

Claims

1. A hybrid hemofiltration cartridge comprising:
 - a. a low-flow hollow-fiber hemofilter (FIG. 1) having a filter shell (101) with a blood inlet (102), a blood outlet (103) and an ultrafiltrate port (104);
 - b. a sorbent regeneration stack (FIG. 2) fluidly connected to the ultrafiltrate port, said stack comprising a urease-carbon layer (201), a zirconium phosphate resin layer (202), a hydrous zirconium oxide bead layer (203), and a bicarbonate buffer layer (204) contained within a column shell (205);
 - c. a microfluidic pump assembly (FIG. 3) comprising an mp6 diaphragm pump (301) and concentrate reservoirs including a NaHCO_3 reservoir (302) and a $\text{CaCl}_2/\text{MgCl}_2$ reservoir (303), the pump assembly being configured to circulate ultrafiltrate through the sorbent stack and meter concentrates into regenerated dialysate;
 - d. an EEPROM integrated circuit (401) on the cartridge storing a lot ID (402), a capacity byte (403) and an expiry bit (404);
 - e. an inline sensor suite (FIG. 5) comprising a urea optic sensor (501), a pH sensor (502), a conductivity probe (503) and a transmembrane pressure sensor (504); and
 - f. electrical and fluid interfaces configured to couple the cartridge to a pump cradle and controller such that sensor outputs and EEPROM data are read by the controller, which regulates the micro-pumps and transitions the cartridge among safe states;wherein the cartridge is a single-use sterile module for use in the TraceLoop ecosystem.
2. The cartridge of claim 1, wherein the urease-carbon layer (201) contains immobilized urease covalently bound to silica and activated carbon beads, the zirconium phosphate layer (202) contains acid and sodium forms of zirconium phosphate to exchange ammonium for H^+ and Na^+ , the hydrous zirconium oxide layer (203) adsorbs phosphate and bicarbonate, and the bicarbonate buffer layer (204) releases sodium bicarbonate to maintain pH.
3. The cartridge of claim 1, wherein the microfluidic pump assembly (301–303) comprises multiple diaphragm pumps controlled independently to implement single-loop regeneration, twin-column staggered regeneration or a sterile bag fallback loop.
4. The cartridge of claim 1, further comprising valves and flow paths configured to switch between a regenerated dialysate loop and a sterile bag loop in response to sensor readings exceeding preset thresholds or the EEPROM expiry bit being set.

5. The cartridge of claim 1, wherein the EEPROM capacity byte (403) is decremented after each regeneration cycle and the controller prevents further use of the cartridge when the capacity byte reaches zero.
6. The cartridge of claim 1, wherein the conflict-graph logic executed by the controller enforces non-conflicting pump operations, monitors sensor signals and EEPROM status, and transitions the system among safety states S1, S2 and S3 as defined above.
7. A method of operating a hybrid hemofiltration cartridge comprising the steps of:
 - a. connecting the cartridge to a patient blood circuit and a pump cradle;
 - b. pumping patient blood through the low-flow hemofilter (101–104) while drawing ultrafiltrate through the sorbent regeneration stack (201–205) using the micro-pump assembly (301);
 - c. measuring urea, pH, conductivity and transmembrane pressure using sensors (501–504) and reading the cartridge's EEPROM (401–404);
 - d. replenishing bicarbonate and divalent cations using pumps (302, 303) as controlled by the controller;
 - e. decrementing the capacity byte (403) after each regeneration cycle; and
 - f. transitioning to a sterile bag loop and setting the expiry bit (404) when sensor thresholds are exceeded or the capacity byte reaches zero.
8. The method of claim 7, wherein the sorbent stack includes two parallel columns and the controller alternates flow between them to allow staggered regeneration.
9. The method of claim 7, wherein the controller implements conflict-graph logic to prevent simultaneous activation of pumps that would cause reverse flow or unsafe pressures.
10. The method of claim 7, wherein the cartridge and controller together provide continuous renal replacement therapy at low blood flows using less than one litre of dialysate.