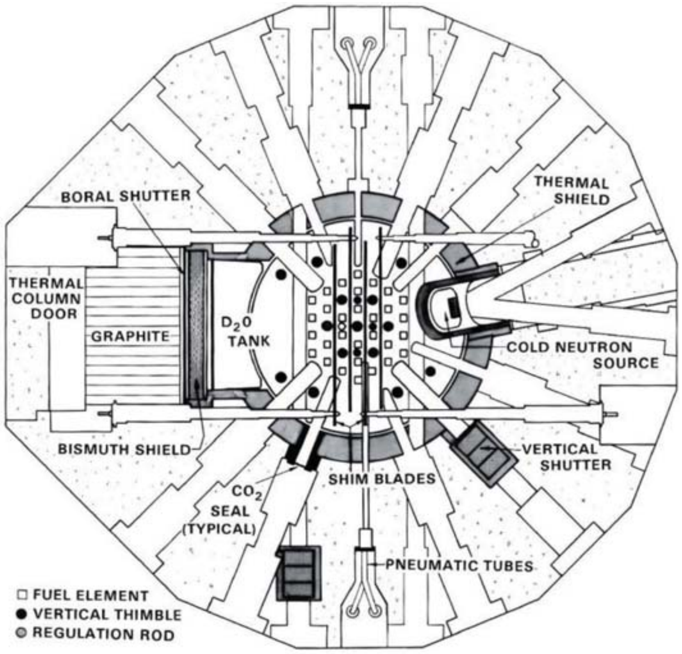
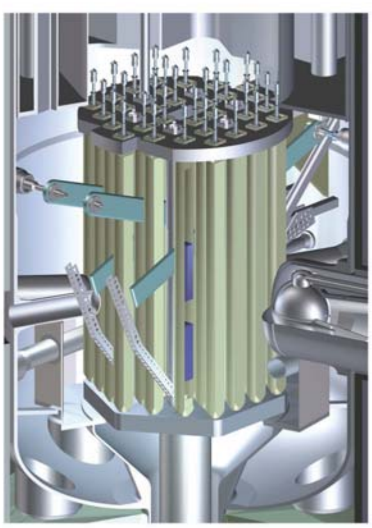
International Tables for Crystallography (2018). Vol. H, Figure 2.3.6, p. 73.



(*a*)



(*b*)

Figure 2.3.6
The NBSR at the National Institute of Standards and Technology Center for Neutron Research. Part (*a*) is a plan view (reproduced from Rush & Cappelletti, 2011) while (*b*) is a recent cutaway view of the reactor core showing the liquid-hydrogen cold source on the right-hand side.

are shown in Fig. 2.3.6. Note the presence of numerous beam tubes that allow neutrons to be taken out from the vicinity of the reactor core. This view of the NBSR (Fig. 2.3.6*a*) shows provision for a cold neutron source, and for beam tubes to transport cold neutrons to experiments, but it was years before any cold neutron source was installed. The first cold source, installed in 1987, was frozen heavy water; this was replaced in 1995 by a liquid-hydrogen cold source, and that was upgraded in turn in 2003. The NBSR first went critical in December 1967; the history of its subsequent development and use in neutron-beam research has been recounted by Rush & Cappelletti (2011).

The HFR at the Institut Laue–Langevin (ILL), considered to be the premier source for reactor-based neutron-beam research, serves as our second example. It too uses highly enriched uranium, here in a single centrally located U_3Al_x-Al fuel element, and it relies on heavy water for moderator and coolant. It operates at 58 MW and the thermal neutron flux is 1.5 × 10^{15} n cm^{-2} s^{-1}. The reactor incorporates two liquid-deuterium cold sources, operating at 20 K, and a graphite hot source operating at 2000 K. In the HFR, being of modern design and purpose-built for neutron-beam research, the beam tubes do not view the core directly, but are 'tangential' to it (Fig. 2.3.7); this reduces the unwelcome fast-neutron component of the emerging beams. The HFR achieved criticality in July 1971. More details on this reactor can be found in the 'Yellow Book' which is maintained on the ILL web site, https://www.ill.eu.

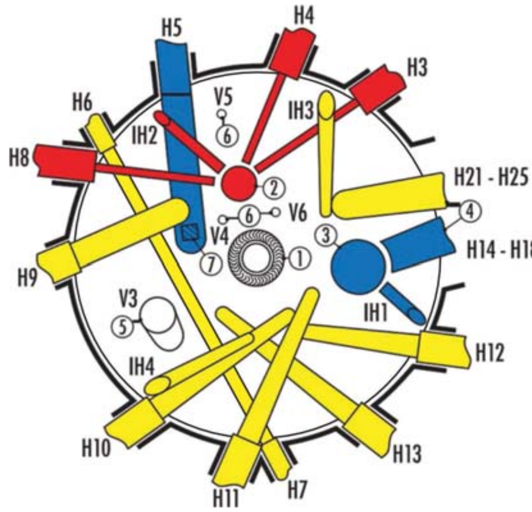


Figure 2.3.7
Schematic diagram of the HFR operated by the Institut Laue–Langevin in Grenoble, France. It has a compact core – the beam tubes avoid viewing the central core in favour of the surrounding moderator. This reactor also features hot (red) and cold (blue) sources. (Diagram reproduced with permission from the ILL from The Yellow Book 2008, https://www.ill.eu/fileadmin/users_files/Other_Sites/YellowBook2008CDRom/index.htm.)

From the opening paragraph of this section, it might be concluded that the more heavy water deployed, and the more highly is the uranium enriched in the fissile isotope ^{235}U, the greater the neutron fluxes that can be obtained. This conclusion would be correct, but concerns about nuclear proliferation have brought a shift to the use of low-enrichment uranium (LEU) in which the ^{235}U is enriched to less than 20%; however, in some reactors highly enriched uranium (HEU) with enrichment levels greater than 90% remains in use. Table 2.3.3 gives pertinent details on a number of research reactors important for neutron diffraction. Additional reactors are listed by Kisi & Howard (2008) in their Table 3.1, and a complete listing is available from the International Atomic Energy Agency Research Reactor Database (IAEA RRDB, https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx).

2.3.3.3. *Spallation neutron sources*

The bombardment of heavy-element nuclei by high-energy protons, *i.e.* protons in the energy range 100 MeV to GeV, causes the nuclei to break up with the release of large numbers of neutrons. The word 'spallation' might suggest that neutrons are simply being chipped off the target nucleus, and indeed neutrons can be ejected by protons in a direct collision process with transfer of the full proton energy, but such simple events are relatively rare. In most cases there is a sequence involving incorporation of the bombarding proton into the nucleus, intra- and internuclear cascades accompanied by the ejection of assorted high-energy particles, including neutrons, and then an 'evaporation' process releasing neutrons from excited nuclei with

references