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Tectonic events and nuclear facilities

N. A. Chapman, H. Tsuchi and K. Kitayama

Nuclear power had its origins over half a century ago, during the Cold War. Some eight years after the first nuclear reactors for plutonium production had begun operation in the USA, as part of the Manhattan Project, the first reactor to produce electricity entered service in late 1951 (EBR-1, in Idaho, USA). Just two years later, in 1953, President Eisenhower made his famous "Atoms for Peace" proposal, which effectively launched commercial nuclear power generation and led to the formation of the International Atomic Energy Agency (IAEA).

The spread of nuclear power was slow during the early 1950s, with only the USA, the Soviet Union and the UK having operating power reactors by 1958. In 1959, France and Germany began their nuclear power operations. Nuclear power plants (NPPs) began real commercial development in the early 1960s, led by the Pressurized Water Reactor design (PWR, originally developed for submarine propulsion units), and there was a rapid spread worldwide during the 1970s and 1980s (Figure 1.1). By the mid 1980s, although the number of NPPs being put into operation was at its peak (in 1985, when 42 NPPs were brought into operation), nuclear power was actually entering a marked decline. In 1986, further development of the nuclear industry essentially stopped in many European countries, primarily caused by reaction to the Chernobyl accident in the former Soviet Union (Ukraine).

However, other nations continued expansion, particularly in the Asia–Pacific region and, although the average number of NPPs commissioned each year since 1990 has only been about five, what has been called a worldwide "nuclear renaissance" was considered to be underway in the early years of the present century. Countries that had not ordered NPPs for decades were showing a new interest in nuclear power and the growth of nuclear power in Asia continued, especially in India and China. This resurgence is seen by many as partly a response to the drive to reduce greenhouse gas emissions and partly as a desire by nations to ensure security of electricity supply, independent of the political uncertainties of fossil fuel imports. By the beginning of 2008, there were 439 NPPs in operable condition worldwide, 34 under construction, 93 planned and 222 proposed (World Nuclear Association, 2008). The NPPs that are operating, under construction, or already closed down are located on 237 sites spread around the globe. In a period of about fifty years, nuclear power has reached a point where it is generating about 370 GW of electrical power, around 16% of the world's electricity supply.

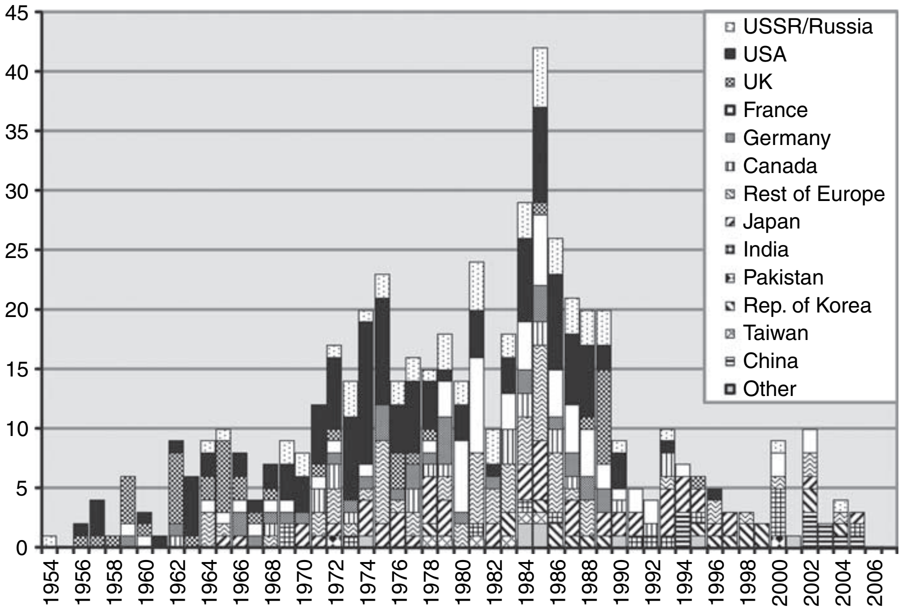

Fig. 1.1 Temporal and geographical spread of nuclear power by country. Shown are the number of nuclear power plants coming into operation each year, from the dawn of nuclear power until the end of 2007. The rapid growth in the 1970s and 1980s is evident, as is the even more marked decline in the early 1990s. Not all countries are shown individually; "Rest of Europe" shows NPPs in Europe excluding France, Germany and the UK (the early developers). Data taken from the World Nuclear Association database.

The widespread use of small nuclear reactors for research purposes or isotope production is often overlooked when considering the global distribution of nuclear reactors. Around 280 research reactors exist today, in 56 countries, although there were more in the 1970s; their distribution includes many more countries than have NPPs, including several small and developing countries (e.g. Bangladesh, Algeria, Colombia, Ghana, Jamaica, Libya, Thailand and Vietnam all currently have research reactors). There is a trend now to decommission many research reactors and repatriate the fuel to the countries that provided them. More than 360 reactors have been closed over recent years.

1.1 Tectonics and nuclear power plant location

The same half-century also saw the dawn of our current understanding of global tectonic processes, with the explosion in knowledge and research into "seafloor spreading"; then the development of plate tectonic theory, beginning in the early 1960s at about the same time that the first nuclear electricity was being generated. Strikingly, it was another aspect of nuclear energy that pushed forward our ability to build our present understanding of tectonic processes. The 1963 nuclear test-ban treaty proscribed the use of above-ground nuclear

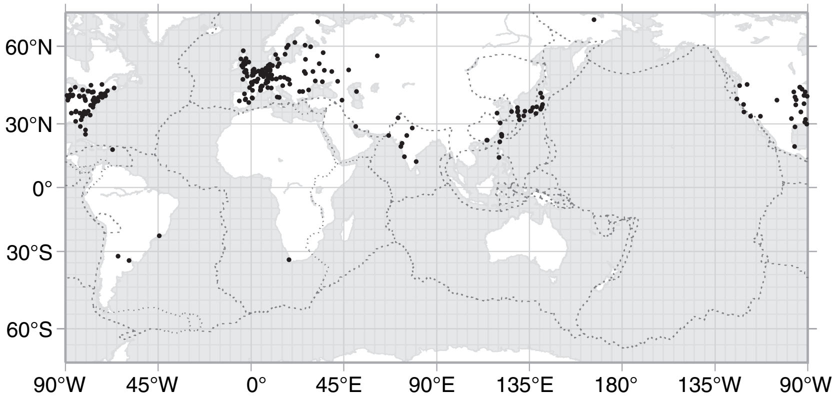

Fig. 1.2 Locations of NPPs (black dots) are shown with respect to the outlines of Earth's major active plate boundaries (gray dotted lines).

weapons testing. In order to monitor compliance, the Worldwide Standardized Seismograph Network (WWSSN) was set up and the greatly improved data that it provided allowed the precise mapping of global earthquake zones that was to underpin plate tectonic concepts.

Figure 1.2 shows the locations of operating NPPs worldwide with respect to their global-scale tectonic setting. It can be seen that NPP sites are preponderantly located in relatively "quiet" regions of the world, in Europe, Russia and North America. However, it is apparent that many NPPs and several nuclear power nations also lie in highly active regions, close to active plate margins.

Regions of the world that most clearly need to consider elevated probabilities of tectonic impacts on existing or proposed NPPs include the western USA, southern Europe, Iran, Turkey, Pakistan, Taiwan, the Philippines, Indonesia, China, Japan and Korea. Ironically, it is in these latter regions that we are currently seeing the most rapid actual expansion of nuclear power, or interest in developing new nuclear power programs.

That NPPs, with their requirement to be fail-safe in the event of accidents, could be at risk from tectonic events, most specifically from earthquakes, was realized early on, but the first NPPs were located with relatively little consideration of possible tectonic impacts. In the first decade of nuclear power, those constructed in Europe were anyway in what is generally regarded tectonically as a relatively quiet region of the world, although two of the first five power plants built in the initial stage of nuclear power in the USA were in California, in the seismically more active western part of the country. This led to several problems that are discussed later in this chapter and by Reiter (Chapter 20, this volume). The first reactor to be built in Japan came into operation in 1965.

Seismic hazard evaluation and seismic design of NPPs were both common by the early 1970s and have become increasingly well specified and internationalized since that time. All countries have seismic hazard and design codes for NPPs and the IAEA issues general guidance in its Safety Series and Safety Guide reports. These cover techniques for

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evaluating seismic hazard (IAEA, 2002), the evaluation, or reevaluation of seismic hazard at existing NPPs (IAEA, 2003a), the seismic design of NPPs (IAEA, 2003b) and the site characterization work that is needed to evaluate seismic hazard when planning a NPP (IAEA, 2004). Nevertheless, seismic events have caused problems for NPPs in the past and the July 2007 experience of the Niigata–Chuetsu–Oka earthquake in Japan (discussed later in this chapter) shows that they will continue to pose problems in the future.

In plate margin regions, seismicity is not the only tectonic hazard that needs to be considered with respect to NPPs. Sites located on low-lying land near the coast have to consider the likelihood and possible impacts of tsunamis, especially those generated by offshore, ocean trench earthquakes (Power and Downes, Chapter 11, this volume). The December 26, 2004 Great Sumatran earthquake that resulted in widespread and catastrophic tsunami impacts and loss of life around the Indian Ocean caused the automatic shut-down of the Kalpakkam NPP on the east coast of India, which was restarted six days later. The potential for such impacts and means of evaluating them are also discussed in IAEA safety guidance (IAEA, 2003d).

Proximity to active volcanoes and the possible impacts of ash fall, lahars, pyroclastic and lava flows, and other volcanic phenomena also need to be assessed. The concept of volcanic hazard assessment of NPPs has developed more slowly and patchily, even though around a quarter of IAEA member states have Holocene volcanoes within their territories. In the USA, the need to consider volcanism was recognized in NPP siting regulations in the early 1970s. The 1980 eruption of Mount St. Helens strengthened concerns, leading to a number of evaluations of possible volcanic impacts on, and siting guidelines for, NPPs (e.g. Hoblitt *et al.*, 1987). The proximity of a NPP in the Philippines to an active volcano was one of the reasons why it was never put into operation in the mid 1980s. The IAEA issued a provisional safety standard in 1997 and referred to volcanic hazards in its safety guide on “external events other than earthquakes” (IAEA, 2003c). A full Safety Guide on volcanic hazards is currently in preparation (Hill *et al.*, Chapter 25, this volume).

Nuclear power plant designers endeavor to mitigate the impacts of any type of accident or adverse event (i.e. a malfunction), or an event that is natural or operational in origin, by a system known as Defense in Depth (DID). The DID philosophy involves the use of diverse, redundant and reliable safety systems, with two or more systems performing key functions independently, such that, if one fails, another will back it up, providing continuous protection. The systems include both static components of the NPP (physical barriers) and dynamic operational, control and response systems (such as cooling systems, emergency action measures). The static components of the multiple physical DID barriers are the ceramic fuel pellets, the metallic fuel cladding, the reactor pressure vessel, the reactor containment and the surrounding building.

The first level of DID aims at prevention of occurrence of hazardous events. Clearly, this is not possible for tectonic events, other than by locating an NPP in an area where the event is essentially extremely unlikely or impossible during the (geologically short) operational lifetime of the plant. The second level of DID aims at preventing propagation of the impacts and the third level at mitigating the impacts. In both cases, seismic design of reactor systems

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(Section 1.5.1) is a clear example of DID in practice. Generally, the DID expectations on the performance of NPP static barriers are very high.

Defense in Depth was developed early in the history of nuclear power as a conceptually simple, “belt-and-braces” design philosophy, before risk-based, probabilistic techniques were available to quantify the impacts of events (Sorensen *et al.*, 1999). Now that such methods are available and well tested, through integrated analysis of complete NPP systems, it is possible to use quantitative estimates of risk to be more specific about the requisite functions of the static and dynamic DID components for various accident/event scenarios. Risk analysis does not totally supplant the original DID philosophy, however, owing both to uncertainties in risk estimates and the need to provide robust safety systems to reassure the public. Specifically, in the context of the subject of this book, later chapters illustrate the constraints on probabilistic evaluations of tectonic events. Whilst we are now able to develop soundly based estimates of tectonic event likelihood for a particular area or site, the range of agreed values from expert elicitation is often wide and there is generally some uncertainty about the exact nature of impacts on nuclear facilities. We return to this issue later, when considering waste repositories.

1.2 Other nuclear facilities

Nuclear power plants are the most widespread, but not the only types of facility that are required by a nuclear power program. The nuclear fuel cycle also involves fuel fabrication plants and, in some countries, facilities for reprocessing spent fuel once it has come out of the reactors at the end of its useful life. These are major industrial complexes, especially reprocessing plants, which are currently a part of the fuel cycle in France, Japan, Russia and the UK. For nuclear weapons states, such facilities have sometimes been closely linked with weapons production and Russia, the UK and the USA, in particular, have a legacy of old military nuclear facilities (plutonium production reactors and fuel processing plants) that have been, or will need to be, decommissioned.

However, evaluation of the susceptibility of fuel cycle facilities to seismic hazard is generally less advanced than for NPPs and their susceptibility to other tectonic hazards, such as volcanism, has not been widely considered. Chung *et al.* (1990) looked at volcanic hazard to the Idaho National Laboratory, USA, and is one of the few such studies. At the time of writing, an IAEA Safety Guide on seismic hazards to existing nuclear facilities (to parallel IAEA (2003b) for NPPs) was in preparation. The hazard potential in case of seismic impacts varies greatly from one type of facility to another, but most fuel manufacturing and fuel reprocessing facilities include potentially vulnerable components for the movement or storage of gaseous or liquid radioactive materials. Many facilities worldwide are now old and the emphasis today is generally on reevaluation and back-fitting design features to improve robustness and ensure they are at modern levels of standards.

The nuclear fuel cycle center of Rokkasho in northern Honshu, Japan, contains a major new reprocessing facility, which has a seismic design that is intended to withstand an earthquake of magnitude M 8.25. Of course, many countries are not involved in the fuel cycle, only being users of nuclear fuel. Consequently, they only possess NPPs and the necessary storage facilities for radioactive wastes. Even in a seismically "quiet" region such as the Netherlands, the recently constructed HABOG 100-year, passively cooled storage facility for spent fuel and high-level waste contains a number of engineering features (e.g. automatically triggered latches on its massive radiation isolation doors) designed to mitigate the impacts of a low-probability major earthquake if it were to occur when material was being moved in the facility.

Nuclear power production generates radioactive wastes at each step and, although a large proportion of the more radiotoxic and long-lived classes of waste produced over the fifty years of nuclear power is currently in storage, we are now beginning to see the first geological repositories being constructed and operated. The majority of countries with nuclear facilities have surface or near-surface repositories for storing or disposing of their less-active, short-lived radioactive wastes until they have decayed to levels below concern. However, almost all countries have been very slow to site and construct deep (> 300 m) geological repositories for their reactor operating wastes and spent fuel (and vitrified high-level wastes and longer-lived intermediate-level wastes, if they practice fuel reprocessing).

Unlike other fuel-cycle facilities, a deep geological repository is based upon a series of multiple barriers with no dynamic components. Once waste is emplaced, the "engineered barrier system" of solid waste-form, metallic or concrete container and rock or mineral buffer and backfill provide passive isolation, even as the system evolves and progressively degrades over tens of thousands of years. Understanding of the behavior of a geological repository far into the future requires knowledge of the geochemical environment at depth, how water moves through pores and fractures in the rock, how stress affects the stability of the barriers and the rock, and how all of these slowly change in response to external processes and events, such as changing climate and tectonic activity. Vulnerability to tectonic impacts and the hazard potential of the radioactive materials once a repository is completed and sealed are of a different character to those of other nuclear facilities.

The identification of sites that can provide adequate, long-term stability for a geological repository is one of the principal themes of this book. Importantly, the requirements for geological disposal take us much farther into the future when it comes to assessing tectonic stability. This leads us into consideration of the time periods for which potential tectonic hazards need to be evaluated.

1.3 Operational lifetimes with respect to tectonic hazards

Clearly, the main period of concern with respect to potential impacts from tectonic events is during the operational life of a NPP and as long afterwards as spent fuel might continue to be stored at the reactor site. The operational life of the early NPPs was planned to be only a few decades. Many of the earliest power reactors, which were to a large extent developmental, were typically shut down after only five to fifteen years of operation. The Calder Hall reactors in the UK are a famous exception, having operated for over forty-five years before closure, but the typical lifetime of reactors commissioned in the first decade of nuclear electricity was fifteen to twenty-five years. Progressively, a forty-year operational period became typical, then a sixty-year period. Today, considering the difficulties of finding societally acceptable new locations for nuclear facilities of any type, it is common to consider the continued development of existing nuclear power stations sites by the construction of additional or replacement NPPs, such that the lifetime of an NPP site might now stretch over at least one hundred years. Consequently, susceptibility to tectonic hazards needs to be seen over a much longer period than may originally have been envisaged.

The planned lifetimes of other fuel-cycle facilities, such as fuel fabrication or reprocessing plants, are of a similar order to that of an NPP. However, for geological repositories, which aim to isolate long-lived radioactive wastes until they have decayed at least to levels similar to natural uranium ores, we must now consider periods out to thousands or hundreds of thousands of years. Table 1.1 indicates the differences in hazard potential that we need to consider for different types of facility in response to possible tectonic impacts.

Even though a sealed geological repository is expected to provide passive isolation of the waste and containment of radionuclides in a stable deep environment, tectonic processes and events could compromise its overall performance. It is important to emphasize that such impacts are likely to have insignificant consequences in terms of radiological exposure of people, compared to those that might result from a severe damage scenario to an operating NPP or reprocessing plant, but the convention is to treat them equally seriously.

The metric for all possible radiological exposures from all nuclear facilities is that of risk. The topic of risk, expressed in a number of different ways, will be covered in depth in many of the chapters in this book. In the context of tectonic events affecting nuclear facilities, radiological health risk is broadly an expression of the likelihood of an exposure occurring (itself, a function of the likelihood of a disruptive tectonic event occurring) multiplied by the consequences, in terms of the scale and nature of radiological health impact. It is clear that, if the likelihood of an event occurring is extremely small over the vulnerable, operational lifetime of a facility, then even quite large health impacts that might be caused if it were to occur would result in a low estimated risk. Short (in a tectonic time framework) periods of vulnerability will lead to low risks. Long periods of vulnerability, such as those for geological repositories, where it takes thousands to hundreds of thousands of years for the waste to decay to natural levels of radioactivity (Figure 1.3), even if they lead to very low health exposures, can have commensurate risks.

The very much longer periods over which safety assessments are required for geological repositories mean that it is not only tectonic events such as the seismic shaking caused by earthquakes, flooding caused by tsunamis and the eruptions of nearby volcanoes that have to be evaluated. We enter a different realm of possible impacts from slower, long-term processes, along with the possibility of much more infrequent events, when we begin to look out towards 100 000 a or even 1 Ma. Factors that become important include the possibility that active faults may develop or extend into the repository volume, especially where undetected structures at depth might propagate upwards; the cumulative impact of displacements on small fractures in the repository host rock caused by repeated movements along nearby major active faults; slow uplift and erosion of the geological formations

Table 1.1. Period of concern for tectonic hazard evaluation for nuclear facilities and features representing significant risk

Years	Principal features at risk	Comments
Fuel fabrication facilities		
100	Volatile uranium hexafluoride storage, transfer and centrifuge plant	Generally low hazard. Processing of natural uranium with with low activity levels and limited potential for airborne release and transport.
Nuclear power plants		
100	Reactor management systems, including fuel handling, control rods, coolant and emergency coolant systems	Massive concrete containment, pond walls and other foundation structures give considerable structural protection against seismic and many volcanic events. Damage to emergency and control systems, from seismic shaking, volcanic ash or marine flooding, is a key issue. Water has slopped out of open ponds; items have fallen in.
	Spent fuel storage, especially if in water-filled ponds	Potential hazards are high: airborne or waterborne releases of volatile fission products from damaged reactor core or spent fuel in storage. Large areas and large populations could be exposed in severe scenarios.
Fuel reprocessing plants		
100	Fuel storage ponds or dry cask stores	Some parts involve massive concrete containment (storage pond walls, fuel dismantling hot cells, vitrification hot cells). Facilities larger, more spread out, more complex than NPPs. Also likely to have much larger inventories of radioactive materials.
	Liquid chemical extraction process systems, including transfer piping and storage reservoirs and their coolant systems	Hazards probably comparable to or significantly higher than those of NPPs. Slopping, rupture of pipes or storage tanks or loss of coolant to storage tanks could lead to airborne or waterborne releases of volatile fission products. Large areas and large populations could be exposed in severe scenarios.
	Spent fuel storage, especially if in water-filled ponds	
Geological repositories for long-lived radioactive wastes		
∼ 10 000 to several 100 000s	Operational period: surface interim stores and spent-fuel encapsulation hot cells, waste transfer and handling systems (e.g. shaft hoist systems), underground power and pumping systems	Spent-fuel encapsulation plants have similar risks to those at NPPs or fuel processing plants. Many wastes will arrive at interim stores solidified, encapsulated and ready for disposal. Repositories and ancillary facilities thus less susceptible to hazards than NPPs or fuel reprocessing plant. During open, operational period (may be up to 100s of years) hazards principally to surface facilities. Problems underground may cause operational recovery difficulties but unlikely to lead to significant public radiation exposures.
	Post-closure: container–overpack–buffer systems (EBS: engineered barrier system) for spent fuel, vitrified high-level waste and other classes of long-lived waste	The requirement to assess post-closure safety over hundreds of thousands of years means impacts on the EBS become more probable and there are regulatory requirements to understand and assess them in detail. However, potential exposures and risks are generally insignificant.

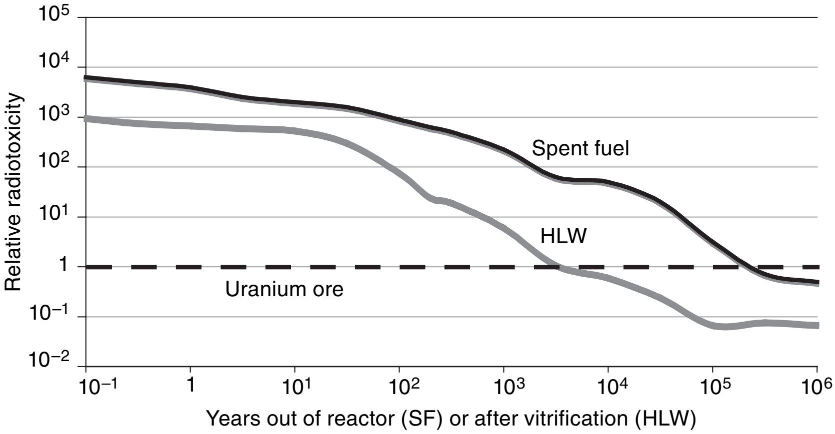

Fig. 1.3 The decline in radiotoxicity of typical spent fuel and vitrified HLW as a function of time, compared to that of an amount of uranium ore equivalent to that used to make the fuel (or the glass from reprocessing it after use). HLW toxicity approaches the toxicity of uranium ore after a few thousand years, while spent fuel takes ∼ 100 000 a to decline to the toxicity of uranium ore.

hosting or overlying the repository; the possibility that a new volcano might form near or even through the repository; possible exposures to larger, infrequent tsunami events caused by sector collapse of distant volcanic islands.

In addition, long-term safety assessments have to account for the impacts of a range of climate change events, the majority of which are not covered in this book, including glacial cycling and its effects on sea level, groundwater flow and chemistry and erosion. One aspect that we do, however, consider in this volume are the impacts of what are generally termed neotectonic processes, such as postglacial faulting and associated earthquakes, caused by the response of the rock mass to loading and then unloading by kilometer-thick ice sheets (Lund and Näslund, Chapter 5, this volume).

1.4 Tectonic problems for early nuclear power plants

We should say at the outset of this section that, while NPPs have certainly suffered damage from earthquakes, there have been no accidents leading to serious loss of containment of radioactive materials from nuclear facilities that are attributable to tectonic processes. Nevertheless, the risk of tectonic impacts has been a serious concern in a number of instances (e.g. the 2007 earthquake impacts on the Kashiwazaki–Kariwa NPP in Japan, discussed later) and has indeed led to the abandonment of some planned facilities.

Possibly the best-known examples are associated with the early development of nuclear power in California. In the 1960s, the Pacific Gas and Electric (PG&E) Company began development of an NPP at Bodega Head, a site located only about 300 m from the edge of the active zone of the San Andreas fault. Faulting observed in the granitic rocks of a shaft constructed for the NPP foundations resulted in an analysis of possible seismic impact.

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A study by the USGS (Schlocker and Bonilla, 1964) concluded that, although the most recent fault displacement in the foundations was probably ∼ 42 ka, this was not certain, and there had been ∼ 7 m total displacement along the fault over ∼ 400 ka. The report concluded that the site was "almost certain" to experience a severe earthquake in the next fifty years (see also, Reiter, Chapter 20, this volume).

The PG&E Company proposed a design for the reactor that would accommodate fault movement but the Atomic Energy Commission (AEC) was unconvinced that other parts of the NPP would be protected and concluded that the site was not suitable; this led to the abandonment of the project in late 1964. The foundation excavations (disparagingly known locally as the "hole in the head") filled with freshwater and are now a coastal wildlife habitat.

The PG&E Company looked elsewhere and selected a site at Diablo Canyon (see cover illustration), where it was thought that there was no evidence of active faulting. The subsequent discovery of a major offshore active fault led to years of investigations and hearings, with revised NPP design and seismic back-fitting; it was one of the main causes of delays that resulted in the first reactor not becoming operational until 1984, fifteen years after the first work on site.

Seismic hazards continued to pose problems to power companies in California throughout the 1970s and 1980s. An NPP was proposed for the Malibu site near Los Angeles in the mid 1960s and eventually abandoned in the early 1970s owing to the likely difficulties of designing and then obtaining a license with respect to seismic impacts. The Vallecitos facility run by General Electric hosted an old fuel test reactor, whose "precautionary decommissioning" took place in 1977 when it was found to lie on the splayed Verona thrust fault. The USGS again carried out detailed studies of the site (Herd and Brabb, 1980), producing evidence for late Quaternary surface rupture caused by the Verona fault. The history of these famous cases is described in depth by various authors, including Novick (1969), Meehan (1984) and Walker (1990) and is summarized by Reiter (Chapter 20, this volume).

The Metsamor NPP in Armenia was closed for four years following the M 7.2 Spitak earthquake in 1988, before one of the units was restarted in 1995. The Kozloduy NPP in Bulgaria suffered slight damage to two old reactor units in 1977, as a result of an earthquake that occurred some 400 km away in Romania. This resulted in design changes to units then under construction. Many countries are now back-fitting seismic protection to NPPs as it has often been found that, on recent evaluation, original seismic designs have underestimated ground motions.

1.5 The current situation with NPPs

As noted earlier in this chapter, the principal focus of developments in evaluation of tectonic hazards to nuclear facilities has been on seismic impacts. The evaluation of volcanic and other tectonic impacts on NPPs, whilst under evaluation, has lagged far behind. The disparity between consideration of seismic and volcanic risks can only be accounted for by a general, seemingly "risk-uninformed," perception of the frequency of earthquakes compared to major volcanic eruptions. Even so, it has been known for decades that volcanism