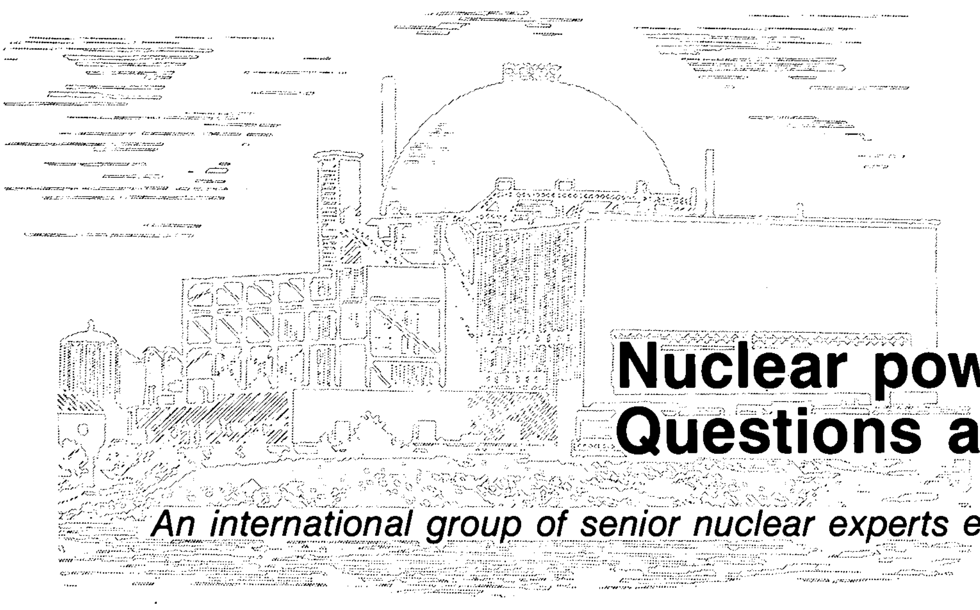


Nuclear power: Questions and answers

An international group of senior nuclear experts examines plant safety

In 1988, the Uranium Institute — a London-based international association of industrial enterprises in the nuclear industry — published a report entitled *The Safety of Nuclear Power Plants.* * Based on an assessment by an international group of senior nuclear experts from eight countries, the report provides an authoritative explanation for non-specialists of the basic principles of reactor safety, their application, and their implications.** The following questions and answers are selected from that report; they address only some of the subjects that the report itself examines in greater detail.

1. To what extent do different countries agree on nuclear safety standards?

Nuclear safety standards are intended to give protection to the public and to nuclear workers against potential risks from the operation of nuclear power plants. Nuclear safety standards do not differ fundamentally internationally, but their detailed implementation varies between different countries because of their different legislative and regulatory backgrounds.

The IAEA has published about 60 Codes of Practice and Safety Guides since 1978, which have become known as the NUSS (Nuclear Safety Standards) programme. These are based on experience from various national systems and practices and approved before final publication by the IAEA's Board of Governors.

* Further information about the report may be obtained from the Uranium Institute, Bowater Houser House, 68 Knightsbridge, London SW1X 7LT, United Kingdom.

** The report presents the group's opinion on the level of safety achieved at Western nuclear power plants with which the experts are directly familiar. Although many of the points made may also be true for non-Western reactors, the report does not cover them except where specifically stated.

The five Codes of Practice cover:

- governmental organization for regulation of nuclear power plants
- safety in nuclear power plant siting
- design for safety of nuclear power plants
- safety in nuclear power plant operation
- quality assurance for safety in nuclear power plants.

The Safety Guides describe methods of implementing specific parts of the relevant Codes of Practice.*

Each country has its own laws and regulations for the protection of the public and nuclear workers from the effects of radiation under normal operation. These laws and regulations vary somewhat from country to country, but all are broadly compatible with the International Commission on Radiological Protection (ICRP) recommendations on acceptable standards of radiation exposures set out in ICRP 26 (1977).

2. Do the licensing procedures differ between countries and do they allow different levels of safety?

The licensing systems and inspection arrangements concerned with nuclear safety for a number of countries show a broad commonality of approach. Each country has governmental bodies with responsibility for atomic energy and for the protection of the public from ionizing radiation.

Before construction of a nuclear power plant, a complex set of procedures is laid down to ensure that a good and thorough design has been worked up and a suitable site chosen. A preconstruction safety report is required.

* See, for example, *General Design Safety Principles for Nuclear Power Plants, A Safety Guide,* No. 50-SG-D11, Safety Series, IAEA, Vienna, 1986.

The license application is scrutinized in great detail by ministry officials and by advisory groups of independent experts assembled for the purpose.

Each country has a licensing and regulatory body which monitors the construction of the plant and the fabrication of its components to see that safety standards are not eroded by failings in quality assurance. Very high standards are demanded, and engineering codes for a number of specifically nuclear and safety-related components are set at more rigorous standards than for other industrial construction. In particular, codes and regulations on the design and fabrication of pressure-bearing components for nuclear applications have achieved a high level of international standardization. Once built, the plant must be properly commissioned before a license to operate it is given. Before the operators are allowed to operate the plant, there are training requirements which they must fulfil. Each country has a body of nuclear inspectors who make on-site visits to monitor the operation of the plant.

Thus, the most important feature in ensuring safe operation of nuclear power plants is universal: a thorough system of control and monitoring of all stages of construction, commissioning, and operation.

3. Is it safer to use coolant under pressure for reactors? Might the pressure vessel fail?

It is safe to use coolant under pressure in a properly designed pressure vessel. The design technology is not unusual or new: it considerably predates nuclear power production.

In all gas and water-cooled power reactors, the coolant has to be subject to greater than atmospheric pressure in order to cool the reactor core effectively at high power and at temperatures which allow the generation of steam suitable for the efficient operation of a steam turbine. Primary operating pressures range from about 20 bar in gas-cooled reactors with steel pressure vessels up to 160 bar in pressurized water reactors (PWRs).

The reactor pressure vessel, the steam generators, the main coolant pumps, the pressurizer, and the connecting piping form the primary pressure boundary of a PWR. In most boiling water reactors (BWRs) and gas-cooled reactors, the reactor pressure vessel itself represents the only large component carrying the primary pressure. It is a priority of all reactor safety technology to make sure that such a component will not deteriorate or disintegrate under operating pressure. The way in which the integrity of the primary pressure boundary is inherently guaranteed, so that it continues to function effectively is summarized below.

The integrity of a pressure-bearing vessel made of steel depends mainly on three parameters:

- the stresses (forces) in its walls
- the toughness of its material
- the size of flaws and other imperfections in the material.

If stresses are low enough, the toughness of the material high enough, and flaws in it small enough, a pressure vessel is certain not to fail. Further, as long as the stresses and the toughness stay within a certain range, even a growing flaw or crack will not cause a pressure vessel to fail rapidly or burst, because a small leak will develop and reduce the pressure long before this could happen.

If these integrity parameters can be kept well within their specified range during fabrication, construction, and lifelong operation of the nuclear power plant, any significant failures of the primary pressure boundary can virtually be excluded.

4. How is a safe pressure vessel designed and manufactured?

By keeping to traditional engineering standards, supplemented by appropriate analysis and testing of the properties of materials and standards.

In designing a reactor pressure vessel, or any other primary pressure boundary component, every effort is made to keep operating stresses low and avoid stress concentration.* Special care is taken to protect the vessel against thermal stresses due to thermal shocks and abnormal temperature changes. To double check the accuracy of these design calculations, a design review is made by an independent expert. In addition, stresses are regularly measured at critical points during component pressure tests.

During recent years, the theoretical analysis and validation of static and dynamic stresses and strains (deformations) in thick-walled steel vessels and the practical experience about operating conditions have become exhaustive. It is therefore possible to be confident that the whole multitude of stresses and strains to be taken into account in the design of a reactor pressure vessel during normal and abnormal conditions can be allowed for. The safety margin against a failure by overstressing is extremely high.

The material must stay tough enough over the whole operating temperature range and under the influence of irradiation. This means selecting a suitable base material and special expertise on careful fabrication technologies like forging, welding, and heat treatment.** All fabrication procedures are strictly specified and controlled. Many test specimens from different positions and different depths in the material are taken after every fabrication step to make sure that the material properties are homogeneous and remain within specified limits.

* Stress concentration is usually due to abrupt changes of structure, for example, holes, and may be several times greater than the stress where there is no abrupt change of structure.

** Base material is the material used for the load-carrying wall of a pressure vessel.

Different reactor types

All nuclear reactors use the heat from a nuclear chain reaction to boil water to make steam. The steam is used in the same way as steam made in a coal-, oil-, or gas-fired power station: it drives a turbine which powers a generator which produces electricity. The chain reaction of fissions of the nuclei of atoms produce energy within the reactor fuel. Each fission splits an atom into new, fission- product atoms, generates a packet of heat, and also expels from its nucleus neutrons which cause further fissions of other atoms. Thermal reactors use moderators to slow the fast neutrons produced by fission so that they can be captured by the fissile uranium-235 atoms more easily. Ordinary water is often used as a moderator. Other moderators used are graphite and deuterium, an isotope of hydrogen, which is used in the form of deuterium oxide–heavy water. (Ordinary water is mostly hydrogen oxide, and contains a small proportion of heavy water.) Heat is removed from the reactor core by a coolant, which directly or indirectly produces steam to operate the turbine and also prevents the reactor core from getting too hot. Neutron absorbing materials, such as boron or cadmium, are used in steel control rods which can be moved in and out of the holes in the core of the reactor in order to control the reaction rate precisely. Each reactor design has its own characteristic safety-relevant features, which determine the design of its safety systems, but the same safety principles apply to all.

Cooling a reactor core with pressurized or boiling water allows high core power densities so that, if the fuel is slightly enriched, large power units can be built inside small reactor vessels. However, there must be high primary coolant pressures in order to reach useful steam pressures and temperatures for efficient operation of the turbo-generator. The integrity of the primary pressure boundary is therefore important for the safety of water-cooled reactors.

In a pressurized water reactor (PWR), the primary coolant water and the secondary feedwater/steam circuit are separated. The steam operating the turbo-generator is therefore not radioactive and the steam-turbo plant can be operated like a conventional power plant.

PWRs can also be built to operate with natural (unenriched) uranium, but need a larger core volume and heavy water as moderator and primary coolant. Pressurized heavy water reactors can be built either as pressure vessel reactors like ordinary PWRs but larger (this kind are usually called PHWRs), or as pressure tube reactors

Reactor type	Fuel	Moderator	Coolant and its approximate pressure in bars (normal atmospheric pressure is about 1 bar)	Steam generation
PWR	uranium dioxide (approx. 3.2% U-235)	ordinary water	pressurized ordinary water (160 bars)	separate circuit
CANDU	unenriched uranium dioxide (0.7% U-235)	heavy water	heavy water pumped at pressure (90 bars)	separate circuit
BWR	uranium dioxide (2.6% U-235)	ordinary water	pressurized ordinary water which boils and produces steam directly (70 bars)	
Magnox	natural uranium (0.7% U-235)	graphite	carbon dioxide (20 bars)	separate circuit
AGR	uranium dioxide (2.3% U-235)	graphite	carbon dioxide (40 bars)	separate circuit
RBMK	uranium dioxide (2.0% U-235; change to 2.4% under way 1988)	graphite	pressurized ordinary water which boils and produces steam directly (70 bars)	

5. *How can unforeseen embrittlement of the steel be avoided?*

The irradiation behaviour of the material of every reactor is carefully monitored during nuclear plant operation, in spite of the enormous amount of irradiation experience which already exists with the few standard steels internationally used. In order to know far enough in advance how much the toughness of the reactor pressure vessel materials will be reduced by the neutron-irradiation, samples of base and welding material are irradiated in a higher neutron flux than the wall of the reactor pressure vessel. Destructively testing these sample specimens enables the future irradiation behaviour of the reactor pressure vessel to be predicted over its lifetime, and adequate toughness in conformity with design codes and requirements can be guaranteed. Unknown properties of materials and their unpredictable change over the service time of a pressure-bearing component can, therefore, reasonably be excluded as a possible cause of pressure vessel failure.

with individual coolant channels which form the primary pressure boundary of the reactor core. CANDUs are this type.

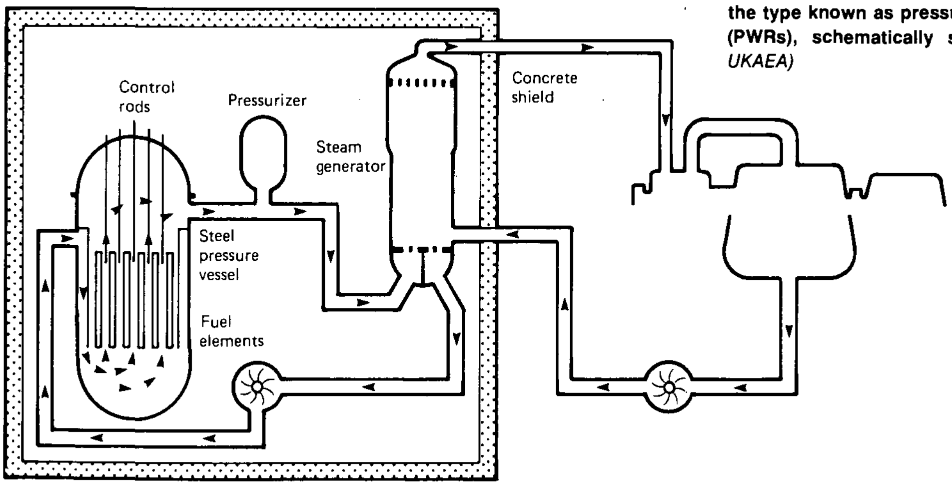
In a boiling water reactor (BWR), the primary cooling water is partially evaporated in the reactor core itself, and the steam generated there is directly used in the turbo generator. The pressure is less than in PWRs. However, it is necessary to take some precautions because of the slight radioactive contamination of the steam-turbo plant, although this is not an important handicap for operation and maintenance.

Magnox reactors are fuelled with natural uranium. They are cooled by carbon dioxide gas at moderate pressure, but can generate steam which gives good thermal efficiency. They have large cores with low power densities, so the pressure vessels which also act as the containment, are also large. (The pressure vessels are steel surrounding the reactor core in early Magnox reactors, prestressed concrete round the core, and heat exchangers in later Magnox reactors.)

Advanced gas-cooled reactors (AGRs) use slightly enriched uranium oxide fuel. They are cooled by carbon dioxide at higher pressure than the Magnox reactors and have improved heat transfer. Their greater core power density allows them to be smaller and more powerful. Their highly reliable prestressed concrete pressure vessels also act as the containment.

The Soviet RBMK-1000 boiling water reactor with graphite moderator and pressure tube coolant channels is a hybrid of different systems. Its main advantage is that large power units can be built without the need to build large, heavy pressure vessels, as for the PWR or BWR, or complicated calendria moderator tanks, as for the CANDU. In order to keep the fuel enrichment low without needing to use heavy water, graphite is used as the moderator.

For each type of reactor, it is not the safety of individual aspects in isolation that has to be considered, but the safety of all the aspects working together, making up the system as a whole, although each aspect has implications for the safety measures needed. Low core density means that temperature rises slowly; higher core density means that heat removal must be more efficient. A partial loss of pressure is not as critical for a gas coolant as there can be no sudden change from liquid to gaseous state. Different moderators have different heat absorptions. Different reactor types have different power coefficients (the power coefficient is the overall change in reactivity in response to all the factors that can affect it). Most have negative fast-acting power coefficients, so that power increases are self limiting; positive power coefficients require control rod response rapid enough to deal with them. Containments do not have to be of any particular kind, what is necessary is that they should be adequate to fulfil the function of preventing the escape of radioactive material.



At the end of 1987, more than half (225) of the world's 417 operating nuclear reactors were of the type known as pressurized-water reactors (PWRs), schematically shown here. ***(Credit: UKAEA)***

6. Can a pressure vessel be manufactured so that it is certain to have no flaw?

Probably not, but the importance of cracks and flaws in pressure-bearing components must be put into a realistic perspective so that the effect of their presence is not overestimated. There is a critical size for such flaws.

Smaller flaws are not important. Undetected bigger flaws can cause wall disintegration under some operating conditions.

Fabrication flaws are detected and assessed without difficulty during the fabrication process. Therefore, the only flaws of significance are those that grow because of the operating cycles of the component. (There is a prescribed limit on the total number of these cycles during the plant lifetime.) However, a flaw which was undetectable during fabrication would have to reach the critical size very rapidly to escape detection and cause problems. Flaws about one-fiftieth of the critical size can be detected by present non-destructive testing methods in thick-walled pressure vessels. This gives a large safety margin.

Extensive technical investigations show that between detectable and critical sizes, there is an intermediate range of crack sizes which would make the vessel leak, giving visible evidence of crack growth long before the critical size was reached. This visible evidence would be supplemented by the results of the continuing in-service inspections for the presence of cracks and growing flaws.

Even if there was no periodic testing at all, the existence of a critical flaw or crack under operating conditions could be excluded by the cold hydro-pressure tests performed before operation and periodically afterwards. The critical crack size under the conditions of the cold hydro test is only about half the size of an operational critical crack. A vessel with a sizeable crack or flaw would therefore fail during the test rather than under high temperature operating conditions.

Small cracks and imperfections can be expected mainly in the neighbourhood of welding seams. To reduce the number and length of welds, and also to reduce the stresses in them, modern high-pressure vessels are made out of seamless forged rings which are only welded together at the circumference to form a vessel.

Thorough and extremely careful non-destructive testing of components of the primary pressure boundary takes place during fabrication and during regular in-service testing periods. Most of this testing is done with ultrasonic flow detectors that are manually or automatically moved, with both manual and automatic signal interpretation. The testing methods are designed to minimize the opportunities for human negligence and include documentation of the results so that the testing and interpretation can be repeated to give an independent analysis which does not rely on the judgement of a single inspector.

Because the growth of cracks under corrosion or fatigue is only of the order of one tenth of a millimetre per year, any cracks would be detected long before their size reached the critical size for in-service conditions at high temperature and power. Growth of cracks to such sizes without prior detection under cold conditions can reasonably be discounted.

7. Can the failure of a pressure vessel be excluded?

Reactor vessel and piping integrity can be assured in several independent ways to such an extent that the fluid system pressure boundary can be considered inherently safe. This is achieved by:

- careful design and complete validated stress analysis
- reliable protection against overpressure
- use of extremely tough material
- limitation of irradiation embrittlement
- reduction of flaws by suitable fabrication methods
- sensible non-destructive testing during fabrication and service.

These measures are supported by:

- cold hydro testing
- leakage detection.

All these guarantee integrity of the reactor pressure vessel and pressure boundaries under all conceivable normal and abnormal operating conditions.

8. How can human error in operation be avoided?

A high proportion of all accidents is caused not by a breakdown of hardware but by human error, failure, and negligence in conjunction with operational or design factors that do not make enough allowance for human factors. This holds for practically all activities making use of technical machinery and tools, whether in traffic and transport, in factories and production technologies, or even in do-it-yourself work and leisure activities.

The TMI accident in 1979 and the Chernobyl disaster in 1986 were mainly caused by human mistakes and incorrect operation. Faulty design was a key factor in the Chernobyl accident because it relied on the operators not making some specific mistakes.

Error, failure, and negligence played some part in other, minor, nuclear incidents; for example, some unplanned transients (changes in the power output of a reactor) could have been stabilized even earlier than they were if operators had taken the correct actions more promptly or the system had been designed to prevent incorrect actions. Safe operation and effective mitigation of incidents has to be guaranteed in spite of human imperfections.

Professional experience, training, and retraining of operators in nuclear power plants is at a level at least as high as that of pilots of well-managed airlines. Although nuclear power plants are complicated to operate, operators have the advantages over pilots that they normally have plenty of time to react and that a potentially dangerous transient can at any time be controlled by a shutdown, while an aeroplane cannot be landed at any time.

In order to exclude human operating failures, operation and operational power changes are largely automated. The main function of the operators is to observe and correct the automatic control systems and to govern the process according to the very strict rules of the operating manual. "Pressing the wrong button" is counteracted by automatic interacting systems wherever safety demands it. Important operating parameters and all activations are continuously documented by recorders and process-computers and monitored by automatic alarms. *The worst thing that can happen after incorrect manual actions is an automatic power reduction or even a shutdown of the plant: this may be inconvenient, but it is quite safe.*

Human failure, error, and negligence during unplanned transients, however, may have much graver consequences than merely a loss of operational availability. Although such transients do not normally develop quickly, but take minutes, the operators need some time to analyse the situation, identify the accident, and decide upon suitable procedures. During this time, they will probably be under some stress. Actions which have to be taken immediately to bring an unplanned transient under control and to mitigate its consequences must, therefore, not be dependent on the operator's ability to act promptly and correctly.

As a general rule, in order to exclude abnormal situations and to guarantee the fulfilment of the fundamental safety objectives, the safety systems are activated and operated automatically rather than manually during at least the first 15 minutes or more. To enable the operators to make intelligent decisions on actions after that, process information is available that allows for quick identification of the accident and understanding of the transient, its history, and its progress.

Computer-based diagnostic systems are increasingly being used to help the operator to detect faults and to give expert advice on corrective actions. Naturally, automation of safety functions and modern information systems also help to improve the normal operation of the plant and to increase its reliability.

9. How can human error during construction be avoided?

Quality assurance in the widest sense of the word is applied in order to exclude the effects of human error on the design of the plant, during the manufacture of its components, and during its construction on site.

In the Western world, engineering knowledge related to all aspects of nuclear safety is so well established and so openly exchanged, nationally and internationally, that the likelihood of a hitherto undetected, basic, safety-significant error or an unrealized gap in broad safety knowledge is very small.

Working results are not only documented and internally double checked, but fully analysed or even recalculated by an independent inspector organization or by the licensing authority itself. The same holds for the specification, the manufacturing, and testing procedures of safety-related and pressure bearing components. The whole process of manufacturing starting with the basic material is critically observed and many specimens are tested by independent quality control groups and by professional inspectors. In particular, the testing of all welds and the evaluation of pressure tests are carried out by at least two independent inspectors according to formal engineering design codes. The results are officially documented so that the judgement on their significance can be reproduced at any time.

It is by this steadily improving network of quality assurance and quality control that human failure or negligence during design and construction can be reduced to very small numbers, and, more importantly, greatly reduced in potential consequences. It ensures that, *although some human error cannot be entirely avoided, by allowing for it in the design, it can be made extremely unlikely that it could cause a dangerous failure.*

Totally flawless technology cannot be achieved or expected, and error-free operators cannot be assumed or required. What the use of automation and extreme quality assurance requirements have achieved is a technology and a means of operating it which give confidence that human failure, error, and negligence and technical imperfections cannot penetrate the defence in depth deeply enough to cause any real danger. In this sense, *the technology is error-tolerant.*

10. Should nuclear power plants be sited underground to help contain radioactive releases?

Although siting reactors underground seems to offer additional environmental protection from accidents leading to large radioactive releases, it does not normally have significant safety advantages. Clearly, putting a reactor plant into a cavern or otherwise entrenching it into the ground does nothing to avoid an accident. The most it could achieve would be to provide a more complex path for radioactive releases resulting from an accident, which could, under some but not all circumstances, lessen the consequences of the accident. In fact, building a reactor underground could well make a power plant less safe. This is because construction, operation, and maintenance would be made more difficult by the extra complications of design and especially, access to an underground plant.

Moreover, seepage of groundwater could cause additional complications. Unless it is in caverns in solid rock, underground siting raises complicated environmental problems about the protection of groundwater. It would be necessary to dig a pit at least 60 metres in diameter and in depth to put the reactor building in. In most places, this would necessitate very carefully engineered isolation of groundwater, since it would probably be used for local drinking water.

Even so, if underground siting would achieve an appreciable gain in safety, the additional engineering and operating difficulties and cost certainly could be met. However, underground siting can only be expected to provide additional safety if the surrounding rock or soil can be made to act as an additional containment to reduce radioactive releases in the unlikely case of grave reactor accidents. The efficiency of a containment, however, depends mainly on the tightness and reliability of many points at which it has to be pierced for pipes, venting, electrical cables, and access of power plant workers, to enable the reactor to be connected with other systems and buildings of the nuclear power plant outside the containment. The tightness of the containment structure itself is much less of a problem. Since a reactor needs the same connections whether it is above or below the ground, the reliability of its overall containment system cannot be markedly improved by underground siting.

Apart from some extra protection against extreme outside influences, such as aeroplane crashes, missile attacks, or warfare, underground siting of nuclear power plants does not offer any additional safety worth the extra complications and cost.

11. What kind of hazards to nuclear power plants occur that originate outside the plants?

External hazards originate outside the site, and may affect the plant or station as a whole. The following external hazards have to be considered and, where appropriate for the particular circumstances of the site, taken into account in the plant design:

- earthquakes
- extreme weather, for example extreme air or sea temperatures, wind speed, rain or snow, lightning, tornados, or hurricanes
- site flooding, for example by tidal waves
- aircraft crashes
- ground settlement and subsidence
- hazards from off-site industrial activity
- dangerous substances
- sabotage.

12. What protection is there against the effects of external hazards?

There are four main protection methods, which are as follows:

- design of essential equipment and structures to withstand hazards;
- physical protection of the plant against the effects of a hazard, for example, by ensuring that it is suitably housed;
- redundancy, diversity, segregation, and separation of essential systems;
- systems to mitigate the effects of hazards, such as fire-fighting equipment.

In order to protect the nuclear power station, especially the reactor, against external hazards, the plant systems and structures are specified and designed in such a way as to ensure that under all foreseeable conditions the reactor can be shut down safely, adequate cooling provided after shutdown, and the integrity of the primary coolant boundary maintained.

External hazards can vary considerably in their effects, but generally the size of the effects tends to be inversely related to the frequency of the hazard. This is allowed for in the design safety criteria which set out the probability of failure of the protective system.

The need to incorporate protection against specific hazards, such as the site dependent hazards, is considered for each individual site.

Earthquakes. The power station is designed to withstand the effects of the maximum expected earthquake, and the reactor designed to be capable of being shut down and cooled to a safe condition after such an event.

Some plants, where earthquakes can be expected reasonably frequently, have seismic detectors installed, and the reactor is capable of being shut down automatically well below the level that could be withstood.

Site flooding. A design basis flood level is specified for each nuclear power station, based on historical records of water levels and tides, and taking into account tidal surges, wave heights, fresh water flows, and any other local phenomena which could affect water levels.

Aircraft crashes. Where the site of the plant makes it reasonable to take aircraft into account, the station layout design takes into account the need to minimize the effects of an aircraft crash on the station site. In addition, low flying flight path restrictions may be imposed.

13. Are nuclear power plants protected against terrorist attacks?

Nuclear power plants are protected against terrorist attacks. All details of security arrangements are not made public because if they were, they might be compromised. In addition, requirements for physical protection are quite different in different countries. Therefore, the matter is discussed here in general terms only.

Nuclear power plants have design features which provide significant inherent protection against terrorists. Most of the vital parts include radioactive materials. Therefore, they are protected with radiation shields. These massive structures also give good protection against potential saboteurs. Safety systems of nuclear power plants have redundancy and diversity. The subsystems are often separated physically from each other. This means that saboteurs must do damage to many systems and in many places in order to cause harm to the public.

Nuclear power plants are also provided with features specially designed for the prevention of terrorist attacks. These security features consist of area zoning, physical barriers, locking systems, control of personnel and vehicle access, and security organization, including guards.

Inherent design features and security arrangements make it very difficult for terrorists to cause damage which has environmental consequences. If terrorists aim actually to cause injury to large numbers of the public, there are far easier and more effective targets in society.

14. Can a nuclear reactor explode like an atomic bomb?

Definitely not, for the reasons directly related to fundamental physics which follow.

A nuclear reactor and an atomic bomb are based on the same phenomenon: the fission of the uranium — or plutonium — nucleus. In both cases, this fission is provoked by neutrons, and produces energy. The process develops along the well-known mechanism of a "chain-reaction": one neutron gives one fission in one uranium nucleus, and this fission emits more than one neutron, for example, two. These two neutrons in turn cause two fissions on two uranium nuclei, and so on. One important aspect of the chain-reaction is the time between two successive steps, which is much shorter in the bomb than in the reactor. However, the main difference is the speed of the energy production, that is, the overall kinetics of the reaction.

In a nuclear reactor in normal operation, the chain-reaction is balanced: at each step, after one fission, exactly one emitted neutron will cause another fission (the other one is prevented from doing so by being absorbed by the material in the control rod). Therefore, the number of neutrons emitted remains the same, and so does the power produced. Only when the reactor is starting up or shutting down, are there increasing or decreasing numbers of neutrons (divergent or convergent actions), but the changes are kept very slow by adjusting the relative number of neutrons (called the reactivity) at each step to a value very close to unity. This is the role of the control rods.

In a nuclear weapon, on the contrary, the increase in the number of neutrons at each step is made as large as possible, so the population of neutrons, and consequently the power, increases very rapidly with time. It is easy to calculate that if the number of neutrons is multiplied by 2 in one millionth of a second, then in less than a thousandth of a second a single neutron will give birth to an astronomical number of neutrons. This can only be achieved with highly enriched uranium or plutonium. Power reactors use only slightly enriched or unenriched uranium or a mixture of plutonium and uranium.

However, the multiplication of neutrons is not that easy, because physical phenomena oppose the divergence of the chain-reaction. The most effective counter-effect comes from the energy developed by the fissions in the system which tends to force the pieces apart. This stops the chain-reaction. In the bomb, this is counteracted by the configuration of the chemical explosives which push the various parts of the fissile material together, opposing the outward trend for long enough to allow the neutron multiplication to be effective, and therefore a large amount of energy to be produced by the corresponding fissions.

It might be imagined that an accidental increase of reactivity in a nuclear reactor would start a similar multiplication of the number of neutrons, and consequently of the power. However, in this case, the counter-effects referred to will be fully effective, and cannot be overcome. There are no explosives to prevent the pieces of uranium going rapidly apart as soon as enough heat is built up. Consequently, the total energy developed in such an accident will be very limited compared to that of even a small A-bomb — of the order of tens of thousands less.

The Chernobyl accident can be used as an illustration. In about four seconds, the reactor power was multiplied by a factor of a 1000, but the total thermal energy produced was limited to a few hundred thousand megajoules, which is equivalent to the energy produced by the reactor in less than two minutes. By comparison, an A-bomb produces a thermal energy of several billions of megajoules.

The explosion in the Chernobyl accident was not a nuclear explosion. When the reactor power was multiplied by 1000, it did create a considerable imbalance between the energy produced and the heat extracted. The fuel over-heated, it fragmentated into minute hot pieces, and these pieces very rapidly vapourized the water molecules present in the cooling system. This very fast vapour production resulted in a shock wave which destroyed the reactor structure, which was not pressure resistant. This destruction was followed by dispersal of the radioactive material. The mechanical energy developed in the Chernobyl accident was probably equivalent to a few hundred kilogrammes of TNT, compared to tens of thousands of tons of TNT in a small (tactical) A-bomb. The physical destruction was highly local.