

Evaluation of Nuclear Spent Fuel Dry Storage Casks and Storage Facility Designs



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07 April 2017

Submitted to the Department of Electrical Engineering at the University of Cape Town in partial fulfilment of the academic requirements for a Master of Engineering degree with specialisation in Nuclear Power

Key Words: DRY STORAGE CASK, EVALUATION, SPENT NUCLEAR FUEL, INTERIM STORAGE FACILITY

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Abstract

Koeberg Nuclear Power Station (KNPS) is the only nuclear power station in Africa and it stores its spent nuclear fuel (SNF) onsite in the spent fuel pool (SFP). Additional aged SNF assemblies are stored in dry storage casks in a facility located on the KNPS site.

This minor research dissertation aims at evaluating various dry storage cask found in open literature. The dissertation provides an overview of cask types, heat transfer, radiation shielding and storage facility types. Specific criteria are required in the selection of casks and the storage facility to house the casks on site. The selection criteria for casks and the storage facility were determined and technically evaluated in this dissertation.

The selected casks were evaluated in terms of SNF criticality, radiation shielding, decay heat removal and heat transfer. Other aspects also determined by calculation were the seismic stability of casks and the cask footprint. The results obtained show the relationship of the spent fuel (SF) packing density between the different casks. Different shielding materials are used in the casks and it aided the heat transfer process to take place with some casks having additional features which included cooling fins and air vents for adequate cooling of the SNF. Through these some trends could be identified which could be used in the selection or design of new storage casks.

Recommendations for further study are to evaluate a greater range of casks to verify and improve upon the relationship of evaluated parameters that were shown in the technical evaluation. These casks should all have similar means of maintaining sub-criticality, shielding and heat removal in order to generate comparable results.

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Acknowledgements

I wish to thank my husband, Angelo and the rest of my family and friends for all their loyal support during this time of research. A special thanks to my UCT supervisor, Dr Fuls for always pointing me in the right direction and keeping me focussed to the very end. Thank you to my Eskom co-supervisor, Carla Terblanche (MEng) for assisting and proof reading my dissertation offering her valuable input. Thank you to my sponsor, Eskom for the financial assistance and time required to complete my dissertation.

Last but not least, I wish to thank my Heavenly Father for the God-given ability and strength to complete this dissertation.

This dissertation is dedicated to my first born son, may you always follow your dreams.

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List of Nomenclature

General symbols/units

| | |
|---------------------|---|
| GWd/MTU | Gigawatt days per metric ton of uranium |
| h | Heat transfer coefficient |
| k_{eff} | Effective multiplication factor |
| k_e | Effective thermal conductivity |
| k | Thermal conductivity |
| MTHM | Metric tons of heavy metal |
| MW _e | Megawatt electrical |
| μSv/h | Micro Sievert per hour (dose rate) |
| Q''' | Volumetric heat generation |
| Q _{tot} | Design heat load |
| Q _{cool} | Cooling load |
| Q _i | Inner heat |
| Q _{shield} | Heat in the shield |
| V | Volume |
| W/m ² | Watt per meter squared |
| $\Delta k/k$ | Units of reactivity |
| η_{fin} | Fin efficiency |

Acronyms and Abbreviations

| | |
|------|---------------------------------------|
| ASCC | Atmospheric stress corrosion cracking |
| BWR | Boiling water reactor |
| CFD | Computational Fluid Dynamics |
| CSB | Cask Storage Building |
| DOE | Department of Energy |
| EIA | Environmental Impact Assessment |
| EPRI | Electric Power Research Institute |
| FA | Fuel assembly |
| HLW | High level waste |

| | |
|--------|---|
| IAEA | International Atomic Energy Agency |
| ILW | Intermediate level waste |
| INL | Idaho National Laboratory |
| IRP | Integrated Resource Plan |
| ISFSI | Independent spent fuel storage installation |
| KNPS | Koeberg Nuclear Power Station |
| LLW | Low level waste |
| MVDS | Modular vault dry storage |
| MPC | Multi-purpose canister |
| NECSA | South African Nuclear Energy Corporation |
| NEI | Nuclear Energy Institute |
| NERSA | Nuclear Energy Regulator of South Africa |
| NNR | National Nuclear Regulator |
| NRC | Nuclear Regulatory Commission |
| NRWDI | National Radioactive Waste Disposal Institute |
| NUREG | US Nuclear Regulatory Commission Regulation |
| PWR | Pressurized water reactor |
| RTD | Resistance temperature detector |
| SA | South Africa |
| SF | Spent fuel |
| SFA | Spent fuel assembly |
| SFP | Spent Fuel Pool |
| SNF | Spent nuclear fuel |
| TISF | Transient Interim Storage Facility |
| UK | United Kingdom |
| US | United States |
| US NRC | United States Nuclear Regulatory Commission |

| | |
|-----------|-------------------|
| U_{235} | Uranium 235 |
| 1-D | One dimensional |
| 2-D | Two dimensional |
| 3-D | Three dimensional |

1. Introduction

1.1 Background

“In the late 1970’s and early 1980’s, the need for alternative storage began to grow when pools at many nuclear reactors began to fill up with stored spent fuel. Utilities began looking at options such as dry cask storage for increasing spent fuel capacity.” (NRC, 2012).

Nuclear technology for SA is receiving the spotlight with the recent announcements of government signing agreements with various countries for technology transfer and to supply 9600 MW_e of nuclear power as indicated in the IRP 2010 document (DOE, 2012). A very significant constant concern raised about nuclear power has been the medium to long term high level waste and the future disposal thereof.

The planning for medium to long term storage or reprocessing of spent fuel are still being evaluated in South Africa (SA) with only low and intermediate level waste being sent to Vaalputs in the Northern Cape (Bredell, 1998). Koeberg Nuclear Power Station (KNPS), the only nuclear power station in Africa stores its SNF on site in the spent fuel pool (SFP) and additional aged spent fuel are stored in casks located inside a storage facility on the reactor site. Space for storage of SNF in casks was evaluated due to the limited storage capacity in the SFP at KNPS. With the selection of casks, a storage facility is also required to house the casks on site and passive cooling takes place.

Dry storage casks are used for the safe interim storage of spent nuclear fuel (SNF). The nuclear fuel is classified as spent or used fuel after it has been utilized and irradiated in a nuclear reactor to generate heat which in turn generates electricity by using a steam turbine and alternator-generator set at the nuclear power station. SNF is defined as high level radioactive waste and is normally stored in the spent fuel pool (SFP), also known as wet storage. The SNF is moved to dry storage casks, hereafter referred to only as casks, after decaying for between 5 and 10 years in the SFP. It is then transported to a reprocessing plant or into casks utilized as interim storage in a storage facility. There are no reprocessing facilities in South Africa neither are there plans to reprocess used fuel from Koeberg Nuclear Power Station (KNPS) (Bredell, 1998). For this reason SNF is stored in casks where they are currently kept on site in a safe, secure and suitable storage facility where passive cooling occurs by natural airflow around the casks.

Casks can be orientated in two ways, namely vertically or horizontally. There are two main classes of materials used in the construction of casks, namely metal and concrete. The outer shell can be made of metal or concrete and is referred to as the cask. Each cask contains a metal canister which houses the SNF assemblies in baskets. Apart from the outer cask, additional stands or

storage plinths are sometimes required which aid the orientation of the cask in a horizontal or secured vertical position.

1.2 Problem statement for research focus

There is a large amount of varying cask designs currently in use in the world. In all cases they are adequate for containing SNF and for the removal of decay heat to prevent the casks from overheating, being damaged, and possibly causing a fuel melt or re-criticality accident. The criteria or preferences in deciding on cask orientations, material and construction could not be found in literature.

This dissertation will focus on the design feature constraints of the casks, determining the suitable cask together with orientation and the storage facility requirements and suitability. The dissertation will not cover any specific nuclear power station but rather highlight design criteria that could be used.

1.3 Research aims and objectives

The aim of the dissertation is to technically evaluate SNF cask technologies available looking at: sub-criticality, shielding and containment, cask passive heat transfer, heat load, seismic stability, and storage facility types. The dissertation will attempt to provide a justification for cask selection while considering the interim storage facility and passive cooling. It will provide a deeper understanding of how these factors affect the selection process.

The research approach adopted will be through collection and review of relevant literature.

The main objectives of this research study are to:

1. Identify the criteria in the selection / design of the cask;
2. Highlight the characteristic differences between the different types of casks; and
3. Identify the most important characteristics when selecting an interim storage facility.

1.4 Structure of the dissertation

The dissertation consists of the following chapters:

Chapter 1: Introduction to the SNF dry storage cask technology.

Chapter 2: The literature review consists of the background, overview of different technologies for casks and storage facilities and previous research conducted in the area of dry storage casks. The

cask options are discussed together with the interim storage facility options for possible future use in SA. A case study of the KNPS and the way forward with cask orientation selection and suitable storage facility based on the selection/ evaluation criteria are discussed in Appendix C.

Chapter 3: A technical evaluation of the dry storage cask types will be conducted. Casks are evaluated by means of criticality, heat transfer/ heat load calculations, convective heat transfer determination and seismic stability.

Chapter 4: The research is concluded with comments and conclusions. Suggestions for future research and development are provided. The areas identified that need further investigation are highlighted in this chapter.

2. Literature Review

2.1 Background to SNF storage

Dry storage casks were first used by Virginia Power, a United States (US) Utility at the Surry Nuclear Power Station in 1986 in Virginia. Due to SFP reaching capacity, an alternative was required (Bodansky, 2004). And the casks chosen were made of metal.

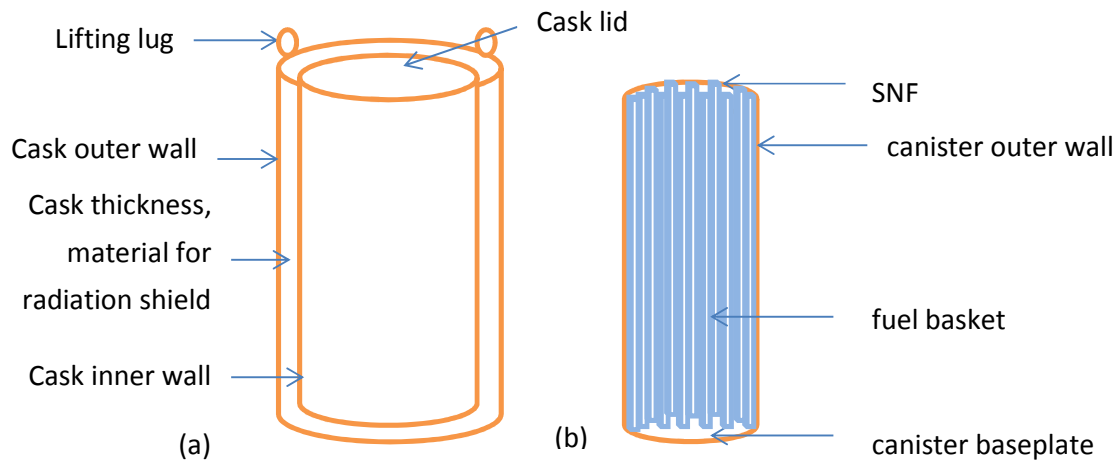


Figure 1: Simple sketch depicting (a) a cask (b) a canister

Definition of a cask: A cask is a storage container in which a canister is placed for interim storage. The cask can be made of either concrete or metal. It may or may not have an inner steel liner. It may or may not have air inlet and outlet vents for cooling of the canister. The cask has metal seals along the lid which ensure sealing from the outside environment.

Definition of a canister: A canister is a metal vessel filled with spent nuclear fuel in a basket for dry storage. The canister can withstand some pressure and is normally filled with an inert gas like nitrogen or helium. The canister has seals along the canister lid which prevents the inert gas from escaping, together with the free radionuclides that may have leaked out of the fuel. The canister normally does not perform a large shielding function, but does contribute to sub-criticality by the basket design or materials of construction.

Together the dry storage cask and canister form the spent fuel storage cask. The cask together with the storage facility design is known as the storage system.

Early casks were made of concrete or metal with a metal canister filled with gas or air instead of water as a coolant (Sovacool, 2012). Gases like helium and nitrogen were used to enhance or replace air to limit oxidation inside the canister and cask.

Below Figure 2 represents a metal storage cask.

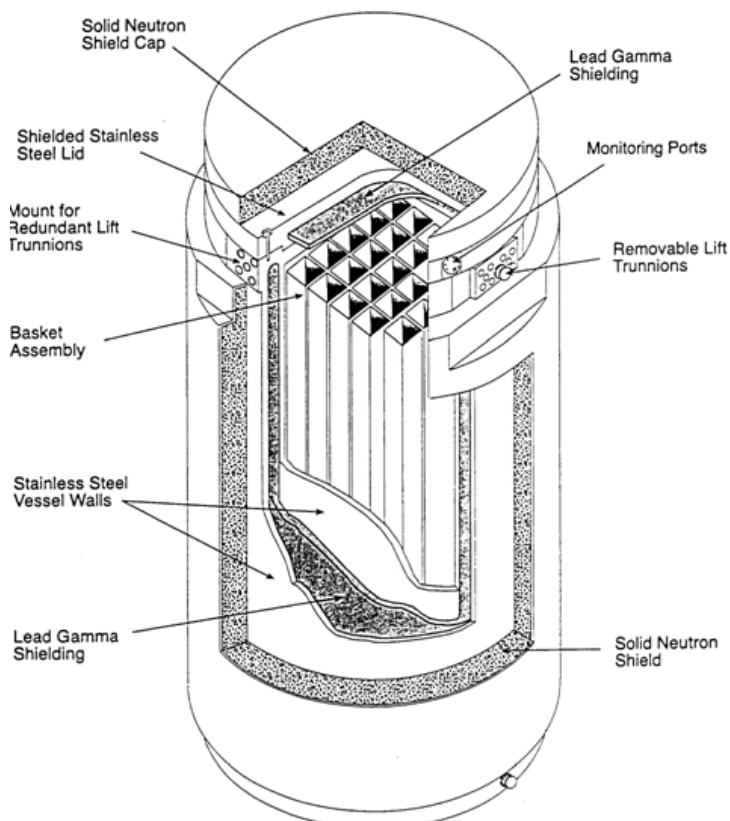


Figure 2: NAC S/T Metal Storage cask (Kessler, 2010)

The metal or concrete outer shell is the cask, where a concrete cask can be seen in the Figure 3. The diagram on the right in Figure 3 shows the inner metal lining of the concrete cask with fin-like structures for an annular air passage to allow a passive convective air flow around the transportable storage canister (TSC).

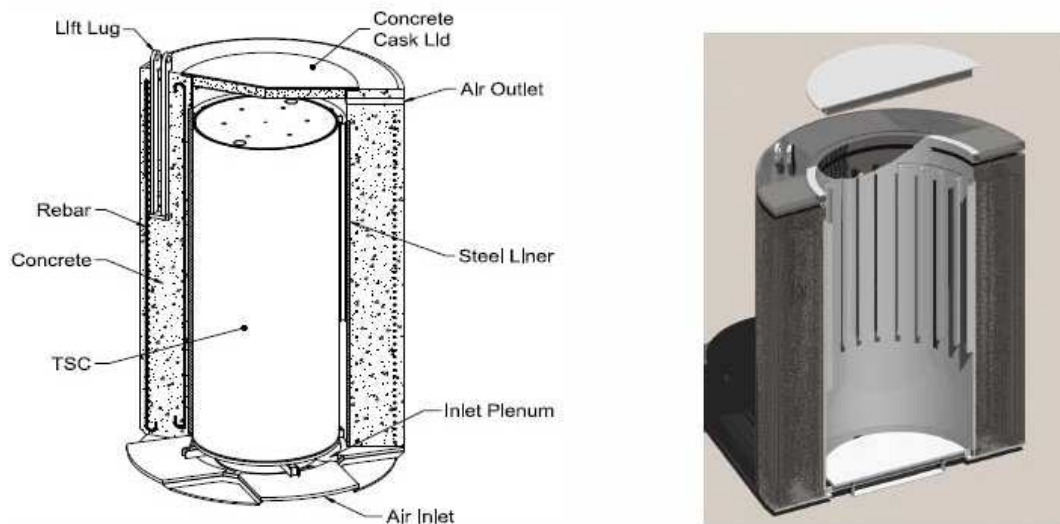


Figure 3: NAC MAGNASTOR Dual Purpose Technology (Kessler, 2010)

These casks hold between 20 and 24 pressurised water reactor (PWR) spent fuel assemblies per cask (Sovacool, 2012). The decay heat is transferred to the canister, cask and surroundings by a combination of processes like conduction, convection and thermal radiation.

All dry storage casks require licensing for either transport, storage or both. It is licensed by the regulatory authority of the country where it will be used.

With 437 nuclear power reactors, in many countries, there are more than 50 sites under general licenses and 15 sites with specific licenses for dry storage casks of SNF (NRC, 2012). At the end of 2009 there was 13856 metric tons of commercial SNF around the world of which approximately 22% is currently being stored in casks (NRC, 2012).

To date no accident events have been reported or documented on dry storage in casks due to natural disasters, sabotage, incidents or accidents (McCullum, 2012). According to the International Nuclear and Radiological Event Scale (INES) there has been no Level 1-3, incidents or Level 4-7, accidents relating to dry cask storage. The INES levels considers 3 areas of impact namely on people and the environment; radiological barriers and control; and defense in depth.

The objective of radiological waste management is to dispose of the waste in such a way that human health, safety and the environment are not adversely affected now or in the future (Carolissen, 2013) and thus not placing the burden of current radiological waste onto future generations.

According to the International Atomic Energy Agency (IAEA) Classification Scheme, radioactive waste can be placed into 5 categories based on the radioactivity levels, namely:

1. Exempt Waste (EW)
2. Very Low Level Waste (VLLW)
3. Low Level Waste (LLW)
4. Intermediate Level Waste (ILW)
5. High Level Waste (HLW)

SNF is classified as high level waste as it is highly radioactive.

An independent spent fuel storage installation (ISFSI) or transient interim storage facility (TISF) is a facility designed and constructed for the interim storage of SNF in casks. These facilities are normally licensed separately from nuclear power plants and are considered independent even though they may be located on the same site as the nuclear power plant.

According to the NNR (NNR, 2013) the spent fuel interim storage strategy involves projects which are embarked upon to ensure continued nuclear safety. The spent fuel interim storage strategy comprises of the following projects for KNPS and SA:

1. License time extension of the use of the existing four spent fuel dry storage casks in the cask storage building (CSB) at KNPS.
2. Acquisition and use of additional casks to be stored in the CSB.
3. Establishment of a Transient Interim Storage Facility (TISF) on the Koeberg site.
4. Establishment of a Centralised Interim Storage Facility (CISF) off site.

This strategy came about as Eskom indicated that the spent fuel storage capacity at KNPS would need to be expanded and thus submitted the proposed strategy above. The NNR formally accepted this strategy subject to the necessary approvals (NNR, 2013).

2.2 Safety of SNF in casks

In 2007 the Electric Power Research Institute (EPRI) and the Nuclear Regulatory Commission (NRC) determined the probabilistic risk assessment values for annual cancer risk from storage of SNF in casks. It was between $1.8E-12$ and $3.2E-14$ per year which points to the casks having a high assurance with respect to safety (McCullum, 2012).

In 2000 the Idaho National Laboratory (INL) proceeded to open a vertical cask after 14 years of successful storage of SNF and found that the long term storage had not caused detectable damage or degrading of the SNF cladding or the release of gaseous fission products (McCullum, 2012).

Casks have been proven to be safe and are used widely in the world as a solution to the accumulation of SNF at reactor sites. SNF dry storage is being used in many parts of the world including the US, Canada, Germany and Russia.

Casks and storage systems should be designed to ensure compliance with the IAEA fundamental safety functions listed below (Seies, 2003):

1. Maintaining subcriticality of SNF to avoid melting which may cause a reconfiguration of the geometry, overall geometry design and use of certain materials.
2. Removal of residual heat from SNF by means of adequate cooling by active or passive means.
3. Confinement and containment of radioactive substances by means of engineered barriers.

The safety fundamentals ensure protection of plant personnel and the public from the safety and health effects of radiation exposure by means of adequate shielding. It also protects the environment from radiation exposure. It ensures that the fuel integrity is maintained by preventing damage, corrosion or oxidation of the SNF.

There are three primary objectives for the cask storage of SNF (NRC, 2006):

1. Prevent criticality accidents of SNF.
2. Appropriate cooling and to prevent heat up of SNF.
3. Shield workers and public by providing a barrier to and containment of radioactivity.

The key technical parameters considered in the safety of SNF storage include (IAEA, 2009):

- Criticality
- Thermal load of SNF
- Burnup of the stored SNF
- Radionuclide inventory of SNF
- Physical integrity of the SNF

These factors have a significant impact on the design and operation of storage facilities and in terms of cost of storage.

2.3 Storage options

SNF dry storage casks are robust systems with no moving parts and it uses the defence-in-depth principle to provide long term protection and storage of SNF up to 50 years. The defence-in-depth principle implies making use of multiple barriers to shield against radiation and to prevent the escape of radioactive material from the nuclear fuel to the environment. These barriers normally include the fuel matrix, fuel cladding and storage container (i.e. cask lids and seals) located in a storage facility (IAEA, 1994).

Table 1 depicts the wet and dry options for spent nuclear fuel storage, showing the heat transfer which takes place, containment mechanism, shielding means, specific features of each as well as examples of such technology.

Table 1: Technical options and applications for spent fuel storage as given by (IAEA, 2009)

| <i>Type</i> | <i>Option</i> | <i>Heat Transfer</i> | <i>Containment (medium)</i> | <i>Shielding</i> | <i>Feature</i> | <i>Examples</i> |
|-------------|----------------------------|--|--|------------------------------------|---|--|
| <i>Wet</i> | <i>Pool</i> | <i>Water</i> | <i>Water/ building</i> | <i>Water</i> | <i>Classic option</i> | <i>Worldwide located either at reactor pools (e.g. Koeberg) or at away from reactor storage facilities</i> |
| <i>Dry</i> | <i>Metal cask</i> | <i>Conduction through cask wall, convection around cask body</i> | <i>Double lid metal gasket (Inert gas)</i> | <i>Metallic wall</i> | <i>Dual purpose, vertical or horizontal</i> | <i>CASTOR, TN, NAC-ST/STC, BGN Solutions</i> |
| <i>Dry</i> | <i>Concrete cask/ silo</i> | <i>Air convection around canister</i> | <i>Cavity lining/ seal welding (Inert gas)</i> | <i>Concrete and steel overpack</i> | <i>Vertical</i> | <i>CONSTOR, HI-STORM/ HI-STAR</i> |
| <i>Dry</i> | <i>Concrete module</i> | <i>Air convection around canister</i> | <i>Canister sealing (Inert gas)</i> | <i>Concrete wall</i> | <i>Horizontal</i> | <i>NUHOMS, NAC-MPC/UMS, MAGNASTOR</i> |
| <i>Dry</i> | <i>Vault</i> | <i>Air convection around thimble tube</i> | <i>Thimble tube (Inert gas)</i> | <i>Concrete wall</i> | <i>Several cases</i> | <i>MVDS, MACSTOR</i> |
| <i>Dry</i> | <i>Drywell/ tunnel</i> | <i>Heat conduction through earth</i> | <i>Canister (Inert gas)</i> | <i>Earth</i> | <i>Below ground</i> | <i>Not commercialized</i> |

Due to the drywell / tunnel concept not being commercialized (IAEA, 2009) it is not included in further evaluations or research.

With the dry storage of SNF in casks, some utilities require storage to take place in either a temporary onsite or central offsite interim storage facility. There are four main types of storage facilities that are utilized, namely:

- concrete pad with fencing to control access;
- concrete pad with metal cladding-type structure similar to that of a warehouse;
- concrete building similar to that of the reactor containment structure; and
- concrete modular storage system located either above or below ground.

The space required for modular storage is also less when considering the amount of SNF that can be stored per square meter in the storage facility. However, it does not provide the arrangement flexibility of free-standing casks.

2.4 Types of Casks

There are many dry storage cask designs available from various international vendors and their technologies are distinguished by the following technical characteristics (IAEA, 2009):

- Heat transfer method
- Type of shielding
- Transportability
- Location with respect to the geological surface
- Degree of independence of the individual storage units
- Storage structure
- Material of construction
- Size
- Modularity
- Spent fuel configuration
- Layout and orientation of the storage containers (horizontal, vertical etc.)
- Methods for fuel handling

The main features of dry storage systems are (V. Roland, 2014):

- A multiple containment barrier
- Passive cooling
- Meeting subcriticality requirements
- Safe handling operations
- Future decommissioning
- Construction and operating cost-effectiveness

The following sections will expand on these variations and provide the information needed to do a technical comparison between the various solutions.

2.4.1 Dry Storage Cask Differences

Casks can be categorised based on the material of construction, orientation during storage, its purpose, and closure mechanism. A single purpose cask is for storage or transport only. A dual purpose cask is for storage and transportation. A multi-purpose cask is for storage, transport and final disposal in a repository. The terms dual and multi-purpose casks are used interchangeably by companies and forms part of marketing as no repository exists where the concept has been

demonstrated for long term storage of SNF using multi-purpose casks. A bare-fuel cask is a cask where the fuel is located directly in the cask by making use of a basket and a canister-based cask contains a canister inside the cask.

The options mentioned above can be seen in Table 2 where the cask type, material of construction, orientation, purpose, closure mechanism and facility types are all interchangeable depending on the selected cask design. The cask design can then be linked to a suitable facility type based on the requirements and the need.

Table 2: Classification of casks for SNF storage

| Cask types | Materials of construction | Orientations | Purposes | Closure Mechanisms | Facility types |
|----------------|---------------------------|--------------|----------|--------------------|---------------------------|
| Bare-fuel | Metal | Vertical | Single | Welded closed | Concrete pad |
| Canister-based | Concrete | Horizontal | Dual | Bolted closed | Pad with metal shed/ barn |
| | | | Multi | | Concrete building |
| | | | | | Vault/ storage modules |

Table 3 highlights the advantages and disadvantages based on casks material of construction namely metal or concrete.

Table 3: Advantages and Disadvantages for different types of casks

| Material of construction | Advantages | Disadvantages |
|--------------------------|--|--|
| Metal | Can be orientated vertically or horizontally. Can be welded or bolted closed. Single, dual and multi-purpose casks. | More expensive than concrete. Certain metals are prone to atmospheric stress corrosion cracking due to chloride levels in sea air for plants located at coastal areas. Tipping of vertical cask could occur due to smaller diameter. |
| Concrete | Could be cheaper due the less expensive manufacturing process and less metal used. Can only be stored vertically. Corrosion resistant. | Could fracture or crack during an impact or seismic incident. Mainly single purpose cask due to weight of large concrete volume. Tipping of concrete cask could occur but has a larger diameter than the metal ask. |

2.4.2 Metal Casks

Metal casks are made of forged steel, cast iron or a composite material, and can be stainless steel, or normal carbon steel, often with a painted outer surface. The material of construction provides the shielding function. They are considered to be dual casks as they can be used for both transport

and storage. These casks can be stored in an open environment on a concrete pad in a vertical or horizontal position. In countries like Switzerland, Belgium, and Germany casks are stored within buildings which are thick concrete walled structures.

Figure 4 to Figure 8 illustrate types of metal casks from a variety of suppliers with the various components identified.

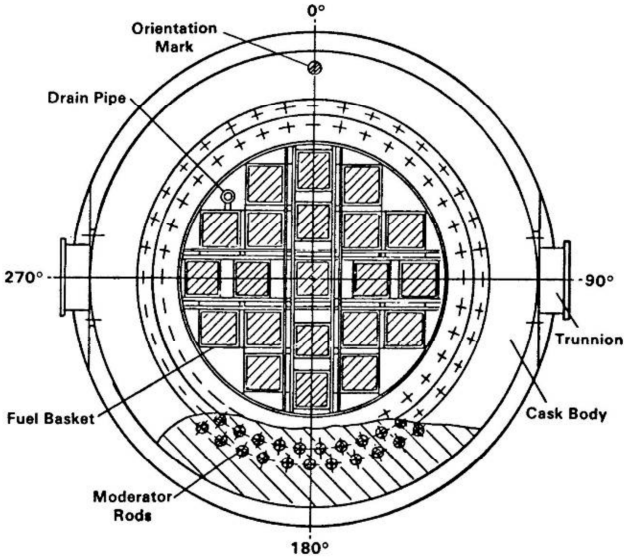


Figure 4: Castor V-21 cross-section (S.R. Greene, 2013)

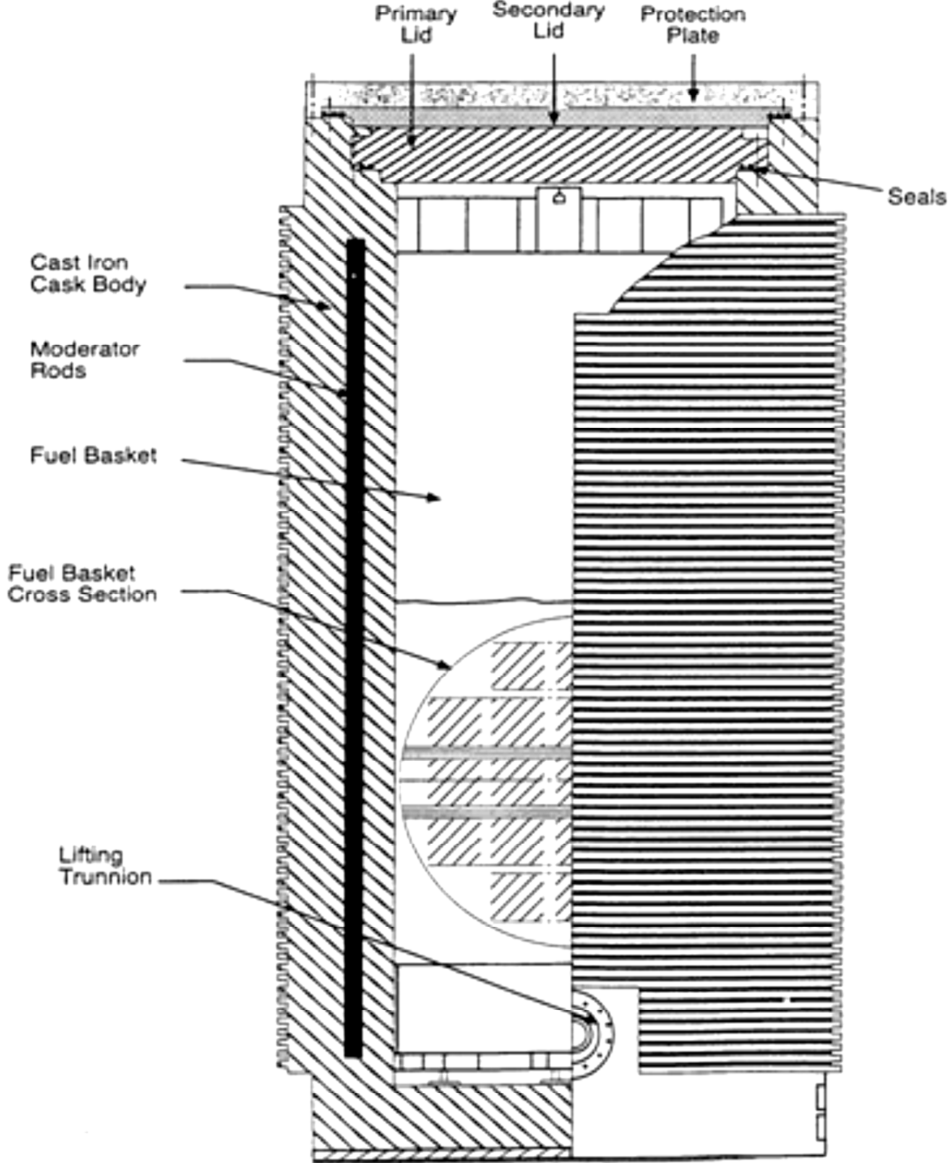


Figure 5: CASTOR V-21 Metal Storage Cask (NEI, 1998)

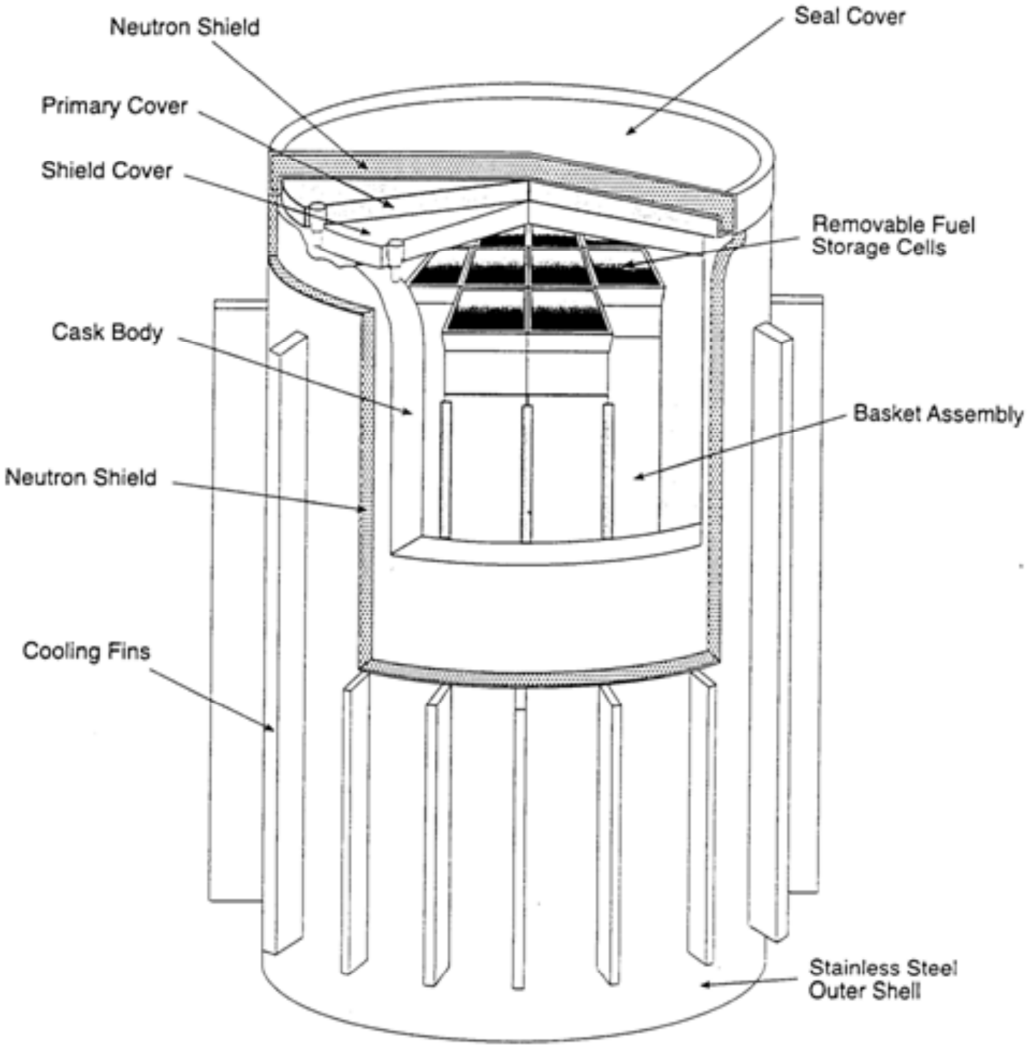


Figure 6: Westinghouse MC-10 Metal Storage Cask (NEI, 1998)

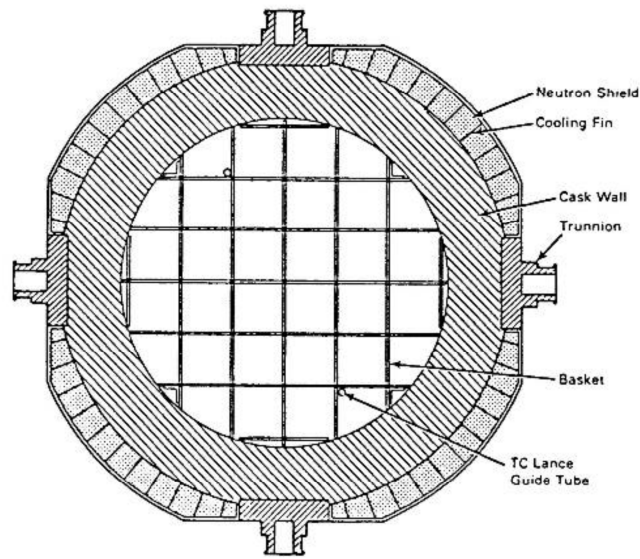


Figure 7: TN-24P cross-section (S.R. Greene, 2013)

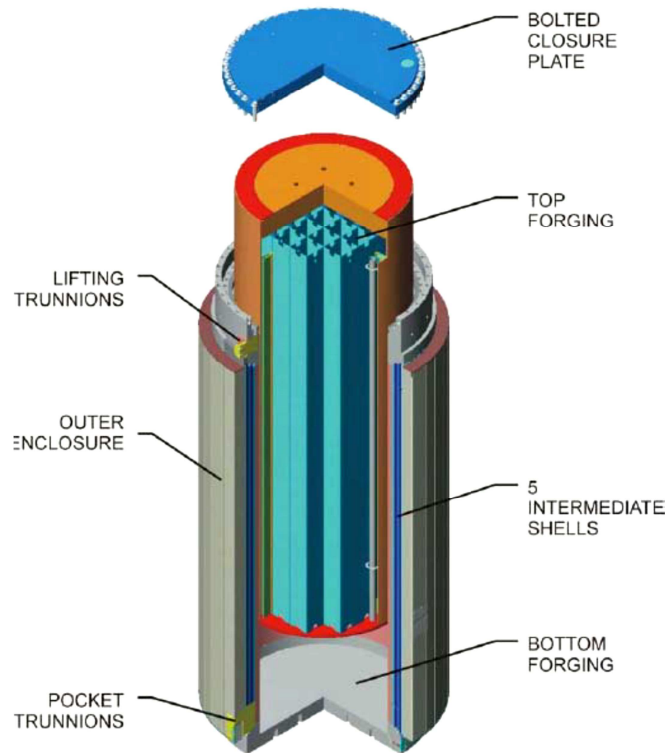


Figure 8: HI-STAR 100 with metal overpack, multi-purpose cask partially inserted (Haire, 2005)

Each component has a specific purpose and function aiding the cask in fulfilling its design function for the storage of SNF.

Figure 9 shows the cask lid pressure monitoring system setup. This is to provide a system that will give an early indication if the lids or seals are leaking.

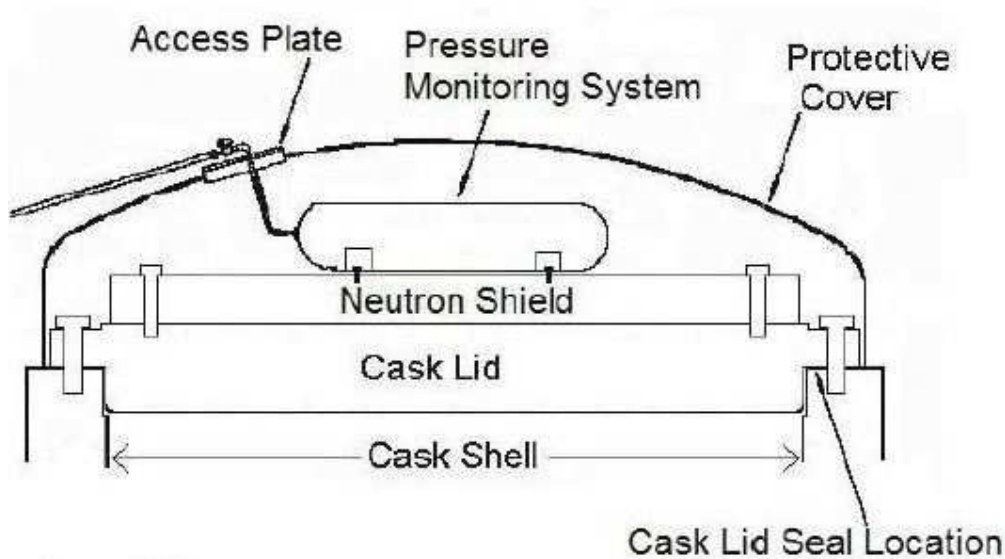


Figure 9: Cask pressure monitoring system (NRC, 2006)

A typical metal cask consists of the following components (IAEA, 2009):

- A basket which supports the fuel assemblies inside the cask and transfers the heat from the fuel assembly to the cask body wall. The material of construction provides neutron absorption capabilities which satisfy the nuclear criticality requirements which prevent fuel criticality.
- The containment vessel which consists of a welded inner shell carbon steel or stainless steel cylinder, bolted lids, two penetrations (one for draining and one for venting) and double metallic O-ring seals with interspace leakage monitoring.
- Gamma shielding is provided by a plate of carbon steel around the inside of the vessel and is welded to the closure flange. The gamma shield also covers the vessel inside shell. This specifically relates to the TN-68 type cask but features in other casks vary with material and thickness of material used.
- Neutron shield in some designs are provided by a borated polyester resin compound inside the vessel wall.
- Protective external cover for protection from atmospheric weather conditions.
- Pressure monitoring system is present as in Figure 9 above.
- Upper and lower trunnions are present for lifting and rotation of the cask.

- Cooling fins are an additional feature in some cask designs and are vertically or horizontally around the cask's outer surface. It aids with the air flow and ultimately aids the heat transfer by increasing the outer heat transfer surface area of the cask.

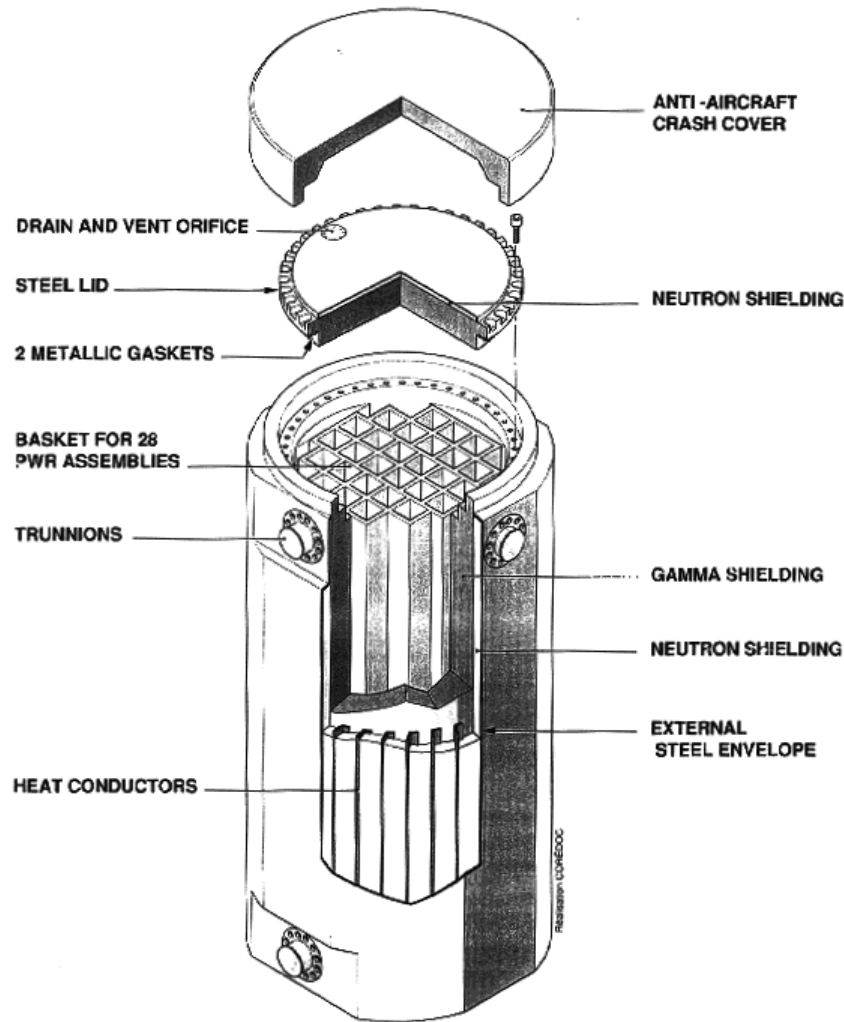


Figure 10: TN-24P cask (Kirchner, 1997)

Metal casks require minimal additional equipment and can be readily relocated to an interim, final, and centralized storage facility or repository. These casks are considered to be a compact system with the ability to be easily rearranged and are easily handled in a storage facility (V. Roland, 2014).

2.4.3 Concrete Casks and modules

Concrete casks

Concrete casks have the same shape as metal casks where the only difference is the concrete overpack as seen in Figure 11, which provides the shielding. The carbon steel liner, seals and lids present in the inner canister cavity provides the containment. The concrete overpack provides structural support, shielding and protection from environmental conditions. Some of the concrete casks have an inner annular air passage to allow the natural circulation of air around the cask. This is for natural convective cooling to take place closer to the canister. This reduces the thickness of the concrete cask and the canister gap. The air is then drawn in closer to the canister and aids the cooling process. There are air inlet and outlet vents in that type of concrete cask as seen below in Figure 11 to Figure 13.

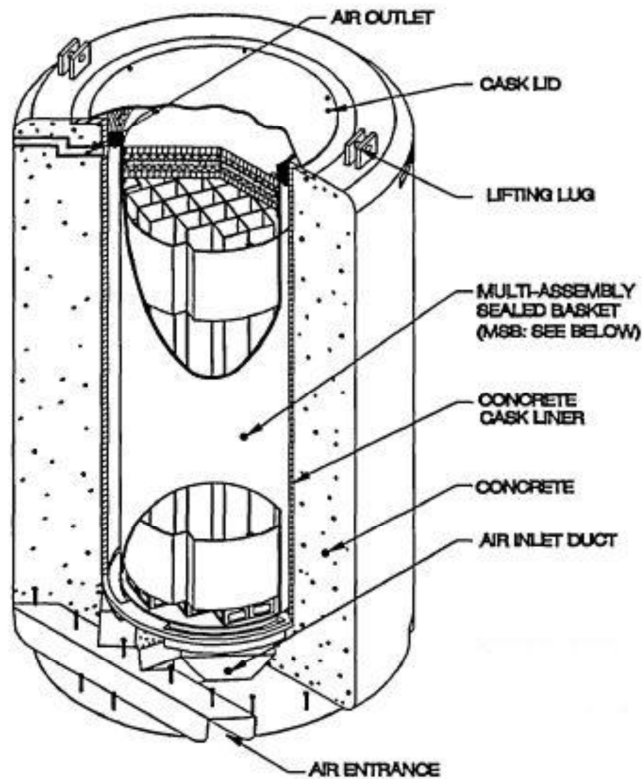


Figure 11: VSC-24 Concrete Storage Cask (Solutions, 2005)

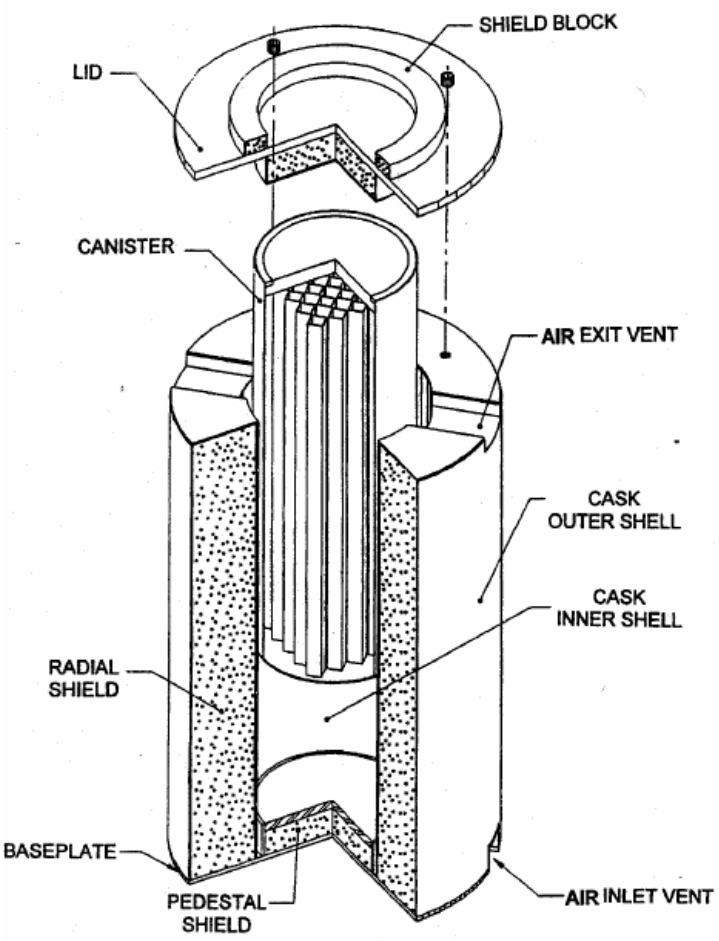


Figure 12: Cross section of the HI-STORM 100, concrete overpack with MPC-24 (Kessler, 2010)

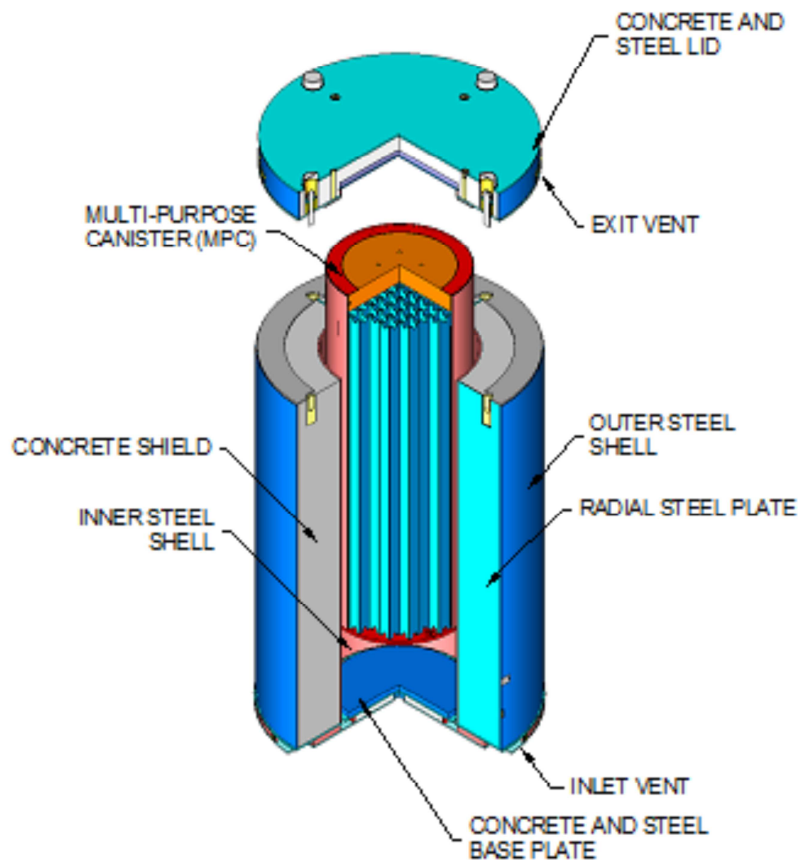


Figure 13: HI-STORM 100 concrete cask (S.R. Greene, 2013)

A typical concrete cask consists of the following components (IAEA, 2009):

- A transportable storage canister when carried inside a transport cask
- A fuel basket
- A shield lid
- Two penetration port covers
- A structural lid

Concrete casks draw in ambient air from the inlet vent and the air is used for cooling of the canister. This heated air is then rejected from the outlet vent above. A cooling path is thus created between the outside of the canister and the inside of the concrete vessel. The thermal shield plate installed in the middle of the annular cooling path prevents radiation heat transfer from the canister to the concrete vessel. It divides the cooling path into two. Heat from the canister warms up the air and gives the buoyancy force thus allowing the air to flow upwards and outwards. The flow rate of the air is determined by the balance between the pressure loss in the concrete cask and the buoyancy force from the heat in the canister. The concrete cask is cooled by its self-sustaining air flow (Saegusa, 2008).

Concrete modules

Concrete modules are similar to concrete cask except that they are horizontal concrete storage systems e.g. NUHOMS storage system as illustrated in Figure 14 and Figure 15.

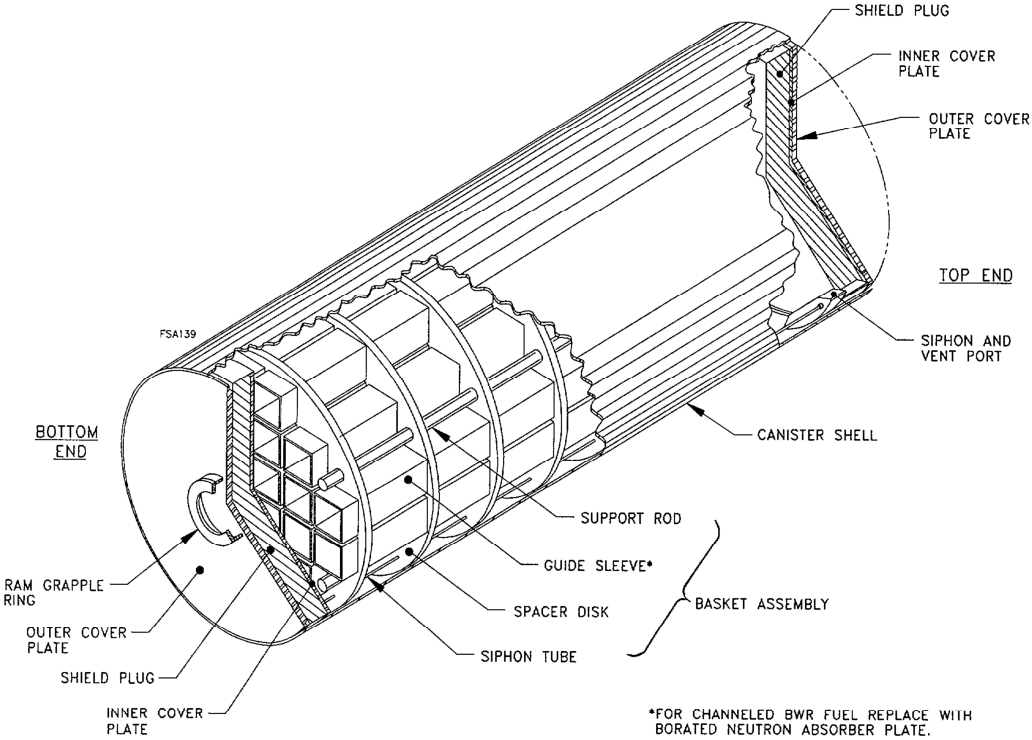


Figure 14: NUHOMS-24P dry shielded canister (S.R. Greene, 2013)

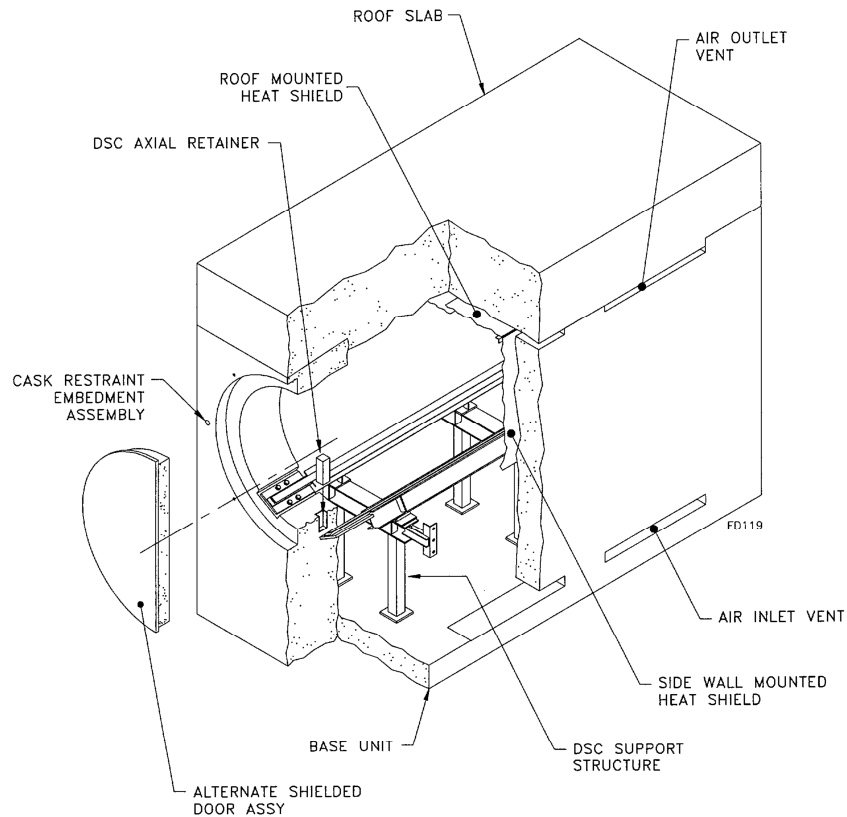


Figure 15: NUHOMS Horizontal Storage Model- HSM Model 80 (S.R. Greene, 2013)

Steel metal canisters are used to contain the SNF in this type of system. The SNF are loaded vertically into the sealed metal canister which are then stored in the horizontal orientation inside the concrete storage module as depicted in Figure 15. The metal canister in Figure 14 uses a double lid closure and are seal welded and tested for leak tightness before being placed inside the concrete module.

Summary

Concrete shielded canister-based systems have the advantage of being more cost effective when compared to metal casks as less metal is used. It has the shielding advantage with the use of concrete overpack or modules and allows local production of light metal canisters (V. Roland, 2014).

The space required for modular storage is also less when considering the amount of SNF that can be stored per square meter in the storage facility. However, it does not provide the arrangement flexibility of free-standing casks.

2.4.4 Vaults

A vault is a reinforced concrete structure containing storage cells made of metal tubes or storage cylinders. Each cell can normally contain one or more SNF assemblies. It is built either above or below ground where the shielding is provided by the surrounding structure. For an above ground structure heat is normally transferred to the atmosphere by natural convection of air over the external surface of the cells. Figure 16 and Figure 17 shows a typical vault.



Figure 16: Modular Vaults Dry Store (MVDS) similar to what is used at Fort St. Vrain (Management, 2014)

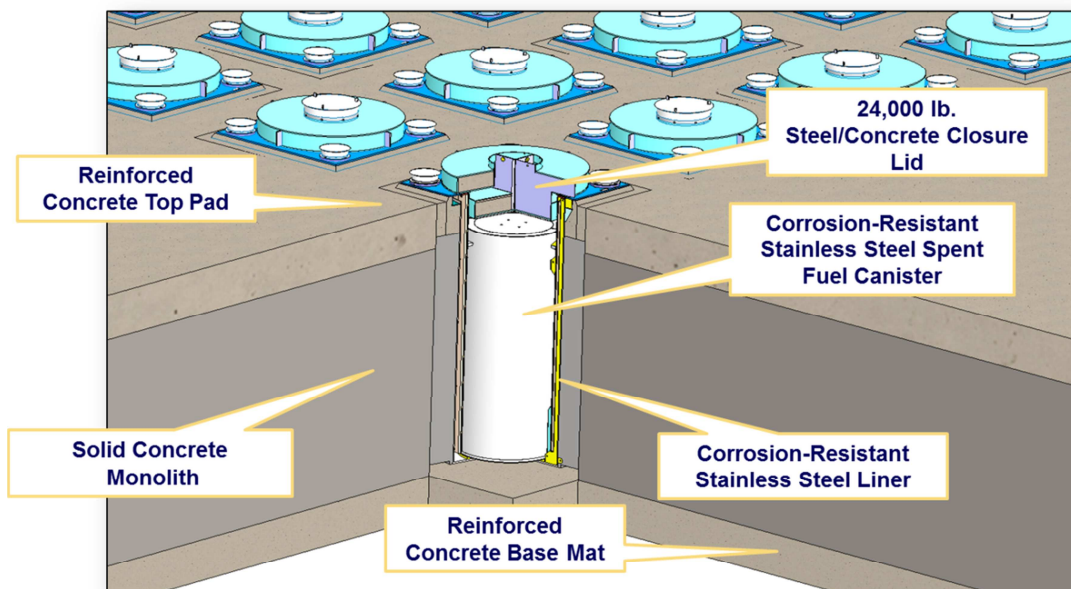


Figure 17: HOLTEC HI-STORM UMAX System (Madigan, 2015)

Another example of a vault is a drywell. It is a stationary, below ground, lined, individual cavity. Each cavity can contain a few SNF assemblies and depends on the used fuel characteristics. Shielding is provided by the earth and the heat is removed by conduction from the fuel through the cavity liner.

Another example of a storage vault is the twin tunnel concept where this is a subsurface storage method and combines the dry well concept with the borehole type placement in geological disposal repository. The concept has not been used on a commercial scale to-date.

Vaults provide large storage capacity for SNF and can accept different fuel types. This is often the preferred solution for long term dry interim centralized storage (V. Roland, 2014). These vaults are passive, natural thermosyphon air-cooling like those at the Fort St. Vrain reactor which is the Irradiated Fuel Storage Facility (IFSF). These are steel-lined, below ground, individual vaults as in Figure 16.

2.5 Types of Spent Fuel Storage Facilities

The Transient Interim Storage Facility (TISF) will be the new storage facility at KNPS for the storage of either vertical casks, horizontal casks or a combination of both depending on the specific site requirements. TISF is also known as ISFSI in other parts of the world but is based on the same design and operational principle. There is currently no ISFSI in South Africa or at KNPS. Currently there is a cask storage building (CSB) located at KNPS which houses four horizontal, metal-type casks. Table 4 indicates the options available for interim storage facilities with their associated advantages and disadvantages.

Table 4: Advantages and disadvantages for different types of dry storage facilities (Vernon, 2014)

| TISF Option | Advantages | Disadvantages |
|-------------------------------------|---|--|
| Concrete pad only | Simplest design offering 100% passive cooling of the casks. Most economical, quickest to design and construct. Most cost-effective of the four options. Withstands effects of earthquakes, soil liquefaction and storm water when suitably designed. Lowest environmental impact and simplest to decommission. Concrete slabs can be constructed modularly or all at once. | Relies on cask's design features to protect the SNF. Cask corrosion concerns. Exposure to atmospheric conditions. Public perception of such a facility might not be favourable. External security measures required. |
| Concrete pad with cladded enclosure | Simple design and easy to construct. Protection from atmospheric conditions. Less expensive when compared to the concrete building. Caters for overhead gantry type crane. Ductile steel structure- can resist large seismic | Additional debris with seismic or tsunami events which may hamper cask retrieval. Facilities inside environment might be difficult to control. Design analysis for passive cooling. |

| TISF Option | Advantages | Disadvantages |
|---|--|---|
| | loads without collapse. Offers adequate security. Can be designed for passive cooling. Public perception more favourable. Easily decommissioned. | |
| Concrete building | Best security. Best in terms of public perception. Controlled environment for dry storage casks. | Complex design. Expensive option to construct. Seismic qualification required. Longest and most complex design to construct. Increase in design time, longer licensing process and increased costs. Facility not easily modularised. Much analysis and design is required to prove passive cooling is possible. |
| Concrete modular storage system (vault) | System offers 100% passive cooling. Largely off-the-shelf system. Pre-designed and quick to construct. System is less expensive than a concrete building. System offers good protection from external events. Offers good security. System is modular as units can be added as required. | More expensive than the pad with clad enclosure. Cask storage system is very visible to public. |

All dry storage facilities are suitable for the interim storage of casks but there are differences between them. These differences play a role in the selection of the most suitable storage facility based on the type of fuel, site requirements and cost implications. These and other factors are normally considered and a decision matrix is formed to narrow down the selection. Table 5 provides examples of dry storage systems in use in other parts of the world.

Table 5: Examples of Dry Storage Systems in use (Twala, 2007)

| Concept/ Model | Vendor | System Classification | Capacity and Fuel Type range | User(s) |
|------------------------------------|---------------------------|---|-------------------------------------|---------------------------------|
| CASTOR | GNS, Germany | Several cask-based, dual-purpose (transport & storage) system | 19-28 PWR | Europe, Asia, North America, SA |
| HI-STAR/ HI-STORM | HOLTEC International, USA | Canister-based, dual-purpose system | BWR and PWR | USA |
| NAC-STC | NAC International, USA | Canister-based, dual-purpose system | 26 PWR | USA |
| NAC Universal MPC System (NAC-UMS) | NAC International, USA | Canister-based, dual-purpose system | 24 PWR or 56 BWR | USA |
| TN-24 | Transnuclear, | Several versions of cask- | 24-37 PWR or 52-97 | Europe |

| Concept/ Model | Vendor | System Classification | Capacity and Fuel Type range | User(s) |
|---|--|---|-------------------------------------|-------------------------|
| | <i>France</i> | <i>based, dual-purpose system</i> | <i>BWR</i> | |
| <i>NUHOMS Horizontal storage module (HSM) Dry shielded canister (DSC)</i> | <i>Transnuclear West, USA</i> | <i>Canister-based, dual-purpose system</i> | <i>24-32 PWR or 52 BWR</i> | <i>USA</i> |
| <i>Modular Vault Dry Storage (MDVS)</i> | <i>Foster Wheeler Environmental Corporation/ ALSTEC, USA</i> | <i>Natural convection vault system; canister-based, modular dry storage</i> | <i>AGR, HTGR, PWR, BWR and VVER</i> | <i>USA, UK, Hungary</i> |
| <i>MACSTOR (modular air cooled)</i> | <i>AECL, Canada; Transnuclear, France</i> | <i>Natural convection vault system</i> | <i>PWR and BWR</i> | <i>France</i> |

Figure 18 illustrates a concrete pad storage facility for vertical concrete casks. This illustrates what a typical storage facility, TISF or ISFSI is like.



Figure 18: Dual purpose canister system on concrete pad, ISFSI at Connecticut, Yankee (D. Vinson, 2011)

2.5.1 Concrete Pad

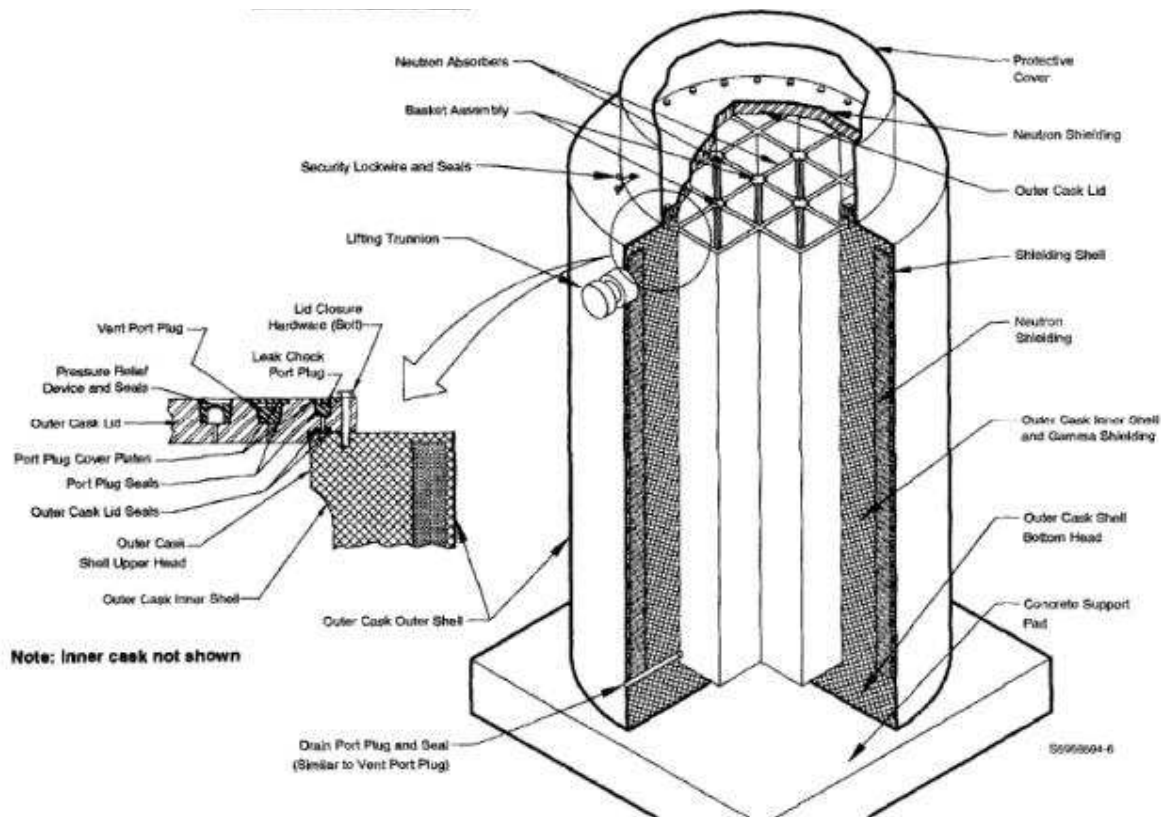


Figure 19: Vertical metal-shielded dry cask system located on a concrete support pad (International, 2012)

The pad is a reinforced concrete slab designed to support the mass of the fully loaded casks. It is specifically constructed to handle the metal or concrete cask weight for interim storage of SNF within casks. This can be seen in Figure 18 and Figure 19. It should be designed to withstand the effects of any natural site phenomena, including the seismic spectrum in a specified design base accident (DBA), soil liquefaction, flooding and severe weather conditions. The design process for such structures is relatively simple when compared to other structures, since the design features of the casks themselves are used to protect the SNF.

The concrete pads allow the outer cask to be passively cooled by ambient air. The concrete pads can easily house vertical casks or horizontal casks with stands.

Concrete pad facilities are the most economical to construct due to their simplicity. However they can introduce other challenges, including corrosion, shielding and public perception concerns. Austenitic stainless steel casks are not always used for this type of facility at the sea side due to the potential of this type of steel undergoing atmospheric stress corrosion cracking (SCC) due to chlorides present in the sea air. These corrosion effects can however be mitigated and monitored.

Many nuclear power stations are located close to the sea and therefore this factor needs to be considered. Component failures can occur in the welded stainless steels in 11-33 year period with an estimated crack growth rate of 0.11 to 0.91 mm/year (US-NRC, 2014). US-NRC states that 304 and 316 stainless steels are susceptible to chloride stress corrosion cracking (US-NRC, 2014). This is mainly due to sensitivity from the welding process and crevice or pitting corrosion which are precursors to SCC.

2.5.2 Concrete Pad with cladded-type structure



Figure 20: Concrete pad with cladded-type enclosure structure as ISFSI facility (Reddit, 2010)



Figure 21: Cask storage facility (building) before Fukushima disaster (Sanono, 2013)

Figure 20 and Figure 21 show examples of concrete pads with cladded-type enclosures. This is similar to the concrete pad design in that it has a reinforced concrete slab to support the casks. It differs from the pad in that it is covered by a warehouse type structure built on top of the concrete pad which protects the casks from some of the atmospheric conditions. The structure would have a steel frame which is clad with a sheeting of suitable material. It also keeps the casks out of direct sight and sunlight. It is fairly quick and inexpensive to build, and allows most of the structure to be manufactured off-site and to be erected onsite. It allows for an overhead gantry type crane for the transportation of casks inside the indoor facility. The steel structure is also ductile, which can resist large seismic loads without collapsing due to the metal's ability to be deformed without losing toughness, pliability and therefore is not brittle. It is suitable for both metal and concrete casks with any orientation and can be designed accordingly provided there is no size or space limitation. Special ventilation systems are required to ensure passive cooling of the casks at all times together with a contingency for power failures or equipment breakdowns. These ventilation systems can also be designed to filter the air thus reducing the environmental corrosive effect on the casks thus extending their storage life.

2.5.3 Concrete Building



Figure 22: Transport and storage casks in the concrete interim storage facility of Gorleben, Germany (Sanono, 2013)

Concrete building example can be seen in Figure 22. A concrete building is similar in design to a concrete containment building where the pad and walls would be constructed from reinforced concrete. The roof structure would either be constructed from concrete or from metal roof sheeting and trusses. It can house vertical or horizontal casks and can be designed accordingly provided there is no size or space limitation. The building structure is required to withstand earthquakes, natural disasters and to protect the casks from damage and severe weather conditions. It also protects the casks from atmospheric SCC. The concrete building is suitable for both concrete and metal casks.

An aspect to consider when choosing such a structure is seismic qualification. Whilst the strong concrete structure offers protection against certain natural and other phenomena, seismic events cannot be allowed to affect the structure causing it to fail. This would prevent and inhibit the safe retrieval of the stored casks. This increases the design and associated costs. This is by far the most costly option to construct due to the use of large amounts of building material and to ensure the seismic stability of the facility.

2.5.4 Concrete modular storage system

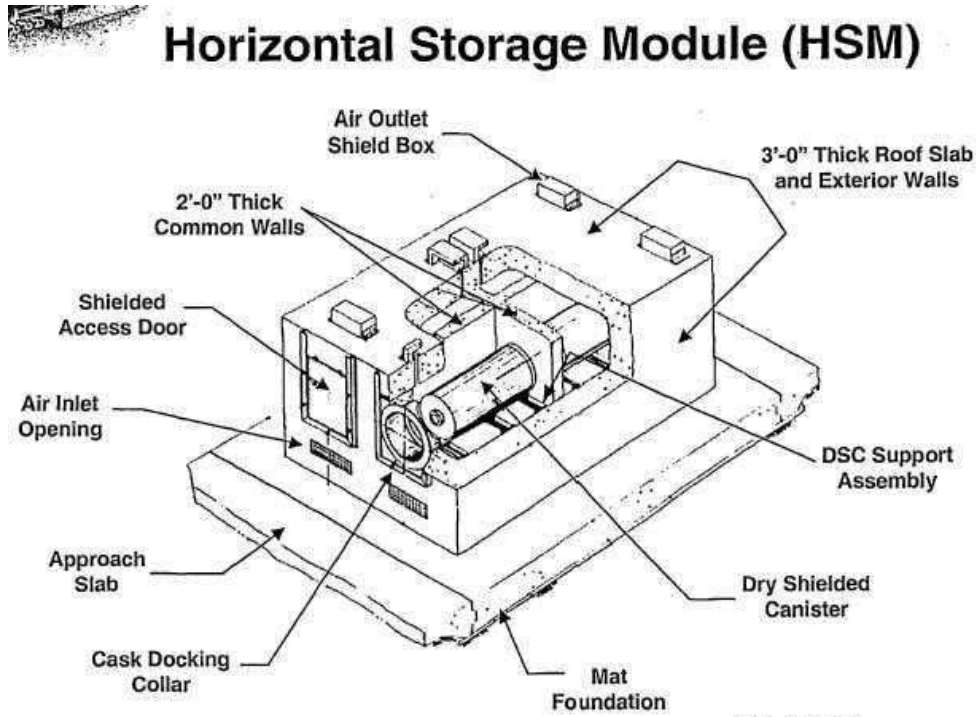


Figure 23: Horizontal storage module showing concrete modular storage (Transnuclear, 2011)

This type of storage is above-ground as can be seen in Figure 23. Currently, this system makes use of austenitic steel canisters into which SNF are loaded (Transnuclear, 2011). These canisters are transported to the storage facility in a metal transport cask. Once at the site the canisters are pushed horizontally out of the metal transport cask and into the concrete constructed overpack. These overpacks are well reinforced to resist seismic and other loads. They are also smaller and less expensive than a complete concrete building, and can be implemented in a modular fashion. The design does rely on vents in the concrete structure to allow heat from the canister to be released to the environment, due to the poor heat conductivity of the concrete. It is important to note that the selection of such a system also selects canister technology for use with the system from a specific manufacturer.

2.5.5 Summary

Table 6 summarises the comparison of dry storage cask options based on the cask characteristic information available. It highlights the design, transport, storage, heat transfer, containment, radiation shielding and feature characteristics. Table 6 is adapted from IAEA TECDOC 1558.

Table 6: Dry storage cask comparison information (Miles Pomper, 2013)

| | Design | Transport | Storage | Heat transfer | Containment | Shielding | Feature | Example |
|-----|---|---|--|--|--|--|----------------------|---------------------------|
| 1 a | Cast metal cask | Bolted secondary lid with elastomer seals and primary lid with metallic seals | Bolted secondary and primary lid with metallic seals | Conduction through basket and cask walls | Double bolted lids with metallic seals | Metallic wall | Dual purpose | GNS |
| 1 b | Massive or composite forged metal cask | Bolted secondary lid with elastomer seals and primary lid with metallic seals | Bolted secondary and primary lid with metallic seals | Conduction through basket and cask walls | Double bolted lids with metallic seals | Metallic wall | Dual purpose | ES, Holtec, MHI, NAC, TNI |
| 1 c | Concrete cask | Concrete cask with bolted lids and elastomer seals | Concrete cask with bolted lids and metallic seals | Conduction through basket and cask walls | Double bolted lids with metallic seals | Concrete wall | Dual purpose | GNS |
| 2 a | Forged metal transport cask and concrete overpack | Forged metal transport cask with bolted lid and elastomer seals | MPC in concrete overpack | Air convection around canister | Double welded lids | Concrete wall | Vertical | ES, Holtec, NAC |
| 2 b | Forged metal concrete cask and simple metal overpack | Forged metal transport cask with bolted lid and elastomer seals | MPC in simple metal overpack | Air convection around canister | Double welded lids | Metallic wall and additional neutron shielding | Vertical | TNI |
| 2 c | Forged metal transport cask and concrete module | Forged metal transport cask with bolted lid and elastomer seals | MPC in concrete module | Air convection around canister | Double welded lids | Concrete wall | Horizontal | TNI |
| 2 d | Forged metal transport cask and underground concrete overpack | Forged metal transport cask with bolted lid and elastomer seals | MPC in concrete module | Air convection around canister | Double welded lids | Concrete wall | Vertical underground | ES, Holtec |
| 3 | Vault | Forged metal transport cask with bolted lid and elastomer seals | Steel lined tubes in massive concrete block | Air convection around tubes | Thimble tube | Concrete | 1 FA/tube | Fort St Vrain, Paks |

2.6 Considerations for cask orientation

2.6.1 Cask footprint requirements

The orientation of the casks in either vertical or horizontal orientation has a direct effect on the footprint of the cask and therefore affects the facility size and conceptual design. The overall design of the facility would be dependent on the land availability on-site and number of SNF and storage casks required in such a storage facility.

Casks are normally freestanding or resting unanchored on a reinforced concrete pad. A facility can be built with concrete floor slabs in 6 m by 6 m sections for the entire concrete floor slab. This is to provide the strength of the floor and better seismic stability.

A typical arrangement of casks on a concrete pad consists of an array of 12 vertical casks in two rows on an 11 m by 29.3 m pad (Bjorkman, 2010) as in Figure 24. The distance from the edge of the pad to centre of the vertical cask would typically be 2.5 m. The distance between the midpoints of two casks would be 5 m. This is to aid the movement of casks between others with cask moving machinery. It also provides the stability that if one cask should fall over that it would not cause a falling domino-effect or damage to adjacent casks.

Horizontal casks would in general require the same passage space between them, even though they occupy a larger rectangular footprint. A storage facility with horizontal casks will be larger than for the same amount of vertical casks by approximately the aspect ratio of the cask.

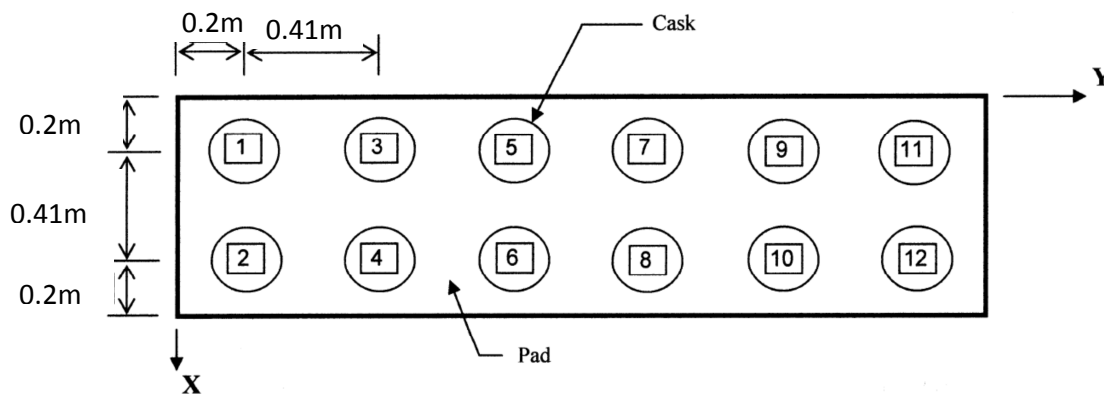


Figure 24: Plan view of 12 vertical casks on storage pad (Bjorkman, 2010)

2.6.2 Effect on heat transfer

A concrete cask with ventilation channels is considered to be reliable and safe and it is cooled by independent natural convection (Saegusa, 2008). Decay heat is generated in the casks as a result

of mainly gamma and beta decay of fission products inside the SNF. The decay heat must be removed and this is through the natural convection of air. The cask draws in ambient air at the bottom of the cask. The air cools the canister containing the SNF. The air heats up and gives a buoyancy induced air flow. The warmer air then rises and leaves the outlet at the top of the cask. The flowrate of the air is determined by the pressure loss in the cask and buoyant force given by the excess heat from the canister. Heat transfer also occurs through the cylindrical wall of a concrete overpack by conduction. Heat transferred from the cask to the environment is therefore by passive means only. When in a vertical orientation, the cooling channels create a chimney effect which enhances the heat transfer and cooling air mass flow.

The average environmental / ambient temperature is 20°C and off-normal ambient temperature is considered to be 45°C. Specific cask designs can be designed to hold approximately 24 PWR SFA with an average burnup of 55GWd/MTU with an average cooling time of 7 years in the SFP (Ju-Chan Lee, 2004). The decay heat load from 24 PWR SFA in one canister would be 25.2kW and the maximum canister wall temperature can be estimated around 170°C (Ju-Chan Lee, 2004) after 7 years of being discharged from the reactor.

To design a suitable storage facility the heat transfer rate from the storage cask to the surrounding air needs to be estimated. The decay heat from the SNF, when casks are placed vertically inside the facility, is transferred by convection to air, radiation and conduction to the concrete floor (Hattori, 1999). It was found that the heat transfer by air convection currents was the most dominant.

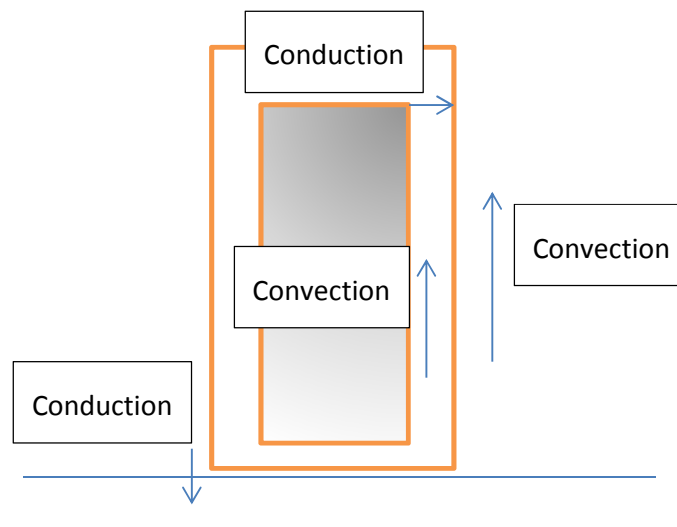


Figure 25: Heat transfer schematic diagram

The heat transfer mechanism inside the facility showed that two kinds of flow existed namely natural circulation in the facility and buoyancy flows near the cask. There is a strong horizontal flow near the floor and an updraft of air over the casks. The temperature profile near the surface of the cask shows that there is a boundary layer that develops. The heat transfer then depends on the boundary layer's interaction with the main natural circulation flow.

Federovich (Federovich, 2007) discusses in his paper the technical issues of wet and dry storage facilities for SNF. The heat transfer processes can be seen in Table 7.

Table 7: Heat transfer for reliable heat removal under normal conditions (Federovich, 2007)

| Storage Type | Processes |
|--|--|
| <i>Water Pools</i> | <ol style="list-style-type: none"> 1. Heat release in fuel matrix due to radioactive decay. 2. Heat conduction in the fuel and through the cladding. 3. Convective heat transfer from fuel rods to pool water due to natural or mixed convection. 4. Evaporation of the water from the pool into the ventilated air flow above water levels; heat release from the pool by evaporation. 5. Condensation of the steam from the steam-air mixture on the relatively cold surfaces of storage elements (metal floor, walls). 6. Heat conduction through the pool construction to environment. |
| <i>Casks</i> | <p><i>Points 1 and 2 above (typical for all kinds of storage).</i></p> <ol style="list-style-type: none"> 3. Convection heat transfer from fuel rods due to natural convection of gaseous coolant inside vertically or horizontally oriented casks. 4. Thermal radiation inside casks, radiation heat transfer between the rows of fuel rods and between the fuel and basket-surrounding elements. 5. Heat conduction through internal elements of the cask and through its thick body wall. 6. Natural convection and thermal radiation from the casks outer surface to the environment. |
| <i>Surface storage (cask, vault, module, and chamber type)</i> | <p><i>Natural circulation and mixed co-current convection (circulation up-flow plus natural convection at the heat-releasing surfaces of the SNF canisters).</i></p> <p><i>Thermal radiation heat transfer from the fuel rods, SNF to the surrounding elements.</i></p> |
| <i>Underground storage</i> | <p><i>Mixed co-current convection (forced flow from air ventilation plus natural convection at heated surfaces).</i></p> <p><i>Thermal radiation.</i></p> <p><i>Evaporation/condensation in air should be included.</i></p> |

From the information provided above it is evident that there are no differences in the heat transfer modes and processes due to the cask orientation.

Heat transfer takes place mainly due to conduction, convection and thermal radiation. It is possible however to have different heat transfer rates due to the cask orientation and outer air cooling on the surface of the cask. Internal and external geometry may enhance natural circulation including the supply of "fresh" cold air. This is mainly achieved by means of cooling fins externally on the casks and other features like air ducts in the cask design.

Common experiments conducted on casks from literature includes heat transfer, pressure drop in vertical casks, natural convection in horizontal casks, modelling of air flows, and heat-mass transfer under normal and accident conditions (Federovich, 2007).

SNF is often first stored in SFP to allow its heat generation and radioactive decay rates to decrease before being moved to thick-walled casks. Chalasani (N.R. Chalansani, 2009) states that fuel rods are normally orientated horizontally during transport and placed vertically for storage. Helium or another non-oxidising gas fills the cask canister for cooling of the SNF. Many 1-D and 2-D models mainly depict conduction and radiation heat transfer when SNF is immersed in an inert gas. Simulations that include buoyancy indicate that natural convection does not affect temperatures within horizontal transport casks. When there is no fluid motion heat is transferred by conduction and radiation only. From his experiment the measured temperature difference increases with heat load and decreases with gas pressure.

2.6.3 Effect on incidents, accidents and ageing

All casks are tested for potential incidents, accidents and ageing. Common tests include controlled drop tests where casks are dropped from a particular height to evaluate its ability to withstand the impact, protect the SNF and maintain its integrity. Other tests include transport accidents and fire test scenarios to ensure that the peak cladding temperature of the SNF is not exceeded. Ageing effects are normally related to the susceptibility of casks experiencing stress corrosion cracking (SCC) and also evaluating the SNF after years in dry storage.

It is believed that horizontal stored casks on plinths behave better in high seismic activity areas where the cask has a greater stability with a lower centre of gravity when stored horizontally. Orientation of the casks during transportation from the SFP to the storage facility is mainly in the horizontal position on a flatbed transport vehicle or vertically if a cask transporter is used as seen in Figure 26.



Figure 26: Spent Fuel Cask transporter (Duerr, 2013)



Figure 27: Self-propelled Spent Fuel Cask Transporter (Power, 2011)

In Figure 27 the canister is being placed in a horizontal storage module and requires a special type of transport machine. Storage casks can be placed vertically or horizontally on a storage plinth or in a concrete modular structure depending on the type of cask selected, space, facility and preference.

There has been no finding where the cask orientation affects the susceptibility of casks to experiencing incidents, accidents or ageing effects.

2.7 Other cask comparisons found in literature

Comparisons between metal and concrete casks have been conducted both technically and economically by Saegusa et al (Saegusa, 2008) in a paper entitled “Topics of research and development on concrete cask storage of spent nuclear fuel.” Table 8 was taken from the published paper for the technical comparison followed by the economical comparison (Table 9).

Table 8: Technical comparison between metal cask and concrete cask (Saegusa, 2008)

| Cask | Metal Cask | Concrete Cask |
|---------------------------------|---|--|
| <i>Approximate weight</i> | <i>110 tons 24 PWR assemblies; or 69 BWR assemblies</i> | <i>180 tons 24 PWR assemblies; or 69 BWR assemblies</i> |
| <i>Major functions</i> | <i>Transport and storage</i> | <i>Storage</i> |
| <i>Containment function</i> | <i>Containment is ensured by metal cask. Metal gaskets are used for the primary and secondary lids of the cask. Pressure between the lids is continuously monitored. The pressure in the cask cavity may be less than or more than the atmospheric pressure. The pressure between the lids is more than the atmospheric pressure.</i> | <i>Containment is ensured by a canister in the concrete cask. Both the primary and secondary lids of the canister are weld-sealed. Pressure between the lids is not monitored. The pressure in the canister cavity may be less than or more than the atmospheric pressure.</i> |
| <i>Shielding function</i> | <i>Stainless steel, carbon steel, cast iron may be used for gamma shielding. Resin and water may be used for neutron shielding.</i> | <i>Concrete and steel may be used for gamma shield. Concrete and resin may be used for neutron shielding.</i> |
| <i>Sub-criticality function</i> | <i>Geometrical configuration of fuel basket and neutron absorber will maintain sub-criticality.</i> | <i>Geometrical configuration of fuel basket and neutron absorber will maintain sub-criticality.</i> |
| <i>Heat removal function</i> | <i>The surface of the metal cask is cooled by natural convection of air.</i> | <i>The surface of the canister is cooled by natural convection of air introduced from the air inlets of the concrete cask.</i> |

Table 8 shows a difference in weight of the two casks and other minor differences but nothing particularly with respect to choosing the metal over the concrete cask or vice versa. The orientation of the metal and concrete cask in the report was not specified.

Table 9: Economical comparison between metal and concrete casks (Lambert, 1993)

| Kinds of cask | Capacity | Unit cost of cask ($\times 10^3$ \$) |
|--|-----------------------|--|
| <i>Concrete cask (storage only)</i> | <i>24 PWR/ 52 BWR</i> | <i>350</i> |
| <i>Concrete cask with transportable basket</i> | <i>24 PWR/ 52 BWR</i> | <i>400</i> |
| <i>Horizontal concrete module (storage only)</i> | <i>24 PWR/ 52 BWR</i> | <i>500</i> |
| <i>Transport/ storage metal cask</i> | <i>26 PWR</i> | <i>1000-1500</i> |
| <i>Shippable storage metal cask</i> | <i>21 PWR</i> | <i>1500-3500</i> |
| <i>Metal cask (storage only)</i> | <i>24 PWR/ 52 BWR</i> | <i>750-1500</i> |
| <i>Metal cask (transport only)</i> | <i>21 PWR</i> | <i>1500-3500</i> |

In Table 9 the costing varies with respect to the designed purpose or function of the cask, time of purchase and material of construction used. It is also known that the size of boiling water reactor (BWR) fuel assemblies are smaller in dimensions than the PWR fuel assemblies by a factor of about 40% (McCullum, 2012), therefore the cask containing the BWR fuel assemblies will be smaller than the cask for PWR fuel assemblies.

The concrete cask has been considered to be more economical than the metal cask by 10-20% by adding capital and operational costs and then conducting the comparison. Saegusi further says that concrete casks are considered to be reliable and safe because it is cooled by independent natural convection.

Table 10 provides spent fuel projections for the US from the Nuclear Energy Institute (NEI) report (McCullum, 2012) based on the current SNF located in the SFP and in casks or dry storage.

Table 10: Spent fuel projections for the US (McCullum, 2012)

| Year | Total Metric Tons of Heavy Metal (MTHM) | SPF (MTHM) | Dry storage (MTHM) | Total of Dry cask systems | Non-transportable | | Transportable | |
|------|---|------------|--------------------|---------------------------|-------------------|----------|---------------|-------------------|
| | | | | | Bare Fuel | Canister | Bare Fuel | Dual purpose cask |
| 2010 | 64461 | 49666 | 14795 | 1242 | 29 | 209 | 136 | 868 |
| 2020 | 87721 | 57611 | 30110 | 2231 | 29 | 259 | 176 | 1767 |
| 2030 | 117071 | 64895 | 52176 | 3593 | 29 | 309 | 216 | 3036 |
| 2040 | 143741 | 65599 | 78142 | 5196 | 29 | 356 | 252 | 4759 |

This highlights the future growth projections in the use of casks in the US and the dependence on interim dry storage as a medium to long term solution of SNF storage. This comes with the continued operation and extensions of power plant lifespans and therefore increasing amounts of SNF. This emphasises the need for the TISF, ISFSI or interim storage facility for the safe storage of casks in South Africa and around the world.

The US currently has 55 licensed ISFSI's (Durst, 2012) which are either concrete pads, pads with sheds, concrete buildings or concrete vault structures as storage facilities. Dry storage is considered safer than pool storage according to Durst. In the absence of national long term SNF storage repository dry storage requires periodic inspections, suitable radiation shielding, appropriate containment and confinement with filtering systems, residual heat removal capability with the importance to safety and prevention of radiation exposure under accident conditions (Durst, 2012). Dry storage must provide adequate natural circulation through the storage racks or casks, together with a cask storage facility (NRC, 2007).

2.8 Gaps in literature

After completing an extensive search on literature pertaining the reasons and criteria for cask and site design, the following gaps were identified:

- No specific focus on metal or concrete cask orientation comparison could be found (vertical vs. horizontal) however limited CFD individual studies were found.
- The effect on heat transfer could be found even though heat transfer modes and internals of the metal cask remain the same with most designs.
- No specific design is evaluated for an ideal TISF or ISFSI. Only guidelines to the design requirements of such a facility are available from the IAEA.
- No research could be found on how the orientation of the cask would affect the actual size of the storage facility for the casks but vertical and horizontal cask footprints and heights were found and thus sizing could be elaborated upon from this information.
- No comparison could be found in the choice of cask type by means of the selection criteria.

3. Technical Evaluation

This chapter focuses on the design features of seven different casks, and how these meet the nuclear safety requirements. For each requirement the design features are translated into a common metric by which the various casks can be compared, in order to draw some conclusions from it. The second part of this chapter evaluates the storage facility features and their specific requirements which drive the overall design.

3.1 Cask design features and requirements

The following requirements have been selected and studied for various casks, with the focus on which design solution is used to meet the requirement:

- SNF criticality also known as reactivity control by maintaining subcriticality of SNF within casks
- Radiation shielding of the environment
- Decay heat removal
- Containment of fission products
- Transportability
- Seismic stability
- Storage life
- Space requirements

The criterion above is discussed below and a comparison table has been drawn for seven cask types being evaluated. The seven cask types being evaluated are:

- Castor V/21
- MC-10
- VSC-24
- TN-24P
- HI-STAR 100
- NUHOMS-24P
- HI-STORM 100

These cask types were selected as they are the most commonly available and used in industry. Figure 28 is used to visualise three of the above-mentioned selected cask designs side-by-side.



Figure 28: Dry storage casks in the background with drywell storage in the front at Idaho National Laboratory (INL) (Management, 2014)

The data tables which are in this chapter are collated from various sources: (MG Raddatz, 1995) (S.R. Greene, 2013) (Rigby, December 2010).

3.1.1 Criticality

Criticality and being critical is the condition of the reactor where the number of neutrons produced by fission in one generation equals the number of neutrons produced by fission in the previous generation i.e. $k_{eff} = 1$, $\rho = 0$.

The effective multiplication factor (k_{eff}) is defined as the factor by which the number of neutrons produced from fission in one generation is multiplied to determine the number of neutrons produced from fission in the next generation. This can be calculated using the six factor formula:

$$k_{eff} = p f \varepsilon \eta L_{th} L_f$$

This equation takes the losses of the thermal and fast neutrons into consideration in a specific sized reactor by making use of the fast non-leakage probability (L_f) and thermal non-leakage factor (L_{th}). Other factors include the resonance escape probability (p), thermal utilization factor (f), fast fission factor (ε) and reproduction factor (η).

The infinite multiplication factor (k_{∞}) is the number of neutrons produced from fission in one generation divided by the number of neutrons produced from fission in the previous generation in a reactor of infinite size i.e. neutron leakage does not occur. The equation used to determine the infinite multiplication factor is known as the four factor formula: $k_{\infty} = p f \varepsilon \eta$.

Reactivity (ρ) is the fractional change in neutron population per generation, or the measure of the departure of a reactor from criticality. Reactivity is zero when the reactor is exactly critical. If positive reactivity is added, reactor power will increase. If negative reactivity is added, reactor power will decrease.

The subcriticality requirement is determined by the total reactivity value (ρ). The reactivity value can be determined by knowing what the effective multiplication factor is.

$$\rho = \frac{(k_{eff} - 1)}{k_{eff}}$$

SNF sub-criticality can be maintained by safe geometrical configuration and additional sub-criticality means such as fixed neutron absorbers and the use of burnup credit.

A neutron absorber, also known as a neutron poison has a large neutron absorption cross section. Some of the neutron poisons deplete as they absorb neutrons while others remain constant. Examples of good neutron absorber materials include boron and gadolinium which are burnable poisons. Silver, indium, cadmium and hafnium are non-burnable poisons.

A thermal neutron absorber is an element that is effective in absorbing thermal neutrons, which have energy less than 0.4 eV. The elements gadolinium, boron, chlorine, hydrogen, helium, lithium and iron are thermal absorbers with a decreasing order of effectiveness.

Boron-10 (B-10) has an absorption cross-section of 3840 barns for thermal neutrons of energy 0.0253 eV. Boron with normal isotopic composition the cross-section is 750 barns. This means there is a high probability that B-10 will absorb a neutron as it collides with the nucleus. This probability changes with the energy level of the free neutron, where B-10 has the highest probability in absorbing slow (thermal) neutrons.

The casks include neutron absorber materials like borated steel which maintains the subcriticality margin in the internals of the dry storage cask. The requirement is that the standard criticality criterion of SNF in the transport or storage cask must have $k_{eff} \leq 0.95$ which equates to a reactivity value of $\rho = -0.05\Delta k/k$ (Bozic, 1996).

The three main parameters driving the criticality of the SNF in a cask are: the fuel type (PWR/BWR); the initial fuel enrichment (typically between 3-5%); and the fuel burnup which is also known as fuel utilisation. The percentage enrichment indicates amount of fissile material (U_{235}) compared to the total mass of uranium. Burn-up, measured in GWd/MTU can roughly be converted into percentage of fissile material consumed (10% burnup roughly corresponds to 100 GWd/MTU (Agency, 2006)).

So, ignoring poisons, one could calculate the percentage burnup and an effective “enrichment” of the spent fuel. Effective SNF enrichment was calculated by taking the initial fuel enrichment and subtracting the percentage burnup. The results are tabulated below. The effective SNF enrichment may determine the design features of the cask which can include geometric spacing, neutron absorbers and material of construction. It could also affect the size of the cask together with the number of used SFA it can contain.

Table 11: Effective spent fuel enrichment after burnup [partially adapted from (Rigby, December 2010)]

| Cask Type | Fuel type and number FA | Fresh fuel enrichment (%) | Maximum Burnup (GWd/MTU) | Burnup (%) | Effective SF enrichment (%) after burnup |
|-----------------------------------|-------------------------|---------------------------|--------------------------|------------|--|
| <u>Storage cask only:</u> | | | | | |
| Castor V/21 | 21 PWR | 3.5 | 35 | 3.5 | (0) |
| MC-10 | 24 PWR | 3.7 | 35 | 3.5 | 0.2 |
| VSC-24 | 24 PWR | 4.2 | 45 | 4.5 | (0) |
| TN-24P | 24 PWR | 3.5 | 35 | 3.5 | (0) |
| <u>Multi-purpose cask:</u> | | | | | |
| HI-STAR 100 | 24 PWR | 4.6 | 38.2 | 3.82 | 0.78 |
| NUHOMS-24P | 24 PWR | 4.2 | 45 | 4.5 | (0) |
| HI-STORM 100 | 24 PWR | 5 | 68.2 | 6.82 | (0) |

One can see from Table 11 that the effective enrichment of SF is nominally zero. The cases where zero enrichment is reported can be attributed to the rough estimate of 10% per 100GWd/MTU, as well as the assumption that no breeding occurs. It is important to note that the zero values have been placed in brackets which mean that even though the theoretical calculation gives a zero answer in reality there will never be 0% enrichment after burn-up. Hence, from the data one cannot use the effective enrichment as a metric to evaluate cask designs to achieve criticality. One can conclude that all casks nominally contain the “same” fuel when viewed from the perspective of effective enrichment.

The easiest way to maintain subcriticality is to space the fuel apart, i.e. have a low packing density. Since all the casks considered have the same fuel type, i.e. same height, one can calculate the fuel mass per cross section area of the cask inside to get an idea of this packing density. This is shown below. Additional measures like boronated plates will enhance the subcriticality, and can be used to achieve a higher packing density. There is a cost trade-off for a large casks giving low density with minimal additional measures, compared to a compact cask with lots of additional material to achieve subcriticality.

Table 12: Subcriticality means and fuel packing density

| Cask Type | Fuel type and number FA | Mass of fuel (kg) | Cask inner diameter (m) | Cross-sectional area (m ²) | Fuel "packing density" (kg/m ²) | Subcriticality means (MG Raddatz, 1995) |
|-----------------------|-------------------------|-------------------|-------------------------|--|---|---|
| Castor V/21 | 21 PWR | 10500 | 2.01 | 3.16 | 3319.0 | <i>Polyethylene rods and plates; fuel basket boronated stainless steel plates.</i> |
| MC-10 | 24 PWR | 12000 | 2.40 | 4.51 | 2659.2 | <i>Boronated neutron poison plates, steel wrappers, BISCO NS-3 neutron absorbing material, and aluminium.</i> |
| VSC-24 | 24 PWR | 12000 | 2.57 | 5.20 | 2309.7 | <i>Poison plates in basket, MTC houses lead and neutron shield cylinders.</i> |
| TN-24P | 24 PWR | 12000 | 1.87 | 2.75 | 4369.3 | <i>Polypropylene disk, resin compound of borated polyester in aluminium containers.</i> |
| HI-STAR 100 | 24 PWR | 12000 | 2.09 | 3.44 | 3484.5 | <i>Steel shell with boron.</i> |
| NUHOMS-24P (canister) | 24 PWR | 12000 | 1.71 | 2.30 | 5225.2 | <i>Stainless steel, basket geometry, solid neutron shield BISCO N3, lead shield.</i> |
| HI-STORM 100 | 24 PWR | 12000 | 2.62 | 5.38 | 2230.9 | <i>MPC-24 basket made from neutron absorber material, concrete cask, steel plates.</i> |

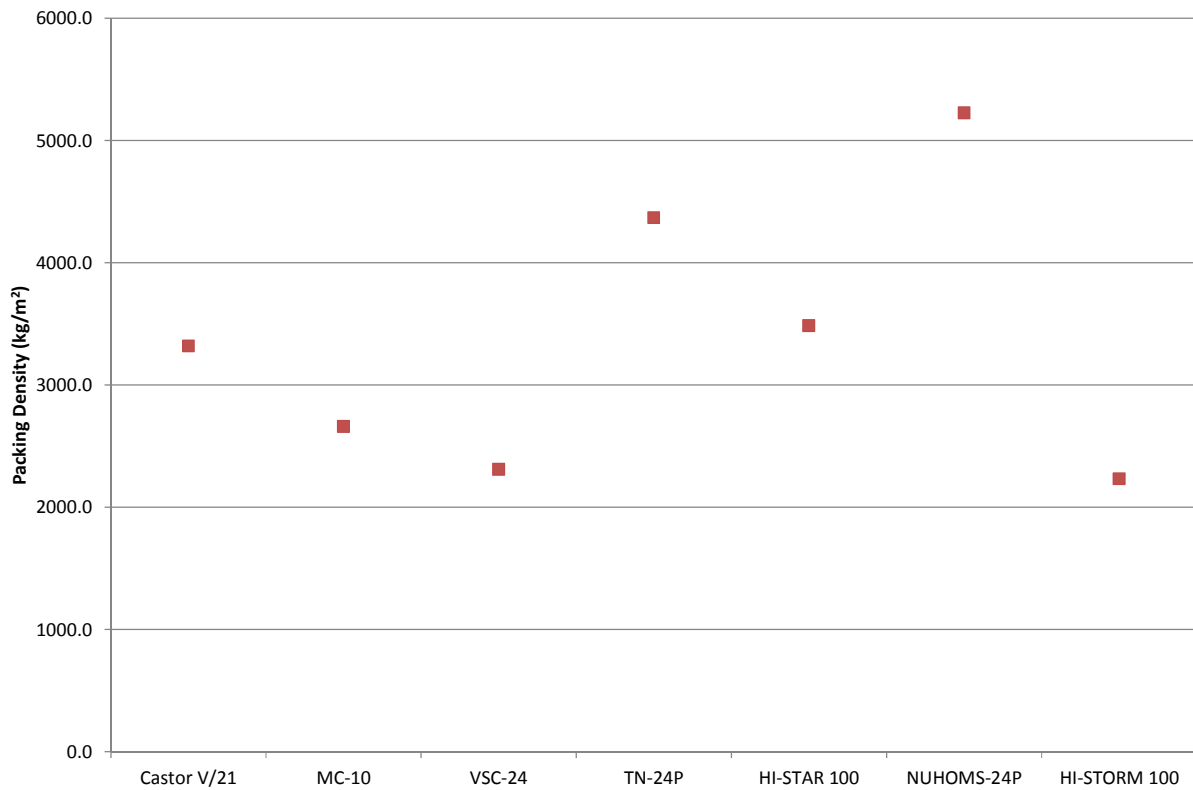


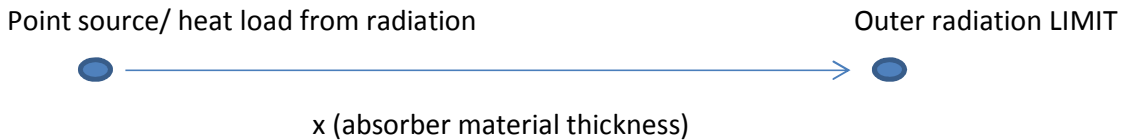
Figure 29: Relationship of spent fuel packing density for different casks

From Figure 29 the average packing density between all the cask types was calculated as 3371 kg/m².

In the NUHOMS 24P the packing density was the highest. It is likely that the solid neutron shield BISCO N3 plays a significant role in achieving the desired subcriticality. On the other hand, the poison plates in the VSC-24 and HI-STORM 100 plays a lesser role, since the cask packing density is fairly low.

3.1.2 Radiation Shielding

Gamma radiation shielding by the casks is normally achieved by means of a certain thickness of concrete, lead or steel around the canister. This is taken into consideration using the initial design heat load of the cask and comparison of the cask wall thickness and gamma radiation.



Other materials can also act as radiation shielding. Polyethylene is used in neutron shielding process as plates between primary and secondary lids and as a plate below the bottom of many of the cask bodies. The purpose of these plates is to slow down (i.e. moderate) the neutrons and the absorption is then by means of the addition of a strong thermal neutron absorber such as boron or cadmium introduced behind the moderating medium.

The equation for linear attenuation: $I(x) = I_0 e^{-\mu x}$

Where:

μ is the linear attenuation coefficient of the absorber material (cm⁻¹)

x is the thickness of the absorber material (cm)

$I(x)$ is the shielded dose rate

I_0 is the initial dose rate from gamma rays

Table 13: Linear Attenuation of Gamma Radiation for different shielding materials (Technology, 2015)

| Material Absorber | Density (g/cm ³) | Linear attenuation coefficient (cm ⁻¹) (for 500keV gamma ray energy) |
|-------------------|------------------------------|--|
| Water | 1 | 0.097 |
| Concrete | 1.5 | 0.15 |

| | | |
|-----------|------|-------|
| Aluminium | 2.7 | 0.227 |
| Steel | 8.05 | 0.34 |
| Lead | 11.3 | 1.64 |
| Uranium | 19.1 | 3.82 |

Table 13 shows the linear attenuation coefficient for typical materials. One can see that for higher density material, the attenuating is larger, and concrete is much less effective than steel for example.

Due to the scattering of the gamma radiation you cannot merely use the above linear relationship. Scattering causes some of the gamma rays to appear back in the path. To take care of this phenomenon a “build-up factor” is used. This build-up factor is a function of gamma energy, distance and material and therefore the equation becomes:

$$I(x) = \beta(E, x, \mu)I_0 e^{-\mu x}$$

In order to obtain good relative shielding capabilities of the different materials and designs it is best to use a shielding program such as Microshield™ or MCNP. However, doing such analyses was out of the scope of this dissertation, as it requires detail information of the fuel composition with radiation spectrum at the given decay age. But, because the mechanism of shielding is to absorb the radiation energy into heat deposited in the material, there might be an observable relationship between shield thickness and heat load.

Figure 30 shows the shield thickness versus heat load, grouped by material type.

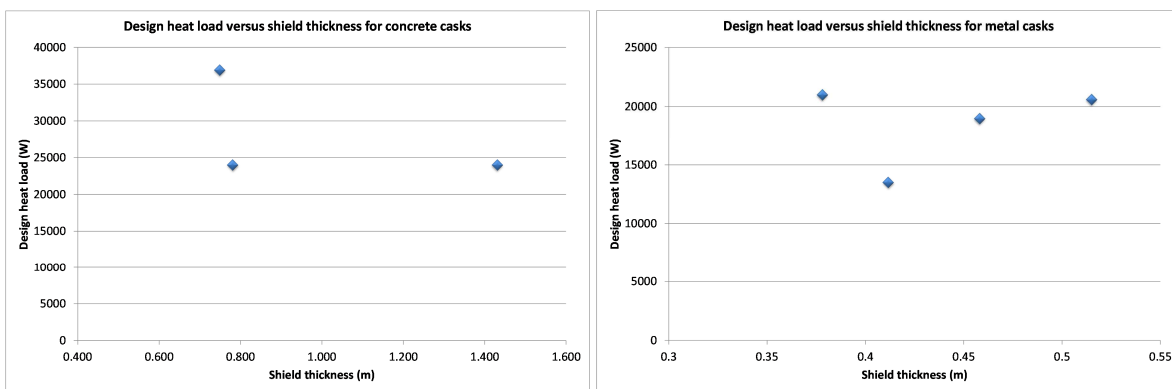


Figure 30: Design heat load versus shield thickness for cask material types

From Figure 30 there is not a very strong observable trend, though for the cases for steel shielding, it does appear to increase with heat load as expected. Also observable is the fact that a much larger concrete shield is needed than steel, mainly due to its lower attenuation coefficient. The effect of radial dispersion due to the increased outer diameter is not factored into this comparison

and could be the reason for the weak trends, assuming the fuel inside all casks are exactly the same.

3.1.3 Decay heat removal and heat transfer

Decay heat is the energy released as a result of radioactive decay process. This energy is emitted in the form of the radiation which is then deposited on surrounding materials as thermal heat.

The heat removal refers to the residual heat remaining inside the cask due to the decay of fission products inside the SNF. This is mainly due to the absorption of gamma radiation. Each cask is designed to remove a certain amount of heat which determines the number of SFA that can be loaded into each cask together with the decay time in the spent fuel pool.

Dry casks are cooled via natural convection of the ambient air. Some casks have design features like fins to assist with the external heat removal. The SNF characteristics and cask geometry also determines the heat removal ability of the cask. Some cask manufacturers require SNF to be stored in SFP from 5 to 10 years to reduce the initial heat load on the cask and consequently the fuel temperature decreases substantially due to the cooling in the SFP and due to the decay of short-lived radioactive nuclides.

From literature the convective heat transfer coefficient for natural convection in air is between 5 and 50 W/m²K (J.R. Welty, 2001). The convective heat transfer coefficient for forced convection of air is between 25 and 250 W/m²K (J.R. Welty, 2001).

The task will be to identify the canister inner temperature of the different designs, and see if there is a correlation between them. One would presume that if all the designs aim to achieve a similar fuel maximum temperature, then the inner canister temperature might be similar.

The design heat load is the total maximum heat generated and transferred to the atmosphere through the cask wall (Q_{tot}). Starting at the inner-most fuel element, its decay energy may be absorbed by the surrounding fuel elements, and conducted through the material as heat to the outer perimeter of the canister. To adequately quantify the amount of energy converted to heat inside the fuel volume requires detailed shielding calculations, like that of Microshield. Unfortunately this is beyond the scope of this mini dissertation. Hence it will be assumed that 50% of the total design heat load (Q_{tot}) is converted to heat in the fuel. This is the same for all the casks, as the fuel volume in the casks is similar as they contain 24 PWR fuel assemblies, except for the Castor V21 which contains 21 fuel assemblies.

The heat deposited in the fuel region will be termed the inner heat (Q_i). The remainder of the heat is deposited in the surrounding shielding material. Because of the very low requirement for

radiation emitted from the cask, one can assume that all the energy eventually gets converted into heat. This is then the heat that must be removed by natural convection.

A differentiation is made between casks with an air gap and those without an air gap. The air gap in some of the casks means that they are internally ventilated. The heat load on the internal cooling is therefore only the heat which reaches the air gap. The remainder of the heat is removed from the outer perimeter of the cask. Therefore any heat that passes the air gap is not heat that requires cooling as this is cooled by another mechanism on the outside of the cask. The concern lies with what is happening closer to the canister and how much heat goes into the air gap. Where there is no air gap it is assumed that all the radiation is converted to heat at the outer perimeter of the cask.

The canister wall will still absorb some of the radiation escaping from the fuel. Due to the nominally small thickness compared to the outer shield, it is assumed that only 5% of the remaining radiation is converted to heat, and rest passes through the air gap.

It is assumed that the radiation deposited as heat into a material is uniformly distributed. This is not completely true because the closer layers have more radiation deposition than the outer layers. Once again, this can really only be accounted for using Microshield. A volumetric heat generation can then be defined as:

$$Q''' = Q_{shield}/(\pi(r_o^2 - r_i^2)H) \quad [W/m^3]$$

For the case where there is an air gap, the “shield” is only the canister wall, giving the cooling load for a ventilated cask as:

$$Q_{cool} = Q_i + Q''' \cdot V_{canister} \quad [W]$$

Where there is no air gap all the radiation is eventually deposited onto the shield, giving:

$$Q_{cool} = Q_{tot} = Q_i + Q''' \cdot V_{cask\ or\ shield} \quad [W]$$

The ambient temperature of the air is typically known, and was assumed to be constant at 20°C (T_a). One can calculate the outer wall temperature of the cask or canister (if there’s an air gap) using:

$$Q_{cool} = h A (T_o - T_a)$$

To calculate the inner wall temperature, one needs to take the geometric change in the diameter into account, as well as the heat being generated inside the shield. Appendix A, Calculation number 3 shows the derivation of the equation:

$$T_i = T_o + \frac{Q'''(r_o^2 - r_i^2)}{4k_e} - C_1 \ln\left(\frac{r_o}{r_i}\right)$$

Because the shields are often complex combinations of various materials, an effective thermal conductivity (k_e) is used (See Appendix C for the geometries). For the Castor V21 the following equation was used:

$$k_e = [k_{rod}\Sigma A_{rod} + k_{steel}(A_{tot} - \Sigma A_{rod})] / A_{tot}$$

For the vertical TN 24P cask the following equation was used:

$$k_e = \frac{[k_{shield}A_{shield} + k_{steel}(A_{tot} - A_{shield})]}{A_{tot}}$$

The total surface area calculated for MC-10 cask utilized the following equation, because of the additional fins on the cask:

$$A = 2\pi r_o H + \eta_{fin} \cdot A_{fin}$$

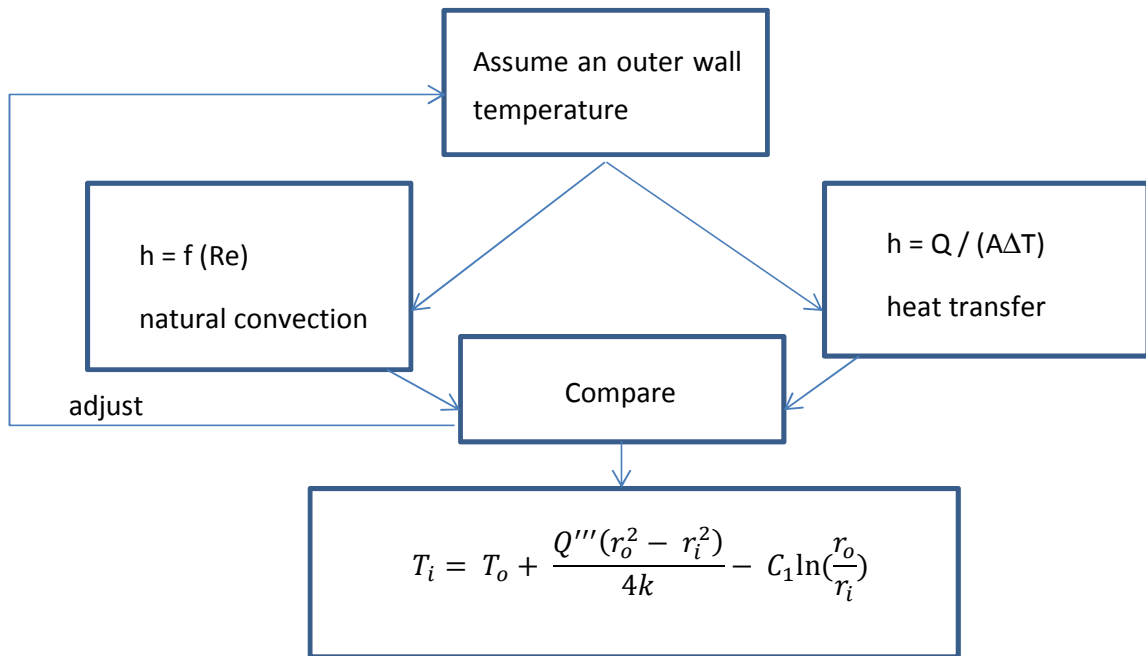


Figure 31: Flow diagram of the methodology to determine the inner cask wall temperature

Figure 31 illustrates the methodology used to determine the inner canister wall temperature. The outer cask wall temperature was assumed with the outer air temperature taken as a constant 20°C. Thereafter, the heat transfer coefficients were determined in 2 ways namely using the natural convection equation for the vertical or horizontal plane depending on the cask orientation as well as the heat transfer equation. The heat transfers from both methods were compared, and if not the same, the outer wall temperature was adjusted. Finally the inner cask wall temperature

was then calculated. Details for the convection correlations used are given in Appendix A. The tables below show the results of the calculations.

Table 14: Comparison of calculated convective heat transfer coefficient

| Cask Type | Additional means of heat transfer (eg.ducts, fins, etc.) | Heat output (W) | Total surface area (m ²) | Average convective heat transfer coefficient, h_{avg} (W/m ² K) |
|--------------|---|-----------------|--------------------------------------|--|
| Castor V/21 | Fins- horizontal (73 fins, 3cm) | 21000 | 47.21 | 5.61 |
| MC-10 | Fins-axial (24 fins, 3cm) | 13500 | 35.8 | 5.32 |
| VSC-24 | Air ducts | 24000 | 21.39 | 7.01 |
| TN-24P | Vertical orientated cask with 44 cooling fins inside the smooth outer layer neutron shield. | 20600 | 37.95 | 6.15 |
| HI-STAR 100 | Vertical orientated cask | 19000 | 33.69 | 5.87 |
| NUHOMS-24P | Horizontal orientated concrete modules with air ducts | 24000 | 24.98 | 6.32 |
| HI-STORM 100 | Vertical orientated concrete cask with air vents | 36900 | 25.13 | 7.47 |
| TN-24P | Horizontal orientated cask with 44 cooling fins inside the smooth outer layer neutron shield. | 20500 | 37.95 | 5.81 |

Table 15: Inner canister temperature calculation

| Cask Type | Cask material | Cask heat output or heat load (W) | Canister wall temperature (°C) | Inner canister temperature (°C) |
|--------------|---------------|-----------------------------------|--------------------------------|---------------------------------|
| Castor V/21 | Metal | 21000 | 98.60 | 105.3 |
| MC-10 | Metal | 13500 | 91.53 | 97.2 |
| TN-24P | Metal | 20600 | 125.95 | 134.2 |
| HI-STAR 100 | Metal | 19000 | 116.92 | 123.9 |
| VSC-24 | Concrete | 24000 | 178.93 | 182.7 |
| HI-STORM 100 | Concrete | 36900 | 215.14 | 226.1 |
| NUHOMS-24P | Concrete | 24000 | 170.76 | 186.1 |

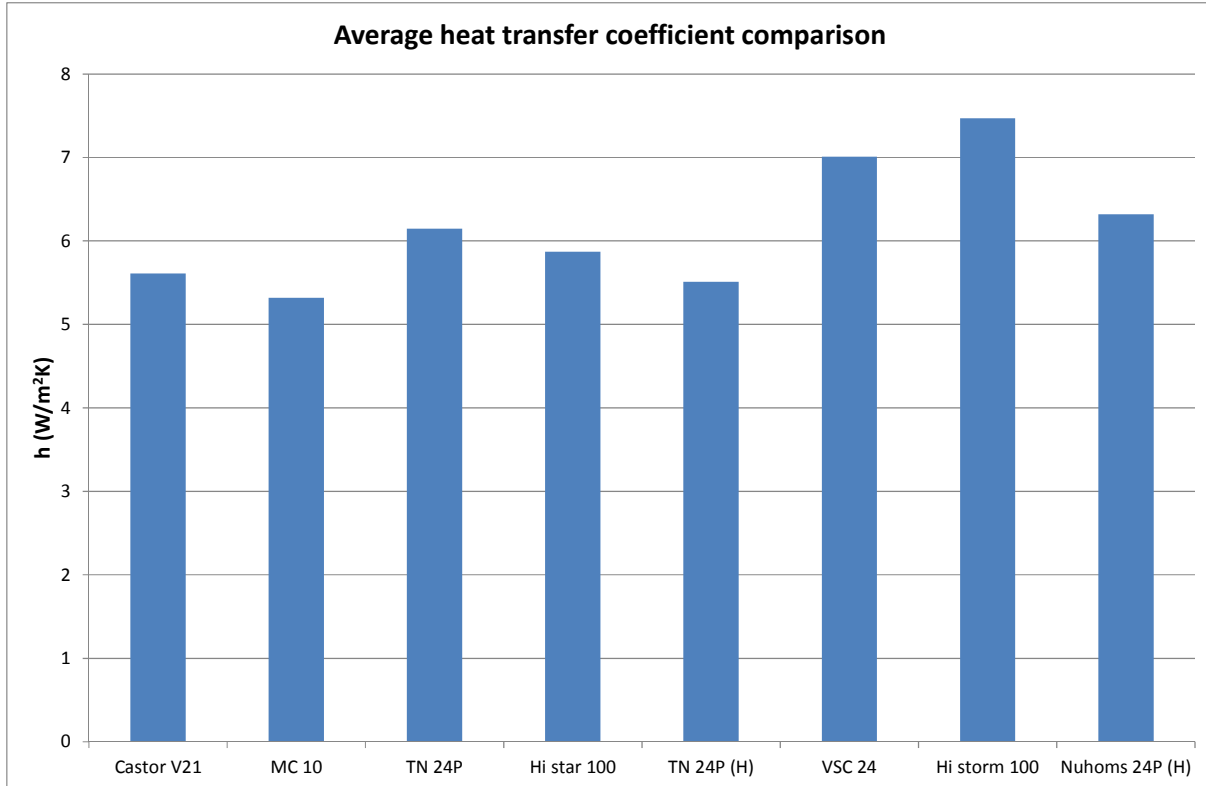


Figure 32: Average heat transfer coefficient comparison

Figure 32 indicates that the average heat transfer coefficients are of the same order of magnitude of typical natural convection heat transfer for all casks. The 3 ventilated casks i.e. VSC 24, HI-STORM 100 and NUHOMS 24P show slightly higher averages of the heat transfer coefficient due to the overall higher cask wall temperature (see

Table 15).

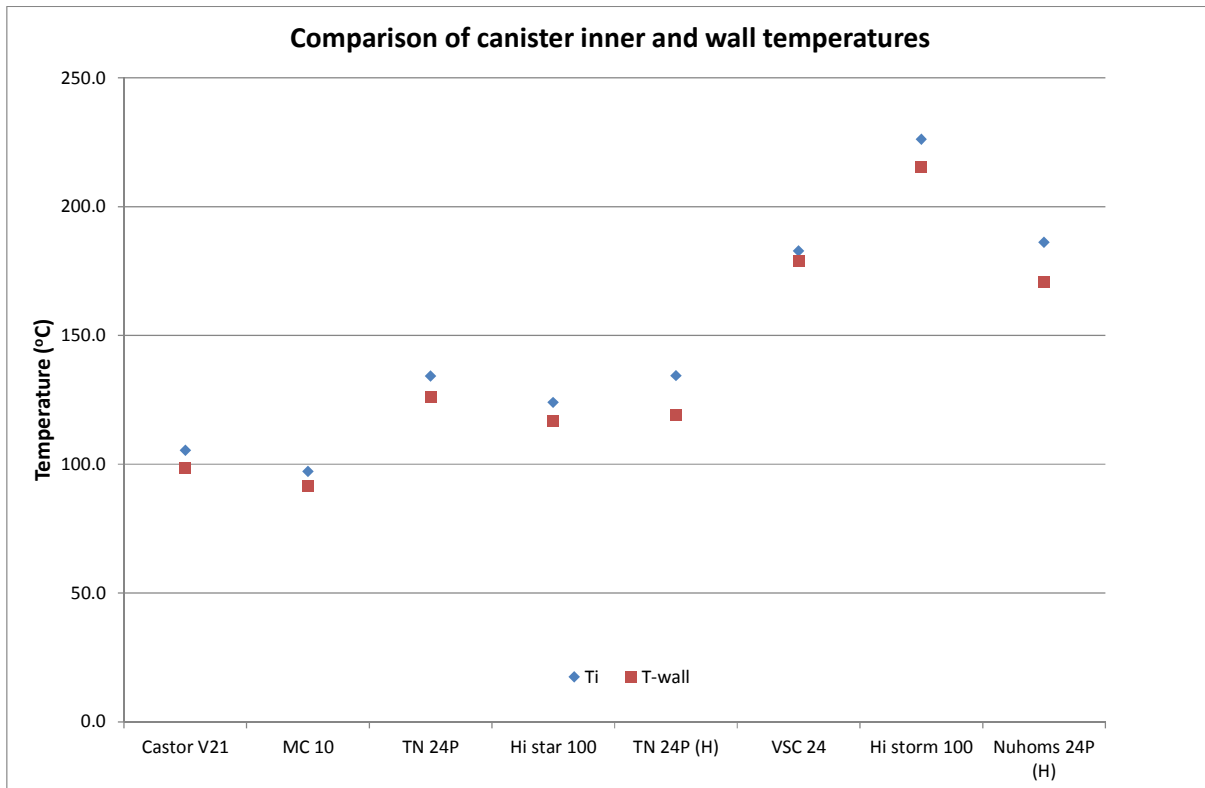


Figure 33: Comparison of the canister inner and wall temperatures

Figure 33 shows the canister inner and wall temperatures and how they are related to each other. The cask with the highest temperatures was the HI-STORM 100 cask which is probably due to the higher design heat load of 36900W. It can also be noted that the 3 ventilated casks on the right hand side of Figure 33 are higher than the non-ventilated casks on the left hand side.

A possible reason for the higher temperatures on the ventilated casks could be due to ignoring the chimney effect on the heat transfer coefficient. The chimney effect would enhance the heat transfer as compared to open natural convection.

A side-line calculation was performed for the VSC 24 cask to check this. An assumption was made for the velocity of the flow using forced convection equations which incorporated the chimney effect.

It was assumed that the temperature entering the air gap was 20°C and the air gap exit temperature was 20°C higher than the air gap inlet temperature, giving the required mass flow. The air gap size was chosen as 40mm, which then gives the local air velocity. Using the hydraulic diameter and the Dittus-Boelter equation for forced convection, a new heat transfer coefficient of

13.16 W/m²K was calculated, which is approximately double as compared to the natural convection result. Using the new coefficient produces a comparable wall temperature of approximately 100°C.

This showed that the chimney effect is significant and helps substantially in the mixed flow cooling through the air gaps of ventilated casks.

3.1.4 Containment of fission products and radiation

Containment of fission products are included in the design of the casks by the inclusion of seals, welded canister lids and a pressure monitoring system for the helium pressure between the cask lids.

Seal types include metal seals, polymers and elastomer seals.

Welded canister lids provide a better means of containment of fission products than using bolted lids. The disadvantage of welded lids is the irretrievability of the SNF at a later stage and would require breaking open the welded lid if the SNF is required to be moved or placed in a different cask.

Table 16 conducts the comparison of the seven cask types. A comparison of the values obtained in calculating the different aspects of the various casks are detailed in Appendix B and the drawing of the cask profiles are in Appendix C.

Table 16: Comparison of cask type with radiation sealing and fission product containment (MG Raddatz, 1995)

| Cask Type | Sealing means | Inert gas | Inspection | Welded/ bolted lid |
|--------------------------|---------------------------------------|-----------|--|--|
| Castor V/21 | Elastomeric and metallic O-ring seals | Helium | Seals tested; Pressure monitoring externally connected to secondary lid | Bolted |
| MC-10 | Metallic O-ring seal | Helium | Pressure monitoring device mounted to primary seal | Primary lid bolted, 3 rd cover welded |
| VSC-24 | Weld sealed | Helium | Sealed by welding | Welded canister, bolted overpack |
| TN-24P | Double metallic O-ring seals | Helium | Pressure monitoring device installed in the double-seal interspace, externally connected | Bolted |
| HI-STAR 100 with MPC-24 | Dual O-ring seals | Helium | Seals tested | Welded canister, bolted overpack |
| NUHOMS-24P (canister) | Seal welds | Helium | Welded sealed | Welded canister, bolted HSM |
| HI-STORM 100 with MPC-24 | Dual O-ring seals | Helium | Seals tested | Welded canister, bolted overpack |

3.1.5 Transportability

The transportability of the metal and concrete casks differ due to a loaded concrete cask weighing considerably more than a metal cask filled with the same amount of used fuel. For this reason some concrete casks remain stationary at its storage location and additional transport casks are required to move the canister filled with the SNF (also known as a transportation cask) from the fuel movement building to the storage facility location where the concrete casks remain stationary either vertically or horizontally.

Table 17: Comparison of cask type and transportability properties

| Cask Type | Maximum loaded Weight (t) | Diameter (m) | Height (m) | Preferred transport position | Additional requirements |
|-----------------------|---------------------------|--------------|------------|------------------------------|-------------------------|
| Castor V/21 | 108 | 2.39 | 4.89 | Vertical or horizontal | Cask is transportable |
| MC-10 | 119.8 | 2.73 | 4.78 | Vertical | Cask is transportable |
| VSC-24 | 126.4 | 3.35 | 5.72 | Vertical | Transport cask required |
| TN-24P | 108 | 2.28 | 5.06 | Vertical or horizontal | Cask is transportable |
| HI-STAR 100 | 121.5 | 2.44 | 5.16 | Vertical | Cask is transportable |
| NUHOMS-24P (canister) | 125 | 1.71 | 4.732 | Horizontal | Transport cask required |
| HI-STORM 100 | 180 | 3.37 | 5.874 | Vertical | Cask is transportable |

From the above comparison the heaviest cask by weight is the HI-STORM 100. For VSC-24 and NUHOMS-24P additional transport casks are required. The actual concrete cask is then stationary and the canister containing the SNF is transported in a transport vessel and placed inside the stationary concrete cask. For the lighter casks like the Castor V/21 and TN-24P the cask is dual purposed for transport and storage. Using a cask for both transport and storage is cost effective as an additional transport cask is not required.

Most of the vertical orientated storage casks can be transported vertically provided that there are no height restrictions especially for ISFSI's that is located on the reactor site and dependant on the cask transporting machinery. For transportation off-site to a repository or long term ISFSI the preference of transportation is horizontally. The horizontally orientated cask is easier transported in a horizontal manner as to ensure ease of insertion into the horizontal storage module or cask like for the NUHOMS-24P.

3.1.6 Seismic Requirements

The seismic requirements refer to the maximum vertical and horizontal ground acceleration the cask can sustain based on its centre of gravity and varies between cask designs. Seismic events are normally classified by the vertical and horizontal ground acceleration where specific values are

given. The casks are then evaluated under these conditions to ensure that the cask and facility design (e.g. concrete pad) is adequate to withstand such movements. Earthquake energy causes ground movement both vertically and horizontally. The earthquake acceleration measurement on the ground is known as the peak ground acceleration (PGA). It is a measure of how hard the earth shakes in a given geographical area and is its intensity. PGA records the acceleration or rate of speed of these ground movements while the peak ground velocity is the greatest speed reached. PGA can be expressed in g which is the acceleration due to the earth's gravity.

$$1g = 9.81m/s^2$$

The ground type can influence the PGA value. Peak horizontal acceleration (PHA) is the frequently used type of ground acceleration and is used in building codes and design hazard risks. Effective peak acceleration (EPA) is the maximum ground acceleration to which a building responds which is usually $2/3$ to $3/4$ PGA. Refer to Appendix A for calculations on the vertical and horizontal generic casks.

Table 18: Comparison of cask types with respect to seismicity

| Cask Type | Orientation | Diameter (m) | Height (m) | Height including stand (m) | Maximum horizontal acceleration (g) |
|-----------------------------------|---------------------------------|--------------|---------------|----------------------------|-------------------------------------|
| <u>Storage cask only:</u> | | | | | |
| Castor V/21 | Vertical (horizontal option) | 2.39 | 4.89 | 4.89 (2.69) | 0.489 (0.88) |
| MC-10 | Vertical | 2.73 | 4.78 | 4.78 | 0.571 |
| VSC-24 | Vertical | 3.35 | 5.72 | 5.72 | 0.586 |
| TN-24P | Vertical (horizontal option) | 2.28 | 5.06 | 5.06 (2.58) | 0.451 (0.88) |
| <u>Multi-purpose cask:</u> | | | | | |
| HI-STAR 100 | Vertical | 2.44 | 5.16 | 5.16 | 0.473 |
| NUHOMS-24P (HSM) | Horizontal | 2.95 | 4.57 (L=5.79) | 5.79 | 0.509 |
| HI-STORM 100 | Vertical | 3.37 | 5.87 | 5.87 | 0.574 |

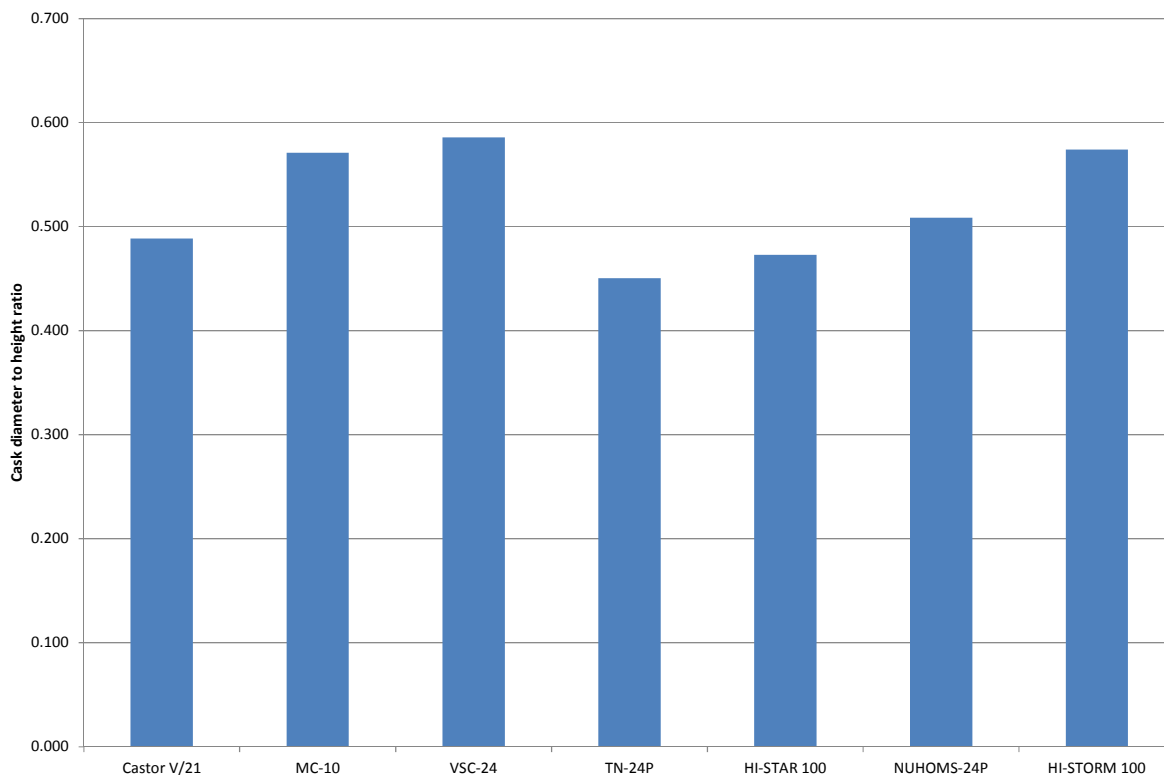


Figure 34: Comparison of diameter to height ratio for casks

The results obtained reported in Figure 34 and Table 18 show the diameter to height ratio for the seven casks and their ability to withstand certain horizontal ground acceleration as this would be part of the selection criteria and is expressed as the maximum horizontal acceleration. VSC-24 has the highest value where the TN-24P has the lowest value. The NUHOMS-24P system is not a concern because it is normally constructed in two rows of 20 casks configuration which provides its stability. Comparatively the maximum horizontal acceleration is dependent on the width and height of the casks which are all of a similar range and results in a similar seismic stability between all the cask designs. For casks with a change in orientation from vertical to horizontal, the horizontal cask offers approximately 2 times more stability to acceleration when compared to the vertical cask. Specific plant related seismic data would be required to make the final selection of the most suitable cask.

3.1.7 Storage life

The storage life of the cask is dependent on the type of environment in which it is stored and its design life. The main concerns are the corrosion, inspection and maintenance of the casks and how it differs with each design. Most cask designs have a similar life span of between 20 and 50

years with the option of re-evaluation with regular inspection after which the life span can be extended as the need arises. This would be as per the cask design and site storage license requirement.

The driving forces for the ageing of the casks include:

- gamma radiation
- neutron radiation
- decay heat
- external environmental effects on the cask like moisture and air pollution
- mechanical stresses from fuel rods, bolted lids and trunnions, and metal seals

Ageing effects are visible as degradation, creep and corrosion.

Table 19: Comparison of cask type and design life

| Cask Type | Design Life (years) | Material | Facility | Storage Orientation | Inspections |
|--------------|---------------------|---|--|---------------------|--|
| Castor V/21 | Up to 50 | Cast iron | Cask on reinforced concrete pad | Vertical | Radiation protection, seal pressures, metal surface for corrosion, condition of bolts |
| MC-10 | Up to 50 | Low alloy steel shielded container with forged steel walls | Cask on reinforced concrete pad | Vertical | Radiation protection, seal pressures, metal surface for corrosion |
| VSC-24 | Up to 50 | Steel basket with ventilated concrete cask | Cask on reinforced concrete pad | Vertical | Radiation protection, concrete structure for defects, condition of bolts |
| TN-24P | Up to 50 | Inner forged steel cylinder with forged steel wall | Cask on reinforced concrete pad | Vertical/horizontal | Radiation protection, seal pressures, metal surface for corrosion, condition of bolts |
| HI-STAR 100 | Up to 50 | Metal canister (MPC-24) with metal overpack | Cask on reinforced concrete pad | Vertical | Radiation protection, seal pressures, concrete structure for defects, condition of bolts |
| NUHOMS-24P | Up to 50 | Dry shielded canister inside concrete horizontal storage module (HSM) | Cask stored in concrete modules on reinforced concrete pad | Horizontal | Radiation protection, concrete structure for defects, condition of bolts |
| HI-STORM 100 | Up to 50 | Metal canister (MPC-24) with concrete overpack | Cask on reinforced concrete pad | Vertical | Radiation protection, seal pressures, concrete structure for defects, condition of bolts |

From Table 19 the comparison shows few differences between the casks especially with respect to the design life and standardised required inspections. The corrosion or any defects found would normally be site specific due to location and exposure to various external environmental elements.

Other factors could also include latent supplier defects and operations involved when moving, filling and transporting of the casks.

3.1.8 Space requirement

Each cask has its own footprint and height dependent on its design dimensions. The footprint is the limiting factor for land area available where the height would affect the inner height of an indoor storage facility.

In addition to the above footprint and height for each cask, additional space is required between casks for ease of movement of machinery, transport vehicle and for inspection purposes. This was highlighted in the literature review chapter. On average the ratio below shows about three times the floor space is required compared to casks on its own which on average equates to 35% more floor area or space required.

Table 20: Comparison of cask type and footprint

| Cask Type | Orientation | Diameter (m) | Height (m) | Access required (m) | Cask footprint (m ²) | Actual area (m ²) | Actual area/ cask footprint |
|------------------|-------------|--------------|---------------|---------------------|----------------------------------|-------------------------------|-----------------------------|
| Castor V/21 | Vertical | 2.39 | 4.89 | 2 | 5.71 | 19.27 | 3.38 |
| MC-10 | Vertical | 2.73 | 4.78 | 2 | 7.45 | 22.37 | 3.00 |
| VSC-24 | Vertical | 3.35 | 5.72 | 2 | 11.22 | 28.62 | 2.55 |
| TN-24P | Vertical | 2.28 | 5.06 | 2 | 5.20 | 18.32 | 3.52 |
| HI-STAR 100 | Vertical | 2.44 | 5.16 | 2 | 5.95 | 19.71 | 3.31 |
| NUHOMS-24P (HSM) | Horizontal | 2.95 | 4.57 (L=5.79) | 2 | 17.08 | 38.56 | 2.26 |
| HI-STORM 100 | Vertical | 3.37 | 5.87 | 2 | 11.36 | 28.84 | 2.54 |

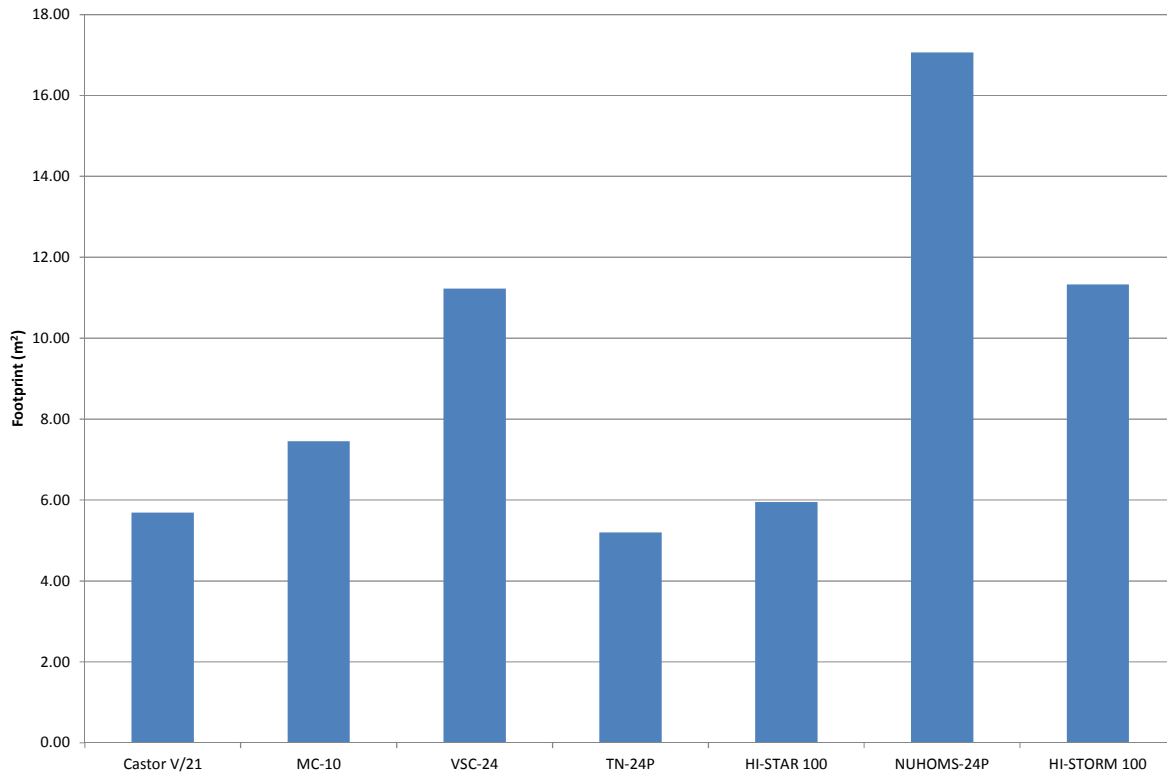


Figure 35: Comparison of cask footprint

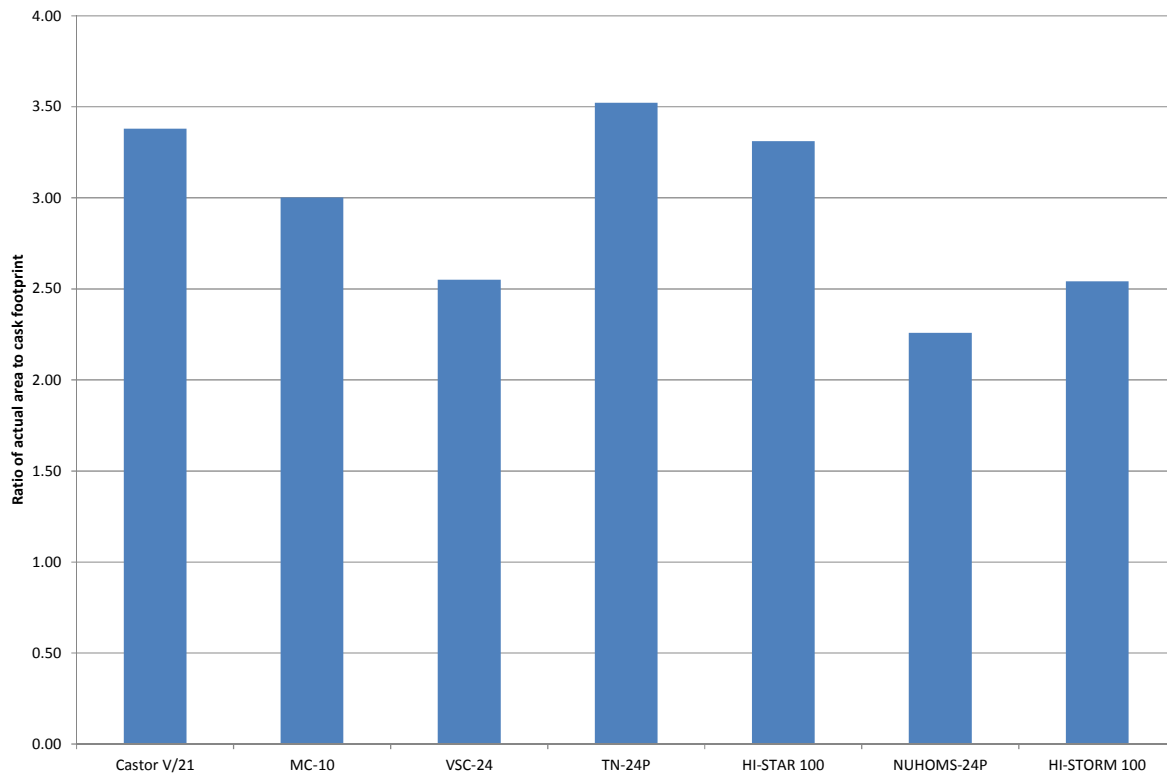


Figure 36: Comparison of actual area to cask footprint

The above comparison evaluates the space required for the casks. It varies with their respective orientation, footprint and amount of space required. The VSC-24 and HI-STORM 100 concrete casks have the greatest footprint. The smallest footprint is with the TN-24P and HI-STAR 100 casks. The greatest ratio of actual area to cask footprint was TN-24P and the lowest was NUHOMS-24P with respect to space required.

The horizontal NUHOMS-24P cask system takes up less floor area or space. If space for a cask storage facility is limited by the space requirements NUHOMS-24P modular system can be used. The modular NUHOMS-24P storage system can fit 2 rows of 20 casks in a back-to-back and 2-stacked configuration, then the inspection area, access area and transportation is less due to the number of casks per square meter being greater. If space is not of concern then any cask option would be suitable.

Figure 37 shows the mass of fuel stored per floor space to give the floor utilization. The maximum ratio was for the TN-24P cask at 655kg/m². The lowest ratio was for the NUHOMS-24P at 311kg/m²but the NUHOMS-24P is however a special cask as these horizontal storage modules can be packed side to side and back to back. So the lowest value is for the VSC-24 concrete cask indicating that you'll need more space to store the same amount of fuel. The average value for floor utilization was 500kg/m².

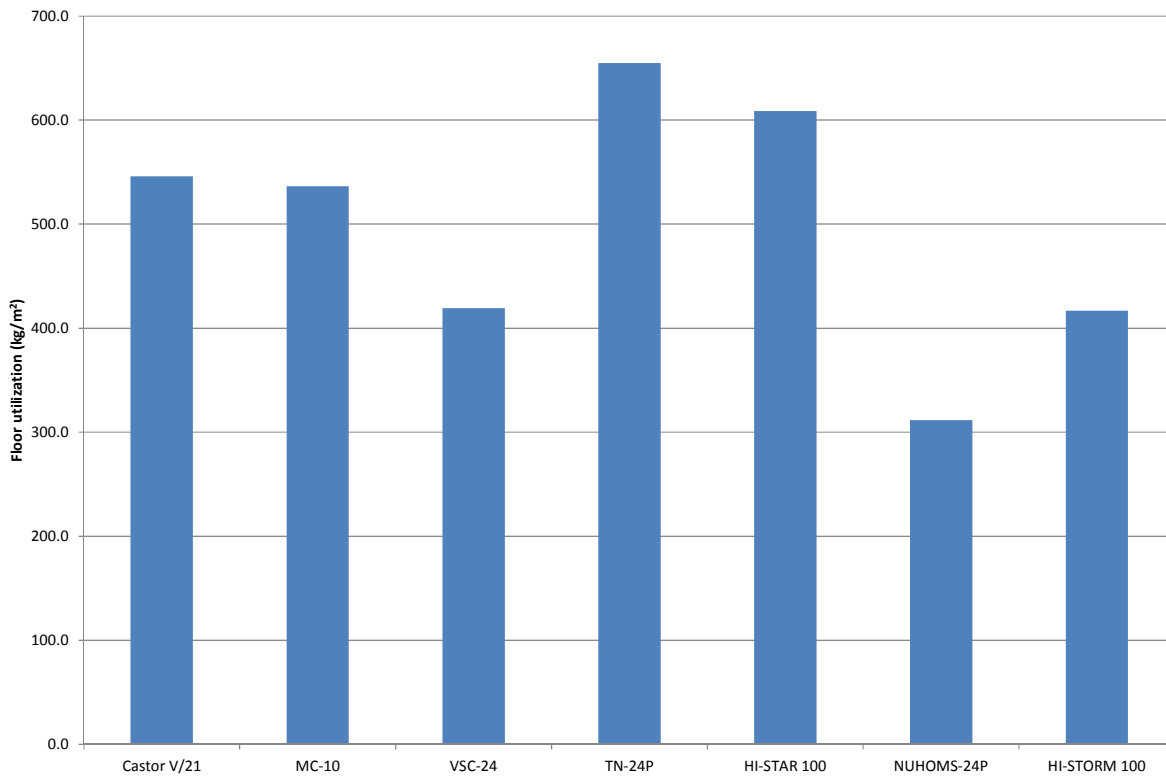


Figure 37: Floor utilization of various casks

3.2 Features and requirements for the selection of storage facility type (establishing selection criteria)

When choosing or deciding on the most suitable option for the storage facility for the dry storage casks there are certain evaluation criteria which are required in the selection process to determine the best possible solution.

The TISF will operate in parallel with the SFP as it is required that SNF be cooled for approximately 5-10 years before SNF can be placed in dry storage.

The casks and the storage facility will have a design lifetime of 20-50 years but can be extended if required but is mainly dependant on evaluations and the licensing conditions granted by the regulatory authority.

The main factors selected and considered for the storage facility are:

- Public perception and visual appearance
- Environmental protection offered by the facility
- Security of the facility
- Site and location of the facility
- Floor loading of the facility
- Modularity for expansion or a phased approach to construction

3.2.1 Perception and visual appearance

Based on an EIA this would determine if the public are under the negative perception that casks which are open to the environment and visible are more harmful to their health than ones located inside an enclosed facility where the casks cannot be seen.

From literature and operational experience around the world many power stations and regulators prefer an outdoor reinforced concrete pad for the cask storage facility.

3.2.2 Environmental protection

Environmental protection offered by the facility is generally evaluated if there is a structural roof present or not. This can limit the exposure of the casks to environmental conditions like rain and direct sunlight. It is possible that if casks are protected from the external environmental conditions that it can offer a longer storage life than those exposed but to a limited extent. Environmental protection of the SNF is already provided by the cask design itself.

3.2.3 Security

The security aspect deals with the accessibility of personnel to the storage facility and a fence or wall boundary is normally required to prevent inadvertent human contact or human error. This is relatively simple to do inside the confines of an existing reactor site where an ISFSI can be located.

3.2.4 Site location

The site and location is of importance especially for the spacing requirements of the cask, whether stored vertically or horizontally in the storage facility. Spacing is important and determines the location and site size needed to accommodate the casks. This also determines the cask quantity that can be stored. This is the main concern when locating the ISFSI at the reactor site with limited space availability.

3.2.5 Floor loading

The floor loading of the facility is important to enable to support the weight of the filled cask for the storage period envisaged. The floor loading is linked to the concrete composition and thickness as well as inclusion of the seismic movement into the design of the facility. Most outdoor ISFSIs make use of reinforced concrete pads for this purpose and the same would apply to indoor storage facilities. Floor loading can be limiting and minimised by incorporating spacing and smaller independent concrete floor sections to spread the loading evenly.

3.2.6 Modularity for expansion or phased approach

This feature is important for the cost-constrained companies where a phased approach to the building of the facility is preferred. A facility design that would be easily extended for future use would be ideal and therefore modularity is used.

3.2.7 Facility comparison

Table 21: Facility comparison for cask storage

| Facility Type | Perception | Environmental protection | Security | Site and location | Floor loading | Modularity for expansion or phased approach |
|------------------------|---|---|--|---|---|---|
| Concrete pad | Unsafe; Casks are easily seen by the public | Open to atmosphere | Fencing and security measures required | Small site required; preferably located on reactor site but can be sited elsewhere | Designed accordingly to withstand fully loaded casks and transportation equipment | Good |
| Concrete pad with shed | Safe; Casks are not seen in enclosure | Limited exposure to air | Secure | Medium site required; preferably located on reactor site but can be sited elsewhere | Designed to handle shed structure and cask loading | Good |
| Concrete building | Safe; Casks are not seen in enclosure | No exposure to environment. Ventilation required. | Secure | Large site required; preferably located on reactor site but can be sited elsewhere | Designed to handle concrete containment structure and cask loading | Limited |
| Vault/modular storage | Safe; Stored fuel cannot be seen in enclosure | No exposure to the environment. Ventilation required. | Secure | Medium site required; preferably located on reactor site but can be sited elsewhere | Designed to handle concrete vault structure and cask loading | Good |

Evaluating the facility comparison in Table 21 shows the criteria evaluated for each storage facility design option. The criteria are all of equal importance but selection of the most suitable facility is dependent on the site-specific requirements, specifications and limitations for a storage facility especially if the ISFSI is located on the reactor site.

Regulatory authority involvement would also influence the decision on the type of storage facility they would be willing to licence. An EIA process would be the best to tackle the public perception and effects on the environment. The other factors can be reasoned and justified in the actual design of the storage facility.

3.3 Summary

The results obtained show the relationship of the spent fuel packing density for different casks with the highest value in the NUHOMS 24P at 5225.2kg/m^2 , lowest was the HI-STORM 100 cask at 2230.9kg/m^2 with an average of 3371.1kg/m^2 .

From the data obtained it was determined that one cannot use the effective enrichment as a metric to evaluate cask designs to achieve criticality. One can conclude that all casks contain the “same” fuel when viewed from the perspective of effective enrichment.

A weak linear relationship exists for the shield thickness versus the design heat load for the metal casks where an increase in the design heat load lead to an increase in the shield thickness. The comparison is however not conclusive for all types of shielding.

The convective heat transfer coefficients were all similar irrespective of cask design and orientation. The minimum value was $5.32\text{ W/m}^2\text{K}$, the maximum was $7.47\text{ W/m}^2\text{K}$ with an average value of $6.2\text{ W/m}^2\text{K}$.

The inner canister temperatures for all the metal casks were similar but were generally higher for the concrete casks. The minimum inner canister temperature was determined to be 97.2°C , the maximum was 226.1°C with an average of 118.9°C when excluding the ventilated casks. The canister wall temperatures ranged from 91.5°C to 215.1°C with an average of 139.6°C . The higher ventilated cask temperatures are probably due to the omission of the chimney effect in the narrow air gap.

The transportability of casks has a limit due to cask weight. Using a cask for both transport and storage is cost effective as an additional transport cask would not be required. Most of the vertical orientated storage casks can be transported vertically provided that there are no height restrictions especially for storage facility's that is located on the reactor site and dependant on the cask transporting machine. For transportation off-site to a repository or long term ISFSI the preference of transportation is horizontally. The horizontally orientated cask is easier transported in a horizontal manner as to ensure ease of insertion into the horizontal storage module in the case of the NUHOMS-24P system.

The horizontal ground acceleration for the seven cask types are compared showing their ability to withstand an earthquake as this would determine the seismic stability which forms part of the selection criteria. These casks were all of a similar range and resulted in a similar seismic stability between all the cask designs. The cask orientation however does play a role in the cask stability where the stability of the horizontal cask handles 2 times larger acceleration than the vertical cask.

So even though stands assist in securing the horizontal casks they offer very little with respect to seismic stability other than what the cask was designed to handle.

Space required for the casks vary with their respective orientation, footprint and amount of access space required is 35% on average. Space for a cask storage facility can be limited by the space requirements, if not any cask can be used.

The facility designs are dependent on the cask designs selected as well as specific plant preferences and could not be evaluated in as much detail like with the cask types.

4. Conclusion

This research dissertation technically evaluated seven types of casks against the identified design criteria. The selected casks were evaluated in terms of SNF criticality, radiation shielding, decay heat removal and heat transfer. Other aspects also determined by calculation were seismic stability of casks and cask footprint. The results obtained show the relationship of the SF packing density of the different casks with an average of 3371.1kg/m^2 . From the data obtained it was determined that one cannot use the effective enrichment as a metric to evaluate cask designs to achieve criticality. One can conclude that all casks contain the “same” fuel when viewed from the perspective of effective enrichment. The heat transfer coefficients were all similar irrespective of cask design and orientation. The inner canister temperatures were similar but were generally higher for the concrete casks with the same result for canister wall temperatures. Comparatively the seismic stability is dependent on the width and height of the casks which are all of a similar range and results in a similar seismic stability between all the cask designs. This is different if the cask orientation differs where the stability of the horizontal cask handles 2 times larger acceleration than the vertical cask.

In conclusion, the objectives of this research dissertation were met and the selection criteria determined and technically evaluated for the casks and storage facility designs. Overall an understanding of the dry cask technology was achieved and the comparison of the seven types of casks brought forth valuable information and insights into this topic of dry cask storage. The facility designs were dependent on the cask designs selected as well as specific plant preferences and could not be evaluated in as much detail like with the cask types.

In hind sight the areas of improvement of this dissertation would be to obtain the latest information from suppliers and to use specific neutronic software to do the seven cask type comparison study with respect to effective SNF enrichment and subcriticality. Other areas for improvement include focusing on SA’s specific need at KNPS and then present realistic solutions. This was not possible due to the time constraints as well as due to the sensitivity nature around this topic of spent fuel storage at KNPS.

Recommendations for further study are to evaluate a greater range of casks to verify and improve upon the relationship of evaluated parameters that were shown in the technical evaluation. These casks should all have similar means of maintaining sub-criticality, shielding and heat removal in order to generate comparable results using Microshield or similar software which was out of the scope for this dissertation.

List of References

- Agency, N. E., 2006. *Nuclear Science: Very high burn-ups in light water reactors NEA No. 6224*, Paris: OECD.
- Bjorkman, G. S., 2010. *Influence of ISFSI Design Parameters on the seismic response of dry storage casks*, Baltimore: US-NRC, Patram.
- Bodansky, D., 2004. Chapter 11. In: *Nuclear Energy: Principles, Practices and Prospects*. New York: Springer, p. 255.
- Bozic, H., 1996. *Concrete spent fuel cask criticality calculation*, Croatia: HND International Conference.
- Bredell, P., 1998. Spent fuel management in South Africa. *IAEA*, pp. 77-81.
- Carolissen, A., 2013. *The future of radioactive waste management in South Africa*. [Online]
Available at: <http://www.radwaste.co.za/NLM%20presentation.pdf>
[Accessed 5 January 2015].
- D. Vinson, R. K. A. M.-T., 2011. *Inventory and description of commercial reactor fuels within the United States*, US: Fuel Cycle Research and Development US DOE.
- Das, K., 2012. *Computational fluid dynamics for spent fuel storage and transportation systems*, Texas: South West Research Institute.
- DOE, 2012. *IRP 2010*, Pretoria: Department of Energy.
- Duerr, D., 2013. *2DM Associates, Inc. Alternative Lifting Methods*. [Online]
Available at: <http://www.2dm.us/EquipmentDesign.htm>
[Accessed 17 July 2015].
- Durst, P., 2012. *Guidance for ISFSI, Safeguards and Security*, s.l.: NNSA.
- Federovich, E. D., 2007. *Technical issues of wet and dry storage facilities for spent nuclear fuel*, St. Petersburg, Russia: Research and Design Institute.
- Haire, M., 2005. *Cask size and weight reduction through the use of depleted uranium dioxide cermet material*, Tucson: WM 05 Conference.
- Hattori, Y., 1999. *Development of numerical analytical method to estimate heat removal characteristics of cask storage facility system*, Tokyo: Central Research Institute of Electric Power Industry.
- IAEA, 1994. *Safety Practices Safety Series No. 118: Safety Assessment for Spent Fuel Storage Facilities*, Vienna: IAEA.

- IAEA, 2009. *IAEA Nuclear Energy Series No. NF-T-3.5 Costing of Spent Nuclear Fuel Storage*, Vienna: IAEA.
- International, H., 2012. *Holtec International*. [Online]
Available at: <http://www.holtecinternational.com>
[Accessed 11 05 2015].
- J.R. Welty, C. W. R. W. G. R., 2001. *Fundamentals of momentum, heat and mass transfer*. fourth ed. Oregon: Wiley.
- John R. Lamarsh, A. J. B., 2001. *Introduction to Nuclear Engineering*. 3rd ed. New Jersey: Prentice Hall.
- Ju-Chan Lee, K.-S. B. K.-S. S. H.-D. K., 2004. *Thermal analysis of a storage cask for 24 spent PWR fuel assemblies*, Korea: Korea Atomic Energy Institute.
- Kessler, J., 2010. *Industry Spent Fuel Storage Handbook*. California: EPRI.
- Kirchner, B., 1997. *WMSYM*. [Online]
Available at: <http://www.wmsym.org/archives/1997/sess18/18-04gif/18-04f1.gif>
[Accessed 25 May 2015].
- Lambert, R., 1993. *Evaluation of comparative system economics and operability of concrete casks for fuel storage*. New York, INIS.
- Lienhard, J., 2012. *A heat transfer textbook*. Second ed. Cambridge: Phlogiston Press.
- Madigan, J., 2015. *Decommissioning San Onofre Nuclear Generating Station*, California: Edison: California Energy Commission.
- Management, O. o. E., 2014. *Energy.gov*. [Online]
Available at: <http://energy.gov/em/em-safely-and-efficiently-manages-spent-nuclear-fuel>
[Accessed 26 March 2015].
- McCullum, R., 2012. *An Overview of Dry Cask Storage*. [Online]
Available at: <http://www.nei.org>
[Accessed 2015 January 2015].
- MG Raddatz, M. W., 1995. *NUREG-1571: Information Handbook on Independant Spent Fuel Storage Installation*, Washington: US-NRC.
- Miles Pomper, N. C. C. M. S. L. F. D.-V., 2013. The Bigger Picture: Rethinking Spent Fuel Management in South Korea. *CNS*, Volume 16, p. 93.
- N.R. Chalansani, M. G., 2009. Natural convection/ radiation heat transfer simulations of enclosed array of vertical rods. *Packaging, Transport, Storage & Security of Radioactive Material*, 20(3), pp. 117-125.

NEI, 1998. *CASTOR V/21 Metal Storage Cask*, s.l.: s.n.

News, W. N., 2014. *South Africa launches radwaste agency*. [Online]

Available at: <http://www.world-nuclear-news.org/WR-South-African-launches-radwaste-agency-0404145.html>

[Accessed 05 January 2015].

NNR, 2013. *NNR Annual Report 2013/2014*, Pretoria: NNR.

NRC, 2006. *Public Report: Safety and Security of commercial spent nuclear fuel storage*. [Online]

Available at: http://www.nap.edu/openbook.php?record_id=11263&page=60

[Accessed 5 January 2015].

NRC, 2006. *Safety and security of commercial spent nuclear fuel storage: Public Report*. [Online]

Available at: <https://www.nap.edu>

[Accessed 20 June 2015].

NRC, U., 2007. *Regulation Guide 1.13*, US: US NRC.

NRC, U., 2012. *US NRC*. [Online]

Available at: <http://www.nrc.gov/waste/spent-fuel-storage/dry-cask-storage.html>

[Accessed 5 January 2015].

Power, 2011. *Power*. [Online]

Available at: <http://www.powermag.com/self-propelled-spent-fuel-cask-transporter/>

[Accessed 17 July 2015].

Reddit, 2010. [Online]

Available at: <https://www.reddit.com>

[Accessed 20 March 2015].

Rigby, D. B., December 2010. *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel*, US: US Nuclear Waste Technical Review Board.

Roncati, D., 2010. *Iterative calculation of the heat transfer coefficient*, Ferrara: Progettazione Ottica Roncati.

S. Rokita, T. H. G. C., 2006. *The South African Experience in Spent Fuel Management at the Koeberg Nuclear Power Plant*, Vienna: NNR, IAEA.

S.R. Greene, J. M. S. M., 2013. *Storage and transport cask data for used commercial nuclear fuel*, Tennessee: Advanced Technology Insights LLC.

Saegusa, T., 2008. Topics of research and development on concrete cask storage of spent nuclear fuel. *Elsevier ScienceDirect: Nuclear Engineering and Design*, Volume 238, pp. 1168-1174.

Sanono, 2013. *Sanono Free Safety*. [Online]
Available at: sanonofresafety.files.wordpress.com/2013/06
[Accessed 11 May 2015].

Seies, I. S. S., 2003. *Design of Fuel Handling and Storage Systems for Nuclear Power Plants, Safety Guide No. NS-G-1.4*, Vienna: IAEA.

Sibiya, G., 2000. *Radioactive waste disposal challenges that face the South African nuclear energy industry*. Port Elizabeth, WM Conference.

Smith, S. W., 2010. Development of a strategy for the management of PBMR spent fuel in South Africa. *Elsevier ScienceDirect: Nuclear Engineering and Design*, Volume 240, pp. 2415-2420.

Solutions, B. F., 2005. *VSC-24 Concrete Storage Cask*, s.l.: BNG.

Sovacool, B. K., 2012. *The National Politics of Nuclear Power: Economics, Security and Governance*. s.l.:s.n.

Technology, N. I. o. S. a., 2015. *Basic Physics of Nuclear Medicine*. [Online]
Available at: [https://en.wikibooks.org/wiki/Basic Physics of Nuclear Medicine/Attenuation of Gamma Rays](https://en.wikibooks.org/wiki/Basic_Physics_of_Nuclear_Medicine/Attenuation_of_Gamma_Rays)
[Accessed 24 June 2015].

Transnuclear, 2011. *NUHOMS® 37PTH Dry Shielded Canister*, Columbia: s.n.

Twala, V. G., 2007. *Evaluation of spent nuclear fuel management options for South Africa*, Johannesburg: University of Johannesburg.

Ucsusa, 2010. *Ucsusa*. [Online]
Available at: <http://www.ucsususa.org>
[Accessed 14 January 2015].

US-NRC, 2014. *San Onofre Safety*. [Online]
Available at: <https://sanonofresafety.files.wordpress.com/2011/11/stresscorrosioncrackingnrcslide2-2014-07-14.jpg>
[Accessed 25 May 2015].

V. Roland, M. C. Y. G., 2014. *Dry storage technologies: Keys to choosing among metal casks, concrete shielded steel canister modules and vaults*, France: IAEA-CN-102/14.

Vernon, M., 2014. *Pre-feasibility Study on TISF Facility*, Cape Town: Internal.

WM, 2010. *WM2010 Conference*, s.l.: s.n.

Appendix A. Calculations

1. Heat transfer calculation

To calculate convective heat transfer the following equation is used:

$$Q = hA(T_w - T_a)$$

Where:

Q is the cask design heat load, J/s or W

h is the heat transfer coefficient, W/m²K

A is the heat transfer cross sectional area, m²

T_w is the temperature of the cask wall, K

T_a is the temperature of the air, K

The heat transfer of the casks outer surface can be increased by the addition of external cooling fins which increases the heat transfer capability by increasing the outer surface area. These fins can be longitudinal or transverse on the outer surface of the cask.

For a cask with convective cooling:

$$\frac{Q}{A} = h_c(T_w - T_a)$$

This equation can be used for the surface heat load to calculate the heat transfer per surface area (kW/m²).

2. Determination of the heat generation term

$$Q_i = 50\% Q_{total}$$

$$Q''' = \frac{Q_{total} - Q_i}{\pi(r_o^2 - r_i^2)H}$$

Where: Q_{total} is the design heat load of the cask in kW.

Q_i is the heat inside the cask from the spent fuel assumed as a percentage of the total cask heat.

Q''' is the heat generation term which is assumed to be uniform within the shielding material

and the difference between the design heat load and heat inside the cask.

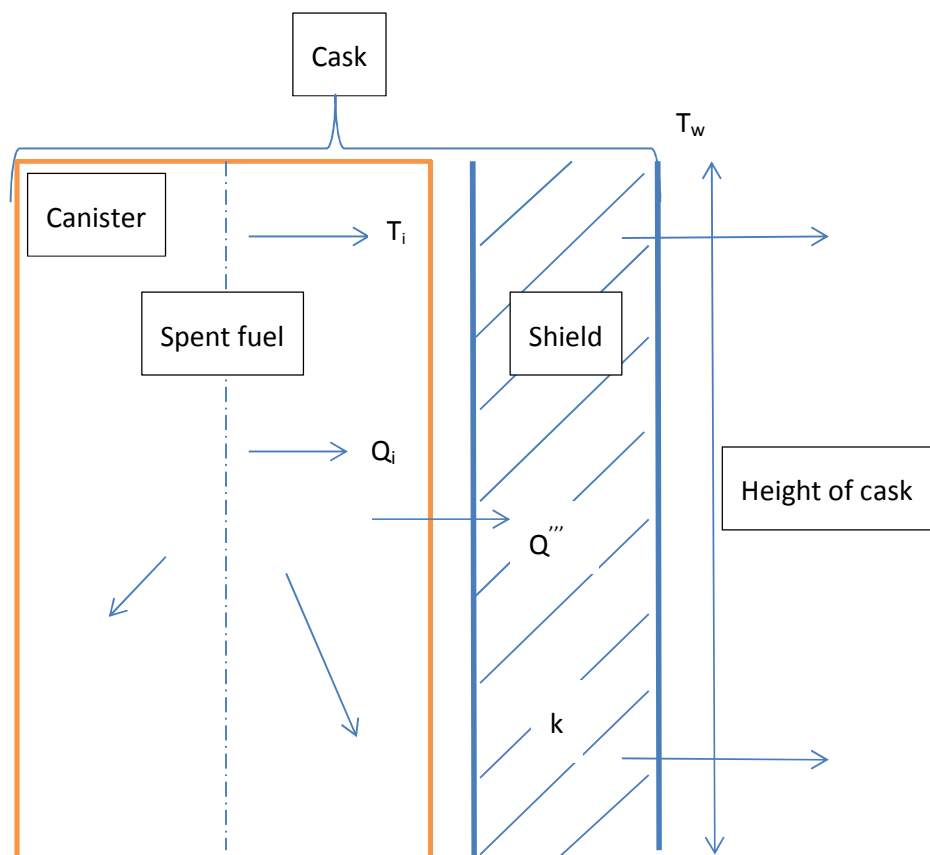


Figure 38: Schematic diagram of the cask to illustrate heat generation term

3. Calculation for determining the canister wall temperature

$$\frac{d}{dr} \left(r \frac{dT}{dr} \right) = \frac{Q'''}{k} r \dots (1)$$

$$\text{Integrate: } \frac{dT}{dr} = -\frac{1}{2} \frac{Q'''}{k} r + \frac{C_1}{r} \dots (2)$$

$$\text{On inner wall: } Q_i = -\frac{k2\pi r_i H}{dr} dT$$

$$\text{Therefore if } r = r_i \text{ then: } \frac{dT}{dr} = -\frac{Q_i}{k2\pi r_i H} dT$$

$$\text{Substituting into equation (2): } -\frac{Q_i}{k2\pi r_i H} = -\frac{1}{2} \frac{Q'''}{k} r + \frac{C_1}{r}$$

$$C_1 = \frac{Q'''}{2k} r_i^2 - \frac{Q_i}{k2\pi H}$$

$$\text{Integrating equation (2): } \int_T^{T_o} T = -\frac{Q'''}{4k} r^2 + C_1 \int_r^{r_o} \ln(r)$$

$$T_o - T = -\frac{Q'''}{4k} (r_o^2 - r_i^2) + C_1 \ln\left(\frac{r_o}{r_i}\right)$$

To determine the inner wall temperature: $T_i = T_o + \frac{Q'''}{4k} (r_o^2 - r_i^2) - C_1 \ln\left(\frac{r_o}{r_i}\right)$

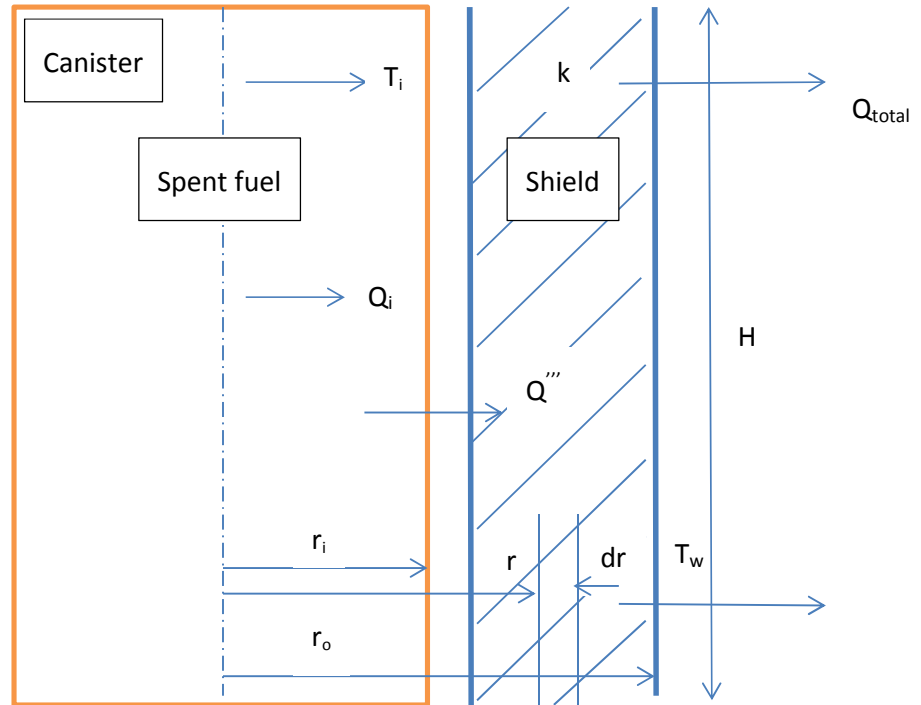


Figure 39: Schematic diagram of the cask to illustrate the heat generation term

4. Convective heat transfer coefficient calculation

Below are the equations used for natural convection of an isothermal plate. These dimensionless numbers used in natural convection heat transfer coefficient correlations.

$$Nu = hL/k$$

$$Pr = \mu C_p / k$$

$$Gr = L^3 \rho^2 g \Delta T \beta / \mu^2$$

$$Ra = Gr \cdot Pr$$

Where:

Nu is the Nusselt Number

Pr is the Prandtl Number

Gr is the Grashof Number

Ra is the Raleigh Number

For vertical casks it is considered to be a plane wall and the length or height of the cask is used in the equations.

For horizontal casks it is considered to be a cylinder and the diameter of the cask is used in the equations above.

Assumptions:

1. Radiative cooling is minimal and can be neglected in the following calculations.
2. Outside the cask convective cooling occurs passively due to the air currents and buoyancy-induced air flow.
3. Through the metal or concrete cask conduction takes place. This occurs more in the metal cask than the concrete cask as metal is a better conductor of heat and therefore greater cooling occurs.

a. **For a horizontal cylinder/ cask:**

Natural convection heat transfer from an isothermal horizontal cylinder (Lienhard, 2012):

$$Nu = \left\{ 0.60 + \left(\frac{0.387 Ra^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{9/16}\right)^{8/27}} \right) \right\}^2$$

$$\text{for } Ra \leq 10^{12} \quad Ra = Gr \cdot Pr$$

Natural convection heat transfer coefficient correlations in SI units for an isothermal horizontal cylinder: Fluid = air

Table 22: Input data for horizontal cask

| Input parameter | Symbol | Units | Input value |
|-------------------------------------|--------------|-------------------|-------------|
| Fluid temperature | T_{∞} | °C | 20 |
| Surface temperature | T_s | °C | 45 |
| Film temperature | T_f | °C | 33 |
| Cylinder diameter | D | m | 2.4 |
| Fluid density | ρ | kg/m ³ | 1.1 |
| Fluid viscosity | μ | Ns/m ² | 0.0000187 |
| Fluid specific heat | C_p | J/kgK | 1000 |
| Fluid thermal conductivity | k | J/smK | 0.027 |
| Fluid thermal expansion coefficient | β | K ⁻¹ | 0.003411 |

Table 23: Calculation solutions for horizontal cask

| Parameter | Symbol | Units | Calculated Value |
|--------------------------------------|------------|--------------------|------------------|
| Temperature difference | ΔT | °C | 25 |
| Absolute film temperature | T_f | °C | 306 |
| Prandtl Number | Pr | Dimensionless | 0.7 |
| Grashof Number | Gr | Dimensionless | 3.46exp10 |
| Raleigh Number | Ra | Dimensionless | 2.4exp10 |
| Nusselt Number | Nu | Dimensionless | 317 |
| Convective heat transfer coefficient | h | W/m ² K | 3.65 |

b. For a vertical cylinder/ cask modelled as a flat plate:

Correlation 1 for all values of Ra (Lienhard, 2012):

$$Nu = \left\{ 0.825 + \left(\frac{0.387 Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{Pr} \right)^{9/16} \right]^{8/27}} \right) \right\}^2$$

Correlation 2 for $Ra < 10^9$:

$$Nu = \left\{ 0.68 + \left(\frac{0.67 Ra^{\frac{1}{4}}}{1 + \left(\frac{0.492}{Pr} \right)^{9/16}} \right) \right\}^{4/9}$$

$$Gr = D^3 \rho^2 g \Delta T \beta / \mu^2$$

Natural convection heat transfer coefficient correlations in SI units for an isothermal vertical plane: Fluid = air

Table 24: Input data for vertical cask

| Input parameter | Symbol | Units | Input value |
|---|---------|----------|-------------|
| Height of surface | L | m | 6 |
| Fluid or volumetric thermal expansion coefficient | β | K^{-1} | 0.003411 |

This input data is in addition to Table 22.

Table 25: Calculation solutions for vertical cask

| Parameter | Symbol | Units | Calculated Value |
|--------------------------------------|------------|---------------|------------------|
| Temperature difference | ΔT | $^{\circ}C$ | 25 |
| Absolute film temperature | T_f | $^{\circ}C$ | 306 |
| Prandtl Number | Pr | Dimensionless | 0.69 |
| Grashof Number | Gr | Dimensionless | 5.76exp11 |
| Raleigh Number | Ra | Dimensionless | 3.99exp11 |
| For all values of Ra: | | | |
| Nusselt Number | Nu | Dimensionless | 818 |
| Convective heat transfer coefficient | h | W/m^2K | 3.68 |

Table 26: Results and data used in calculations

| | Vertical cask | Horizontal cask |
|---|-----------------------|-----------------------|
| | R_3 | R_3 |
| Characteristic length (m) | L=6 | D=3.1 |
| T_{max} ($^{\circ}$ C) | 250 | 250 |
| T_a ($^{\circ}$ C) | 20 | 20 |
| T_i ($^{\circ}$ C) | 100 | 100 |
| T_s ($^{\circ}$ C) | 45 | 45 |
| ID (m) | 2.9 | 2.9 |
| OD (m) | 3.1 | 3.1 |
| thickness (m) | 0.2 | 0.2 |
| g (m/s^2) | 9.81 | 9.81 |
| k_{air} (W/m.K) | 0.027 | 0.027 |
| ν (m/s)kinematic viscosity | 1.93×10^{-5} | 1.93×10^{-5} |
| Pr | 0.69 | 0.7 |
| β | 0.003143 | 0.003143 |
| Ra | 3.99×10^{11} | 2.4×10^{10} |
| Gr | 5.76×10^{11} | 3.46×10^{10} |
| Nu | 818 | 317 |
| h_{avg} (W/m ² .K) (natural circulation) | 3.68 | 3.65 |
| A (m ²) | 70.69 | 42.42 |
| Q/A (W/m ²) | 92 | 91.3 |
| Q (W) | 6503.5 | 3872.95 |

5. Seismic stability calculation

The centre of gravity (CG) of the cask is determined by the shape and orientation of the cask. The CG provides the average location of the weight of an object. This affects the cask's stability when seismic events occur. This also provides the guidance to the spacing requirements of the casks on a storage pad or in a structural facility thus allowing tilting without falling over or complicating the stability of each cask.

a. Vertical Cask

Where:

CG is the centre of gravity

H is the height of the cask

R is the radius

Eg. For a cask height of 6 m, radius of 1.5 m and weight of 120 tons.

Forces at work on the vertical cask:

1. Horizontal force
2. Downward force due to gravity and mass of the object
3. Opposite force to the horizontal force
4. Opposing force to the gravity and mass of the object

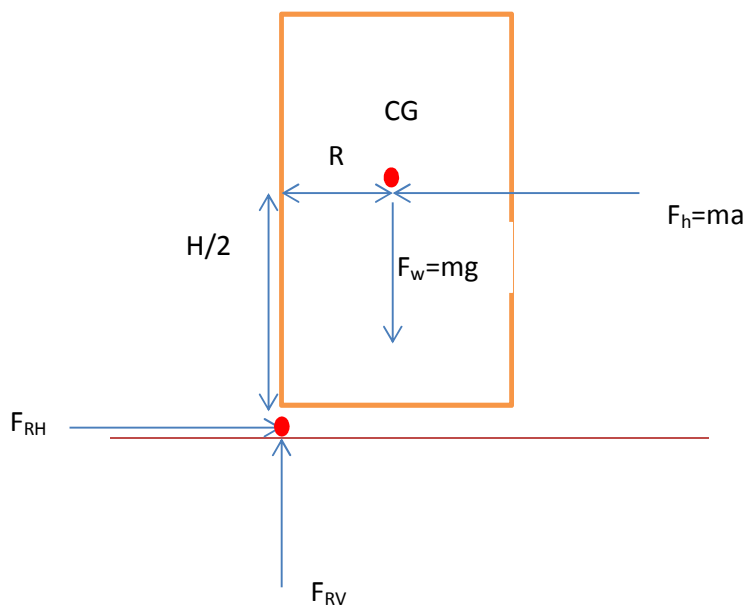


Figure 40: Schematic diagram of a vertical cask

For the cask:

$$F_h \cdot (H/2) > F_w \cdot R$$

$$m \cdot a \cdot (H/2) > m \cdot g \cdot R$$

$$a > g \cdot R / (H/2)$$

$$a/g > R / (H/2)$$

$$a' > D/H$$

$$a' > \frac{3}{6} = 0.5g$$

b. Horizontal Cask

Eg. For a cask length of 6m, diameter of 3 m and weight of 120 tons. Horizontal cask height of 3.2 m when on a plinth. Centre of gravity (CG) is represented by the red dot.

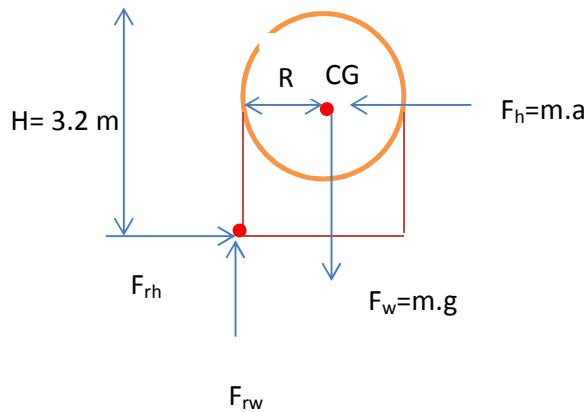


Figure 41: Schematic diagram of a horizontal cask

For the cask:

$$F_h \cdot (H/2) > F_w \cdot R$$

$$m \cdot a \cdot (H/2) > m \cdot g \cdot R$$

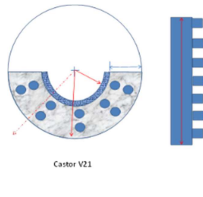
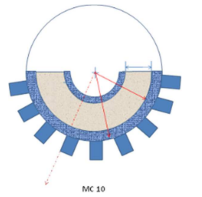
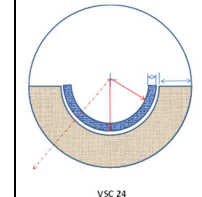
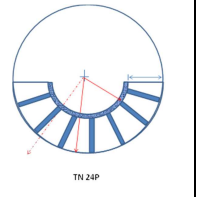
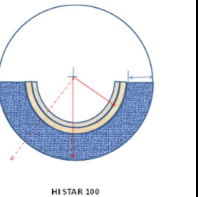
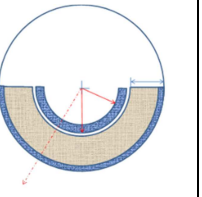
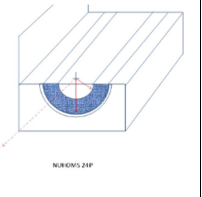
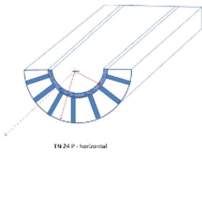
$$a > g \cdot R / (H/2)$$

$$a/g > R / (H/2)$$

$$a' > D/H$$

$$a' > \frac{3}{3.2} = 0.94g$$

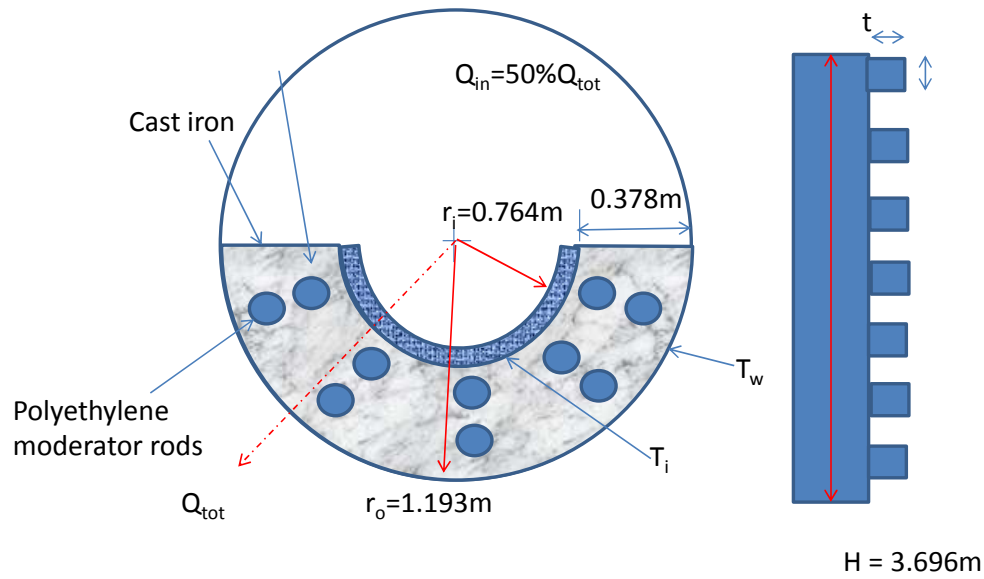
Appendix B. Cask Comparison

| Cask Type | Castor V21 | MC 10 | VSC 24 | TN 24P | HI-STAR 100 | HI-STORM 100 | NUHOMS 24P | TN 24P |
|---|---|---|---|--|---|---|---|---|
| Geometry |  |  |  |  |  |  |  |  |
| Orientation | Vertical | Vertical | Vertical | Vertical | Vertical | Vertical | Horizontal | Horizontal |
| Total area [m ²] | 47.21 | 35.80 | 21.39 | 31.38 | 33.69 | 25.13 | 24.98 | 37.95 |
| Heat load, Q _{tot} [W] | 21000 | 13500 | 24000 | 20600 | 19000 | 36900 | 24000 | 20500 |
| Heat generated, Q _i [W] | 10500 | 6750 | 12000 | 10300 | 9500 | 18450 | 12000 | 10250 |
| Heat, Q''' [W/m ³] | 1077.11 | 462.98 | 1121.92 | 991.93 | 950.82 | 2845.04 | 4111.11 | 1854.05 |
| Heat generated in the shield, Q _{shield} [W] | 10500 | 6750 | 600 | 10300 | 9500 | 922.5 | 600 | 10250 |
| Heat from inner cask for cooling, Q _{cool} [W] | 21000 | 13500 | 12600 | 20600 | 19000 | 19373 | 12600 | 20500 |
| Effective Thermal Conductivity, k _e [W/m.K] | 66.3 | 45 | 50.2 | 45.7 | 49.5 | 50.2 | 50.2 | 45.7 |

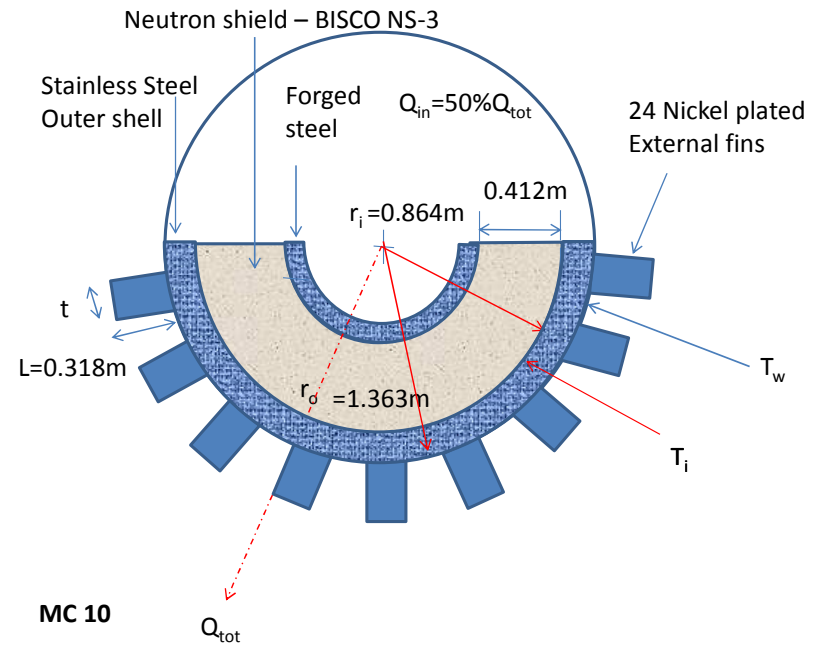
Appendix B. Cask Comparison

| | | | | | | | | |
|---|--|--------------------------------|---|--------|--------|---|-------------------|--------|
| Average Heat transfer coefficient, (h) [W/m².K] | 5.61 | 5.32 | 7.01 | 6.15 | 5.87 | 7.47 | 6.32 | 5.51 |
| Cask wall temperature, T_{wall} [°C] | 98.61 | 91.53 | 178.93 | 125.95 | 116.92 | 215.14 | 170.76 | 118.94 |
| Cask inner wall temperature, T_{in} [°C] | 105.3 | 97.2 | 182.7 | 134.2 | 123.9 | 226.1 | 186.1 | 134.3 |
| Assumptions | | | No chimney effect | | | No chimney effect | No chimney effect | |
| Fins/ air vents | 73 external circumferential fins; 132 internal polyethylene rods. | 24 external longitudinal fins. | 4 air inlets on top and 4 at the bottom. Air gap between steel and concrete layer. | | | 4 air inlets on top and 4 at the bottom. Air gap between steel and concrete layer. | Air channels | |

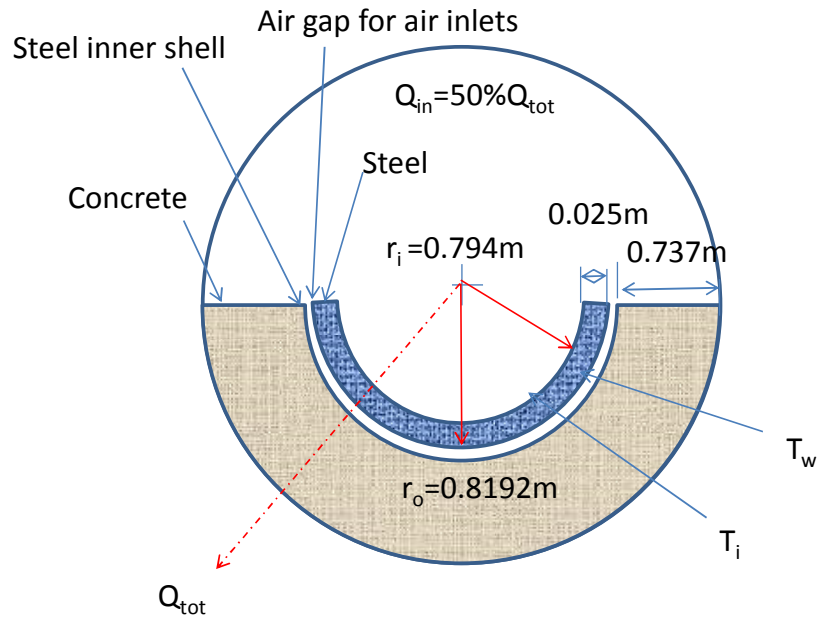
Appendix C. Cask Profiles



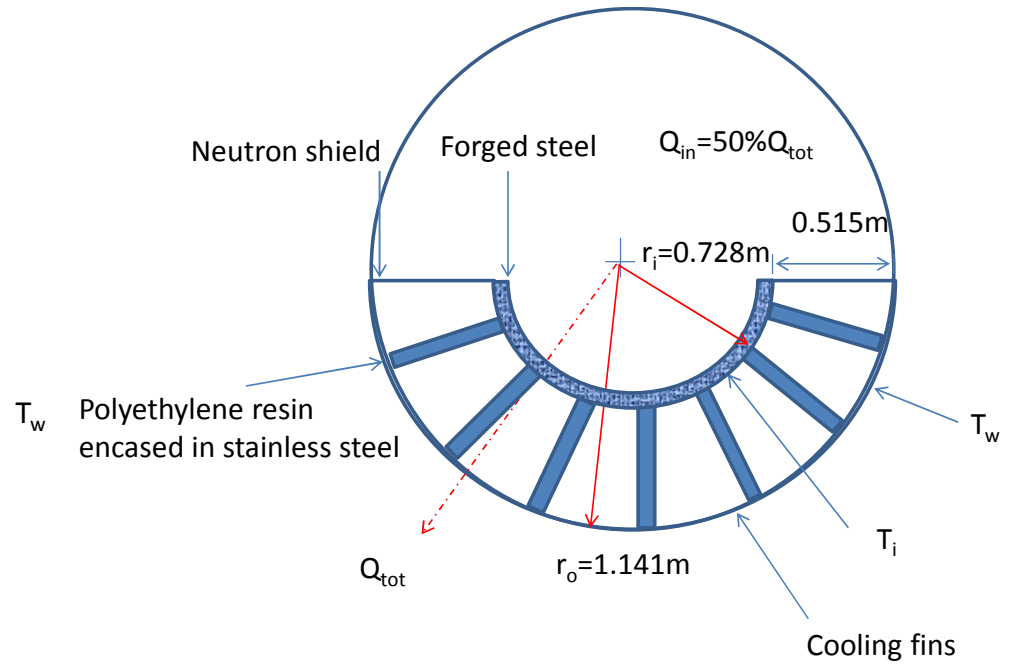
Castor V21



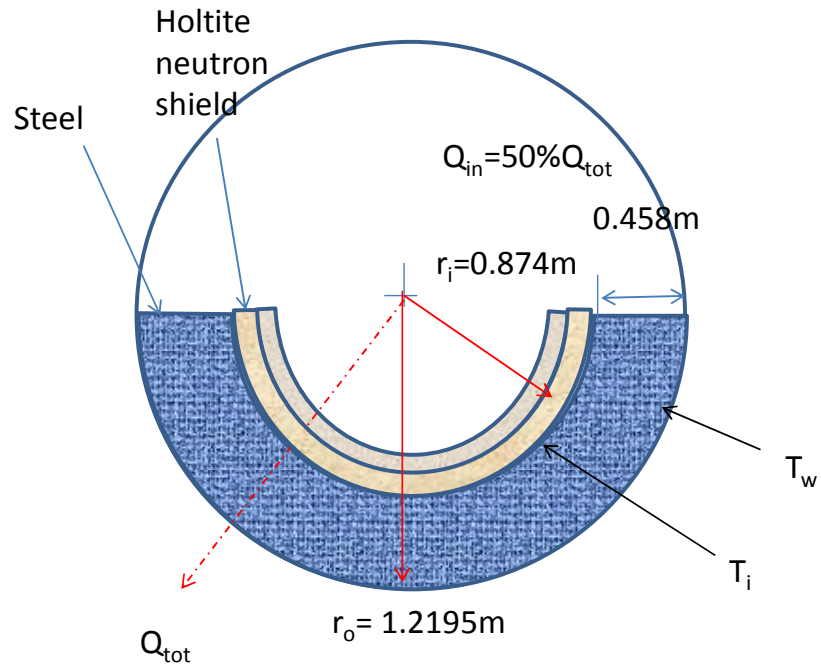
MC 10



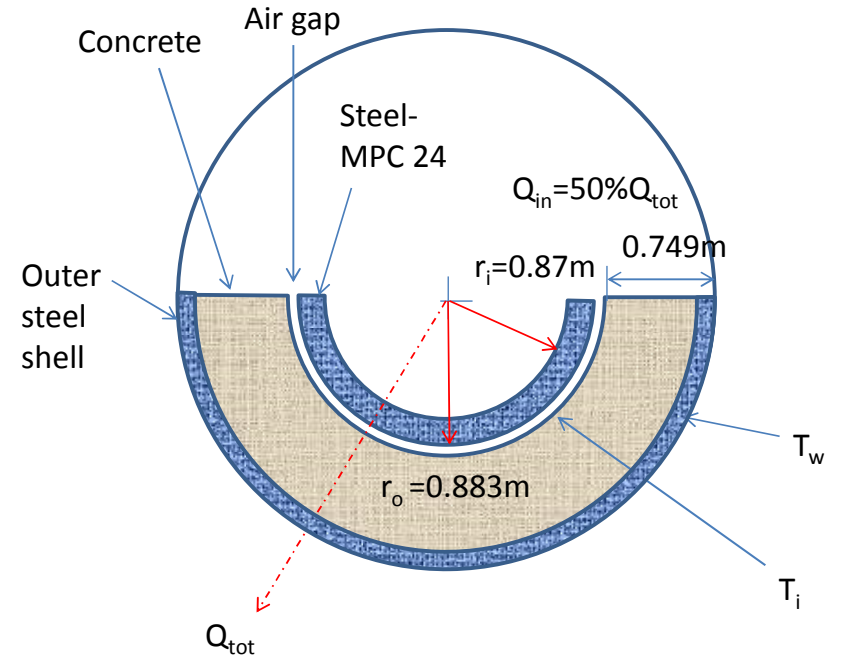
VSC 24



TN 24P



HI STAR 100



HI STORM 100

