Introduction

Koeberg Nuclear Power Station (KNPS) is currently in the process of applying for a licence extension. Its nuclear installation licence is valid for 40 years, and approval by the National Nuclear Regulator (NNR) is required to continue its safe operation beyond the 40-year licensing period. This storybook aims to clarify the facts relating to KNPS and how the safety of the plant is assured. More information is available publicly, for example, the Public Information Document. The following topical issues relating to Koeberg are covered in this storybook:

- The safety of Koeberg,
- Preventing human error,
- The containment integrity,
- The seismic hazard assessment,
- Radioactive waste management,
- Radioactive liquid and gaseous waste (including tritium).

1. How safe is Koeberg?

Koeberg is safe because it is well-designed, properly operated, maintained and tested. It has kept up to date with modern practices through lessons learnt from events such as Chernobyl and Fukushima and it is regularly subjected to reviews by independent international organisations and the National Nuclear Regulator (NNR).

In line with industry safety standards to achieve optimum safety, Koeberg Nuclear Power Plant operates using a **'defence-in-depth' approach**. Key aspects of the approach are:

- High-quality design and construction.
- Equipment that is not prone to human error or requires human intervention.
- Comprehensive monitoring and regular testing to detect equipment or operator failures.
- Multiple backup systems to prevent damage to the nuclear fuel and prevent radioactive releases.
- Multiple physical barriers to confine radioactive material and prevent significant releases.
- Mitigating actions (emergency plans) in the unlikely event of radioactive releases.

The safety provisions include a series of physical barriers (also termed fission product barriers because they contain or prevent the release of fission products) between the radioactive nuclear fuel and the environment and the provision of multiple safety systems. The fission product barriers at Koeberg are:

- The fuel is in the form of solid ceramic pellets, packed inside sealed zirconium alloy tubes to form fuel rods (**first fission product barrier**).
- These fuel rods (grouped into fuel assemblies) are confined inside a large steel reactor pressure vessel and its associated pipework. The reactor pressure vessel steel walls are 200mm thick with an additional 7,5mm thick stainless-steel cladding (**second fission product barrier**).
- All this, in turn, is enclosed inside a robust reinforced concrete containment structure with vertical walls 900mm thick (**third fission product barrier**).

This amounts to three fission product barriers around the nuclear fuel, and the integrity of the barriers is continually monitored. The fuel cladding is monitored by measuring the amount of radioactivity in the cooling water. The high-pressure cooling system is monitored by monitoring the amount of water leaking from the system. The containment structure's stress and deformation are monitored quarterly and an integrated leak rate test, i.e., pressuring the buildings with air and measuring the air leaking out of the buildings at 4 atmospheres of pressure, is performed every 10 years.

These physical fission product barriers are shown in Figure 1.

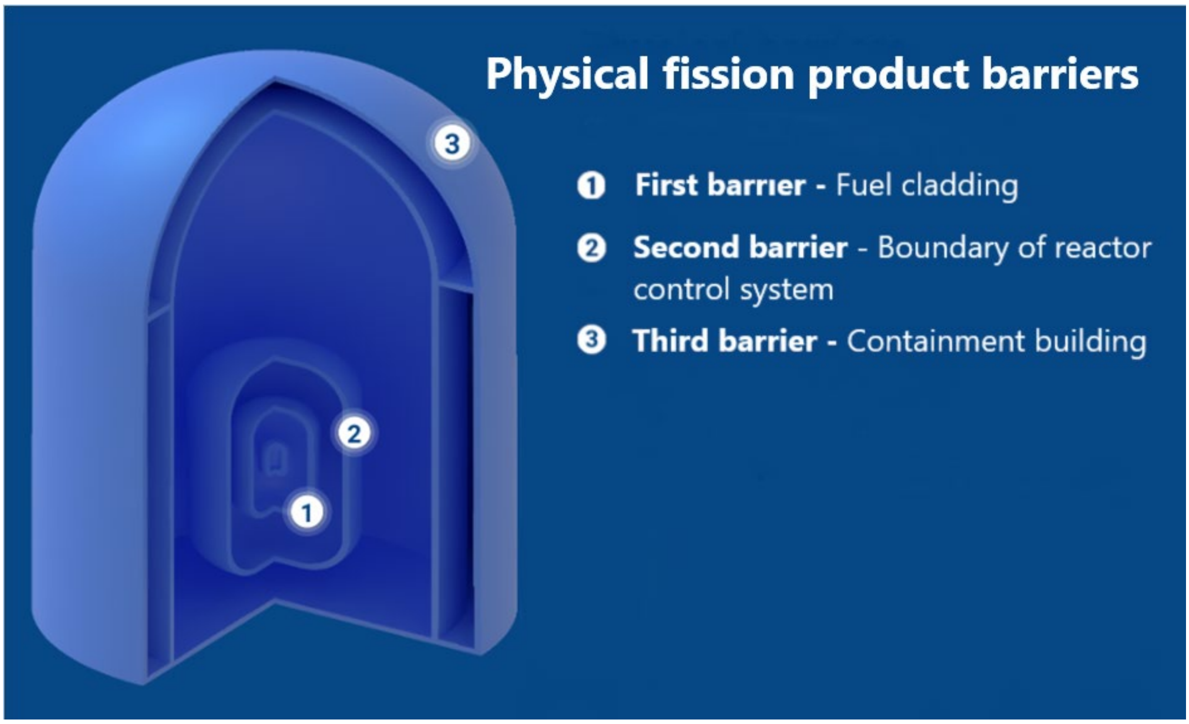

Figure 1: Physical fission product barriers

Chernobyl - A different safety philosophy: early Soviet-designed reactors

On 26 April 1986, the number four reactor at the Chernobyl Nuclear Power Plant in the former Soviet Union lost control during improper testing at low-power operations which resulted in an explosion and fire that demolished the reactor building and released large amounts of radiation into the atmosphere. As safety measures were ignored, the uranium fuel in the reactor overheated and melted through the protective barriers. The disaster at the Chernobyl Nuclear Power Plant in Ukraine was the result of major design deficiencies in the RBMK (Reaktor Bolshoy Moshchnosty Kanalny) type of reactor, the violation of operating procedures and the absence of a good nuclear safety culture. One peculiar feature of the RBMK design was that it had a positive void coefficient of reactivity. This meant that as more voids (bubbles) formed in the reactor, the power increased, resulting in further heat and more voids in the reactor coolant. It also did not have a robust containment building.

Koeberg, like other similar, more modern designs is significantly different from Chernobyl. Koeberg has a negative void coefficient of reactivity which is much safer. It also has a robust containment building. Most importantly, Koeberg has a good nuclear safety culture and is subjected to regular reviews by external, independent organisations such as the World Association of Nuclear Operators (WANO) and the International Atomic Energy Agency (IAEA).

A strong culture for safety is illustrated in Figure 2 below (courtesy of IAEA):

Figure 2: IAEA approach to nuclear safety culture

The Chernobyl accident was a unique event and the only time in the history of commercial nuclear power that radiation-related fatalities occurred. The main positive outcome of this accident for the industry was the formation of the World Association of Nuclear Operators (WANO), which Eskom is affiliated with.

Fukushima Daiichi

On 11 March 2011, Japan experienced a magnitude 9 earthquake which was followed by a tsunami with wave heights of more than 10 meters. There were eleven reactor units in the affected region and all shut down automatically as designed. The initial earthquake and the subsequent earthquakes did not cause significant damage to any of the reactor units, but they were vulnerable to the tsunami that followed.

Power from the grid or backup generators was available to provide electrical power to cooling water pumps at eight of the eleven reactor units which were all safely shut down. Three reactor units at Fukushima Daiichi overheated due to a lack of electrical power for cooling the reactor and the nuclear fuel melted, releasing radioactivity into the environment.

The Koeberg site is an area of low seismicity when compared to the Fukushima Daiichi plant location. However, preparedness for an earthquake remains essential. Koeberg is designed for a magnitude 7 earthquake with a focal point 8km from Koeberg. It has a terrace level of 8m above sea level to protect against tsunamis.

The event at Fukushima highlighted that additional portable backup electrical supplies that cannot be affected by a tsunami are amongst the critical equipment needed to prevent damage to the reactor. Other aspects are additional cooling water supplies, the ability to remove hydrogen from the reactor, and an effective emergency plan, amongst others.

Following the lessons learnt from Fukushima, Koeberg has purchased additional portable electrical backup supplies to power its safety systems and has updated its emergency plan. Koeberg also has passive hydrogen recombiners in the reactor buildings to prevent hydrogen explosions. Additionally, a backup cooling water supply capability currently exists and another two, seismically robust water supply tanks are being constructed.

Figure 3 below (courtesy of IAEA) provides a comparison of the level of safety of nuclear energy versus other sources of electrical energy. The safety of nuclear energy is comparable to wind and solar energy.

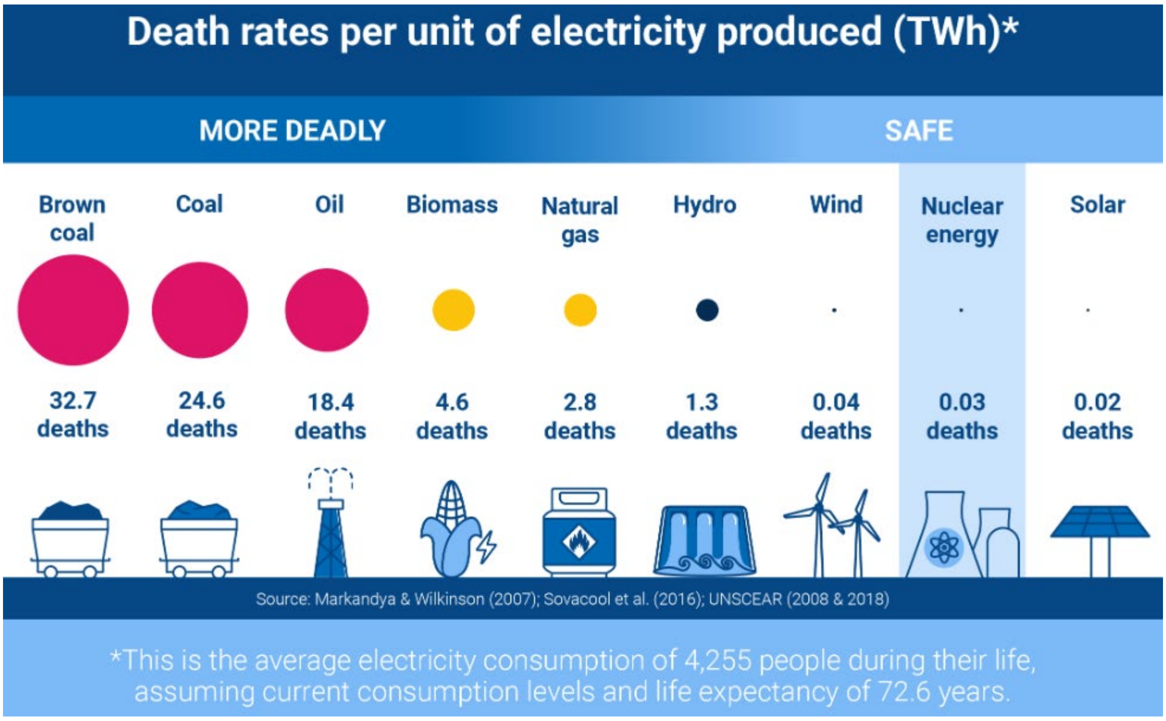

Figure 3: Comparison between nuclear energy and other energy sources

In conclusion, Koeberg is safe because it is a well-designed, properly operated, maintained and tested plant. It has kept up to date with modern practices through lessons learnt from events such as Chernobyl and Fukushima and it is regularly subjected to independent international organisations and the NNR. This is underscored by 40 years of safe, reliable operation.

2. What is Koeberg doing to reduce human error?

Our nuclear oversight bodies (IAEA, WANO, etc.) require all commercial nuclear utilities to have a Human Performance (HP) Programme, and Koeberg is no exception.

All workers at Koeberg, including contractors, undergo an HP awareness session as part of their induction to enter the Koeberg site. This introduces them to error-reduction methods and tools when performing their work which helps them to work safely. All workers must be re-assessed and re-authorised on the use of HP tools every two years which is controlled by the Fitness for Duty (FFD) Programme.

The tools are error-reduction techniques and are intended to reduce their vulnerability to error-likely situations.

Koeberg has an established Human Performance programme which encompasses more than just the worker and preventing slips and mistakes at the job site. It also addresses the organisational factors that influence worker behaviours that can sometimes create error-likely situations. Two supporting programmes are the Corrective Action Programme (CAP) and the Observation Programme:

CAP is where all workers (Eskom and contractors) can report issues they encounter at the job site. These issues are then screened, coded, graded, and assigned an appropriate level of investigation if warranted.

The Observation Programme allows leaders and peers to observe worker behaviours in the field and capture (in real-time), how workers perform tasks, adhere to standards and expectations, as well as identify obstacles they encounter.

Human performance is also an important element of a safety culture. Koeberg has developed a strong nuclear safety culture (NSC) following international standards. A healthy NSC enables good human performance and plant safety performance, preventing human error. In addition to the two supporting programmes mentioned above, nuclear professionals at Koeberg apply the following human performance tools (see Figure 4) to conduct work safely and reliably:

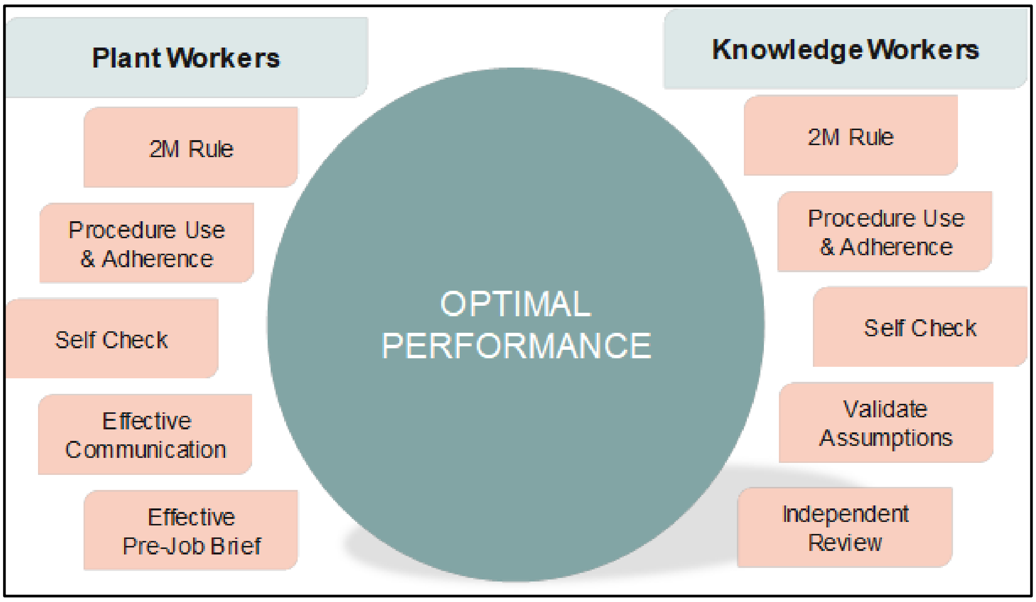

Figure 4: Human performance tools

In summary, Koeberg has a well-established HP programme which forms part of a broader safety culture programme aimed at reducing human error and improving safety.

3. The Koeberg containment buildings

As described above, the radioactive reactor core is enclosed inside a robust reinforced concrete containment structure. Below are the facts linked to the safety and structural integrity of the containment buildings.

What is the function of the containment buildings?

The containment building houses the reactor pressure vessel and associated reactor cooling systems, steam generators, and other important components needed to produce steam to generate electricity. Its main function is to contain the release of radioactive material in the unlikely event of a nuclear accident. To achieve this, the design comprises very thick, highly reinforced and post-tensioned concrete walls (providing the strength) and an internal steel liner (providing the leak tightness).

Figure 5: The Koeberg containment building

What are the concerns raised with the containment buildings at Koeberg?

There are two main concerns raised. Firstly, the containment buildings are located close to the sea, so they are exposed to high levels of chlorides. The chlorides penetrate the outer layer of concrete and if not treated may cause corrosion of the steel reinforcement. This results in spalling (delamination) of the concrete. Secondly, a crack in the domes of the containment buildings was noted several years ago.

How much of the surface area of the containment building is affected by delamination?

The outer surface areas facing the seaside are the most affected. A total of approximately 700m^2 per building is affected. The surface area already repaired is approximately 500m^2 per building. Therefore, about 4% of each of the building's surface areas still needs to be repaired and is planned as part of ongoing maintenance.

The delamination process is shown in Figure 6.

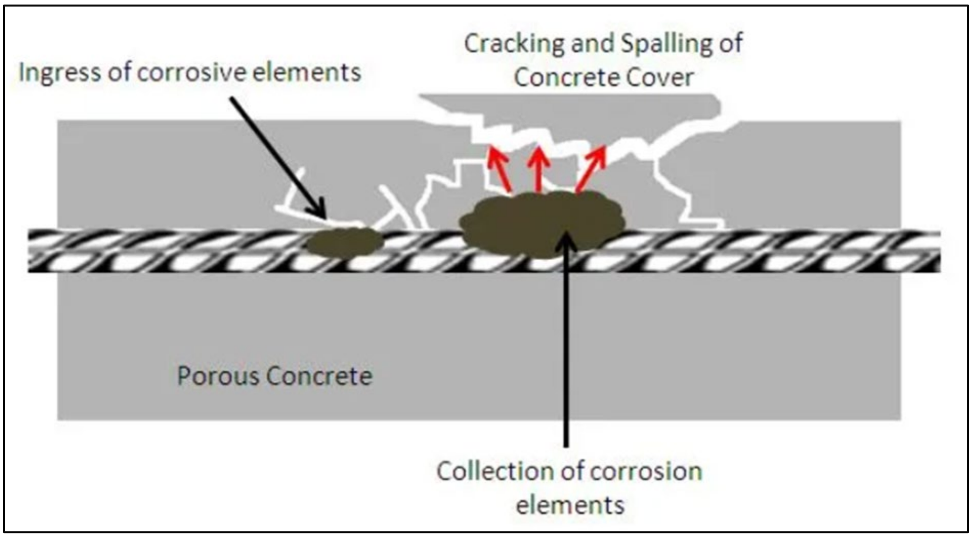

Figure 6: Outer surface delamination (spalling)

How does the delamination affect the structural integrity of the containment buildings?

The delamination does not affect the structural integrity of the containment buildings because the delamination only affects the outer layer of the concrete. The concrete wall is 900mm thick, and delamination typically only affects about 80mm (less than 10% depth).

The cross-section of the containment wall is shown in Figure 7.

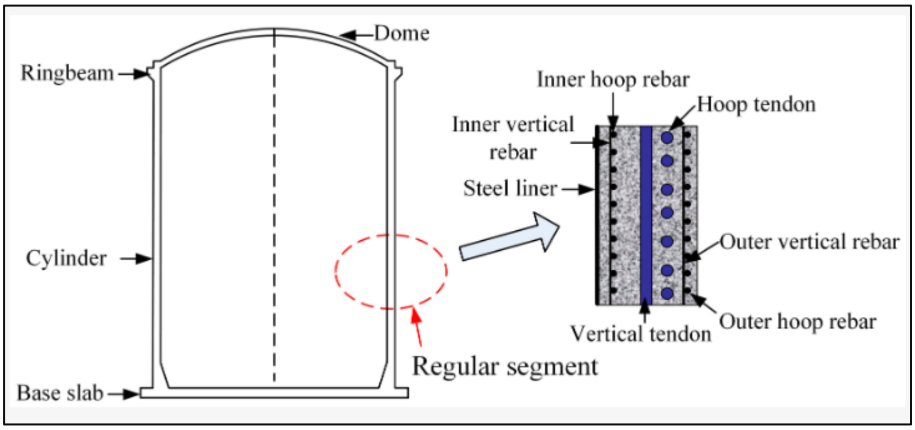

Figure 7: The containment building and cross-section of the wall

How is the concrete surface delamination managed to ensure the structural integrity is unaffected?

In the past, patch repairs of the delaminated areas were done by excavating the damaged areas, replacing reinforcing steel as needed and filling the excavated areas with new concrete. Visual inspections are done to determine if there are new areas of delamination and to monitor the levels of chloride and the depth of the chloride in the concrete. When required, further repairs are scheduled.

Theoretical modelling has been used to study the overall effects and concluded the structural integrity remains acceptable.

What is the long-term plan to address the damaging effects of chloride?

An expert panel has advised Eskom to install an impressed current cathodic protection (ICCP) system to protect the steel reinforcement and post-tensioning ducts from corrosion. ICCP systems are commonly used to protect steel reinforcement in concrete exposed to corrosive environments (e.g., bridges, dams). The ICCP system is at an advanced stage of development and installation is expected over the next few years. A mock-up system has been built and tested.

How does the crack in the dome affect the structural integrity of the containment building?

The crack in the dome of the containment building does not affect the structural integrity of the containment building. Although it is a 110m long crack along the circumference of the dome, it is monitored and has been sealed and painted. It is similar to cracks noted in containment buildings in other countries. It is not unusual for concrete to crack and design codes allow for cracks in concrete. This crack is specifically monitored during the containment building pressure tests and evaluated by international experts. The crack has not grown even when the building was subjected to the pressure tests and it is not a concern for the structural integrity of the containment building.

Figure 8: Containment dome crack sealed and coated

How can we be sure that the containment building will be able to perform its function when needed?

The containment building is subjected to a variety of monitoring, testing, inspections and analyses as part of the Koeberg license conditions. The results all indicate that the containment building is fit for purpose and can continue to safely perform its function for the additional 20 years of extended operation. Some of these tests, monitoring, inspection and analysis include:

- The strain in the concrete is monitored every quarter and the results do not indicate any concerns with containment integrity.
- The tension in the concrete's prestressed cables is monitored every quarter (using dynamometers installed on a sample of cables) and the results do not indicate any concerns with containment integrity.
- Visual inspections of the concrete are done every outage (about every 18 months). While there have been additional areas of delamination noted, there were no concerns related to structural integrity observed during the visual inspections.
- The 10-yearly pressure test was completed on both containment buildings in 2015 and the tests passed. Another test will be done during the next shutdowns of each unit and the results will be evaluated by international experts.
- An analysis of the concrete strains and dynamometer measurements shows that the containment building is safe to continue for another 20 years, with ongoing testing and monitoring.

Will contaminated substances leak through the cracks in the concrete?

- No, contaminated substances will not leak out through the cracks in the concrete. Firstly, the leak-tightness is provided by a 6mm thick steel liner on the inside of the concrete containment building and not the concrete. Secondly, the cracks and delamination only affect the outer surface of the 900mm thick, vertical reinforced concrete walls. The dome is 800mm thick.

Has the containment structure monitoring system functionality been fully restored as recommended by the IAEA?

The full functionality is currently being restored. The dynamometers have been calibrated and the repair of the invar wires and pendulums is currently in progress. However, monitoring of the containment structure continues to be done using the available monitoring equipment and through visual inspections. The available monitoring instruments provide for an integrated view/status of containment.

In the absence of a fully functional monitoring system, can the containment building structure continue to be monitored?

Yes, monitoring of the containment building can continue using the remaining available monitoring equipment. Breakages and failures are expected over time and the monitoring system consists of several complementary structural monitoring systems.

For the pressure test of the containment buildings, additional temporary monitoring instruments are fitted to supplement the existing monitoring instruments.

What is the long-term plan for the containment monitoring system?

The current containment monitoring systems are considered adequate and will be repaired as breakages occur. However, a modification is planned to install new monitoring instruments in the medium to long term that will enable enhanced monitoring of the containment building structure as part of Eskom’s continuous improvement effort.

How can the public be sure that the containment building can function safely during the period of long-term operation (LTO)?

An analysis of the ageing of the containment building structure was completed in line with international standards which shows that the containment building is safe for an additional 20 years.

Testing, monitoring and inspections will continue during the period of LTO and these tests are termed license-binding surveillances. That is, they are done under the license issued by the National Nuclear Regulator and overseen by them.

This monitoring and the 10-yearly pressure test which will be done during the next outage on unit 1 and unit 2, will demonstrate on an ongoing basis throughout the life extension that the containment buildings remain within design criteria and are safe.

4. Koeberg's seismic hazard assessments

As for any nuclear power plant, the location of Koeberg was carefully selected, taking into consideration several factors as prescribed by the international standards and regulatory requirements available at the time of selecting the site.

The primary site selection criteria are to ensure that there is no undue risk to the health and safety of the public due to the operations of Koeberg. One of the factors evaluated during the site selection is seismology – the study of earthquakes that may affect Koeberg. The first studies for the selection of a suitable site for Koeberg were carried out in the 1960s and 1970s which led to Duynefontyn as the preferred site for Koeberg.

The Western Cape is characterised by low levels of seismicity compared to, for example, Japan or California. This means that there is a very low chance that an earthquake will cause serious damage to Koeberg. However, it is essential that Koeberg is prepared for an earthquake.

Koeberg was designed to withstand a magnitude 7 earthquake with a focal point 8km from Koeberg based on the criteria from Dames and Moore seismic analyses conducted from 1973 to 1981. (Dames and Moore was a pioneer in civil engineering based in the USA).

Since then, Eskom has commissioned four seismic hazard assessments for Duynefontyn, the Koeberg site. These seismic hazard assessments are shown below:

- Council for Geoscience (1999 and again in 2005)
- Rizzo Associates (2008)
- Interim Seismic Evaluation (2022)
- Council for Geoscience Probabilistic Seismic Hazard Assessment (PSHA) (2021 -2024)

The most recent study, PHSA (2024), was commissioned due to limitations in the Dames and Moore and other earlier assessments, to apply the latest data, techniques and standards, and to meet regulatory requirements.

The PSHA utilised the most modern methodologies and standards in the world which ensures that Koeberg's seismic hazard assessment is comprehensive and comparable to the best in the world. An international team appointed by the Council for Geoscience performed the multi-year study.

The Interim Seismic Evaluation (2022) was performed to verify the robustness of the Koeberg plant against a significant seismic event and assist with the justification of LTO while the PHSA was being finalised.

Koeberg's ability to withstand a major earthquake is due to its robust design. In addition, the nuclear island (consisting of the containment building and other essential structures) is built on 1829 bearings that act as shock absorbers to reduce the damaging effects of an earthquake in the unlikely event that one would occur and will allow the safe shutdown of the power station.

The PSHA study is now complete and provides an excellent, state-of-the-art assessment of the seismic situation of the Koeberg site. All the known, unknown and postulated faults and inputs have been considered in the study. The robustness of the plant against the outcome of the PSHA (i.e., the seismic event determined by the study) is enveloped by the Interim Seismic Evaluation performed for LTO. Therefore, the Interim Seismic Evaluation provides assurance that the Koeberg plant is and remains robust against significant seismic events.

5. Radioactive waste management

Safety of radioactive waste

Eskom's radioactive solid waste storage and disposal processes comply with the NNR requirements and are in line with international standards. The storage of low-level solid waste in trenches is safe. The waste itself has only low levels of radioactivity and the waste containers are robust.

A similar method of disposal of low and intermediate-level solid waste is used safely in many countries including France, USA and UK. The storage of spent fuel in spent fuel pools and dry storage casks has been done safely for decades at Koeberg and in many other countries. The approach used by Eskom for the storage of spent nuclear fuel is also commonly used in the USA and Europe.

An important factor in the safety of solid waste management has been the robust design of the waste containers (concrete drums, steel drums and dry storage casks) and the spent fuel pool cooling systems which comply with stringent regulatory criteria.

Types of radioactive waste produced

As part of normal operations and ongoing refurbishments, Koeberg produces gaseous, liquid and solid radioactive waste. The gaseous and liquid waste is treated and only discharged under controlled conditions when it is within safe, allowable limits as prescribed in regulatory requirements. The treatment of liquid and gaseous waste generates solid, low and intermediate-level radioactive waste which is sealed in steel or concrete containers (depending on the type of waste). The waste containers (design, testing, contents and transportation) are subjected to strict international and regulatory requirements to ensure that the solid waste will be safely contained. The solid high-level waste (used/spent fuel) is first stored in the spent fuel pool and then transferred to dry storage casks stored on the Koeberg site.

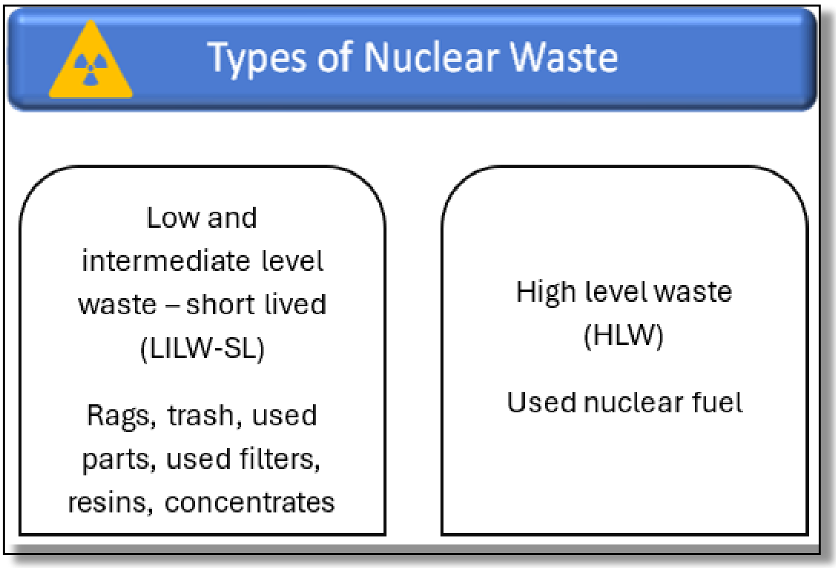

Figure 10: Examples of the various types of nuclear waste

For more information, the Public Information Document for the long-term operation of Koeberg can be accessed with this link:

https://www.eskom.co.za/wp-content/uploads/2023/11/240-165294677_Rev3_PID_for_LTO_English.pdf

Low and intermediate-level radioactive waste (LILW - SL)

Low and intermediate-level waste constitutes approximately 97% of the waste produced. The low-level waste (LILW-SL) contains relatively low levels of radioactivity and the likelihood of the drums leaking and affecting the environment is low. The LILW-SL concrete and steel drums are designed to contain waste materials safely and prevent leakage. The waste is compressed into sealed, clearly marked, steel drums and stored onsite until they are transported to the designated national waste disposal site at Vaalputs in the Northern Cape. Higher radioactivity level resins and concentrates from the treatment of liquid and gaseous effluent are solidified by mixing them with cement and pouring them into concrete drums before being transported to Vaalputs. Waste packages comply with stringent regulatory acceptance criteria to ensure that the waste can be transported and disposed of safely.

The national waste disposal facility is designed to protect human health and the environment and has monitoring systems in place to mitigate the risk of environmental impact. The facility is managed by the Nuclear Energy Corporation of South Africa on behalf of the National Radioactive Waste Disposal Institute (NRWDI). Only a small percentage of available storage space has been used thus far.

Figure 11: Radioactive waste in steel drums stored at Vaalputs National Waste Disposal Facility

Figure 12: Radioactive waste in concrete waste drums stored at Vaalputs National Waste Disposal Facility

High-level waste

High-level waste (should spent nuclear fuel eventually be declared as such) makes up approximately 3% of the waste produced. It consists of small pellets of uranium oxide stacked into a fuel rod (see Figure 13). The fuel assembly consists of multiple rods fixed together to form a rectangular shape as shown.

Spent fuel is stored in spent fuel pools (see Figure 14) and in dry storage casks at Koeberg (see Figure 15). Provision for additional fuel storage casks is planned and will be available when needed. Spent fuel pools and dry storage casks are safe and reliable means to store spent fuel. The approach is widely used and aligned with international practices.

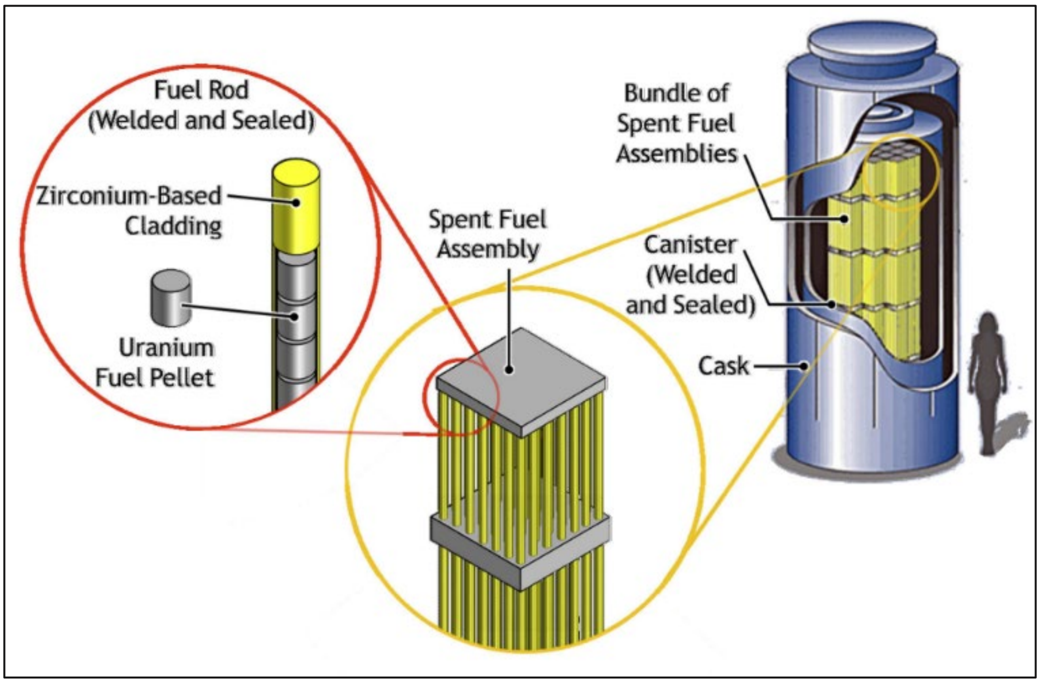

Figure 13: High level waste - spent nuclear fuel stored in casks

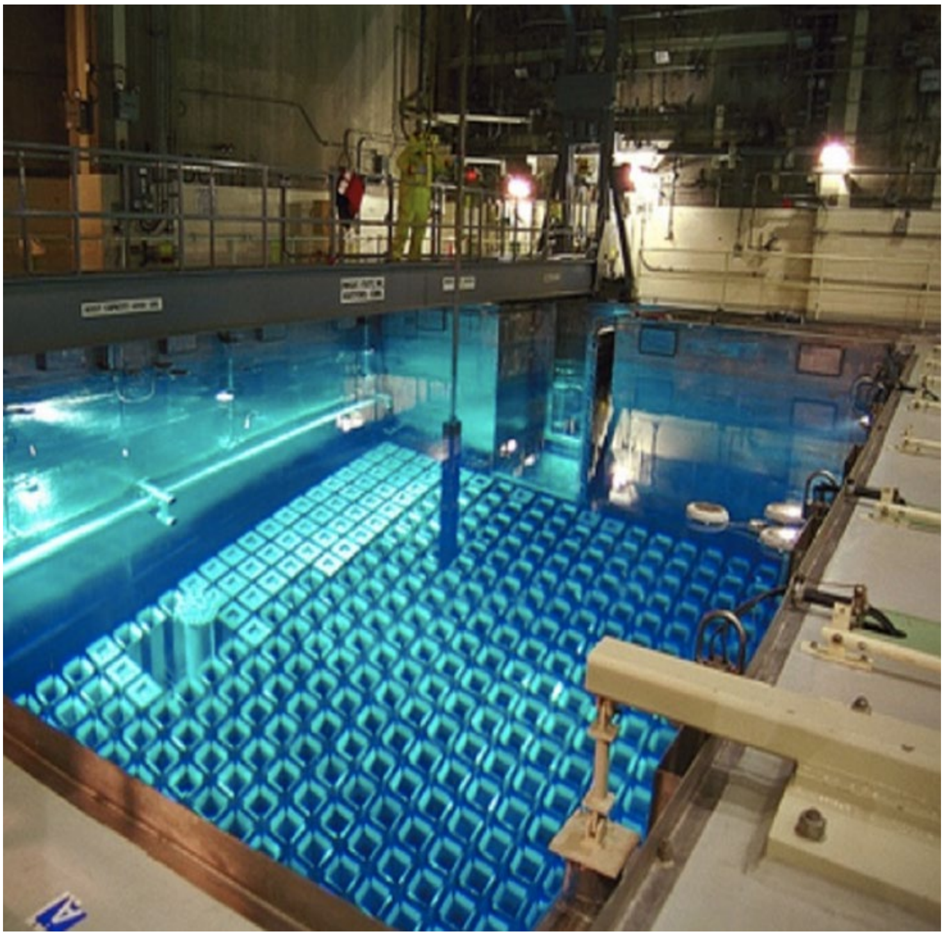

Figure 14: Spent fuel pool

Figure 15: Dry cask for nuclear fuel storage

Volume of high-level and low-level waste produced over the 20-year life extension

The total volume of low-level waste produced during the 20-year life extension is estimated to be less than 10,000m^3. This volume includes the volume of the waste packaging, i.e. the concrete and steel drums. The total number of spent nuclear fuel assemblies produced during the 20-year life extension is estimated to be 1750. These fuel assemblies can be stored in approximately 60 dry storage casks which will occupy an area of about 600m^2.

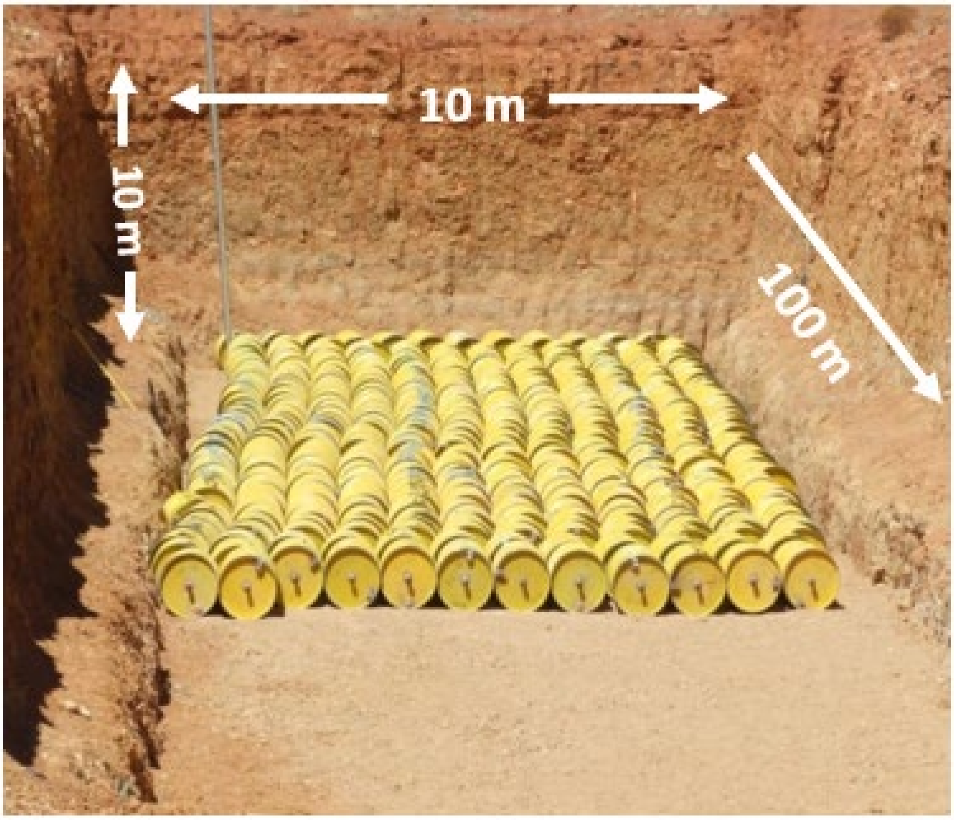

Figure 16: The volume needed for the low-level waste produced during the 20-year life extension

Figure 17: An example of a dry cask storage area for spent nuclear fuel

How safe is Eskom's approach to radioactive waste storage and disposal?

Safety of radioactive waste

Eskom's radioactive waste storage and pre-disposal processes and the Vaalputs disposal activities comply with the NNR requirements and are in line with international standards. The storage of LILW-SL in trenches is safe. The waste itself has only low levels of radioactivity and the waste containers are robust. The waste containers and their contents comply with stringent waste acceptance criteria.

A similar method of disposal of low and intermediate-level waste is used safely in many countries including France, USA and UK. The storage of spent fuel in spent fuel pools and dry storage casks has been done safely for decades at Koeberg and in many other countries. The approach used by Eskom for the storage of spent nuclear fuel is also commonly used in the USA and Europe.

An important factor in the safety of waste management has been the robust design of the waste containers (concrete drums, steel drums and dry storage casks) and the spent fuel pool cooling systems which comply with stringent regulatory criteria.

6. Radioactive liquid and gaseous waste (including tritium)

During normal operation of the nuclear power plant, some radioactive effluent (including tritium) is released under controlled conditions and within allowable limits, using Koeberg's radioactive effluent monitoring systems and processes.

Radioactive gases and liquids are treated by the Koeberg waste management systems and processes to minimise the radioactivity and to within allowable limits before it is released into the environment. Effluent that is discharged includes tritium in liquid form and gaseous form. Tritium exists naturally in the environment but is also produced by man-made nuclear reactions such as nuclear power plants.

The liquid and gaseous effluent discharged to the environment is minimised and complies with the maximum annual effective dose limit as set by legislation. The effective dose limit set by legislation for members of the public as a result of all authorised actions is 1mSv per annum, while the individual dose constraint applicable to Koeberg for a representative person is 0,25mSv per annum. This is well below the average background radiation levels of approximately 2,4mSv per year.

The average annual dose for a person living near Koeberg is generally more than 100 times lower than the dose received from natural background radiation. Therefore, the likelihood of any health effects due to Koeberg operations is very low. Tritium has no chemically toxic effects on the human body other than its radioactivity. However, as can be seen by the trend below, the radioactivity from effluent discharged (including tritium) is well within legislative requirements and on a decreasing trend.

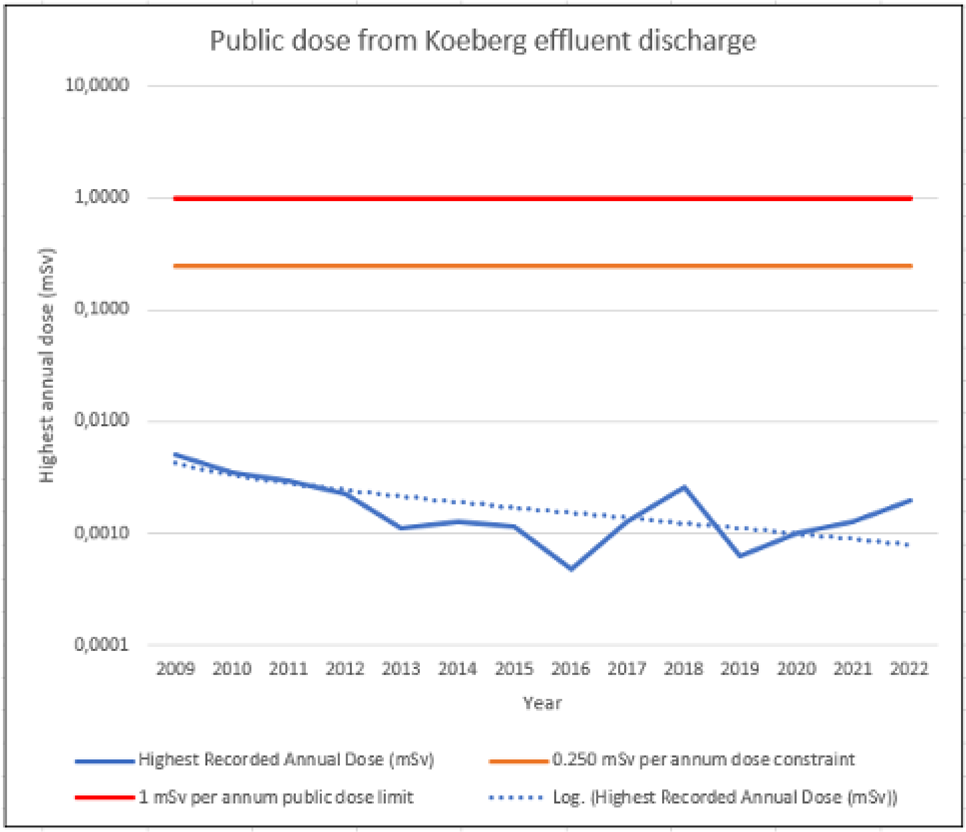

Figure 18: The trend of public dose due to Koeberg's effluent discharges (including tritium)

At Koeberg tritium is monitored in the reactor coolant water, air inside containment, and all gases and liquids released from the plant. The maximum annual exposure is generally less than 0,002mSv, which is 100 times less than the maximum allowed exposure per year.