Chernobyl Anniversary

Nuclear reactor safety – how far have we come since Chernobyl?

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Summary

The Chernobyl accident exposed serious weaknesses in how nuclear reactors were designed, operated and regulated. This article briefly explains what went wrong and the wide-ranging consequences that followed. It then looks at how the international community responded, including the creation of stronger safety rules and regular peer reviews under the Convention on Nuclear Safety. The paper also examines how modern reactor designs have improved, focusing on Small Modular Reactors (SMRs). These newer reactors use simpler designs, passive safety features, and stronger containment to make accidents less likely and easier to manage. Overall, the article shows that nuclear safety has advanced significantly since 1986, although continued attention and international cooperation remain essential.

Keywords: Chernobyl, Nuclear safety, Convention on Nuclear Safety, Small Modular Reactors (SMRs)

Introduction

There are certain catastrophic events from the past that are indelibly etched into our collective memories. Mention maritime disasters for example, and the Titanic disaster immediately springs to mind. But in the nuclear world, it is undoubtedly Chernobyl. Sadly, it often takes disasters such as these to trigger much needed changes to safety standards. Following the sinking of the Titanic for example, sweeping changes in safety regulations, international maritime law, and ship design were rapidly brought about. In a similar way, the Chernobyl disaster precipitated profound changes across environmental, political and safety spheres. This article reviews post-Chernobyl developments in nuclear safety and assesses current reactor safety, focusing on Small Modular Reactors (SMRs).

The causes, consequences and aftermath of the Chernobyl disaster have been extensively documented and discussed. Several articles on this topic have been published in the Loss Prevention Bulletin; see, for example *Chernobyl, 30 Years On*[1]. As a lead into this article, a brief description of the accident and its consequences is presented below.

Overview of the Chernobyl disaster

The Chernobyl RBMK reactor had several design flaws which significantly impacted the severity of the accident. However, it was an ill-conceived and poorly executed test which initiated the sequence of events that led to the disaster.

The test

A key safety function of a nuclear reactor is the removal of heat from its core. As with all nuclear reactors, the Chernobyl primary cooling system was backed up by an emergency cooling system, designed to automatically start up if the primary system failed. However, the diesel-powered emergency coolant pumps took about a minute to come to full power. So, the aim of the test was to determine if the inertia from the steam turbines as they wound down, would provide sufficient electrical power to bridge the power gap until the diesel generators were fully up to speed.

The accident

On the afternoon of 25 April 1986, preparations for the test began. The reactor power was reduced, but due to unexpected problems and a shift change, the test was delayed. This led to the reactor running at low power making it difficult to control. A further sharp drop in reactivity prompted operator actions that put the reactor into a very unstable state. These actions, which involved removing nearly all the control rods, violated safety protocols and left the reactor extremely vulnerable to an uncontrolled power surge.

At around 1:23 a.m. local time on 26 April, the test began. The operators shut off steam to the turbines, which reduced the cooling water flow. At the same time, due to the special characteristics of the reactor at low power, and the low cooling water flow, large amounts of steam began to form in the reactor core. This led to a dramatic increase in the reactor's energy output. A desperate attempt to insert all the control rods, designed to shut down the reactor, ironically resulted in a further increase in reactor power due to control rods being tipped with graphite. Seconds later, a huge steam explosion blew off the reactor's 1,000-tonne lid. A subsequent graphite fire sent radioactive particles high into the atmosphere.

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The consequences

Inter alia, the significant consequences of the Chernobyl disaster were as follows[2]:

- The initial explosion resulted in the death of two workers. Twenty-eight of the firemen and emergency clean-up workers died in the first three months after the explosion from Acute Radiation Sickness and one of cardiac arrest.
- The entire town of Pripyat (population 49,360), which lay only three kilometres from the plant was completely evacuated 36 hours after the accident. During the subsequent weeks and months an additional 67,000 people were evacuated from their homes in contaminated areas and relocated on government order. In total some 200,000 people are believed to have been relocated because of the accident.
- There have been at least 1800 documented cases of thyroid cancer in children who were between 0 and 14 years of age when the accident occurred. This is far higher than normal.
- The psychological effects of Chernobyl were, and remain, widespread and profound, and have resulted for instance in suicides, drinking problems and apathy.
- Some 150,000 square kilometres in Belarus, Russia and Ukraine are contaminated and stretch northward of the plant site as far as 500 kilometres. An area spanning 30 kilometres around the plant is considered the "exclusion zone" and is essentially uninhabited.

What was wrong with the Chernobyl RBMK design?

Some insight into the design flaws of the Chernobyl reactor design can be understood by considering two of the basic safety functional requirements of a nuclear reactor, namely containment of radioactive material and control of reactivity.

Containment of radioactive material

This reactor did not have what is known as a containment structure, i.e. a concrete and steel dome over the reactor itself designed to keep radiation inside the plant in the event of an accident. Instead, it had an industrial building and a lightweight steel top shield over the core.

Control of reactivity

Reactivity control is defined as the mechanism used to regulate the rate of the nuclear chain reaction within a reactor, primarily achieved through the insertion and movement of neutron absorbing control rods, which manage the number of absorbed neutrons.

In terms of control of reactivity, the Chernobyl reactor had two critical design flaws which profoundly exacerbated the severity of the accident.

- Positive Void Coefficient: The RBMK reactor, used at Chernobyl, had what is known as a Positive Void Coefficient. This meant that as the coolant water boiled and steam was produced, the reactivity of the reactor increased, causing the reactor to become dangerously unstable under certain conditions, particularly during low power operations, as was the case during the ill-fated safety test that preceded the explosion.
- Control rod design: The control rods in the Chernobyl reactor included graphite tips that had unintended consequences. When inserted into the reactor, the graphite tips temporarily displaced water, and increased reactivity before the neutron absorbing section could take effect. This initial increase in reactivity was counterproductive, especially during emergency shutdowns. Additionally, the emergency shutdown system was also flawed in that it took 18 to 20 seconds to fully insert the control rods. This delay was critical during the emergency situation when rapid action was needed to stabilise the reactor.

The international response to the incident

IIn the wake of the Chernobyl disaster, the IAEA played a central role in coordinating the international response to the accident, including assistance through its Technical Cooperation Programme to reduce the impact of the disaster and mitigate its consequences. Two conventions were adopted soon after the disaster:

- The Convention on Assistance in the case of a Nuclear Accident; and
- The Convention on Early Notification of a Nuclear Accident.

But what of the safety of reactors themselves? In the aftermath of both the Chernobyl and Three Mile Island accidents, a 'Convention on Nuclear Safety' (CNS)[3] was drawn up, also under the auspices of the IAEA. The objectives of this convention are to:

- achieve and maintain a high level of nuclear safety worldwide;
- to establish and maintain effective defences in nuclear installations against potential radiological hazards in order to protect individuals, society and the environment from the harmful effects of ionizing radiation from such installations; and
- to prevent accidents with radiological consequences and to mitigate such consequences should they occur.

The convention creates obligations on State Parties to implement certain safety rules and standards at all civil facilities related to nuclear energy. These include issues of site selection; design and construction; operation and safety verification; and emergency preparedness. It also obliges Parties to submit reports on the implementation of their obligations for "peer review" at meetings that are normally held at IAEA Headquarters. This mechanism is the main innovative and dynamic element of the Convention.

The CNS was adopted in Vienna on 17 June 1994 and entered into force on 24 October 1996.

Furthermore, on 9 February 2015, following the Fukushima nuclear reactor accident, a Diplomatic Conference of the CNS was held in Vienna. The main outcome of the Diplomatic Conference was the adoption of the 'Vienna Declaration on Nuclear Safety'[4] by the Contracting Parties to the CNS. The Declaration includes a political commitment by the Contracting Parties that:

- New nuclear power plants are to be designed and constructed with the objective of preventing accidents. In the event of an accident, no long-term external protective measures should become necessary.

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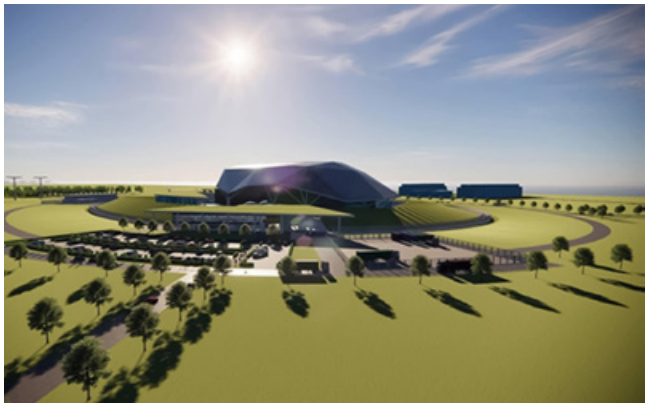
- Existing nuclear power plants should as far as possible be brought into line with the technical criteria and standards applicable to new nuclear power plants.

As of April 2024, there were 65 signatories to the CNS including the UK, USA and all EU countries.

Small modular reactors — a case study of the application of the CNS to new reactor designs

In the past few years, world-wide interest has grown in a new class of reactors known as Small Modular Reactors (SMRs). Typically these have a power output of 300MW_e or less, considerably lower than current commercial reactors, which have a typical power output of 1000MW_e*

Like all modern reactors, SMRs are designed to adopt the principle of 'Defence in Depth', described by the IAEA as 'a hierarchical, multi-level protection strategy to maintain physical barriers between radioactive materials and the environment'. For SMRs, this principle is enhanced by integrating inherent safety features, passive systems, and simplifying designs,



aiming to eliminate human intervention or external power or force to shut down systems. Examples of passive systems are:

- Gravity driven cooling systems. These rely on the natural circulation of coolants, driven by differences in temperature and density to remove heat from the core. Should power or coolant be lost, gravity driven cooling systems can prevent overheating and maintain safe operating conditions.
- Passive containment cooling. This safety feature uses natural convection and radiation to transfer heat from the containment structure to the environment, helping to maintain the containment's integrity, ensuring that radioactive material remains safely contained.

Like all modern reactors, SMR containment structures are being engineered to provide a robust barrier to prevent the release of radioactive materials into the environment during normal operation, maintenance, and potential accident scenarios. They are typically comprised of a steel or concrete shell, which encloses the reactor pressure vessel and other critical components. These structures must be designed to withstand various external and internal hazards, including earthquakes, aircraft impact, and pressure build-ups from potential accidents.

All these safety features serve to provide defence in depth for SMRs.

In addition to their safety benefits, SMRs also offer several other advantages over large scale reactors, such as:

- Siting flexibility. SMRs can be sited in locations that are not suitable for large reactors such as remote areas and sites with limited water and space.
- Greater scalability. The modular design allows for the addition of more modules as demand increases, providing flexibility for energy needs.
- The factory production of components can minimise construction errors and reduce the time required for installation; and
- Versatility in applications. SMRs can provide power for various applications, including industrial processes such as hydrogen production

Progress in design and construction of SMRs

The Nuclear Energy Agency (NEA), which operates under the framework of the Organisation for Economic Cooperation and Development, now regularly issues an NEA Small Modular Reactor Dashboard. The latest version was issued in July 2025[5] and reflects the growing world-wide interest in SMRs. The Dashboard highlights significant progress in developing and deploying them. For example, it identifies:

- 127 different SMR designs, 51 of which are involved in pre-licensing or licensing processes.
- Seven designs which are operating or under construction. There are two operating reactors — in Russia and China. In the UK, Rolls Royce has been selected as the preferred bidder to develop SMRs. It is currently going through the Office for Nuclear Regulation's Generic Design Assessment process.

Conclusion

The Chernobyl disaster underscored the risks associated with insufficient safety culture and suboptimal reactor designs. Although the RBMK reactor was specific to the Soviet Union, the incident led to a comprehensive global re-evaluation of nuclear safety procedures. In response, international efforts accelerated the integration of safety standards and peer review frameworks. Contemporary nuclear reactors reflect lessons learned from Chernobyl by incorporating, amongst other things, passive safety mechanisms, robust containment structures, and advanced real-time monitoring, thus greatly increasing defence in depth, and reducing the probability of comparable incidents. This article has examined the emergence of Small Modular Reactors (SMRs), which not only feature these enhanced safety measures but also offer additional benefits attributable to their reduced scale.

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* The Chernobyl reactor had a power output of 1000MWe_e

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