

2.9. *IN SITU* CHEMICAL-REACTION CELLS

O'Brien *et al.* (2011) explain the trade-offs for such experiments in detail and have shown that it is possible to extract useful structural information. Large-volume cells that used to be exclusively the domain of neutron diffraction and EDXRD have now also been adapted for angular-dispersive powder diffraction with, in some cases, increased speed and information content. For instance, Wragg *et al.* (2012) studied an industrial methanol-to-olefin conversion process with *operando* time- and space-resolved diffraction. The sample is rapidly scanned up and down to provide one-dimensional spatial information. The results complement earlier experiments performed with a microreactor. Jacques *et al.* (2011) extracted three-dimensional information by using dynamic X-ray diffraction computed tomography (XRD-CT). They measured over 50 000 diffraction patterns on beamline ID15 at the ESRF with different sample orientations, positions and temperatures. From this huge amount of data, they reconstructed the catalyst body in three dimensions with a diffraction pattern assigned to each volume unit within the sample as a function of time. With this information, they were able to follow the evolution of the catalytically active phase throughout the sample. Wragg *et al.* (2015) have since performed Rietveld analysis on voxels from the XRD-CT data for a methanol-to-olefin reactor bed. It is also worth mentioning work by Jensen *et al.* (2007), performed on beamline 1-ID at APS Argonne National Laboratory, investigating the kinetics of nanoparticle formation involving a sol-gel reaction in supercritical CO₂ at 10 MPa. The reaction was studied with XRD and small-angle X-ray scattering (SAXS) in a large 30 ml vessel. In a different application, Friščić *et al.* (2013) mounted a laboratory-scale 10 ml ball mill on the ID15 beamline in order to study mechanochemical reactions, which are used in numerous industrial production processes. By averaging ten 400 ms frames, they obtained sufficiently good data to perform full-pattern refinements and kinetic analysis, providing information about otherwise completely inaccessible processes. We therefore foresee a bright future for such extreme high-energy applications together

with large-volume studies, since they provide a useful bridge between the academic and industrial worlds.

2.9.3.4. Cells specifically for neutrons

2.9.3.4.1. Introduction

The special characteristics of neutrons imply both advantages and challenges for the design of *in situ* experiments and their associated equipment. The differences in penetration depths between X-rays and neutrons and the correspondingly smaller scattering cross sections for neutrons, together with the much lower flux densities, imply that cells for neutrons are quite different from the miniature capillary cells for X-rays described in the previous sections. Above all, the sample volume is by necessity often much larger than the equivalent volume required for a laboratory X-ray or synchrotron experiment. However, the ability of neutrons to penetrate deep into sample environments has been of great importance for studying samples at very low temperature, under high pressure or within strong magnetic fields. Similarly, reaction cells for *in situ* investigations profit from the ability of neutrons to penetrate through thick-walled vessels, for example for studying gas–solid reactions under high pressure. Only relatively recently, with the availability of high-energy synchrotron beamlines (>100 keV), can X-rays effectively compete with neutrons in this domain. Even in these cases, the very different scattering properties of neutrons (*e.g.* the strong variation of cross section with isotope) means that some measurements that are challenging, if not impossible, with X-rays can become quite feasible with neutrons. The solid–gas reaction of intermetallic phases with H₂ gas is a good example, where the positions of the interstitial H atoms can be located within a heavy-metal hydride (Kamazawa *et al.*, 2013). Similarly, the hydration of cement has been investigated many times, with improved time resolution resulting from developments in neutron optics and detector performance. *In situ* studies of oxidation reactions have also benefited from the better ability of

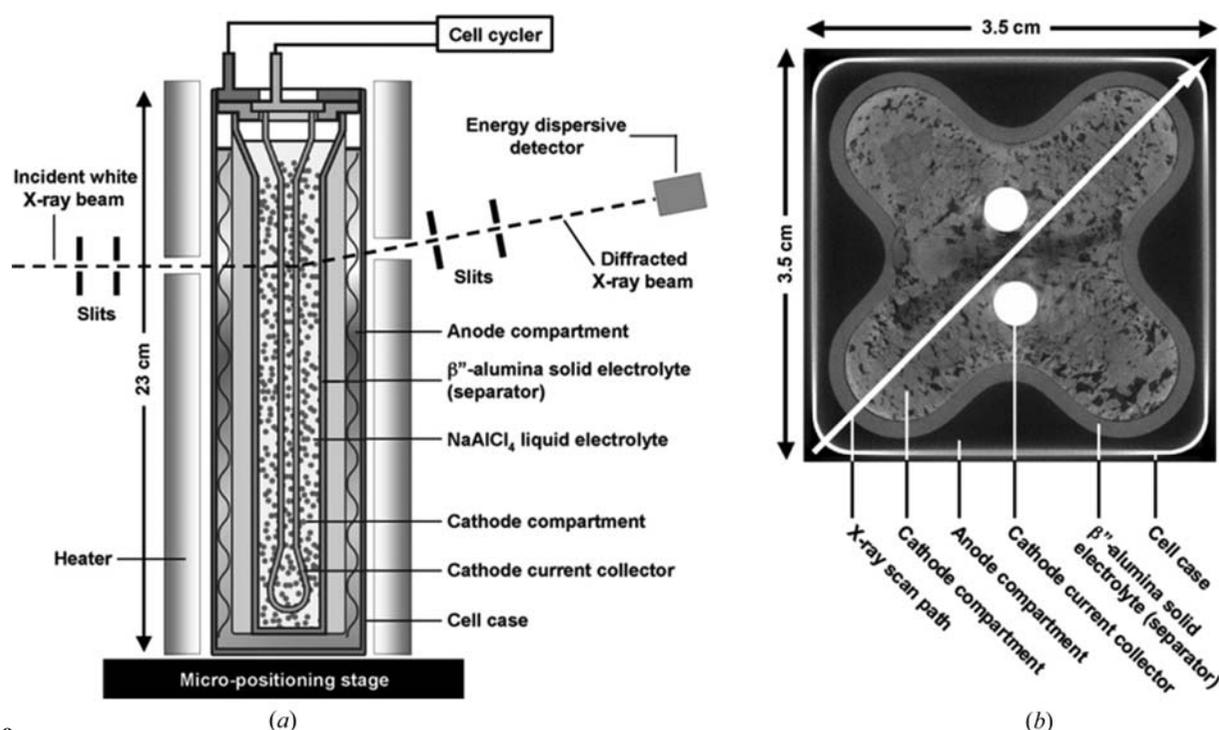


Figure 2.9.9

(a) Schematic of a sodium-halide cell in an *in situ* synchrotron EDXRD experimental setup. (b) Cross-sectional computed tomography image of a cell. The arrow along the cell diagonal denotes the path of the X-ray line scans used in this work. This corresponds to an X-ray penetration depth of up to 50 mm. Adapted from Rijssenbeek *et al.* (2011) with permission from Elsevier.