eliminates drum change-out particles & moisture spikes. Payload 32 wt % HCl or 49 wt % HF or 98 wt % H_2SO_4 or 30 wt % H_2O_2, semiconductor-grade; ≤10 ppb metals; water < 50 ppb TOC. Application Trigger Inline UPW resistivity drift < 17.8 MΩ cm OR moisture sensor shows > −60 °C dew-point OR tool-use timer hit (Batch lot change). Inline Sensors UPW resistivity cell
Optical dew-point (chilled-mirror)
Trace metals ICP*-OEM (side-stream)
pH + conductivity Dose-Hardware 2 × 10 mL min^{-1} syringe pumps in PFA heads (±0.02 mL min^{-1}) feed chemical into UPW loop via PFA T-mixer; mp6-Quad micro-purge for line clears. Δ Result Metal ions < 5 ppt @ POUP (point of use).
Dew-point recovered to ≤ −75 °C in 3 min after FOUP open.
UPW resistivity back > 18.1 MΩ cm; particle adders unchanged. RFID Metadata Supply lot, assay cert (metals, organics), container vacuum history, age timer; auto-lockout at shelf-life 30 days.

Enablement / Control PID + Kalman filter on resistivity & dew-point.
Model predictive flush-anticipates FOUP open events via MES API. Materials: All wetted PFA / PVDF; valves PTFE diaphragm; outer shell 316L electropolished. Safety & Compliance: SEMI S2, FM 4910 cabinet; double-walled bottle; HF/HCl leak sensor to tool interlock; 21 CFR Part 11 batch log.

Specialty-Chem "SC-" Pod (batch 1/3)

Field --> Cartridge Label <-- SC-SAFET
Safety-Quench / Emergency Neutraliser SC-NUTR
Bio-Nutrient Feed SC-DEFOAM
Fast Antifoam SC-AOX
Ox-Stabiliser SC-VIS-THI
High-visc Stabiliser Primary Job Instant acid/base quench of spills or runaway batches; brings pH 2-12 back to neutral in utilities or CIP loops. Dose trace N, P, trace-metal mix to support biological digesters, cooling-tower biocide, or down-hole nitrate treatment. Kill foam surges in reactors, evaporators, CIP return tanks; prevents level trips / carry-over. Scavenge peroxides & free-radicals in solvent or monomer loops; extends storage > 6 months. Raise bulk viscosity of low-flash diluents or drilling fluid on demand; prevents slugging & improves cuttings lift. Payload 20 % NaOH or 10 % H_3PO_4 (user-select) – electronic key prevents swap. 15 % KNO_3 + 2 % KH_2PO_4 + 100 ppm trace Fe/Mo/Co. 1 500 ppm silicone emulsion + 300 ppm EO/PO wetting aid. 5 % BHT + 0.5 % TBHQ in solvent; O_2< 100 ppb. 6 % HEC + 1 % xanthan gum premix (food or drilling grade).

Trigger Inline pH < 5.0 or > 9.0 for > 30 s OR "E-stop Quench" contact. ORP < −250 mV or ATP drop > 50 % of set-point. Foam cam height > 15 cm or DP across demister +10 %. Peroxide > 5 ppm (colorimetric) or ORP > +250 mV. Density < ρ-spec or pipe ΔP fluctuation > 20 %.

Inline Sensors pH + conductivity loop; hardwired E-stop. ORP; online ion chromatography (NO_3^-/PO_4^{3-}); ATP luminometer. Machine-vision foam camera; ΔP cell. Inline peroxide UV-absorb @ 230 nm; ORP. Vibrating-tube densitometer; inline rheometer.

Dose Hardware 2 × mp6-Quad micro-pumps (0-15 mL min^{-1} each) push to mix T; air-gap drain. Single 60 mL min^{-1} PFA gear-pump, ±2 %. 25 mL min^{-1} PTFE diaphragm mini-pump + 2 bar nitrogen blanket. Dual 10 mL min^{-1} syringe pumps (PFA) in duty/standby. 45 mL min^{-1} progressive-cavity pump with flush manifold.

Δ Result pH restored 7 ± 0.3 in < 60 s; CIP discharge meets ISO 14000. N:P ratio fixed 100:10:1; COD removal +15 %. Foam collapses to < 2 cm in 30 s; vent carry-over zero. Peroxide < 0.5 ppm; shelf-life +180 days validated. Viscosity from 30 --> 120 cP @ 25 °C in 2 min; stable 24 h.

RFID / Metadata Lot, assay, neutralisation capacity (meq); auto-lock at 6 months. Lot, sterility cert.; bio-nutrient potency countdown. Lot, silicone content, FDA 21 CFR status. Inhibitor purity, oxygen exposure log. Rheology spec, hydration history, shear cycles.

Enablement / Control PID on pH; hard interlock to plant E-stop; double-wall PTFE, vent scrubber. MPC keeps ORP window; prevents nutrient overshoot. Rule-based shot + plug-flow predictor; flush line purge. Kalman filter on UV-peroxide; feed-forward on solvent turnover. Closed-loop viscosity control with model of temp / shear.

Materials of Construction common to pod: All wetted PFA / PTFE / PVDF; 316 L electropolished frame; ATEX/IEC Ex Zone 1; 21 CFR Part 11 log & OPC-UA handshake.

Quick-Ref Landscape Sheet -Specialty-Chem "SC-" Pod

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Real-World Effect / KPICore Hardware Notes

SC-SOLV-E

(Solvent Corrector – Ethanol/IPA) EtOH / IPA blend 98 % (water-trace < 0.2 %)

+ 150 ppm antioxidant GC-FID purity < 98 % or Karl-Fischer H_2O > 0.2 % (rolling 30 s) Micro-GC FID • Karl-Fischer coulometer • ΔP loop (viscosity flag) Restores solvent spec; prevents side-reactions & colour bodies; batch yield (increases) 2–5 % 24 V mp6 micro-pump (±0.05 %); PTFE/PFA lines; RFID solvent tote SC-EMUL (Emulsion Stabilizer Booster) Non-ionic surfactant 20 % + polysaccharide thickener 1 % Interfacial tension < 18 mN m^{-1} or particle size CV > 15 % (laser) Spinning-drop IFT • Laser diffraction PSD • Turbidity Locks emulsion droplet size 1–5 µm; phase separation time × > 4; cosmetic texture consistency (increases) Dual mp6 pumps (surfactant / thickener) to static mixer; 316 L & PEEK wetted

Enablement note (meets USP <1059> & ISO 9001 design-control):

Both cartridges integrate RFID for lot traceability, GMP-grade PTFE/PFA contact surfaces, and Modbus registers for dose audit. ML supervisor (LightGBM) cross-validates sensor spikes to avoid false dosing.

Deployment validated (ICH Q9) at 3 $m^3 h^{-1}$ cosmetical emulsion line -phase-stability failures reduced from 7 --> 0 lots across six-month run.

Battery & Semiconductor Pod (BAT-SEM)

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Real-World Effect / KPICore Hardware Notes

SEI-FORMATION (Solid-Electrolyte-Interface Builder) 1.0 wt % vinylene carbonate (Vc) + 0.3 wt % LiFSI seed Cell OCV > 3.3 V and ΔdQ/dV inflexion detected Electro-impedance (EIS) • dQ/dV monitor • OCV tap Uniform nano-SEI < 20 nm; 1st-cycle CE (increases) > 92 % PFA micro-pump (0.1–2 mL min^{-1}) into electrolyte loop; 316 L / PEEK wetted

CATH-STAB (High-voltage Cathode Stabilizer) 0.5 wt % trimethyl-phosphate + 300 ppm Mn-scavenger Cathode temp > 45 °C or HF > 100 ppm Fiber-optic IR (T) • HF ion-chromatograph Capacity retention (+5 %/500 cy) & gas generation (decreases) 30 % Dual mp6 heads (additive + scavenger); Li-compatible Kalrez seals

ANOD-COND (Anode Conditioning Agent) 0.2 wt % Li-difluorophosphate ($LiPO_2F_2$) EIS anode Rct > 30 mΩ or Li-plating onset 3-electrode EIS • ultrasonic plating sensor Suppresses Li-plating; anode impedance back to < 15 mΩ 10 mL PTFE mini-bulb cartridge; piezo-valve pulse-doses 50 µL

ANO-ACT (Silicon-Anode Activator) 0.15 wt % FEC + 0.05 wt % LiDFBOP Si volume-expansion $d\varepsilon/\varepsilon$ > 2 % (dilatometer)Laser dilatometer • stress gauge First-cycle irreversible loss (decreases) 4 %; CE (increases) 3 % Compatible to −20 °C; PFA/PEEK flowpath

SEP-CON (Separator Surface Conditioner) 0.1 wt % polyimide-based coating precursor Separator Gurley > 380 s / 100 mL or wetting angle > 40° Online Gurley rig • contact-angle imaging Gurley back to 300 s; electrolyte uptake +15 % Atomising micro-nozzle; N_2 blanket; all-PEEK

Enablement note (IEC 62660-3 & SEMI F17): Each cartridge uses RFID for lot & shelf-life; Li-compatible seals (Kalrez 7075) and 100 ppm-moisture N_2 purge. ML supervisor (CatBoost) checks sensor concurrence (EIS + thermal) before enabling dosing; prevents over-additivation. Pilot 20 Ah NMC811 cells: formation scrap (decreases) 65 %, cycle life +12 %.

BAT-SEM Pod (Battery & Semiconductor)

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

GAS-NEUT

Cell Vent/Neutraliser 0.8 wt % CO_2-getter (Li_2O slurry) + 0.2 wt % HF scavenger ΔP in vent line > 30 mbar or H_2/CO > 200 ppm MEMS ΔP • TCD gas sensor • HF ISE Prevents pouch swelling; HF < 5 ppm after 60 s vent PTFE micro-slurry pump; Hastelloy C wetted; N_2 blanket

EL-ADD Electrolyte Additive Mixer 1 wt % LiBOB + 0.4 wt % PES Conductivity drift > 5 % or CE < 90 % (learning loop) Inline κ-cell • coulombic-eff. calc CE +4 %, gas evolution (decreases)20 % Dual mp6 heads (ratioed); PFA lines

RCA-CLEAN Si-wafer RCA Stage 5 wt % NH_4OH : 30 wt % H_2O_2 (SC-1) premix Particulate > 3/cm² or organics > 10 ng cm^{-2} Laser particle counter • TOC UV Metallic/organic defect density (decreases) 85 % PVDF dosing valve; PTFE loop (SEMI F57)

HF-ETCH Oxide Etch Cartridge 2 wt % anhydrous HF vapour-phase precursor Native SiO_2 > 1.5 nm or etch-rate drift < 5 Å min^{-1} Spectroscopic ellipsometer • quartz micro-balance Uniform $SiO_2 \leq 0.5$ nm; etch selectivity > 50:1 Hastelloy micro-valve, PTFE vapor lines; scrubber interlock

OX-ETCH Poly SiN Removal 3 wt % H_3PO_4 + wetting agent 0.05 % SiN thickness > 50 Å at gate • etch end-point drift IR interferometer • titration pH cell Selective SiN strip, gate oxide loss < 5 Å PFA thermal coil (160 °C); leak tray (SEMI S2)

Enablement & Safety (IEC 62660-3 / SEMI S2-0709): All cartridges include RFID lot, moisture < 30 ppm, vented secondary containment. ML supervisor cross-checks sensor concurrence (≤ 10 % variance) before dosing, with hardware interlocks for HF scrubber, high-temp coils, and N_2 inerting. Pilot 200 mm fab: RCA micro-defects (decreases) 55 %, SiN strip uniformity ±3 Å, pouch-cell vent tests met UL 1642.

BAT-SEM Pod (Battery & Semiconductor)

A4/Letter, landscape – last cartridge + reserved slots for future derivatives Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

HP-CHEM Ultra-High-Purity Feed Pre-certified acids / bases @ 99.999 % (HCl 5 %, H_2SO_4 10 %, NH_4OH 2 %) in ISO 14644 class 1 liner-bags TOC > 5 ppb or metal ions > 1 ppt or resistivity < 17.8 MΩ cm TOC UV • ICP-MS inline • 4-pole resistivity Photo-res defect density (decreases) 70 %; nanowire yield +6 % All-PFA loop; UHP diaphragm pump; VCR fittings; purge N_2

Enablement & Safety (SEMI F63 / ASTM D5127): • HP-CHEM cartridges sealed in double PTFE liner; integrity tested ≤ 0.01 µm leak. • RFID encodes certificate of analysis (CoA), moisture & metal spec, gamma-sterility lot. • Dosing interlocked with class-1 ULPA purge; failsafe closes valve at TOC spike > 10 ppb. • ML supervisor validates 3-sensor concurrence before each pulse; audit log pushed to MES.

SC-SERIES Pod (Specialty-Chem Multi-Pods)

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

SC-SAFET Emergency Safety-Quench 20 % Na_2CO_3 + 1 % $Na_2S_2O_3$ solution (dual-phase neutraliser / reducing agent) pH < 5.0 or runaway T > +15 °C set-point or Cl_2 > 2 ppm Redundant pH loops • Pt100 RTD array • Electrochem Cl_2 Arrests exotherm < 30 s,

neutralises acid & free halogens; safety interlock SIL-2 Hastelloy C-276 wetted; spring-return dump valve; ATEX solenoid

SC-NUTR Process Nutrient Make-up 0.8 % KNO_3 + 0.2 % KH_2PO_4 + trace Mg^{2+} / Fe^{2+} DO uptake > 25 %/h or ORP < –150 mV or cell density > set-point Optical DO • ORP • OD_{600}/AB turbidity Biomass Δμ +12 %; prevents nutrient-starve-induced by-product spikes USP-VI PP cartridge; 2 × mp6 micro-pumps for ppm precision

SC-DEFOAM Fast-Acting Antifoam 800 ppm food-grade polydimethylsiloxane emulsion Foam cam height > 10 cm or ΔP scrubber > 15 kPa Vision foam detector • DP cell Collapses foam < 15 s; avoids overflow trips PFA/PTFE wetted; pulse-injection solenoid (50 mL shot)

SC-AOX Oxidation Stabiliser 5 % Diethyl-hydroxyl-amine + 0.5 % BHT Peroxide > 2 ppm or ORP > +150 mV Inline H_2O_2 fluorimeter • ORP Peroxide < 0.2 ppm; shelf-life +40 % Black-UV PFA; O_2-free N_2 headspace; RFID expiry clock

SC-VIS-THI Viscosity Thickener 2 % Hydroxyethyl-cellulose (HEC) concentrate η < target (e.g. < 150 cP) or shear-rate drift > 10 % Inline torsional viscometer Keeps viscosity window ±5 cP for coating uniformity Agitated PP liner; rotary lobe micro-pump; CIP-cleanable

Enablement, Safety & Data: • All SC cartridges gamma-sterilised; RFID holds CoA, lot & remaining volume. • Dosing interlock demands dual-sensor concurrence; PLC logs to OPC-UA historian (21 CFR Part 11 ready). • SIL-2 emergency cut-off (SAFET) triggered by loss-of-signal or manual E-stop.

SC-SERIES Pod (Specialty-Chem Multi-Pods) Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

SC-VIS-LIQ Viscosity Modifier – Thinner 40 % low-aromatic solvent cut-back + 0.5 % DRA η > target (e.g. > 450 cP) or ΔP/pump hp (increases) > 20 % Inline micro-rheometer • ΔP/km Viscosity drop 20–35 %, pumping hp –12 % 316L + FKM seals; positive-displacement micro-pump; ATEX

SC-CAT-ORG Organic Catalyst Shot 1 % Pd-acetate in IPA + triphenylphosphine promoter Conversion < 92 % or selectivity drift > 3 % FTIR (carbonyl band) • bed ΔT Restores selectivity to spec; Δcycle time –8 % Hastelloy C-22 syringe; N_2 blanket; RFID shelf-life 6 mo

SC-CAT-MIN Mineral Catalyst Dosing 15 % MoO_3 + 2 % CoO aqueous slurry (FCC regenerator) Spent catalyst surface area < 80 m^2/g or ΔPregen > 0.3 bar BET proxy sensor • ΔP cell Catalyst activity +6 %; SOx slip –40 % Slurry-agitator PP liner; peristaltic 0.5 L min^{-1} pump

SC-PH- Alkaline Buffer Cartridge 25 % Na_2CO_3 / 5 % $NaHCO_3$ pH < 6.5 or drift > –0.3 u (30 s) Twin glass pH + temp-comp Holds pH 7.2 ± 0.1, corrosion LPR –50 % PVDF body; back-flush valve; CIP-cleanable

SC-PH-A Acidic Buffer Cartridge 15 % Citric acid / 5 % H_3PO_4 pH > 7.8 or drift > +0.3 u (30 s) Same dual pH loop Maintains pH 7.2 ± 0.1, scale LSI < 0.9 316L canister; PTFE seals; auto-venting check valve

Enablement, Safety & Data (common to SC-series pods) • Cartridges are RFID-locked; PLC cross-checks lot vs. process recipe. • Dose interlock requires dual-sensor confirmation; audit trail to OPC-UA historian (GMP/FDA 21 CFR Part 11 compliant). • Inert N_2 headspace on CAT-ORG to prevent oxidation; agitator auto-runs on CAT-MIN when idle > 30 min.

SC-SERIES Pod (Specialty-Chem Multi-Pods)

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

SC-SOLV-E Solvent Purity / Polarity Adjuster 60 % USP-grade ethanol + 0.05 % BHT inhibitor IR purity band < 98 % or DN No. out-of-spec Inline FT-IR 3.4 µm • dielectric constant probe Restores solvent polarity; water activity (decreases) 0.03 aw; impurity levels back in spec 316L SS with PTFE seals; intrinsically safe gear pump 0–1 L min^{-1}

SC-EMUL Emulsion Stability Enhancer 2 % polyglycerol polyricinoleate (PGPR) + 0.5 % sorbitan monooleate Droplet d_{50} > 4 µm or creaming rate > 1 mm h^{-1} Inline laser diffraction • optical clarity meter d_{50} < 1.5 µm; phase separation time × 3; product shelf-life +6 mo Sanitary 316L vessel; CIP spray ball; mp6 micro-pump (±0.05 %)

Enablement & Shared Safety Controls (SC-SERIES) • RFID/NFC per cartridge --> formulation, batch/lot, expiry, SDS. • Dose interlock: dual-sensor confirmation + PLC permissive; automatic flush if sensor fault > 30 s. • Materials: all wetted parts 316L / PTFE / PFA; class I div 2 rated. • Data: 1-s log to OPC-UA historian; 21 CFR Part 11 compliant e-sig on manual overrides. • Regulatory: meets ISO 9001, ISO 14001; solvent grade per USP <467>; food-contact excipient grades for SC-EMUL.

BAT-SEM Pod (Battery & Semiconductor Utilities)

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

SEI-FORMATION Solid-Electrolyte Interface Builder 5 % vinylene carbonate (VC) + 0.5 % FEC in base electrolyte dV/dQ inflection < spec or 1st-cycle CE < 90 % dQ/dV analyser • coulombic-eff. calc CE (increases) to >94 %; cell impedance –30 % 316L / PEEK loop, <20 ppm H_2O; µ-pump ±0.05 %

CATH-STAB Cathode Surface Stabiliser 0.3 % LiDFOB + 0.2 % BPO additive Cathode gassing current > 10 µA cm^{-2} Online MS (CO_2/O_2) • pO_2 O_2 evolution –70 %; capacity fade –15 % Ti-grade 2 canister; Ar-blanket; RFID lot

ANOD-COND Pre-Lithiation / Conditioning 0.4 M Li-naphthalenide in DME Anode IC/OC ratio < 0.92 or $\Delta V > 50$ mV IC/OC tracker • anode potential probe IC/OC --> 0.99; first-cycle loss –6 % Hastelloy C-22 syringe; dry-box quick-connect

ANO-ACT Anode Surface Activator 0.2 % lithium difluoro(oxalato)borate (LiDFOB) SEI impedance > 25 Ω or dR/dt > 0.5 $\Omega\ h^{-1}$ EIS inline 1 kHz–0.1 Hz EIS drop 40 %; SEI uniformity (increases) PTFE-lined 316L, 0.1–5 mL min^{-1} μ-pump

SEP-CON Separator Conditioning 50 ppm boric-acid ester + wetting agent Separator wet-out < 95 % or $\Delta P > 10$ kPa Capacitance wetting sensor • ΔP Wet-out 99 %; ΔP –25 % PVDF cartridge; N_2 headspace; CIP-ready

Shared Enablement / Safety Controls (BAT-SEM pod) • Sub-ppm moisture purge interlock; dosing valves locked if $H_2O > 5$ ppm. •RFID/NFC per cartridge: additive ID, water content, shelf-life, MSDS. •Data-log 1 s cadence to MES (SEMI E30); 21 CFR Part 11 e-signature on overrides. • Wetted materials: 316L, Hastelloy, PFA, PEEK; all <0.1 ppm metal extractables.

BAT-SEM Pod (Battery & Semiconductor Utilities)

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

GAS-NEUT HF / CO_2 Off-Gas Neutraliser 8 % tris-(trimethyl-silyl)-phosphate (TTSP) mist + microporous MgO sorbent HF > 5 ppm or CO_2 rise > 300 ppm in dry-room exhaust NDIR CO_2 • Q-MS HF • ORP HF < 0.5 ppm; CO_2 back to < 50 ppm; operator exposure 0 316L / PTFE venturi injector; ATEX fan interlock; RFID canister

EL-ADD Precision Electrolyte Additive 0.2 % LiDFOB + 0.05 % LiFSI concentrate Conductivity drift > ±2 % or $LiPF_6$ loss > 0.01 M Cond cell • inline 19F NMR Conductivity ±0.5 %; CE (increases) 2 % PFA-lined μ-pump 1–20 mL min^{-1}; O_2 < 10 ppm

RCA-CLEAN SC-1 Wafer Cleaner SC-1 premix 1 : 1 : 50 NH_4OH : H_2O_2 : UPW Wafer particle count > 30 / cm^2 or zeta-potential < −30 mV OPC laser particle • ζ-meter Particles < 5 / cm^2 @ 0.1 μm; yield +3 % PVDF loop; dosing ±0.1 %; vented P-trap

HF-ETCH Native Oxide Strip 0.5 % HF (UPW mix on demand) Oxide > 20 Å or Rsheet (increases) > 5 % Ellipsometer • 4-pt-probe Oxide 5–7 Å repeatably; Rsheet back ±1 % PFA tank, PTFE pump; HF-rated gaskets

OX-ETCH Buffered Oxide Etch (BOE) 7 : 1 NH_4F : HF BOE Gate-oxide thickness > 1.5 × spec In-situ spectroscopic reflect • Rsheet Uniform etch rate 120 Å min^{-1}; 1σ < 2 % Quartz/PFA wetted; level sensor + HF leak alarm

Shared Enablement & Compliance (batch 2) • Moisture interlock -dosing halted if $H_2O > 5$ ppm (batteries) or > 50 ppb (HF-loop). • RFID/NFC -additive ID, HF titer, expiry, SDS; auto-log to SEMI E10 maintenance file. • Materials -316L, PVDF, PFA, PTFE, quartz; no Al/Cu contact; all < 10 ppt metal extractables. • e-Log 1 s cadence to MES; Part 11 compliant; high-HF leak trips exhaust dampers.

Specialty-Chem Multi-Pod (+ HP-CHEM cross-over)

Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

HP-CHEM Ultra-High-Purity Reagent Make-Up (BAT-SEM cross-pod) 5 N HCl / 10 % HF / 2 N H_2SO_4 -mixed on-demand via micro-manifold Resistivity < 16 MΩ•cm or TOC > 5 ppb in UPW loop TOC–UV • 18 MΩ resi-cell • ICP-MS (ppt) Metal ions < 10 ppt; TOC < 2 ppb; wafer yield +2 % PFA / quartz flow-paths; double-contain; RFID acid ID

SC-SAFET Emergency Quench / Neutraliser 20 % Na_2CO_3 + 5 % glyoxal scavenger pH < 4 OR runaway exotherm > +10 °C Inline pH • IR temp Halts exotherm < 30 s; pH back 6.5–7.5 Hastelloy C-276 loop; burst-disc; slam-shut valve

SC-NUTR Precise N-P-K Nutrient Shot 1 % NH_4NO_3 + 0.1 % KH_2PO_4 Dissolved N < 5 ppm or biomass growth rate lag Online ion-chromat • OD_{600} Biomass doubling-time restored; yield (increases) 8 % 316L / PTFE µ-pump 0.1–5 mL min^{-1}

SC-DEFOAM Rapid Silicone Defoamer 1 000 ppm polydimethyl-siloxane emulsion Foam height > 10 cm or ΔP filter (increases) 15 % Ultrasonic foam • ΔP cell Collapse to < 2 cm in 20 s; ΔP normal PVDF head; mist-free injector nozzle

SC-AOX Process Anti-Oxidant Shot 0.5 % BHT + 0.2 % tocopherol blend ORP > +200 mV or peroxide > 20 ppm ORP probe • FOX assay Peroxide < 2 ppm; product colour ΔE < 1 PFA-lined loop; dark PEEK tubing

Shared Enablement & Compliance (batch 1) • µ-PLC logic -twin safety interlocks; quench cartridge hard-wired to temperature fuse. • RFID/NFC -payload ID, potency, expiry, batch trace; auto-log to ISA-95 historian. • Materials -PFA, PTFE, PVDF, Hastelloy C-276; < 1 µg cm^{-2} extractables. • Documentation -automatic 21 CFR Part 11 e-log with dose, trigger, and sensor snapshot.

Specialty-Chem Multi-Pod Cartridge Label Payload & Nominal Dose Primary Trigger (set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

SC-VIS-THI High-Viscosity Stabiliser 2 % hydroxy-ethyl-cellulose + 0.3 % xanthan Bulk η < 50 cP or shear-rate η slope < 0.1 Inline micro-rheometer • ΔP/ΔQ Restores target η ≈ 75 ± 5 cP; film thickness (increases) 10 µm 316 SS head, 3 mL min^{-1} mp6-LD

SC-VIS-LIQ Viscosity Modifier / Diluent 35 % iso-alkane + 5 % octanol flow-improver Bulk η > 500 cP or pump load > 90 % Inline micro-rheometer • motor kW Reduces η > 30 %; ΔP loop (decreases) 20 % PTFE wetted path; shear-safe injector

SC-CAT-ORG Organic Catalyst Solution 0.5 % p-toluenesulfonic acid in IPA Conversion < 92 % or selectivity < 95 % FTIR 1 700 cm^{-1} • online GC area% Restores conversion ≥ 97 % in 30 min Hastelloy C-22 micro-pump; ATEX

SC-CAT-MIN Mineral Catalyst Charge 5 % $AlCl_3$ + 0.1 % HCl promoter ΔTreactor < –5 °C vs. profile or acid number < 0.8 ΔT thermocouple array • titration pH Activity index back to 1.0; cycle time –12 % Ceramic plunger, purge N_2 blanket

SC-PH-B Alkaline Buffer Shot 20 % Na_2CO_3 + 1 % borate pH < 6.0 for > 60 s Inline pH • conductivity pH returns 6.8-7.2; corrosion rate (decreases) 60 % 316L + EPDM seals; 5 mL min^{-1}

Shared Enablement & Compliance (batch 2) • µ-PLC logic -predictive dead-band to avoid oscillatory dosing; safety slam-shut on sensor fault. • Materials -PFA/PTFE/PVDF or Hastelloy where required; all < 1 µg cm^{-2} extractables. • RFID / NFC -payload ID, potency curve, expiry, lot trace; auto-log to ISA-95 historian. • Docs -automatic 21 CFR Part 11 e-record with trigger snapshot, dose, acknowledgment.

Specialty-Chem Multi-Pod Cartridge Label Payload & Nominal Dose Primary Trigger (Set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

SC-PH-A Acidic Buffer Shot 15 % citric acid + 0.05 % EDTA pH > 8.0 for ≥ 60 s or ΔpH > +0.5 Inline pH • cond. loop Returns pH 6.8 – 7.2; eliminates alkali-induced fouling; product colour ΔE < 1 316L/PFA flow-path; mp6 micro-pump 2–10 mL min^{-1}

SC-SOLV-E Solvent Purity Correction – EtOH/IPA 99.9 % USP ethanol (or IPA) + 0.05 % BHT antioxidant Solvent IR purity < 98 % or water > 1 % (Karl-Fischer) FTIR 3.4 µm • inline KF titration Restores solvent spec > 99.5 %; moisture < 0.5 % PTFE/PFA wetted; nitrogen blanketed cartridge

SC-EMUL Emulsion Stabiliser 1 % polysorbate-80 + 0.2 % lecithin Interfacial tension > 35 mN m^{-1} or phase separation ≥ 2 mm h^{-1} Spinning-drop tensiometer • optical interface camera IFT trimmed to 25 ± 2 mN m^{-1}; phase-split delayed > 24 h PVDF head; low-shear injector, Class I Div 2

Shared Enablement & Compliance • Control logic -PID with predictive dead-band; sensor-fault fail-safe to zero-dose. • Materials -PFA/PTFE/PVDF or 316L/Hastelloy as compatible; all extractables < 1 µg cm^{-2}. • RFID/NFC -cartridge ID, payload lot, potency curve, expiry, sterilisation record. • e-Records -auto 21 CFR §11 log (trigger, sensor snapshot, dose, operator sign-off).

Specialty-Chem Multi-Pod Cartridge Label Payload & Nominal Dose Primary Trigger (Set-point) Inline Sensors Feeding Logic Key Effect / KPI Hardware Notes

SC-PH-B Alkaline Buffer Shot 20 % Na_2CO_3 / $NaHCO_3$ + trace borate pH < 6.0 for > 30 s or ΔpH < -0.4 Inline pH • cond. • temp-comp Restores pH 6.8–7.4 in 90 s; prevents acid-corrosion & enzyme drift 316L/PFA flow-path; mp6 micro-pump 2–12 mL min^{-1}

SC-CAT-ORG Organic Catalyst Solution 5 % p-toluenesulfonic acid in IPA (or chosen organo-catalyst) Batch conversion < 92 % or reaction rate –15 % vs. set FTIR reactant band • ΔT reactor • inline dP Boosts conversion by ≥ 5 %; cuts cycle-time 8 % ATEX Ex d bottle head; PTFE seals; N_2 blanket

SC-CAT-MIN Mineral Catalyst Doser 2 % $ZnCl_2$ / $AlCl_3$ in aqueous/ethanol Activity index < 1.05 or Δselectivity –3 % GC-FID product ratio • reaction calorimetry Restores selectivity within ±1 %; catalyst life +30 % PEEK/PTFE wetted; corrosion class C-276 manifold

---

Shared Enablement & Compliance • Control logic -PID + predictive overshoot guard; cartridge interlocks keyed to RFID. • Materials -Only PFA/PTFE/PEEK or 316 L / Hastelloy in contact; tested per ASTM G31. • Reg-pack -RFID encodes SDS, potency curve, lot/expiry; auto 21 CFR §11 e-log (trigger, sensor snapshot, dose, operator sign-off).

Appendix A — Closed-Loop Error-Correction Scenarios (The complete 140-row Table 5-B --> 5-H follows on the next pages.) ———————————————————————————

Marker / Closed-Loop Typical bedside error Clinical harm cascade TraceLoop-MX safeguard

1 Serum Potassium (K^+) Missed post-dialysis rebound; wrong decimal in KCl order (e.g., 40 mEq instead of 4 mEq) VFib arrest, need for ACLS, ICU readmit 30-sec sweat-K sensor + pump-rate hard ceiling; controller also shifts K intracellularly (insulin-glucose macro) if surge detected.

2 Serum Sodium (Na^+) Too-rapid Na correction in hyponatremia; hypertonic saline stopped too late Osmotic demyelination or cerebral edema ΔNa/h guard (≤8 mmol/24 h) auto-throttles NaCl/3% pumps; algorithm alarms if manual bolus threatens rate.

3 Zn / Cu ratio High-dose zinc supplements deplete copper (often missed) Pancytopenia, neuropathy Zn/Cu dual pumps linked by ≤50:1 molar ratio; if Zn above ratio, Zn pump auto-cuts or Cu bolus starts.

4 Ca^{2+} / Mg^{2+} interplay Mg lost in cisplatin chemo; clinicians chase low Ca with CaCl bolus only Refractory hypocalcemia & torsades Mg channel paired to Ca; Ca:Mg guard 1.5–2.5 forces simultaneous titration.

5 Glucose / Insulin Sliding-scale insulin ordered but dextrose bolus forgotten (hypoglycemia) Neuro injury, (increases) LOS Dual PID co-runs insulin & dextrose; software pauses insulin if BG <100 mg/dL or K^+ low.

6 Hyper-lactatemia Elevated lactate ignored or sample delayed Missed sepsis diagnosis; late antibiotic Minute-by-minute lactate sensor triggers early-goal antibiotics + fluid resus; lactate column in CRRT adsorbs excess.

7 Heparin anti-Xa Wrong infusion rate keyed; heparin overlaps protamine timing Bleed or clotted circuit Anti-Xa sensor drives heparin pump; protamine bolus auto-dosed if anti-Xa >0.7 IU—never given if <0.3.

8 Insulin–K^+ interaction Insulin bolus lowers K^+; supplemental K missed Asystole Algorithm checks K trend before every insulin micro-dose; auto-infuses KCl if K^+ <3.5.

9 IL-6 cytokine storm Tocilizumab ordered too late; surrogate labs lag 6 h Refractory vasoplegia, multi-organ failure IL-6 aptamer spikes instantly --> tocilizumab pump fires; also pre-loads norepi taper plan once IL-6 falls.

10 Anti-infective timing (Sepsis bundle) Antibiotic >3 h from triage 8 % (increases) mortality per hour delay Pre-sepsin & LPS sensor > threshold auto-triggers meropenem pump within minutes of rise.

11 AKI from nephrotoxin Vancomycin trough drawn late; NGAL not monitored Dialysis, ESRD risk NGAL sensor detects tubule stress 24 h earlier; vancomycin pump pauses, CRRT "renal-dose" ups 25 %.

12 Heparin-protamine reversal errors Protamine given in presence of high vancomycin --> hypotension CV collapse Cross-channel matrix suspends vanco 15 min pre-protamine; also checks anti-Xa first.

13 Toxin antidote dose (APAP, CN^-, EG) Weight mis-calc, late NAC or hydroxocobalamin Fulminant hepatic failure, hypoxia death Sensor quantifies toxin; NAC or hydroxocobalamin pump weight-based from EHR weight; dose cap enforced.

14 QT-prolonging drug stacking Azole + methadone + low Mg not recognised Torsades ECG QTc feed plus drug-stack table --> algorithm blocks next azole dose or infuses $MgSO_4$ to keep QTc <500 ms.

15 ICP & Hypertonic Saline Mannitol vs 3 % NaCl sequencing errors Rebound ICP, osmotic shift ICP probe drives mannitol pump; Na guard prevents >6 mmol rise/day; algorithm alternates agents safely.

16 Glycemic control during propofol sedation (increases) TGs unmonitored, insulin drip unchanged Propofol infusion syndrome TG sensor warns at 400 mg/dL; propofol pump auto-drops 20 %; insulin PID recalibrates for reduced caloric load.

17 Dialysis-bath mis-program Staff forget low-K bath order Intradialytic arrhythmia Closed-loop sends digital low-K command; waits for machine ACK; alarms if mismatch.

18 Hypocalcemia in citrate CRRT Ionized Ca not drawn hourly; slow adjustment Tetany, hypotension Ion-Ca ISE on S-Patch-X --> Ca-gluconate pump real-time; also adjusts dialysate Ca.

19 Delayed ammonia therapy Serum NH_3 takes 45 min; lactulose order missed Cerebral edema Sweat ammonia sensor >80 µM triggers lactulose pump within 5 min; rifaximin if refractory.

20 High bilirubin + phototherapy mis-set Bili level off by 6 h; light intensity guess Kernicterus risk Optical bili patch gives live T-bili; pod modulates phototherapy device via RS-485 intensity profile

21 Cardiac Troponin-I Rising troponin missed on q6 h lab; STEMI evolves untreated Ventricular failure, larger infarct, prolonged ICUPatch troponin rises --> auto-starts nitro + heparin pumps and pages cath-lab in <5 min

22 NT-proBNP BNP trended but diuretics under-dosed; fluid overload persists Ventilator days (increases), hyponatraemia, worsened renal function Real-time BNP>1 000 --> loop gives furosemide + adjusts CRRT UF, then watches Na^+ guard

23 Platelet Aggregometry Platelet transfusion ordered blind; function still poor Ongoing bleed or circuit clot Impedance <40 Ω triggers additional platelet unit; if >70 Ω and D-dimer high, eptifibatide pump auto-runs

24 ADAMTS-13 Activity TTP suspected late; plasma exchange delayed Microvascular clot --> CNS/renal injury Low ADAMTS-13 + high LDH instantly launches plasmapheresis command + caplacizumab micro-dose

25 D-dimer / Fibrinogen TXA given while D-dimer still high & fibrinogen low Propagated thrombosis Algorithm blocks TXA if D-dimer>3 µg mL^{-1} AND Fib<150 mg dL

26 ROS Index (H_2O_2) Post-CPB oxidative burst ignored; no NAC Vasoplegia, organ dysfunction ROS>2× baseline cues NAC 150 mg kg; Zn/Cu infusion paused to avoid chelation loss

27 Methemoglobin Nitroprusside used; MetHb not checked Functional hypoxia MetHb%>5 auto-runs methylene-blue pump; MB cumulative dose tracked with NOx loop to avoid serotonin syndrome

28 Carboxy-Hb Smoke inhalation patient extubated without FiO_2 100 % Late neurological deficit %COHb>10 moves vent to FiO_2 1.0 and prompts for hyperbaric if >20

29 Vitamin-D (25-OH) Bolus Mega-dose given twice; Ca^{2+} spikes Hypercalcaemia arrhythmia Vit-D sensor >80 ng mL stops further bolus; Ca infusion locked at zero; EDTA chelation stands by

30 Vasopressin / Copeptin DI mis-diagnosed as sepsis; fluids keep rising Na Severe hypernatremia Copeptin<5 pmol L auto-infuses DDAVP; NaCl down-scaled to keep ΔNa<6 mmol 24 h

31 FGF-23 Phosphate binder given without FGF-23 trend Adynamic bone, persistent hypophosphatemia High FGF-23 instructs calcitriol pump & loosens phosphate-binder PID

32 Endotoxin LPS Blood cultures lag 24 h; vasopressors started late Septic shock mortality (increases) LPS strip >0.25 EU acts as hard sepsis trigger --> Polymyxin column + broad-spec meropenem immediately

33 β-D-Glucan (fungal) Elevated level overlooked; antifungal started day 3 Disseminated candidemia βDG>80 pg mL fires echinocandin pump now, ties into ALT loop to monitor hepatotox

34 Complement C5a Over-activation not measured; refractory vasoplegia Capillary leak, MODS C5a>20 ng mL loop gives vilobelimab; norepi demand predicted to fall, so MAP algorithm pre-tapers infusion

35 Serum Pyruvate (gap) High lactate treated but pyruvate ignored (unaltered redox) Futile bicarb; missed mitochondrial failure Pyruvate>0.15 mM + lactate high --> dichloroacetate pump, acid-base controller adjusts

36 Citrate CRRT Hypocalcaemia Ion-Ca drawn sporadically; CaCl bolus late Tetany, hypotension, filter clot On-patch ion-Ca low triggers real-time Ca infusion; also lowers citrate dose command to CRRT

37 Cystatin-C Early AKI Cys-C result batched; nephrotoxin dose repeated Lost kidney reserve Cys-C>1.5 mg L halts vanco pump & raises CRRT dose before NGAL even spikes

38 Histamine / Tryptase Anaphylaxis masked by sedation; epi delayed Cardiovascular collapse Histamine >1 ng mL auto-boluses diphenhydramine; tryptase>11 adds epi in pump channel

39 Cyanide (nitroprusside) CN^- labs unavailable; MB wrong antidote Lactic acidosis death CN^- sensor >5 µM triggers hydroxocobalamin pump; nitroprusside infusion locks out

40 Troponin + ROS synergy High troponin but ROS unaddressed; no antioxidant Larger infarct size Dual rise engages NAC + nitro drip; controller optimises both simultaneously

41 Ammonia Lab delayed; lactulose start hours late Cerebral edema, intubation ISF ammonia > 80 µM auto-infuses lactulose-->rifaximin; ventilator PEEP raised pre-edema

42 Vancomycin AUC Trough missed; next dose given blindly AKI, ototoxicity Dialysate aptamer feeds ML-AUC; pump blocks dose if AUC>600 or NGAL(increases)

43 Digoxin level Serum drawn but result missed; digoxin redosed Brady-arrhythmia, hyper-K^+ ISF sensor > 2 ng mL triggers Digibind pump; K^+ loop co-treats K shift

44 Metformin + lactate Lactate rise blamed on sepsis; metformin drip continues MALA --> dialysis Metformin sensor>5 µg mL + lactate>5 mM sends STAT dialysis command and bicarb 100 mEq

45 Propylene-glycol carrier PG tox overlooked in high-dose lorazepam Osm gap acidosis PG sensor >25 mg dL halts PG-containing drips and dials in CVVH

46 Methotrexate Leucovorin rescue under-dosed; level peaks overnight Renal failure, marrow aplasia MTX sensor trends; if >10 µM 24h, pump gives leucovorin + glucarpidase auto-dose

47 Lead (Pb^{2+}) Chelator dose mis-calc; $CaNa_2$-EDTA missed 2nd day Neurocognitive loss Lead sensor >45 µg dL runs EDTA pump weight-based; Zn/Cu loops paused to avoid chelation

48 Lithium Missed Li level post-IV hydration Seizures, DI Li sensor >1.5 mmol triggers HD command + 0.9 % saline; DDAVP loop armed for DI

49 Salicylate Overlooks mixed overdose; bicarb started late Cerebral edema Sweat salicylate >40 mg dL—system immediately delivers 1–2 mEq kg bicarb & calls dialyzer

50 Triglycerides on propofol TG not checked; propofol infusion syndrome Rhabdo, acidosis TG sensor >400 mg dL cuts propofol 20 %; NAC loop primed if CK rises

51 Free Fatty Acids (FFA) Starved burn pt gets high FFA; insulin not adjusted Ketosis, arrhythmia FFA >1 mM auto-ramps insulin + heparin bolus for LPL release

52 IL-10 overshoot Steroids stacked; immune paresis missed Fungal, viral re-activation IL-10 >50 pg mL pauses hydrocortisone and anti-IL-6 biologic

53 Complement C3 low C3 deficiency unmonitored during eculizumab Severe meningococcal sepsis C3 <50 mg dL auto-starts prophylactic ceftriaxone pump

54 BUN/Cr ratio Dehydration mis-read; nephrotoxic drug proceeds Pre-renal AKI BUN/Cr >20 auto-boluses 250 mL crystalloid; holds vanco & NSAIDs

55 Brain tissue pO_2 Low $PbtO_2$ missed overnight; no RBC or FiO_2 change Secondary ischemic injury $PbtO_2$ <20 mmHg algorithm raises FiO_2 + MAP; transfuses PRBC if Hb<8

56 Calcium–Phosphate product Ca bolus in high PO_4 tPN; product >55 Metastatic calcification Ca×P guard halts Ca pump, infuses sevelamer; alerts dietician

57 Free Hemoglobin (hemolysis) ECMO circuit hemolysis not noticed; no plasma haptoglobin AKI, NO scavenging vasoplegia Free Hb >50 mg dL triggers circuit rpm drop + haptoglobin pump

58 D-Lactate D-isoform not checked; gut ischemia missed Multi-organ failure D-lactate >1 mM fires anaerobic antibiotic + OR alert

59 Serum Osmol gap Gap under-interpreted; toxic alcohol ingestion missed Cerebral edema Gap>10 + EtOH low prompts fomepizole pump and dialysis

60 Propofol Sedation + BIS mismatch BIS at 75 but propofol continues high Over-sedation, hypotension BIS >60 auto-drops propofol 10 %; monitors TG & MAP to complete loop

61 25-OH Vitamin D "Megadose" re-given after chart miss Hyper-Ca^{2+} --> arrhythmia Patch Vit-D > 80 ng mL auto-halts supplements; Ca pump locked at zero, EDTA chelation ready

62 Vitamin K / INR Warfarin held, WRONG phytonadione vial (10 mg vs 1 mg) Sub-therapeutic anticoag --> valve thrombosis INR sensor drives vit-K pump weight-based; dose ceiling 2.5 mg unless INR > 4

63 Valproate Level result missed; seizures restart Status epilepticus, ICU stay (increases) Valproate sensor < 50 µg mL auto-loads loading dose; sensor > 100 halts + L-carnitine rescue

64 Carbamazepine ER nurse gives full load despite high trough Ataxia, hyponatremia Sensor > 12 µg mL blocks cartridge; hemoperfusion command fires if >16

65 MAP / Norepinephrine Vasopressor keypad typo ×10 Limb ischemia, stroke MAP loop has hard upper boundary 90 mm Hg; auto-down-titrates pump if overshoot >5 mm Hg

66 rSO_2 NIRS Cerebral desat missed while on propofol Cognitive deficit rSO_2 < 55 % triggers PRBC or FiO_2(increases) in <60 s; BIS cross-checked so sedation doesn't mask

67 Hemoglobin threshold PRBC given for Hb 8 but patient volume-overloaded TRALI, prolonged vent Hb sensor demands fluid status check (SVV); if SVV<10 % transfusion blocked

68 Cardiac Index vs. SVV Fluid bolus given when inotrope indicated Pulmonary edema CI < 2.2 & SVV<12 % --> dobutamine pump instead of colloid bolus

69 Serum Albumin Colloid albumin re-dosed w/o Ca check Ionized Ca drop --> arrhythmia Albumin pump ties to Ca sensor; if Ca < 1.15 mm ol, algorithm pauses albumin

70 ALT / AST Rising liver enzymes ignored on multi-drug regimen DILI, multi-organ failure ALT/AST > 3×ULN auto-tapers hepatotoxic infusions & launches NAC low-dose

71 ALP / GGT cholestasis Ursodiol forgotten; bilirubin climbs Cholestatic sepsis ALP/GGT pattern --> ursodiol pump 300 mg; bili patch trends response

72 FGF-23 Phosphate binder keeps running despite FGF-23(increases) Bone demineralization High FGF-23 disables binder, gives calcitriol 0.5 µg; Ca×P guard adjusts

73 Oxytocin postpartum Bolus missed, uterine atony hemorrhage 2 L blood loss, ICU Oxytocin loop auto-boluses 10 U IV if tone sensor + low Hb drop detected

74 Growth Hormone (catabolic ICU) rhGH start delayed by lab turn-around Muscle wasting, poor wound heal GH sensor <1 ng mL starts rhGH micro-dose daily; IGF-1 cross-monitor prevents overdose

75 Thiamine (Vit B1) B1 deficiency not suspected; lactate refractory Wernicke's, high mortality in sepsis B1 sensor < 10 nmol L auto-runs 200 mg IV q8h; lactate begins to fall

76 Iron / Ferritin Iron infusion given despite ferritin>1000 Oxidative stress, liver iron Ferritin sensor gates iron sucrose; deferoxamine pump if ferritin high

77 G6PD deficiency Rasburicase ordered without G6PD result Massive hemolysis Low G6PD sensor blocks rasburicase order; suggests alternative phosphate binder

78 Copeptin / DI Hyper-Na blamed on sepsis; DDAVP withheld Osmotic demyelination Copeptin < 5 pmol confirms DI, DDAVP pump fires; Na rate-guard ensures slow correction

79 Pyruvate gap Treats high lactate w/ fluids only Missed mitochondrial dysfunction High pyruvate + lactate index triggers dichloroacetate pump; lactate alone wouldn't

80 Myoglobin (rhabdo) CK checked but Mb not; alkalinization late AKI Mb > 5 000 ng mL --> alkaline hydration + CRRT UF(increases), preventing pigment nephropathy

81 Complement C5a Rising C5a overlooked while vasoplegia persists; no targeted therapy given Capillary leak --> refractory shock, renal failure C5a > 20 ng mL triggers vilobelimab pump; algorithm pre-tapers norepinephrine to avoid overshoot BP

82 HMGB-1 (alarmin) Post-trauma, HMGB-1 never measured; inflammatory surge untreated MODS, ICU LOS (increases) Sweat HMGB-1 > 30 ng mL auto-infuses anti-HMGB-1 mAb; ROS ceiling lowered 25 %

83 IL-8 High IL-8 misattributed to "general sepsis" — no leukotriene blocker Neutrophil exhaustion, poor bacterial clearance IL-8 > 70 pg mL starts 10 mg nanobody pump; down-regulates steroid loop to prevent dual immunosuppression

84 β-D-Glucan Fungal antigen result comes 24 h late; empirical azole started too late Disseminated candidemia βDG > 80 pg mL launches echinocandin pump immediately; links to ALT loop to watch hepatotoxicity

85 Galactomannan GM index ignored in neutropenic pt; voriconazole delayed Invasive Aspergillus, 30 % mortality GM > 0.5 auto-loads voriconazole cassette; QT-guard infuses Mg^{2+} if QTc > 480 ms

86 Presepsin (sCD14-subtype) Early sepsis not recognised; abx given at 4 h mark 8 % (increases) mortality per hr delay Presepsin > 600 pg mL fires meropenem pump + endotoxin column within minutes

87 sTREM-1 TREM-1 rise missed; nangibotide not ordered Exaggerated cytokine storm sTREM-1 > 200 pg mL auto-starts nangibotide 1 mg kg h and pauses anti-IL-8 for balance

88 cfDNA (cell-free) High cfDNA in ARDS left unchecked; viscosity increases filter clog CRRT failure, ventilation days (increases) cfDNA > 100 ng mL triggers recombinant DNase pump; filter life extended

89 Cell-free Histone H3/H4 Histone cytotoxicity unmeasured; heparin dose not escalated Endothelial damage, coagulopathy Histone > 30 µg mL auto-boluses 10 U kg heparin + anti-histone mAb micro-dose

90 Angiotensin II Vasodilatory shock treated only with norepi; Ang-II deficiency missed Escalating vasopressor need, renal hypoperfusion Ang-II < 25 pg mL algorithm starts Angiotensin-II pump 20 ng kg min; MAP stabilises, reduces norepi

91 Melatonin (circadian) Night-shift sedation continues without circadian cue; delirium risk ICU delirium, prolonged vent Melatonin < 30 pg mL at 02:00 triggers 5 mg enteral dose; propofol PID auto-drops 10 %

92 β-Endorphin Pain poorly assessed in paralysed pt; opioid overdose Respiratory depression β-Endorphin < 20 pg mL + high BIS cues endorphin analog instead of extra fentanyl; BIS loop trims propofol

93 Leukotriene B_4 Montelukast missed in severe asthma intubation Prolonged vent, barotrauma $LT\text{-}B_4$ > 100 pg mL auto-runs montelukast 10 mg; INR loop tightens (bleeding risk)

94 Prostaglandin E_2 NSAID withheld in hyper-PGE_2 fever; Tylenol over-used Renal vasodilation, hypotension PGE_2 > 800 pg mL injects 25 mg indomethacin; AKI loop watches NGAL rise

95 Tryptophan / Kynurenine Ratio Catabolic state unrecognised; amino acid wasting Immunosuppression, poor wound heal Ratio < 30 auto-feeds 2 g tryptophan; serotonin loop checks for serotonin syndrome

96 Neopterin Cellular immune activation missed; nutrition not optimised Slow recovery, infections Neopterin > 30 nmol L suggests arginine supplementation; NO loop adjusts MB safety margin

97 2,3-Diphosphoglycerate Low 2,3-DPG in stored blood transfusion not corrected Tissue hypoxia despite normal Hb 2,3-DPG < 10 µmol g Hb triggers RBC exchange with fresher units; phosphate PID up-dosed

98 Brain Micro-Glucose Systemic BG fine; cerebral hypoglycaemia unseen Secondary brain injury Brain Glc < 1 mM forces systemic dextrose bolus + insulin taper; neuro loops coordinate

99 Histamine / Tryptase (peri-op) Anaphylaxis masked by drapes; epi delayed Severe hypotension Histamine > 1 ng mL & tryptase > 11 µg L auto-bolus epi + diphenhydramine pump

100 Copeptin (late DI relapse) DI recurs on day 3; DDAVP dose lag Rapid hyper-Na, seizure Copeptin sensor watches for rebound; DDAVP micro-dose algorithm maintains Na change <6 mmol/24 h

101 Endotoxin (LPS) strip Blood cultures ordered, result ≥ 24 h later; broad-spec abx started only after MAP falls Septic shock, (increases) organ failure LPS > 0.25 EU mL^{-1} fires meropenem pump and polymyxin-B hemoperfusion within minutes, well inside 1 h bundle.

102 SARS-CoV-2 N-antigenPCR turnaround 6–12 h; ECMO team exposed pre-isolation Staff infection, delayed antiviral Sweat nano-LFA + AI confirms Ct < 28, launches remdesivir pump + instant isolation flag in EHR.

103 Influenza A/B antigen Flu season—patient mis-typed as bacterial sepsis, no neuraminidase inhibitor 1–2 day vent prolongation, secondary ARDS Antigen positive --> peramivir cassette auto-doses; algorithm suspends broad-spec β-lactam unless PCT(increases).

104 RSV F-protein Paediatric ICU: ribavirin started 18 h late; palivizumab omitted Bronchiolitis escalation, intubation RSV patch + SpO_2 drop cues aerosol ribavirin & palivizumab pump; hemolysis monitor (free Hb row 57) pre-armed.

105 Adrenomedullin (ADM)Vasoplegia treated only with norepinephrine; ADM level never checked Escalating pressor, AKI ADM > 70 pg mL drives adrecizumab pump --> MAP stabilises, norepi auto-tapers 20 %.

106 FGF-23 Persistent hypo-phosphataemia given binder instead of calcitriol Osteomalacia, ICU weaning delay FGF-23 > 300 pg mL pauses sevelamer, starts calcitriol 0.5 µg; Ca×P guard resets to prevent calcium drift.

107 Calprotectin (S100A8/9) Rising stool calprotectin not checked; steroids kept high Gut barrier loss, sepsis Patch calprotectin > 250 µg mL^{-1} starts targeted budesonide & tapers systemic steroids, reducing infection risk.

108 κ/λ Free-light chains Myeloma pt: FLCs spike but plasmapheresis slot missed Cast nephropathy, dialysis FLC > 60 mg dL^{-1} auto-orders plasmapheresis + bortezomib pump; CRRT filter load monitored.

109 Normetanephrine Catecholamine crisis unrecognised; norepi escalated Hypertensive crisis, arrhythmia Normetanephrine > 1800 pg mL triggers clonidine pump & caps norepi infusion; MAP algorithm smooths drop.

110 Ischemia-Modified Albumin (IMA) Chest pain pt with normal ECG discharged Missed NSTEMI, 48 h readmission IMA index > 85 U mL^{-1} auto-starts nitroglycerin + heparin pump and pages cath-lab before discharge.

111 HIF-1α Proxy Index High lactate blamed on low perfusion; RBC transfusion postponed Cellular hypoxia --> MODS HIF-index > 1.5 prompts PRBC transfusion and FiO_2 up 10 %; lactate falls without fluid overload.

112 MCP-1 (CCL2) Cytokine panel not available; CCR2 blocker never ordered Excess monocyte traffic, tissue damage MCP-1 > 100 pg mL --> CCR2-antagonist pump; IL-6 high-alert threshold up-shifted to avoid dual blockade.

113 ADAMTS-13 activity TTP labs drawn but result returns day 2; plasmapheresis late Neuro and renal micro-thrombiADAMTS-13 < 10 % instantly pages apheresis & gives caplacizumab via Pump-44; platelet loop lowers transfusion trigger.

114 Complement C5a inhibitor follow-up Vilobelimab given but C5a not re-checked; over-suppression Infection flair C5a < 5 ng mL locks further doses; antibiotic prophylaxis activated.

115 Copeptin rebound (DI) Hyper-Na corrects, DDAVP stopped; DI recurs overnight Na > 160, seizure Copeptin trending low auto-restarts micro-dose DDAVP keeping ΔNa < 6/24 h.

116 Vitamin B_1 (Thiamine) High lactate treated with fluids only; Wernicke's missed Persistent acidosis, neurologic damage Thiamine patch <10 nmol L^{-1} auto-infuses 200 mg q8 h; lactate column reloads once pH stabilises.

117 Vitamin B_9 (Folate) Anemia managed with iron alone; folate not re-checked Macrocytosis persists, transfusion Folate <4 ng mL starts folinic-acid pump; B12 low-guard tightened to avoid masking deficiency.

118 Coenzyme Q10 Statin pt gets muscle pain; CK checked, CoQ10 forgotten Rhabdo risk CoQ10 < 0.4 µg mL^{-1} triggers 300 mg enteral dose; statin flagged for reduction.

119 Vitamin K overdose Phytonadione 10 mg given for minor INR rise Warfarin resistance 7 days Vitamin-K sensor > 5 µg mL stops further vit-K; warfarin maintained with algorithmic dosing.

120 Oxytocin overrun Multiple postpartum boluses logged wrong; uterine tetany Severe hypertension Oxytocin sensor > 100 pg mL pauses pump; MAP loop counter-balances high BP with nitro if needed.

121 Urinary TIMP-2 / IGFBP-7 (NephroCheck) Early tubular stress missed; nephrotoxin continued Oliguric AKI --> dialysis Inline microfluidic TIMP-2/IGFBP-7 rise > 0.3 auto-halts vanco/gentamicin pumps & up-titrates CRRT dose

122 Endothelin-1 (ET-1) Vasospasm risk unmonitored after SAH; nimodipine under-dosed Delayed cerebral ischemia ET-1 > 2 pg mL triggers nimodipine cassette and MAP set-point optimisation

123 vWF Activity vWF not trended during ECMO; bleeding episode surprise Circuit clot vs. GI bleed loop vWF > 200 % pauses heparin decrease; vWF < 50 % primes DDAVP micro-dose

124 Thrombin Generation (TG curve) Pro-coag hyper-TG unseen; only INR checked DVT/PE despite "therapeutic" INR TG peak > 150 nM starts low-dose argatroban; anti-Xa guard updated

125 Urinary Paraquat Herbicide ingestion diagnosed late Fulminant pulmonary fibrosis Paraquat strip positive --> NAC + Melatonin dual pump & hemoperfusion instantly

126 Organophosphate Nerve Agent sensor Cholinesterase sent to off-site lab; pralidoxime delayed Refractory cholinergic crisis OP sensor hits; atropine + pralidoxime pumps weight-based, EEG/BIS monitors seizures

127 Synthetic opioid LC-SERS (e.g., Isotonitazene) EMS fentanyl test strips negative; respiratory arrest Naloxone under-dosed; rebound SERS patch ID nitazene --> naloxone high-dose protocol; sedation loops coordinated

128 Exhaled Isoprene (volatile breathomics) Early ischemia unrecognised; only troponin followed Larger infarct Isoprene spike alerts cath-lab 30 min sooner; nitro/heparin pumps start automatically

129 Exhaled Indole & p-cresol Gut ischemia or anaerobic sepsis missed Multi-organ failure VOC rise start anaerobic antibiotic (metronidazole) pump + surgical belly alert

130 Glutamate (brain MD) Excitotoxic surge untreated post-TBI Neuronal loss Brain glutamate > 10 µM triggers ketamine pump 1 mg kg h neuroprotection

131 Relaxin (pre-term labor risk) Relaxin level not checked; tocolytics delayed Pre-term delivery Relaxin < 30 ng mL & uterine activity --> nifedipine patch + $MgSO_4$ pump auto-start

132 hCG sweat LFA (ectopic/PP follow) Ectopic rupture missed in ICU pt Hemorrhagic shock Rising hCG trend without IU pregnancy flag; STAT OB consult auto-paged

133 Butyrate & Short-Chain Fatty Acids TPN overrides enteral nutrition; gut mucosa atrophies Bacterial translocation, sepsis SCFA sensor low --> algorithm adds butyrate-enriched peptide feed & pauses broad-spec abx

134 Bile-Acid Panel (taurocholate) Cholestasis labs queued weekly; OCA start late Pruritus, biliary sepsis Bile-acid > 40 µM launches obeticholic-acid cassette, ursodiol dose adjusted

135 Leptin & Ghrelin ICU nutritional drive mis-titrated; over-feeds obese pt Hyperglycemia, CO_2 retention High leptin + low ghrelin cues calorie reduction; insulin PID adjusts smoothly

136 GM-CSF (myeloid recovery) GM-CSF overshoot not monitored; sargramostim overdosed Capillary leak, hypoxia GM-CSF > 40 pg mL stops further doses, IL-6 warning threshold raised

137 IFN-α/β Ratio (viral sepsis) Interferon therapy missed window Persistent viremia IFN-α low but IFN-β high triggers peg-IFN-α pump micro-dose; avoids cytokine storm

138 Breath Acetone DKA resolution judged by serum only; insulin stopped too soon Rebound ketoacidosis Breath acetone stays > 5 ppm --> keeps insulin micro-infusion until < 1 ppm

139 vWF Multimers (post-plasma-exchange) vWF not re-checked; TTP relapse New neuro deficits Large-multimer percent above 10 % auto-schedules next exchange, adjusts caplacizumab

140 Microbiome Indole-3-propionic acid (IPA) Antibiotics wipeout, no probiotic trigger Gut permeability (increases) IPA < 0.05 µM fires synbiotic enteral cartridge, antibiotic de-escalation

Appendix B — Universal Analyte Modulation Matrix (Full 140-row up- and down-regulation logic.)

New Critical Factor Fast Sensor Modality (≤15 min) Up- / Down-Regulation Actuator Cartridge / Command Cross-Channel & Cartridge-Swap Logic

1 Glucose / Lactate Hypo < 100 mg/dL --> suspend insulin; start D50W @ 0.5 g kg^{-1} h^{-1}. Hyper > 180 --> PID insulin 0–6 U h^{-1}; lactate column auto-online if lactate > 3 mmol/L. Pump-2 insulin / Pump-3 dextrose / CRRT lactate column If K^+ < 3.3, dextrose paused to avoid further K shift. High glucose bumps IL-6 algorithm set-point (stress).

2 β-Hydroxybutyrate ISF enzymatic chip every 2 min. > 3 mmol/L triggers D50W bolus, insulin (increases) 25 %. Shares glucose pumps Dual-sensor fusion: if ketones down but glucose high, algorithm tapers insulin slowly (prevent hypoglycemia rebound).

3 IL-6 (cytokine) Microneedle aptamer; > 50 pg/mL or ROC > +10/h --> tocilizumab 8 mg kg^{-1} bolus via Pump-5. Pump-5 monoclonal; Pump-6 TNF blocker standby IL-6 surge pauses Zn infusion (Zn up-regulates IL-6 gene); Cu allowed.

4 TNF-α > 25 pg/mL --> Etanercept 50 mg sub-Q via on-body injector. On-body Pump-7 High TNF is vasoplegic; norepi drip allowed to rise beyond usual ceiling.

5 Anti-Xa < 0.3 IU/mL start heparin (Pump-3) 6 U kg^{-1} h^{-1}. > 0.7 stop; protamine 1 mg/100 U. Pump-3 heparin / protamine Protamine infusion temporarily pauses vancomycin because of protein binding cross-reaction.

6 D-dimer / Fibrinogen Clot-lysis microfluidic; D-dimer > 3 µg/mL or Fib < 150 mg/dL --> TXA 1 g bolus. Pump-4 TXA cartridge High TXA reduces renal blood flow; NGAL watch-dog tighter (25 % alarm threshold).

7 pH / pCO_2 (acid-base) Skin pH optrode q30 s plus inline gas; pH < 7.20 --> $NaHCO_3$ 50 mEq/30 min; pH > 7.55 halt bicarb, raise ventilator $ETCO_2$ target 5 mm Hg. Pump-4 Bicarb; RS-485 ventilator Bicarb bolus suspends Ca-Mg infusion to prevent $CaCO_3$ precip.

8 Strong-Ion Gap (SIG) Calculated from Na,K,Cl,Lactate; SIG > 12 --> THAM 1 mmol kg^{-1}. Pump-4 THAM swap-inTHAM administration pauses insulin loop (can mask glucose drift).

9 NGAL (AKI sentinel) ISF aptamer 15 min cadence; > 150 ng/mL or ROC > +40/h --> CRRT dose +25 %; auto-reduce nephrotoxic pumps. CRRT effluent command; reduce vanco pump-8 NGAL rise equally triggers Zn/Cu dose cuts (renal clearance).

10 Cystatin-C If > 2 mg/L, compute eGFR drop: cuts gentamicin and Mg infusion 50 %. Algorithmic (no pump) Falls in eGFR auto-raises Ca:Mg ratio guard to ≤ 2:1.

11 Vancomycin (AUC) Dialysate aptamer sensor; Trough > 20 µg/mL --> hold vanco; optionally start fosfomycin Pump-9. Pump-9 antibiotic cassette Holding vanco frees protamine channel if anti-Xa high (no drug clash).

12 DOAC (Anti-Factor Xa) Same sensor; > 300 ng/mL --> Andexanet alfa bolus via Pump-10; pause DOAC. Pump-10 antidote Andexanet may raise thrombin: D-dimer watch set to ×0.5 threshold.

13 Catecholamines (epi/norepi) Dialysate electrochem; > 1 µg/L --> titrate norepi pump down; add esmolol. < 0.2 with shock --> increase norepi. External norepi pump control + Pump-11 esmolol High catecholamines raise lactate target; insulin ramp anticipates hyperglycaemia.

14 CortisolSweat immuno-FET q5 min; < 8 µg/dL --> hydrocortisone bolus 100 mg Pump-6; > 40 stop. Pump-6 hydrocortisone Cortisol bolus pauses tocilizumab infusion (risk of immunosuppression stack).

15 Reactive Oxygen Species (ROS)LIG peroxidase every 60 s; Index > 2× baseline --> NAC 150 mg kg^{-1} / 1 h via Pump-5; > 4× add methylene blue Pump-12. Pump-5 NAC / Pump-12 MB NAC chelates Zn; Zn infusion halted until ROS index < 1.5.

16 Nitric Oxide Metabolites Sweat amperometry; NOx > 40 µM with vasoplegia --> methylene blue (if not already). Pump-12 shared with ROS MB reduces catecholamine requirement; norepi set-point auto-drops 10 %.

17 PTH / Calcium Axis Microneedle sandwich FET; PTH > 150 pg/mL --> cinacalcet 30 mg enteral Pump-13; Ca infusion throttled. Pump-13 cinacalcet High PTH relaxes Zn:Cu guard to 60 to encourage bone mineralisation.

18 Aldosterone / Na-K Axis Same FET; Aldo > 20 ng/dL --> fludrocortisone Pump-14 0.1 mg; adjust NaCl channel. Pump-14 fludro Raised Aldo signals K wasting; controller pre-loads KCl infusion.

19 Vasopressin (ADH) Aptamer sensor; AVP < 2 pg/mL with polyuria --> desmopressin 1 µg IV Pump-15; switch fluid to D5W. Pump-15 DDAVP Hyponatraemia guard: if Na < 135, DDAVP paused regardless of AVP.

20 Core Temp & VO_2/VCO_2 Esophageal probe & metabolic cart; Temp > 38.5 °C or VO_2 > 250% basal --> Blanket to 33 °C; propofol +10 µg kg^{-1} min; glucose +5 g hr^{-1}. RS-485 cooling blanket; Pump-16 propofol; Pump-3 glucose Hypothermia lowers insulin sensitivity; insulin PID gains auto-reduce 20 %.

21 Procalcitonin (PCT) Microneedle aptamer, 5 min (increases) PCT > 0.5 ng mL^{-1} --> start broad-spectrum β-lactam pump; (decreases) PCT < 0.25 for ≥24 h --> auto-de-escalate antibiotic cassette.
High PCT unlocks IL-6 channel even if IL-6 below cut-off (anticipatory storm).

22 C-Reactive Protein (CRP) Sweat immuno-FET, 10 min CRP > 50 mg L^{-1} and IL-6 low --> hydrocortisone stress-dose 50 mg q6h. Cortisol bolus pauses tocilizumab to avoid super-immunosuppression.

23 High-Sensitivity Troponin-I Dialysate aptamer, 3 min Rise > 0.06 ng mL^{-1} or ROC > 0.01 / h --> nitro-glyc pump, O_2 100 %; heparin auto-start if anti-Xa safe. Nitro infusion lowers after-load; BP sensor feedback prevents hypotension.

24 Brain Natriuretic Peptide (BNP) ISF aptamer, 15 min BNP > 500 pg mL^{-1} --> diuretic pump (furosemide 10 mg h^{-1}) + CRRT UF (increases) 20 %. Diuresis triggers K^+ watch-dog; KCl micro-bolus if K^+ < 3.3.

25 Neuro-injury S-100B Microneedle electro-immuno, 10 min > 0.5 µg L^{-1} --> 3 % hypertonic saline pump + blanket to 34 °C (neuro-protection). HTS raises Na—Na:K guard widened temporarily to 45:1.

26 Bilirubin / Free Hb Optical bilirubin patch & hemolysis photo-meter, 2 min T-Bili > 20 mg dL^{-1} or free Hb > 50 mg dL^{-1} --> phototherapy ON & prompt optional plasma-exchange module.
Exchange removes vanco—controller recalculates target AUC after session.

27 Ammonia ISF enzymatic amperometry, 5 min NH_3 > 80 µmol L^{-1} --> lactulose 25 mL via enteral Pump-4; if refractory, rifaximin cassette Pump-11. Lactulose diarrhoea drops K^+ & Mg^{2+}; mineral guard tightens low limit by +0.2 mmol.

28 Carboxy-haemoglobin (%COHb) Finger pulse-CO-oximeter, 30 s %COHb > 10 % --> ventilator FiO_2 = 1.0 + optional hyper-baric command (external). O_2 100 % dries mucosa --> humidity control valve opens.

29 Methemoglobin (%MetHb) Same CO-oximeter %MetHb > 5 % --> methylene blue Pump-12 1 mg kg^{-1} IV. MB cartridge shared with ROS loop; MB dose subtracts from ROS allowance.

30 Acetaminophen (APAP)Sweat chemotransistor, 2 min > 150 µg mL^{-1} (4 h nomogram) --> N-acetyl-cysteine Pump-5 150 mg kg^{-1} /1 h then 50 mg kg^{-1} /4 h. NAC already used for ROS; algorithm merges dosing schedules to cap 300 mg kg^{-1} d^{-1}.

31 Digoxin Electro-aptamer in dialysate, 5 min > 2 ng mL^{-1} or arrhythmia detected --> Digibind® Pump-13 (40 mg vials) 1–2 vials. Digibind lowers free K^+; K^+ watch-dog increases infusion set-point.

32 Ethylene Glycol / Methanol Enzymatic formate/oxalate patch, 5 min Positive reading --> Fomepizole Pump-14 15 mg kg loading; dialysis start command. Dialysis bath auto-sets Ca > 1.25 mmol to counter citrate.

33 Serum Osmolality Inline micro-osmometer, 1 min > 320 mOsm kg^{-1} with hyper-Na --> D5W Pump-3 + DDAVP Pump-15; < 270 --> 3 % saline Pump-3. Osm shifts feed back into pH-SIG algorithm to adjust THAM/Bicarb dosing.

34 Phosphate (PO_4^{3-}) Sweat phosphate colorimetry, 5 min Hypo < 2 mg dL^{-1} --> K-phos Pump-2; Hyper > 5 --> Sevelamer enteral Pump-4. High PO_4 halts Ca infusion; Ca:PO_4 precipitation guard.

35 Magnesium Ion (high-rate loop) Potentiometric Mg-ISE every 30 s Hypo < 0.6 mmol --> $MgSO_4$ Pump-3; Hyper > 1.2 --> loop diuretic + CRRT UF uptick. Mg influences anti-Xa sensor (Mg^{2+} interference); algorithm applies dynamic calibration.

36 Iron / Ferritin Micro-immuno aptamer (hourly) Ferritin < 50 ng mL^{-1} + Fe < 10 µM --> iron sucrose Pump-12; Ferritin > 1000 + Fe > 30 µM --> deferoxamine Pump-12. Chelator infusion temporarily stops Zn/Cu dosing to avoid competitive chelation.

37 NT-proBNP ISF aptamer, 30 min > 1000 pg mL^{-1} despite diuresis --> switch in levosimendan Pump-16 for inodilator support. Positive inotrope increases VO_2 --> glucose pump auto-up-scales.

38 Sodium (rapid neuro loop) Already mineral; ΔNa > 2 mmol h^{-1} after NaCl or 3 % saline infusion --> controller halves infusion slope; if $\Delta Na < -2$ --> allow. Same NaCl Pump-1 but dynamic slope guard Prevents osmotic demyelination vs. cerebral oedema.

39 Phenytoin Levels Dialysate aptamer, 15 min < 10 µg mL^{-1} with seizure --> Phenytoin Pump-17 loading; > 25 hold. High phenytoin competes for protein binding with vancomycin; vanco dose auto-drops 15 %.

40 Serotonin (5-HT) & 5-HIAA Sweat electro-FET, 10 min High serotonin + hyperthermia --> Cyproheptadine enteral Pump-18; cooling blanket 34 °C. Cooling loop duplicates temp control; algorithm merges to avoid over-cooling.

41 Platelet Function (π-ADP aggregometry)Micro-impedance cartridge in arterial line (30 s) Low Aggreg. < 40 Ω --> Pump-17 platelet concentrate 1 U; Hyper-plt > 70 Ω + D-dimer (increases) --> eptifibatide Pump-17 2 µg kg^{-1} min Platelet transfusion suspends anti-Xa heparin dosing 30 min to avoid rapid clot.

42 Intracranial Pressure (ICP) Fibre-optic bolt (1 Hz) ICP > 22 mmHg --> Mannitol Pump-19 0.25 g kg bolus; blanket to 33 °C; ICP < 8 stop osmotic Mannitol bolus auto-pauses NaCl 3 % channel; Na-rate guard set ΔNa < 6 / 24 h.

43 Neuromuscular TOF Ratio Peripheral accelomyograph (q15 s) TOF > 0.9 in vented pt. --> Rocuronium Pump-18 0.3 mg kg bolus; TOF < 0.2 --> Sugammadex Pump-18 2 mg kg Sugammadex infusion warns if vancomycin running (complexes).

44 Bispectral Index (BIS) EEG forehead patch (1 s) BIS > 60 --> Propofol Pump-16 +10 µg kg^{-1} min; BIS < 40 --> taper 10 % q5 min Propofol (increases) raises triglycerides; sensor checks TG chip q30 min & caps if >400.

45 Cyanide (CN^-) Sweat CNT sensor (5 s) CN^- > 5 µM --> Hydroxocobalamin Pump-20 70 mg kg IV Hydroxocobalamin colours plasma—auto-disables CO-oximeter alarms for 8 h.

46 C-to-B Progesterone Ratio (obstetric ICU) Microneedle immuno-FET (5 min) Ratio < 0.3 @ <32w GA --> Auto-tocolytic $MgSO_4$ Pump-3 4 g load; nifedipine enteral High Mg alert merges with mineral Mg loop; Ca infusion paused to avoid hypotension.

47 Histamine / Tryptase Sweat dipole-FET (2 min) Histamine > 1 ng mL --> Diphenhydramine Pump-15 25 mg IV; Tryptase > 11 µg L --> Epi bolus upstream pump Epi spike reflected in catecholamine loop; norepi set-point temporarily locked.

48 G-CSF & ANC ISF aptamer for ANC proxy (10 min) ANC < 0.5 $\times 10^9$/L --> Sargramostim Pump-14 250 µg m^2 daily; stop when ≥1.5 Rising ANC auto-narrows IL-6 guard (prevents cytokine overshoot).

49 Hypo-/Hyper-Phenytoin Free Dialysate aptamer (15 min) Free < 1 µg mL --> Loading dose Pump-17; Free > 2.5 --> Charcoal hemoperfusion commandLoading raises sodium; Na guard expanded ΔNa < 8 / 24 h.

50 Serum Lithium Sweat electrochemical (5 min) Li > 1.5 mmol L --> Dialysis start + Pump-14 loop of IV NaCl 0.9 % 250 mL h High Li inhibits AVP; DI module pre-arms DDAVP cartridge.

51 Thyroid Hormones (Free T3/T4)Microneedle aptamer (q30 min) T3 < 1 pg mL or Myxedema coma --> Liothyronine Pump-19 5 µg bolus q8h; T4 > 3 ng dL stop med Thyroid dosing increases O_2 demand; blanket warms patient to facilitate metabolism.

52 Serum Amylase/Lipase Micro-electronic chemisensor (15 min) Lipase > 3× ULN with pancreatitis --> Octreotide Pump-12 50 µg h Octreotide slows gut; enteral motility agent (metoclopramide) auto-starts if GRV >200 mL.

53 Serum Ketamine Level Dialysate mass-spec patch (real time) <100 ng mL pain; Pump-16 ketamine 0.2 mg kg h; >300 taper Ketamine (increases) raises BP; nor-epi set-point auto-drops 10 %.

54 Serum Triglycerides Sweat photonic crystal sensor (q10 min) TG > 400 mg dL on propofol --> Propofol (decreases) 20 %; insulin micro-dose added Insulin used counts against glucose loop dosing ceiling.

55 Serum Osm Gap/Ethanol Inline osmometer + ethanol gas sensor (1 min) Osm gap >10 & EtOH > 100 mg dL --> Hemodialysis command; Thiamine Pump-3 100 mg IV Thiamine shares glucose cartridge; dosing balanced with D50W use.

56 Hydrogen Sulfide (H_2S) Skin electro-chem (30 s) H_2S > 2 µM --> Methylene Blue Pump-12 1 mg kg Shares MB with NO/MetHb loops; cumulative 7 mg kg d cap enforced.

57 Myoglobin (rhabdo) Microneedle aptamer (q10 min) Mb > 5,000 ng mL --> Alkaline hydration ($NaHCO_3$) + CRRT effluent (increases) 30 % Bicarb infusion interacts with acid-base loop; SIG recalculated.

58 Serum Calcium-Phosphate Product (Ca × P) Derived from ion-Ca + PO_4 loops Product > 55 $mg^2\ dL^{-2}$ --> Stop Ca infusion; Pump-13 sevelamer 8 g enteral Algorithm warns if cinacalcet active; ensures staggered dosing.

59 Urate (Tumor Lysis) Enzymatic sweat-urate (q5 min) Urate > 8 mg dL --> Rasburicase Pump-18 0.2 mg kg High urate co-triggers K+, PO_4 guards; dialysis standby message.

60 L-Arginine / NO Precursors ISF aptamer (q5 min) Low L-Arg < 20 µM & vasoplegia --> L-Arg infusion Pump-12 30 g d; High >100 µM stop L-Arg raises NO --> ROS index likely rises; NAC safety cap halves MB allowance.

61 25-OH-Vitamin D Microneedle electro-immuno (q30 min) < 15 ng mL^{-1} --> Cholecalciferol Pump-21 200 000 IU enteral; > 80 --> pause supplementsHigh Vit-D raises Ca --> Ca pump suspends until Ca×P < 55

62 Vitamin K / INR Micro-PT sensor (q2 min) INR > 3.0 (bleeding) --> Phytonadione Pump-22 10 mg IV; INR < 1.5 on valve --> warfarin cassette resumes Vit-K bolus pauses TXA loop 6 h (pro-thrombotic synergy)

63 Valproate LevelDialysate aptamer (q15 min) < 50 µg mL^{-1} seizures --> Valproate Pump-23 load; > 100 --> L-carnitine pump + CRRT clearance Carnitine raises ammonia; NH_3 loop set lower trigger (60 µM)

64 Carbamazepine Same aptamer < 4 µg mL --> oral load Pump-24; > 12 --> Hemoperfusion command Hemoperfusion also clears digoxin; Digoxin loop widens upper limit 10 %

65 Midazolam Sweat SERS nano-tag (q2 min) < 50 ng mL w/ high BIS --> Midazolam Pump-16 (increases); > 300 & BIS<40 --> taper pump High Midazolam depresses MAP --> MAP loop allows norepi bump auto

66 Mean Arterial Pressure (MAP) Invasive arterial line (beat-to-beat) MAP < 65 mmHg --> Norepi titration; MAP > 90 --> Nitroprusside Pump-25 0.3 µg kg-¹ min Nitro (increases) cyanide risk --> CN^- loop (45) tightens trigger to 2 µM

67 Cerebral rSO_2 (NIRS) Forehead NIRS (1 Hz) rSO_2 < 55 % --> Blanket 33 °C off, adjust $PaCO_2$ +5, RBC transfusion Pump-26 RBC transfusion raises K^+; K^+ loop threshold lowered to 5.0

68 Hemoglobin / Hct Inline optical (q30 s) Hb < 7 g dL-¹ --> RBC Pump-26 1 U; Hb > 18 polycythemia --> phlebotomy command RBC transfusion triggers CaCl bolus to replace citrate Ca bind

69 Cardiac Index / SVV Pulse-contour monitor (5 s) CI < 2.2 L min-¹ --> Dobutamine Pump-27; SVV > 15 % --> colloid bolus Pump-28 Fluid bolus dilutes minerals; mineral PID auto-boosts Zn, Mg 10 %

70 Serum Albumin Sweat photonic-crystal (q15 min) Alb < 2.5 g dL-¹ --> 25 % Albumin Pump-29 100 mL; Alb > 5 stop Albumin colloid shifts Ca; ionised Ca sensor recalibrates after bolus

71 ALT / AST Microneedle electro-enzyme (q10 min) > 3× ULN --> NAC Pump-5 if not active; hold hepatotoxic drugs NAC shared with ROS & APAP loops; cumulative cap 300 mg kg-¹ d

72 Alkaline Phosphatase / GGT Same chip (increases) Cholestasis pattern --> Ursodiol Pump-30 300 mg enteral Ursodiol bile acid loss reduces fat vit absorption --> Vit-D loop re-checks 6 h

73 BUN / Cr Ratio Inline micro-BUN & Cr (q5 min) Prerenal ratio > 20 --> Crystalloid Pump-31 250 mL; Low ratio + oliguria --> diuretic halt Fluid resusc dilutes Na; Na guard widened ΔNa < 8 per 24 h

74 IL-10 (Anti-inflam.) Microneedle aptamer (q10 min) IL-10 < 5 pg mL & TNF high --> Hydrocortisone bolus; IL-10 > 50 --> taper steroids High IL-10 pauses biologic anti-cytokine dosing (tocilizumab)

75 Complement C3/C4 Sweat immuno-FET (q30 min) Low C3 < 50 mg dL-¹ --> Fresh-frozen plasma Pump-32; High + SLE crisis --> Eculizumab Pump-32 900 mg Eculizumab increases infection risk; Procalcitonin loop lowers start-antibiotic threshold to 0.25

76 Free Fatty Acids (FFA) ISF amperometry (q5 min) FFA > 1 mmol L-¹ with insulin mid --> Insulin (increases) 20 %; heparin 5 U kg bolus (lipoprotein lipase release) Heparin bolus flags anti-Xa guard to 0.8 IU upper limit

77 Vitamin B1 (Thiamine) Sweat enzymatic sensor (q30 min) < 10 nmol L-¹ --> Thiamine Pump-33 200 mg IV q8h Thiamine administration reduces lactate; lactate column standby paused.

78 Folate (B9) Microneedle electro-immuno (q1 h) < 4 ng mL-¹ --> Folinic acid Pump-34 25 mg IV Folate (increases) can mask B12 deficiency; B12 loop set lower alert 150 pg

79 Coenzyme Q10 Sweat voltammetric redox (q1 h) < 0.4 µg mL-¹ + high troponin --> CoQ10 Pump-35 300 mg enteralCoQ10 increases warfarin metabolism; INR loop raises phytonadione alert

80 Gamma-Butyric Acid (GABA) ISF micro-dialysis + enzymatic (q5 min)Low GABA + high BIS --> Propofol/Midazolam check; High GABA --> Flumazenil Pump-36 0.2 mg Flumazenil lowers seizure threshold; EEG seizure loop set tighter detection

81 Cholinesterase Activity (BChE) Dry-film Ellman electro-sensor (30 s) BChE < 3 kU L^{-1} --> Atropine Pump-37 2 mg IV push then 2 mg h^{-1}; Pralidoxime Pump-38 30 mg kg load Atropine tachycardia raises VO_2 --> glucose loop pre-emptively increases dextrose 5 g h^{-1}

82 Blood Lead (Pb^{2+}) Microneedle anodic-stripping Pb electrode (q5 min) Pb > 45 µg dL^{-1} --> $CaNa_2$-EDTA Pump-39 50 mg kg d ÷4 doses EDTA chelates Zn/Cu --> mineral controller halves Zn/Cu infusion during therapy

83 Blood Mercury (Hg) Same ASV sensor Hg > 20 µg L^{-1} --> Dimercaprol Pump-39 3 mg kg IM q4h Dimercaprol dose ties into ROS loop: MB allowance halved to avoid oxidative stress

84 Blood Arsenic ASV gold-film sensor (q5 min) As > 10 µg L^{-1} --> DMSA Pump-39 10 mg kg PO q8h DMSA also lowers Cu; Cu low-guard lowered to 60 µg dL

85 Blood Thallium CNT electro-potentiometry (q5 min) Tl > 2 µg dL^{-1} --> Prussian Blue Pump-40 250 mg kg d enteral Prussian Blue diarrhea activates K^+ watch-dog (loss)

86 Salicylate Level Sweat colorimetric strip (2 min) > 40 mg dL^{-1} --> $NaHCO_3$ Pump-4 1–2 mEq kg h + dialysis command Bicarb bolus syncs with acid-base loop; SIG recalculated

87 Theophylline Dialysate aptamer (q15 min) > 20 µg mL^{-1} --> Charcoal hemoperfusion command; β-blocker Pump-41 Hemoperfusion clears midazolam; sedative loop auto-increases dose 10 %

88 Methotrexate (MTX) ISF aptamer (q15 min) > 10 µM (24 h) --> Leucovorin Pump-42 50 mg IV q6h; > 50 µM add Glucarpidase Pump-42 50 U kg Leucovorin raises B9; folate loop pauses folinic bolus to avoid overshoot

89 Metformin & Lactate Enzymatic metformin sensor + lactate (q5 min) Metf > 5 µg mL & Lactate > 5 mM --> Dialysis start + Pump-4 bicarb 100 mEq Dialysis message also enables phosphate bath mod per PO_4 loop

90 Piperacillin/Tazobactam AUC Dialysate β-lactam aptamer (q10 min) AUC < 200 --> Pump-43 piperacillin bolus; AUC > 400 hold next dose High β-lactam lowers K^+ (renal loss) --> K^+ infusion set-point +10 %

91 Fentanyl Plasma Level Sweat SERS patch (q2 min) < 1 ng mL with pain-score (increases) --> Pump-16 fentanyl (increases) 25 %; > 3 taper Fentanyl vasodilation drops MAP --> MAP loop tightens norepi floor

92 Dexmedetomidine ISF aptamer (q5 min) L < 300 pg mL & BIS > 60 --> Pump-17 Dex load; L > 1100 pg mL halt Dex bradycardia triggers HR watch-dog: atropine contingency

93 Exhaled Isoflurane (%) Gas analyzer in vent (q10 s) < 0.5 % in targeted sedation --> Vaporizer command (increases); > 1.2 % (decreases) Volatile anesthetics raise lactate; lactate loop sets column standby

94 ADAMTS-13 Activity Microneedle fluorogenic (30 min) < 10 % + TTP labs --> Plasma-exchange command + Caplacizumab Pump-44 10 mg IV Exchange lowers vWF multimers; platelet loop adjusts threshold 5 Ω lower

95 Antithrombin-III ISF aptamer (q30 min) AT-III < 70 % on heparin --> AT-III concentrate Pump-45 50 IU kg; > 120 % hold Raising AT-III drops heparin dose 20 % in anti-Xa loop

96 G6PD Activity Microneedle enzymatic (single run) Low G6PD + oxidative drug --> stop rasburicase; prep RBC transfusion Pump-26 RBC transfusion boosts Hb; Hb loop suspends EPO if running

97 Brain Tissue pO_2 ($PbtO_2$) Licox probe (1 Hz) $PbtO_2$ < 20 mmHg --> FiO_2 +10 %; MAP +10 mmHg; mannitol if ICP high FiO_2 (increases) interacts with $ETCO_2$ loop; algorithm balances gas goals

98 Gastro-tonometric pCO_2 ($PgCO_2$) Gastric tonometry (q5 min) $PgCO_2$ gap > 15 mmHg --> fluid bolus + inotrope bump; consider dobutamine Pump-27 Fluid bolus dilutes minerals: mineral PID pre-compensates 5 %

99 Phenobarbital Dialysate aptamer (q30 min) < 15 µg mL seizures --> Pump-46 phenobarbital load; > 40 hold + dialysis Dialysis message cross-checks MTX & metformin loops to co-clear

100 Propylene Glycol (PG) (IV med excipient) ISF enzyme (q30 min) PG > 25 mg dL or osmol gap > 10 --> Hemodialysis command; switch infusions to PG-free formulations Dialysis also removes lactate; lactate loop loosens column target

101 Endotoxin (LPS) Microneedle electro-aptamer (q5 min) LPS > 0.25 EU mL^{-1} --> Polymyxin-B hemoperfusion command; meropenem Pump-47 pre-dose Polymyxin column also adsorbs IL-6 --> cytokine loop raises IL-6 alert threshold 10 pg mL^{-1}

102 HMGB-1 (alarmin) Sweat SERS tag (q10 min) HMGB-1 > 30 ng mL^{-1} --> Anti-HMGB-1 mAb Pump-48 2 mg kg HMGB-1 neutralisation lowers ROS; ROS loop NAC ceiling lowered 25 %

103 Interleukin-8 (IL-8) Microneedle aptamer (q5 min) IL-8 > 70 pg mL^{-1} --> Anti-IL-8 nanobody Pump-48 10 mg IL-8 fall improves neutrophil chemotaxis; PCT loop widens antibiotic stop margin

104 β-D-Glucan (Fungal Ag) ISF fluorescence (q15 min) > 80 pg mL⁻¹ --> Echinocandin Pump-49; stop broad-spectrum β-lactam Echinocandin hepatic AE --> AST/ALT loop sets lower alert (2× ULN)

105 Galactomannan Sweat immuno-FET (q15 min) Index > 0.5 --> Voriconazole Pump-49 load; repeat q12 h Voriconazole prolongs QT --> ECG QTc watch-dog engages; Mg set-point +0.1 mmol

106 Adrenomedullin (ADM)Dialysate aptamer (q5 min) ADM > 70 pg mL⁻¹ with vasoplegia --> Adrecizumab Pump-50 2 mg kg ADM neutralisation raises MAP; norepi pump auto-tapers 20 %

107 FGF-23 Microneedle electro-immuno (q30 min) FGF-23 > 300 pg mL⁻¹ --> Calcitriol Pump-51 0.5 µg daily; lower phosphate binder target High FGF-23 signals PO_4 retention; PO_4 loop low-guard lifted to 2.5 mg dL

108 Copeptin (AVP surrogate) Sweat aptamer (q10 min) Copeptin < 5 pmol L⁻¹ + hyper-Na --> DDAVP Pump-15; > 35 stop DDAVP infusion tightens Na change ≤6 mmol 24 h (Na loop)

109 Leukotriene B_4 Skin micro-LC-EC (q10 min) LT-B_4 > 100 pg mL⁻¹ --> Montelukast Pump-52 10 mg enteral Montelukast may raise INR; Vitamin-K loop sets lower phytonadione start 2.5 mg

110 Prostaglandin E_2 Sweat electrochemical (q5 min) PGE_2 > 800 pg mL⁻¹ --> Indomethacin Pump-52 25 mg IV q6 h NSAID nephro-risk; NGAL loop lowers AKI trigger to +30 ng mL⁻¹

111 Ischemia-Modified Albumin (IMA) Microneedle colorimetric (q2 min) IMA index > 85 U mL⁻¹ --> IV Nitroglycerin Pump-25 & O_2 100 % NTG vasodilates --> MAP loop lowers upper nitroprusside limit

112 Brain Microdialysate Glucose Neuro-MD catheter (q1 min) Brain Glc < 1.0 mM --> systemic glucose + dextrose Pump-3; > 5 mM taper insulin Brain glucose loop supersedes systemic insulin PID gains for 30 min window

113 Calprotectin (S100A8/9) ISF immuno-FET (q15 min) > 250 µg mL⁻¹ gut flare --> Budesonide Pump-53 enteral; TNF blocker standby Steroid starts pause Vit-D bolus (osteopathy) <--> FGF-23 guard adjusts

114 2,3-DPG (RBC O_2 unloading) Optical RBC flow-cell (q30 min) Low < 10 µmol g Hb --> Exchange transfusion command; ensure phosphate repletion Phosphate binder stopped; Ca×P guard recalculated

115 Free-κ / λ Light Chains Dialysate immuno-turbid (q30 min) FLC > 60 mg dL⁻¹ --> Plasmapheresis command; Bortezomib Pump-54 Plasmapheresis lowers vWF; ADAMTS-13 loop delays Caplacizumab

116 Serum Pyruvate Sweat enzymatic (q5 min) Pyruvate > 0.15 mM with Lactate high --> Dichloroacetate Pump-55 50 mg kg DCA lowers pH; acid-base loop tightens bicarb guard

117 Normetanephrine ISF enzymatic (q10 min) > 1800 pg mL⁻¹ --> Clonidine Pump-56 0.3 mg IV then 0.5 µg kg h Clonidine hypotension interacts with MAP loop; norepi floor raised

118 Neopterin Sweat immuno-FET (q30 min) > 30 nmol L^{-1} signifies cellular immunity activation --> optimize nutrition: Pump-30 Ursodiol paused, add arginine feed bolus Arginine raises NO; NOx loop (16) adjusts MB safety margin

119 Tryptophan / Kynurenine Ratio Microneedle tandem mass (q30 min) Low ratio < 30 (catabolic) --> Tryptophan Pump-57 2 g enteral; High > 70 --> IDO inhibitor Pump-57 Tryptophan supplementation increases serotonin; 5-HT loop checks for syndrome

120 D-Lactate (gut ischemia) ISF stereospecific enzymatic (q5 min) D-Lac > 1 mmol L^{-1} --> Broad-spectrum anaerobic antibiotic Pump-58 + surgical alert Antibiotic load monitored by β-lactam AUC loop; renal dosing adjusts if NGAL rise

121 SARS-CoV-2 N-Antigen Sweat nano-LFA (2 min) Positive w/ Ct < 28 --> Pump-59 remdesivir 200 mg LD then 100 mg q24 h; optional mAb Pump-60 Remdesivir hepatotoxic --> ALT/AST loop (71) lowers alert to 2 × ULN

122 Influenza A/B NA-Ag Microneedle electro-LFA (5 min) Positive --> Pump-61 peramivir 600 mg IV; stop broad-spec abx Peramivir nephro-clear --> NGAL loop tightens AKI trigger

123 RSV F-Protein Sweat aptamer (5 min) Positive --> Aerosol ribavirin command; Pump-62 palivizumab 15 mg kg Ribavirin hemolysis risk --> free Hb loop (26) low-ers alert to 30 mg dL^{-1}

124 Presepsin (sCD14-subtype) Microneedle immuno-FET (5 min) > 600 pg mL^{-1} --> Antibiotic escalation Pump-47 + Endotoxin column auto-on Endotoxin column already in loop 101; columns serialized to avoid pressure (increases)

125 sTREM-1 Sweat aptamer (5 min) > 200 pg mL^{-1} --> Nangibotide Pump-63 1 mg kg h × 72 h Nangibotide infusion pauses anti-IL-8 dosing (row 103) for cytokine balance

126 miR-122 (Liver Injury) ISF qPCR-chip (10 min) > 2000 cp µL --> Halt hepatotoxins; low-dose NAC Pump-5 12 mg kg h NAC cumulative cap shared with APAP & ROS loops

127 Cell-free Histone H3/H4 Dialysate ELISA (15 min) > 30 µg mL^{-1} --> Heparin Pump-3 10 U kg bolus; anti-histone mAb Pump-64 Heparin dose reconciled with anti-Xa loop; protamine guard pre-armed

128 cfDNA (DAMP burden)Microfluidic PicoGreen (10 min) cfDNA > 100 ng mL^{-1} --> Recombinant DNase Pump-65 5 mg aerosol IV DNase reduces viscosity—CRRT filter life extended; algorithm defers filter swap

129 Complement C5a Aptamer (q10 min) C5a > 20 ng mL^{-1} --> C5a inhibitor (Vilobelimab) Pump-66 800 mg LD C5a block raises infection risk; PCT loop start threshold 0.2 ng

130 sFLT-1 / PLGF Ratio (preeclampsia) Microneedle duplex immuno (15 min) Ratio > 85 --> Apheresis command + NO-donor patch Pump-67 NO donor vasodilates—MAP loop upper limit lowered by 10 mmHg

131 Angiotensin II ISF nano-immuno (5 min) Low < 25 pg mL^{-1} & vasodil shock --> Ang-II Pump-68 20 ng kg min; High > 100 --> ARB Pump-68 Ang-II raises aldosterone; Aldo loop (18) widens NaCl guard

132 Oxytocin Sweat aptamer (5 min) Post-partum atony: Oxytocin Pump-69 10 U IV; > 100 pg mL^{-1} --> haltOxytocin bolus drops BP; MAP loop norepi floor raised temporarily

133 Melatonin ISF electro-chem luminescence (30 min)< 30 pg mL^{-1} at 02:00 --> Melatonin Pump-70 5 mg enteral; > 120 stop Melatonin improves sleep; propofol requirement auto-drops 10 %

134 β-Endorphin Sweat SERS (5 min) < 20 pg mL^{-1} w/ pain (increases) --> Endorphin analog Pump-71; High > 100 taper opioid pumpEndorphin analog lowers BIS, sedation loop adjusts propofol –5 %

135 Acetoacetate ISF enzyme (2 min) > 3 mM (DKA) --> Insulin (increases) 20 % + IV $NaHCO_3$ guard; when < 0.5 stopAdds to β-OHB loop synergy; algorithm computes "Ketone Gap"

136 MCP-1 (CCL2) Microneedle aptamer (5 min) > 100 pg mL^{-1} --> CCR2 antagonist Pump-72 CCR2 blockade may elevate IL-6; IL-6 loop raises high alert 70 pg

137 miR-21 (AKI/Sepsis marker) ISF qPCR-chip (15 min) > 1500 cp µL --> Pre-emptive CRRT start; adjust nephrotoxin pumps miR-21 rise lowers NGAL trigger to +20 ng mL^{-1} confirmatory

138 HIF-1α Proxy Index (pO_2+lactate) Derived algorithm (1 min) Index > 1.5 --> RBC transfusion Pump-26 + FiO_2 (increases) 10 % RBC transfusion K load managed by K^+ loop

139 IGF-1 Sweat immuno-FET (q30 min) < 70 ng mL^{-1} in burns --> rhIGF-1 Pump-73 100 µg m^2 q12h; > 300 stop IGF-1 (increases) lowers glucose; insulin PID gains auto-reduce 15 %

140 Growth Hormone (GH) ISF aptamer (q30 min) > 10 ng mL^{-1} (acromegaly crises) --> Octreotide Pump-12; Low < 1 catabolic ICU --> rhGH Pump-74 0.1 mg daily Octreotide slows gut; if enteral feed residual >250 mL, motility agent loop fired

Layer Trigger class Max response latency Permitted actuator scope Examples

L-0 Vital Override Threat-to-life markers where minutes matter ≤ 5 s (hard real-time) May halt any lower-layer infusion, fire any antidote, command ventilator / dialysis MAP < 50, K^+ > 6.5, Ca^{2+} < 0.8, CN^- > 5 µM, ICP > 30 mmHg

L-1 Guard-Rail Balancer Biochemical pairs whose correction can create the opposite error ≤ 30 s Scales paired pumps to maintain ratio windows; may veto each other Zn(increases) cancels Cu(decreases), insulin dose halves if K^+ < 3.5, protamine pauses if anti-Xa < 0.3

L-2 Optimiser / Steward Non-lethal deviations that affect LOS / organ recovery ≤ 5 min Fine PID tuning, nutrition tweaks, antibiotic de-escalation IL-6 40-->20, Vit-D 30-->50, Melatonin circadian dosing

Actuation always flows top-down: L-0 commands override L-1 & L-2; L-1 may modify or cancel L-2 but never L-0.

Appendix C— Knock-Down Interaction Matrix (core examples)

Primary Deviation --> Secondary channel automatically down-scaled / blocked Rationale

Zn (increases) (Zn:Cu > 50) --> Cu infusion up OR Zn pump down Prevent copper-deficiency cytopenia

Insulin bolus --> KCl infused if K^+ < 3.5 Avoid insulin-triggered hypokalemia

Protamine dose --> Vancomycin pump paused 15 min pre/post Prevent protein-binding displacement hypotension

EDTA chelation (Pb/Hg/As) --> Zn/Cu pumps halved EDTA strips beneficial metals; replenish later

Methylene-Blue (MetHb, NO loops) --> SSRI / 5-HT loop blocked Reduce risk of serotonin syndrome

Steroid bolus (Hydrocortisone) --> Tocilizumab biologic paused Combine = over-suppression --> infection

Echinocandin start (β-D-Glucan) --> Azole pump vetoed Avoid redundant hepatotoxic combo

High NAC (>300 mg kg^{-1} d) --> Zn pump paused NAC chelates Zn, would drop ratio

DDAVP micro-dose --> Hypertonic saline locked out for 4 h Prevent rapid osm shift

RBC transfusion --> K^+ watch-dog threshold lowered to 5.0 Stored blood dumps extracellular K^+

The matrix is implemented as a conflict-graph; edges carry rule-IDs so the controller can trace why a channel is suppressed._____

Annex O Smart-Cartridge Architecture, μ-Band Metadata & Adaptive Hierarchy

O-1 Overview

The system now includes at least one replaceable therapeutic or process-control cartridge (pump, sorbent, or fractionator) that stores, in on-board non-volatile memory, both static metadata (drug/chemical class, concentration, batch limits) and dynamic-safety metadata (μ-band thresholds, ratio constraints, incompatibility list).

A controller reads this metadata on hot-swap and enforces a four-tier control stack:

Tier Function

L-0 Vital-override (hard limits)

L-1 Guard-rail balancer (ratio & conflict graph)

L-2 Optimiser / PID or MPC

L-μ Training tier (probe pulses inside μ-band to learn J_{patient/process})

O-2 Cartridge EEPROM Schema

Field Type Example

cart_id 16-bit 0x01AF

class_code 8-bit 0x07 (albumin split module)

concentration float32 8.0 (% PEG)

max_mg_per_kg_day float32 6.5

mu_band array<float32,2>[n] alb_purity:[92,96]

hard_limits array<float32,2>[n] tmp_pf3:[50,150]

ratio_vector float32[3] P1=0,P2=1,P3=0

incompat_list var-length byte[] class_codes {0x05,0x0C}

O-3 μ-Band Probe Rule

While every monitored variable X remains inside [μ-LOW, μ-HIGH] the controller injects a probe of magnitude

$\Delta U = \lambda\,(\mu_\mathrm{high} - \mu_\mathrm{low}),\;\; \lambda \le 0.05$ \Delta U = \lambda\,(\mu_\mathrm{high}-\mu_\mathrm{low}),\;\; \lambda\le0.05ΔU=λ(μhigh−μlow),λ≤0.05

records ΔX, updates the relevant Jacobian row by recursive least squares, and halves λ when the 95 % CI of that row falls below ½ the population SD.

O-4 Conflict-Graph Arbitration

Each cartridge's incompat_list populates edges in a directed graph G.

During scheduling, any candidate actuation u_j is vetoed if class_code_j conflicts with any active edge vertex.

Graph update latency < 50 ms.

O-5 Fallback State Machine

Event State transition

EEPROM read error SAFE-MONITOR (all pumps 0)

Hard-limit breach BYPASS_STAGE for that slot

Battery < 10 % MAINTENANCE_DRIP (preset cocktail)

O-6 Representative Bench Data—Smart Cartridge Lockout

Albumin split cartridge (class 0x07) + Protamine cartridge (class 0x05)

Lockout latency: 38 ms; no simultaneous energisation observed in 10^4 test cycles.

Annex P Extended Claim Set (Smart Cartridge & μ-Band)

1. A closed-loop therapeutic system comprising: (a) a sensor array that simultaneously measures at least twenty biochemical variables in a human subject; (b) a plurality of replaceable cartridges, each including a memory storing: (i) a chemical-class code, (ii) μ-LOW and μ-HIGH thresholds for at least one of the biochemical variables, and (iii) a list of incompatible class codes; (c) a controller executing a hierarchy wherein: (i) a vital-override layer disables any cartridge when a hard limit stored in the memory is exceeded; (ii) a guard-rail layer suppresses actuation of any cartridge whose class code appears in the incompatible list of an active cartridge; (iii) an optimiser layer adjusts cartridge actuation with a proportional-integral-derivative algorithm; and (iv) a training layer injects probe pulses inside the μ-LOW/μ-HIGH band to update a patient-specific Jacobian matrix. 2. The system of claim 1 wherein the memory further stores a ratio vector to at least three principal vertices, and the guard-rail layer maintains predefined linear constraints on the weighted sum of vertex magnitudes. 3. The system of claim 1 wherein the probe pulse amplitude is automatically scaled according to the stored μ-band width. 4. The system of claim 1 wherein each cartridge is physically locked out when a forward-looking dose-budget calculation projects that its mg kg^{-1} per 24 h ceiling will be exceeded within the next thirty minutes. 5. A method of plug-and-play fractionation control comprising: reading μ-band and hard-limit metadata from a precipitation cartridge; maintaining albumin purity within 92-96 % by adjusting split-ratio only when albumin purity lies outside the μ-band; injecting ±1 % split-ratio probes when purity lies inside the μ-band; and bypassing the cartridge if trans-membrane pressure reaches 150 mm Hg. ---

Annex Q Industrial-Process Embodiment Throughout this Annex, each instance of the term “human subject” shall be read as “process fluid,” and sensor variables such as pH, red-ox potential, chlorine residual or dissolved-oxygen concentration may be substituted for patient-specific biochemical analytes. Except as so substituted, the same cartridge architecture, μ-band hierarchy and controller logic—and the same claims with the word “therapeutic” deleted—are incorporated herein by reference and apply mutatis mutandis to industrial continuous-flow operations.