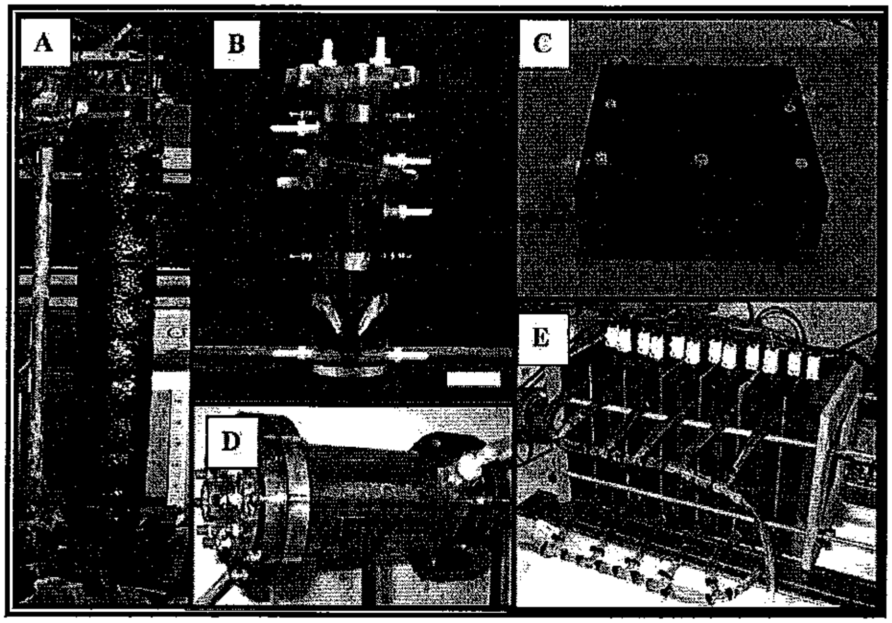

FIGURE 3. MFCs used for continuous operation: (A) upflow, tubular type MFC with inner graphite bed anode and outer cathode (*35*); (B) upflow, tubular type MFC with anode below and cathode above, the membrane is inclinated (*36*); (C) flat plate design where a channel is cut in the blocks so that liquid can flow in a serpentine pattern across the electrode (*17*); (D) single-chamber system with an inner concentric air cathode surrounded by a chamber containing graphite rods as anode (*34*); (E) stacked MFC, in which 6 separate MFCs are joined in one reactor block (*25*).

the cathode relative to that of the anode (*28*) and the surface of the membrane (*29*). The power density (*P*) produced by these systems is typically limited by high internal resistance and electrode-based losses (see below). When comparing power produced by these systems, it makes the most sense to compare them on the basis of equally sized anodes, cathodes, and membranes (*29*).

Using ferricyanide as the electron acceptor in the cathode chamber increases the power density due to the availability of a good electron acceptor at high concentrations. Ferricyanide increased power by 1.5 to 1.8 times compared to a Pt-catalyst cathode and dissolved oxygen (H-design reactor with a Nafion CEM) (*29*). The highest power densities so far reported for MFC systems have been low internal resistance systems with ferricyanide at the cathode (*6*, *18*). While ferricyanide is an excellent catholyte in terms of system performance, it must be chemically regenerated and its use is not sustainable in practice. Thus, the use of ferricyanide is restricted to fundamental laboratory studies.

It is not essential to place the cathode in water or in a separate chamber when using oxygen at the cathode. The cathode can be placed in direct contact with air (Figures 2e, 3c, 3d), either in the presence or absence of a membrane (*30*). In one system a kaolin clay-based separator and graphite cathode were joined to form a combined separator–cathode structure (*31*). Much larger power densities have been achieved using oxygen as the electron acceptor when aqueous-cathodes are replaced with air-cathodes. In the simplest configuration, the anode and cathode are placed on either side of a tube, with the anode sealed against a flat plate and the cathode exposed to air on one side, and water on the other (Figure 2e). When a membrane is used in this air-cathode system, it serves primarily to keep water from leaking through the cathode, although it also reduces oxygen diffusion into the anode chamber. The utilization of oxygen by bacteria in the anode chamber can result in a lower Coulombic efficiency (defined as the fraction of electrons recovered as current versus the maximum possible recovery; see below) (*30*). Hydrostatic pressure on the cathode will make it leak water, but that can be minimized by applying coatings, such as polytetrafloroethylene (PTFE), to the outside of the cathode that permit oxygen diffusion but limit bulk water loss (*32*).

Several variations on these basic designs have emerged in an effort to increase power density or provide for continuous flow through the anode chamber (in contrast to the above systems which were all operated in batch mode). Systems have been designed with an outer cylindrical reactor with a concentric inner tube that is the cathode (*33*, *34*) (Figure 3d), and with an inner cylindrical reactor (anode consisting of granular media) with the cathode on the outside (*35*) (Figure 3a). Another variation is to design the system like an upflow fixed-bed biofilm reactor, with the fluid flowing continuously through porous anodes toward a membrane separating the anode from the cathode chamber (*36*) (Figure 3b). Systems have been designed to resemble hydrogen fuel cells, where a CEM is sandwiched between the anode and cathode (Figure 3c). To increase the overall system voltage, MFCs can be stacked with the systems shaped as a series of flat plates or linked together in series (*25*) (Figure 3e).

Sediment MFCs. By placing one electrode into a marine sediment rich in organic matter and sulfides, and the other in the overlying oxic water, electricity can be generated at sufficient levels to power some marine devices (*37*, *38*). Protons conducted by the seawater can produce a power density of up to 28 mW/m^2. Graphite disks can be used for the electrodes (*12*, *37*), although platinum mesh electrodes have also been used (*38*). "Bottle brush" cathodes used for seawater batteries may hold the most promise for long-term operation of unattended systems as these electrodes provide a high surface area and are made of noncorrosive materials (*39*). Sediments have also been placed into H-tube configured two-chamber systems to allow investigation of the bacterial community (*12*).

Modifications for Hydrogen Production. By "assisting" the potential generated by the bacteria at the anode with a small potential by an external power source (>0.25 V), it is possible to generate hydrogen at the cathode (*40*–*43*). These reactors, called bioelectrochemically assisted microbial reactors (BEAMRs) or biocatalyzed electrolysis systems, are not