Introduction to nuclear fission and fusion energy technologies

Nuclear energy is as natural as fossil energy and renewable energy. Since long time before mankind started to develop technologies to provide energy from fusion of light atomic nuclei and from fission of heavy atomic nuclei, nature has been releasing energy from fusion and fission processes: Fusion of hydrogen to helium nuclei is the energy source of stars like the sun. Moreover, on the planet Earth already 2 billion years ago natural nuclear fission reactors became active after water had intruded into the porous material of uranium deposits to act as moderator of fission neutrons. This happened e.g. in West Africa, near Oklo in present-day Gabun, where these natural fission reactors stayed active for about 200 000 years till the available uranium was sufficiently depleted to let the nuclear fission chain reaction finally stop.

Concerning the use of *nuclear fission energy* by means of artificial nuclear fission power plants it can be stated that all relevant technologies for allowing an economical use of nuclear fission energy, and this in an environmentally safe way, are available at least in principle (see Chap. 1: Principles of fission reactors, Nuclear power plants, Economic aspects, Safety questions). This holds for the whole chain of processes, from mining uranium deposits, operating nuclear power plants inherently safe – with respect to the nuclear fission chain reaction as well as to the removal of afterheat from radioactive decays after stopping of the nuclear chain reaction – without any risk of a large accident (high temperature reactor, HTR), to finally the safe deposition of radioactive waste.

According to the meanwhile rather sophisticated and reliable probabilistic safety analysis (see Chap. 2), for light water reactors (LWR) in operation at present the risk of a large accident with release of a high amount of radioactivity has to be expected as one within about a hundred thousand to one million years of reactor operation (i.e., for the about 350 LWRs in operation at present worldwide, one large accident within a period of about 1000 years).

Nuclear fuel and the complete nuclear fuel cycle from mining of uranium to the treatment of radioactive waste is presented in Chap. 3, including recovery of major actinides as further fuel and deposition, respectively, after transmutation of minor actinides to short-lifetime radioactive waste.

The nature, sources, concentrations, exposures, measurement technologies for and effects of natural and artificial radioactivity are described in Chap. 4.

At present, R & D on evolutionary improvements of nuclear power plants (NPP) to be built within the near future of the next decades (generation III NPP) is underway

– to decrease further the risk of large accidents of LWRs (main activities in USA, France, Japan),
– to avoid totally the risk of a large accident with HTRs, inherently safe in any respect by physical principles (main activities in China, South Africa, USA and Russia, Japan).

Furthermore, R & D on revolutionary improvements of NPPs to become available after some decades of further development (generation IV NPP) is studied at present:

– very high temperature reactors (VHTR),
– supercritical water-cooled reactors (SWR),
– lead- and sodium-cooled fast neutron reactors with breeding potential (LFR and SFR, heading for closed fuel cycle),
– gas-cooled fast reactors (GFR), and molten-salt reactors (MSR), including burning of actinides from radioactive waste possible with accelerator-driven systems (ADS), heading for largely reducing the amount of radioactivity of nuclear waste to be finally deposited.

  (These investigations are pursued in an international cooperation within the Generation IV International Forum of – at present – 10 countries: USA, France, Japan, UK, Canada, South Korea, South Africa, Argentina, Brazil and Switzerland, and furthermore EURATOM. Further countries like e.g. China and India exhibit high interest in these developments.)

– Thorium-fueled advanced heavy-water reactor (ThHWR), and possibly other reactor types as well. (Main activities in India.)

Furthermore, to enlarge the availability of uranium fuel (from some 100 years at present to possibly many 1000 years) an economical way to extract uranium from sea water is investigated in Japan.

The main challenge in the further development of nuclear fission power technologies is finally to achieve solutions technically as well as economically satisfying.

Concerning the possible use of *nuclear fusion energy* by means of nuclear fusion power plants, until now fusion processes have only been achieved in principle, being rather limited in power and in operation time.

Further necessary steps of the technology development of nuclear fusion power plants in the future are

- to achieve the necessary high fusion power over sufficiently long operation time,
- to develop proper materials with sufficient stability for the first wall of the fusion vessel,
- to extract the rather high thermal power from the walls of the fusion vessel,
- to breed the necessary tritium fuel for fusion by neutron-lithium interactions inside the walls of the fusion vessel and to extract it,
- finally to prove the technology of a nuclear fusion power plant to be sufficiently economical.

To achieve these goals rather different options for fusion technologies are pursued at present (see Chap. 5):

- magnetic confinement of the hot fusion plasma, initially heated up with HF and neutral atom beams (see Chaps. 6 and 7);
- inertial confinement of the fusion plasma initially heated up with lasers and laser-generated X-rays (Chap. 8), with electric pulse generated X-rays (Chap. 9), or with heavy ion beams (Chap. 10);
- muon-catalyzed fusion including the recovery of muons sticking to helium nuclei produced by fusing of deuterium and tritium nuclei (Chap. 11).

There may be further options of initiating fusion to become available, like e.g. initiating the heating of a fusion plasma via standing acoustic waves leading to strong compression shock waves.

To achieve the goals via any of these options, at least 2 to 3 further successive steps of test facilities and demo plants are required, each step rather expensive in manpower and cost, requiring a timespan of 1 to 2 decades for construction and operation. The high expenditures call for international collaborations to pursue these options.

The option most advanced at present is magnetic confinement fusion with a tokamak device. The next step along this line planned by an international collaboration of scientists and engineers from the European Union, Japan, Russia, USA, China and South Korea is the International Thermonuclear Experimental Reactor, ITER.

Nevertheless hopefully all possible promising options of fusion technologies will be pursued till at least one of them has led to a viable technical as well as economical solution.

The availability of sufficient energy, this in an environmentally safe way and at sufficiently low cost, is a limiting factor of further necessary development at least for a large fraction of the world population at present, especially for countries with high and still fast rising populations like e.g. China and India. In this context a proper further development of providing energy from all possible sources of primary energy including nuclear fission and fusion is of outstanding importance.

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