active and highly toxic. In particular, hydrogen selenide, a gas used in some selenization processes, is extremely toxic with an "immediately dangerous to life and health" (IDLH) value of only 2 ppm [218].

There are also environmental concerns for the hazards during the operation of Cu(InGa)Se_2 modules with one potential risk being the leaching of critical materials into rainwater. This only happens if a module is broken or crushed, so the normally well-encapsulated active layers are exposed. An experimental study of the emissions of toxic elements into rainwater from crushed $CuInSe_2$ modules and into soil exposed to the water concluded that no acute danger to humans or the environment is likely to occur [219]. The main hazard during the active life of the $CuInSe_2$ modules is related to fire accidents. A study of the potential risks associated with fires in PV power plants shows that they are very limited [220]. A fire in a commercial-size system could result in harmful concentrations up to 300 m downwind of the fire if most of the $CuInSe_2$ materials are released. With release of 10% of the $CuInSe_2$ materials, concentrations were not harmful even under worst-possible meteorological conditions. The study concluded that there are no immediate risks to the public from fires in sites with $CuInSe_2$ modules.

Concerns for disposal of Cu(InGa)Se_2 have also been tested with respect to leachability. Zn, Mo, and Se are eluted in the highest amounts. On the basis of landfill criteria, $CuInSe_2$ modules will pass requirements in both Germany and the United States [217]. Because of the low volume and leaching rates of critical elements from $CuInSe_2$ modules, they will not be classified as hazardous waste according to most US regulations [221].

The evolution of environmental regulations, disposal options, and economics makes recycling increasingly important. In large-scale use of Cu(InGa)Se_2 modules, the supply of rare elements, in particular indium, but also selenium and gallium, provides a further motivation for recycling. The cost of recycling may be favorably offset if module materials can be reclaimed. In particular, if the glass sheets can be salvaged and reused, there will be a net gain associated with the recycling procedure. Thus, recycling may be an important consideration in the choice of encapsulation method. Double glass structures are functional and may reduce the release of $CuInSe_2$ materials during fires, but may increase the costs for recovering metals and reusing glass plates [221].

13.7 THE Cu(InGa)Se_2 OUTLOOK

Clearly, there has been tremendous progress in Cu(InGa)Se_2 solar cells as evidenced by the high module and cell efficiencies fabricated by many groups, the range of deposition and device options that have been developed, and the growing base of science and engineering knowledge of these materials and processes. There is good reason to be optimistic that cell efficiencies greater than 20% will be achieved before long and that module performance and yield will continue to improve. Still, there is a lack of understanding of many of the critical problems associated with semiconductor processing and a need to devote time and research focus at both the laboratory scale, to address fundamental issues, and on the pilot line, to address equipment and scale-up problems and to validate processes.

From their earliest development, $CuInSe_2$-based solar cells, along with other thin-film PV materials including Cu_2S, CdTe, and amorphous Si, attracted an interest because of their perceived potential to be manufactured at a lower cost than Si wafer-based PV.