Application of the analytic hierarchy process in selecting medium-term storage options for spent nuclear fuel in South Africa

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DECLARATION BY THE AUTHOR

I, Patrick Bonga Dyasi, declare that I carried out the work reported in the following dissertation. I hereby confirm that any help received in preparation for the dissertation and all the sources used have been acknowledged.

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Date: 12 October 2020
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ABSTRACT

South Africa is one of the countries using nuclear power and has prospects to expand its use in the near future. The management of spent nuclear fuel (SNF) from nuclear power plants has become a major issue internationally, with South Africa facing the same challenges as other countries (Bunn *et al.,* 2001; Twala, 2007).

In 2005 the South African government developed a Radioactive Waste Management Policy and Strategy (RWMP&S) for the Republic of South Africa (hereinafter “the Policy”) for the management of its radioactive waste and SNF (DME, 2005). In the Policy, the government recognises that the practice of storing SNF on-site is not sustainable. Therefore, long-term above-ground storage on an off-site facility is needed to buy time until a permanent solution is found.

A number of options for storage systems are available from international vendors. The challenge is to select the most appropriate system for South Africa. The analytic hierarchy process (AHP) is identified as a possible tool to aid the selection process.

The aim of this study is to apply the AHP tool to compare a subset of existing dry storage options currently in use worldwide in a systematic way to decide which of the options is the best to meet South Africa’s needs.

The study gives an overview of the existing dry storage options and related facilities. It also identifies relevant specific criteria and sub-criteria from literature to compare these options. Given time constraints, only three cases were chosen to demonstrate the application of the AHP tool using the identified criteria. Pairwise comparisons are conducted and the ranking of the options is determined.

The AHP is implemented using a Microsoft Excel program. A code that forms part of the North-West University Reactor Code Suite was used to verify the correctness of the calculations performed on the Microsoft Excel program. The results show that a concrete module with an inner canister stored on a reinforced concrete storage pad open to the environment (ConMod) is the best option to meet South Africa’s needs. These results are in agreement with the initial intuitive judgement of the option by the researcher. On the basis of the results obtained from this study, it was demonstrated that the AHP tool can be applied to decide on the available option that will best meet South Africa’s needs.

Keywords: Spent Nuclear Fuel, Analytic Hierarchy Process, Dry Storage Systems, and Medium-term Storage.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFR	Away from Reactor
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BNFL	British Nuclear Fuels Limited
BWR	Boiling Water Reactor
DME	Department of Energy
ENRESA	Empresa Nacional de Residuos Radiactivos S.A.
ENSA	Equipos Nucleares S.A
GNS mbH	Gesellschaft für Nuklear-Service mbH
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRP	Integrated Resource Plan
KNPS	Koeberg Nuclear Power Station
LLW	Low-level Waste
MeV	Mega Electron Volts
μSv/h	microSievert per hour
MVDS	Modular Vault Dry Storage
MWe	MegaWatt Electric
NAC	Nuclear Assurance Corporation
NEA	Nuclear Energy Agency

NNR	National Nuclear Regulator
NPP	Nuclear Power Plant
NWURCS	North-West University Reactor Code Suite
PWR	Pressurised Water Reactor
SGN	Société Générale pour Techniques Nouvelles
SNF	Spent Nuclear Fuel
UK	United Kingdom
USA	United States of America
VVER	Voda Voda Energo Reaktor

NOMENCLATURE

CO_2	Carbon Dioxide
Sr-90	Strontium-90
Cs-137	Caesium-173

1 INTRODUCTION

1.1 Background

Nuclear power has been widely implemented around the world, with 448 reactors currently in operation and 59 under construction (WNA Report, 2018). South Africa is one of the countries with nuclear power and with prospects to expand its use in the near future. South Africa currently operates one nuclear power plant (NPP), known as Koeberg Nuclear Power Station (KNPS), which consists of two pressurised water reactors (PWR) with a capacity of 930 MWe each.

Nuclear power is a technology that can provide substantial baseload electricity generation and minimise dependence on fossil fuels, which will ultimately reduce carbon dioxide (CO_2) emissions (Zakariya, 2016) and related cost. Since in South Africa electricity supply is mostly dependent on coal-fired power generation, additional nuclear power would play a major role in the reduction of CO_2 emissions. However, management of spent nuclear fuel (SNF) from nuclear power plants has been accumulating in storage facilities internationally (Bunn *et al.,* 2001), with South Africa also facing this same challenge (Twala, 2007).

Internationally, three options have been adopted for the management of SNF (Hambley *et al.,* 2016):

(i) "Closed cycle", where the SNF is reprocessed. Reprocessing has been deployed on an industrial scale in a number of countries with large nuclear power programmes (e.g. France, the United Kingdom (UK), Russia and Japan). It has also been carried out in countries such as Switzerland, the Netherlands, Ukraine and Belgium through commercial reprocessing services (IAEA, 2005). Reprocessing reduces the amount of SNF to be managed.

(ii) "Open or Once-through fuel cycle", where the spent fuel is not reprocessed but is directly disposed of following a period of interim storage. A number of countries have preferred this option (e.g. the United States of America (USA), Canada, Sweden, Germany and Finland). However, due to slow progress in the development of SNF disposal facilities, no SNF has been disposed of anywhere in the world. Only a few countries are making significant progress toward implementing disposal facilities. The most notable of these are Sweden and Finland, with the latter at an advanced stage of construction of its facility.

(iii) The third option is "wait and see", where SNF remains and continues to accumulate in storage facilities because no decision has been made on its fate. Examples of these countries are Argentina, Armenia, Brazil, Spain, Bulgaria and Hungary (IAEA, 2005).

South African is among the countries where no decision has been made on how the SNF will be disposed of. In 2005, the South African government developed a Radioactive Waste Management Policy and Strategy for the Republic of South Africa (hereinafter "the Policy") for the management of its radioactive waste and SNF (DME, 2005). In the Policy, the government commits itself to investigating various options for the safe management of SNF and high-level waste. These options include:

(i) reprocessing, conditioning and recycling;

(ii) deep geological disposal; and

(iii) transmutation.

In the Policy, the government recognises that the practice of storing fuel on-site is not sustainable. Therefore, regardless of any SNF management strategy chosen, long-term above-ground storage in an off-site facility is needed for a number of reasons, which include (NRWDI, 2018):

(i) It is necessary to provide sufficient long-term storage capacity away from the KNPS site, as SNF cannot be stored indefinitely on the KNPS site. One of the lessons learnt from the Fukushima accident was the importance of limiting the SNF inventory on-site. On-site storage should only be used for cooling purposes of the SNF (Maree & Carolissen, 2017).

(ii) Eskom is considering an extension of the lifetime of the two reactor units at KNPS from the current 40 years to a possible 60 years of operating life, which means SNF storage capacity additional to the initially expected storage will be required (NNR, 2017). Transfer of SNF from the NPP site to an off-site facility needs to be enabled, for safe plant decommissioning and site restoration following KNPS shutdown.

(iii) Public confidence and trust in the government on SNF management need to be enhanced to address the contentiousness of long-term SNF management.

It should be noted that the term “long-term storage” as referred to in the Policy is herein used interchangeably with the term “medium-term storage” as referred to in the title of this dissertation.

1.2 Problem Statement

Spent nuclear fuel dry storage options are currently in use at NPPs worldwide and dry storage facilities and systems are commercially available on the international market. The research problem that arises, therefore, is deciding which option will best meet South Africa’s needs.

1.3 Purpose and Objectives

The purpose of this dissertation is to demonstrate the application of the analytic hierarchy process (AHP) tool to compare a subset of existing dry storage options currently in use worldwide in a systematic way to decide which of the options is the most suitable for South Africa’s needs.

The objectives of this dissertation are:

(i) To establish criteria and sub-criteria that will be used in deciding which dry storage option is best;

(ii) To determine which dry storage options are currently implemented worldwide;

(iii) To choose a subset of criteria and sub-criteria and a subset of options for the application of the AHP tool in terms of the scope of this study; and

(iv) To apply the AHP tool to the subset of criteria and sub-criteria and a subset of options.

1.4 Assumption

It is assumed in this study that there are no functional dependencies between or within the levels of the hierarchical structure of the AHP tool.

2 LITERATURE REVIEW

This chapter is organised into three sections. In the first section, the theory and application of the AHP tool are given.

In the second section, the basis for the selection criteria and sub-criteria, as well as the justification for each criterion and sub-criterion chosen, is given.

In the third section, a literature review on the dry storage options is given. An overview of countries that have implemented or are planning to implement dry storage of SNF is given. A description of each dry storage option and a description of the facility required for the dry storage of SNF are also given.

2.1 The Analytic Hierarchy Process

There are different tools available on the market used in the decision-making process such as the following (Amorocho-Daza *et. al.*, 2019):

- Analytic Hierarchy Process (AHP);
- Multi-Criteria Analysis (MCA) (Genorowicz, 2013)
- Multi-Attribute Analysis (MAA) (Shevchenko *et.al.*, 2008)
- Elimination Et Choix Traduisant la Realite (ELECTRE);
- Multi-attribute utility theory (MAUT);
- Measuring Attractiveness by a Categorical Based Evaluation (MACBETH);
- Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS);
- Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE).

However, in the literature, no study could be found where these decision-making tools have been used in the selection of dry storage options for SNF. Amongst these decision-making tools, analytic hierarchy process (AHP) is one of the widely used tools in solving a significant number of decision problems across different fields, including economics, medicine, manufacturing, engineering and the environment (Ababio & Mwamba, 2015).

Therefore, the study will focus on the implementation of the AHP to decide which dry storage option is the most suitable for South Africa’s needs. Following the successful demonstration that the AHP tool can be used for evaluating the dry storage options, in follow up studies the other available tools should also be studied and implemented to evaluate dry storage options and these can be benchmarked against this AHP study.

2.1.1 A general definition of the analytic hierarchy process

The analytic hierarchy process (AHP) is a decision-making tool developed by. Saaty T.L in the 1970s (Bhushan & Rai, 2004). Since then and as mentioned in Section 2.1 the AHP methodology has been widely used in solving a significant number of decision problems across different fields, including economics, medicine, manufacturing, engineering and the environment (Ababio & Mwamba, 2015). It helps structure the problem in a manner that is simple to follow and analyse by decomposing the problem into a hierarchy of sub-problems, which can be comprehended and judged subjectively more easily (Bhushan and Rai, 2004). The hierarchy indicates a relationship between elements on one level with those on the level immediately below (Bhushan & Rai, 2004). In the hierarchical structure, the decision problem is modelled in the form of goal, criteria, sub-criteria and options (Ziemba, 2019). An example of the hierarchy structure is shown in Figure 2-1.

The goal is placed at the top in the hierarchy. The goal represents the desired outcome of the decision-making process. On the level below the goal are criteria. The criteria are requirements, principles or standards by which the options are judged when choosing an option that best meets the goal. Below the criteria are sub-criteria. This is because, in some instances, criteria need to be further decomposed. Further division into sub-criteria enables clearer discrimination of the options during the judgement. The last level of the hierarchy is the options. The options are the possible solutions available or identified to meet the goal.

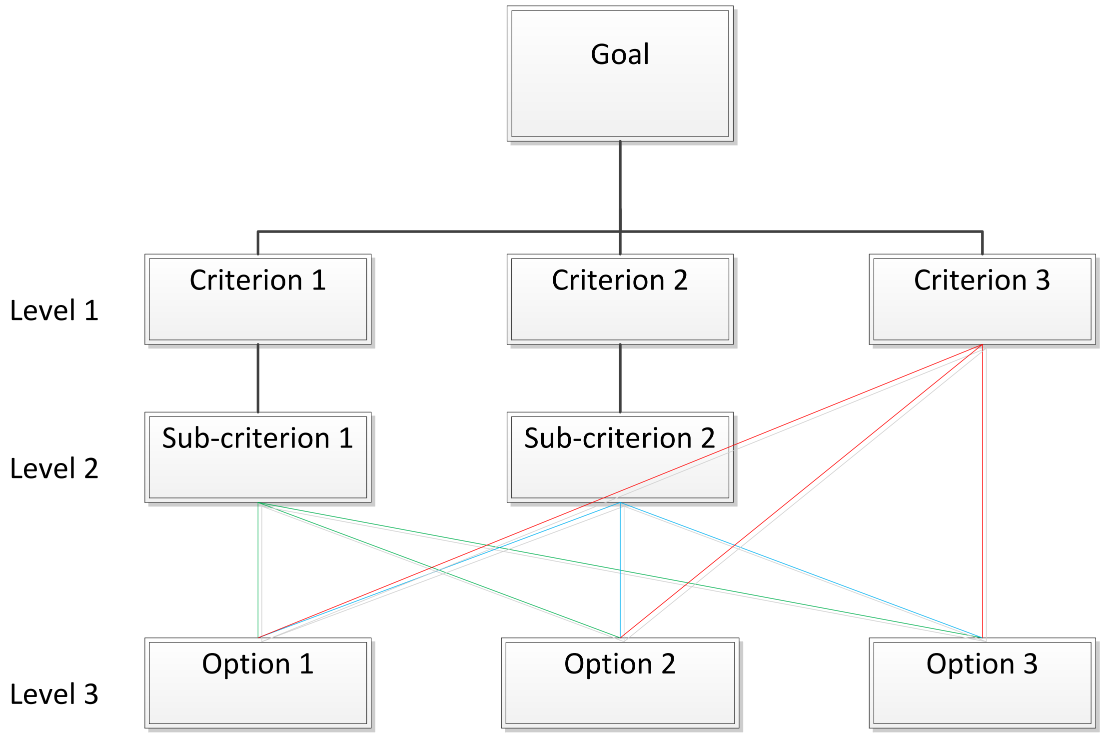

Figure 2-1: Example of the hierarchy structure

2.1.2 Pairwise comparison matrices

To enable judgement, pairwise comparisons are conducted on all levels of the hierarchy. Pairwise comparison is a process of comparing elements of each level of the hierarchy in pairs to judge their importance with respect to the element above them.

In the first set of pairwise comparisons, criteria are pairwise compared in terms of importance with respect to the goal. In the second set of pairwise comparisons, sub-criteria are pairwise compared with respect to their parent criteria for importance. In the last pairwise comparison, the options are pairwise compared with respect to the sub-criteria connected to them. In cases where criteria do not have sub-criteria, options are pairwise compared with respect to the criteria.

In order to make pairwise comparisons, a nine-point scale can be used, which is given in Table 2-1: The Saaty Rating Scale (Saaty, R.W., 1987). This scale is then used to determine how many times more important or dominant one criterion is over another with respect to the goal; how many more times important or dominant one sub-criterion is over another in terms of its parent criterion and how well one option meets the criterion (or sub-criterion if present) compared to another (Saaty, T.L., 2008). The pairwise comparisons obtained for the three levels are then used to construct comparison matrices, as outlined next.

Table 2-1: The Saaty Rating Scale (Saaty, R.W., 1987)

Intensity of importance on an absolute scale	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favour one activity over another
5	Essential or strong importance	Experience and judgement very strongly favour one activity over another.
7	Very strong importance	Activity is strongly favoured and its importance is demonstrated in practice
9	Extreme importance	The evidence favouring one over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

To start, consider first the comparisons associated with the second level of the hierarchy, i.e. the criteria. Assume that there are n such criteria. These criteria must be compared with one another in terms of the goal. The total number of comparisons evaluated will be $n(n-1)/2$. The comparison matrix $\boldsymbol{C}$ is then an $n \times n$ matrix, where each element c_{ij} of the matrix represents a comparison between the i^{th} and j^{th} criterion. The element c_{ji} is set to be $1/c_{ij}$. (See Section 2.1.5 for a justification of this assignment.)

If any criterion has, say p sub-criteria, then these sub-criteria will be compared with one another in terms of the parent criterion. There will be $p(p-1)/2$ comparisons. A

$p \times p$ comparison matrix $\boldsymbol{S}$ would then be constructed for each criterion that has sub-criteria.

Finally, pairwise comparison matrices $\boldsymbol{O}$ will also be constructed for the options. If there are sub-criteria present for any criterion, then the pairwise comparison will be made for each sub-criterion. If there are q options, then there will be $q(q-1)/2$ comparisons for each sub-criterion, resulting in matrices having dimensions $q \times q$. If any criterion does not have sub-criteria, then the pairwise comparisons of the options are made in terms of the criterion itself.

Thus, all the levels of the hierarchy, except for the goal level, will all have pairwise matrices associated with them.

2.1.3 Matrix equation used to determine the ranking of the options

The criteria pairwise matrix $\boldsymbol{C}$ of dimension $n \times n$ will yield a weight vector $\vec{f}$ of dimension n and elements f_i, where $i = 1, n$. The method to reduce the matrix $\boldsymbol{C}$ to the vector $\vec{f}$ is explained in the next section.

If a criterion, say k, does not have any sub-criteria, then the element f_k of the weight vector $\vec{f}$ is used directly to form an element d_m of a composite weight vector $\vec{d}$.

If a criterion, say m, does have sub-criteria, of say number p^m, there will be a pairwise comparison matrix $\boldsymbol{S}^m$ for this criterion, as discussed in the previous section. Superscript is now used to identify the $\boldsymbol{S}$ matrix with the criterion m. The matrix $\boldsymbol{S}^m$ is also reduced to the weight vector $\vec{g}^m$, with elements g_o^m, where $o = 1, p^m$. The method to reduce the matrix to the vector is the same as that for the criteria, described in the next section.

In order to populate the composite weight vector $\vec{d}$ with the elements from $\vec{g}^m$, each element g_o^m must be multiplied by the appropriate element from the weight vector of the criteria level, i.e.

$$d_{m_0+m} = f_m \times g_o^m.$$

Here, m_0 is the last element of $\vec{d}$ that was populated before the current consideration. The dimension of the vector $\vec{d}$, say t, will be the total number of pairwise comparison matrices constructed for the options.

To illustrate the dimension of the vector $\vec{d}$, consider as an example of four criteria, of which two criteria have three sub-criteria each. There will then be six elements for the six sub-criteria, and two further elements for the two criteria that do not have sub-criteria, meaning that the dimension of the vector will be eight.

In addition to the composite weight vector $\vec{d}$, a matrix $\boldsymbol{A}$ is also constructed.

To do this, each of the t comparison matrices for the options is reduced to a weight vector, the method for which is also given in the next section (This method to reduce the comparison matrix to the weight vector is the same whether the criteria, sub-criteria or options are considered.). There will thus be t column weight vectors of dimension q, where q is the number of options. The matrix $\boldsymbol{A}$ is then constructed by setting each column of $\boldsymbol{A}$ so that it has the contents of one of these t weight vectors, in the correct order. The dimension of the matrix $\boldsymbol{A}$ is $q \times t$.

The final equation is then used,

$$\boldsymbol{A}\vec{d} = \vec{r}. \qquad (1)$$

In this equation, $\vec{r}$ is the vector whose elements give the ranking of each of the options considered. Its dimension will be that of the number of options q. The element with the largest ranking will be the best option to choose.

2.1.4 Determining the weights of the pairwise comparison matrices

It was mentioned in Section 2.1.3 that the pairwise matrices yield weighted vectors. This is carried out as follows:

Consider the matrix $\boldsymbol{A}$ of dimension $I \times J$ and with elements a_{ij}, where $i = 1, \ldots I$ and $j = 1, \ldots J$. (The usual convention where the first index of the element is the row position and the second index is the column position is used.)

This matrix is normalised to the matrix $\boldsymbol{B}$ in terms of the columns of $\boldsymbol{A}$ using the following formula for each element b_{ij} of matrix $\boldsymbol{B}$.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{I} a_{ij}}. \qquad (2)$$

A column vector $\vec{c}$, with elements c_i, where $i = 1, \dots I$, is calculated from matrix $\boldsymbol{B}$ using the following equation:

$$c_i = \sum_{j=1}^{J} b_{ij}. \qquad (3)$$

This vector $\vec{c}$ is normalised to a vector $\vec{e}$ with elements e_i, where $i = 1, \dots I$, using the following equation:

$$e_i = \frac{c_i}{\sum_{k=1}^{I} c_k}. \qquad (4)$$

This vector $\vec{e}$ is then the weighted vector derived from the pairwise comparison matrix $\boldsymbol{A}$.

2.1.5 Justification for the weighting scheme and the equation to determine the ranking

In order to gain insight into the process of calculating the weight, an example is considered through which the comparisons can be obtained numerically. Consider three objects 1, 2 and 3 of mass 90 kg, 40 kg and 70 kg respectively.

To rank these masses in terms of their values, one only needs to normalise them, and the resultant weight vector would be their ranking:

$$\begin{bmatrix} 0.45 \\ 0.2 \\ 0.35 \end{bmatrix}. \qquad (5)$$

One can also calculate this weight vector using equations 2 to 4.

First, the comparison matrix A is calculated:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}.$$

Mass one is $90/40$ times heavier than mass two, yielding $a_{12} = 2.25$.

Mass two is $40/90$ times heavier than mass one, yielding $a_{21} = 0.44$. It can be seen that $a_{21} = 1/a_{12}$.

In a similar fashion, the other elements of matrix A can be determined, yielding the matrix

$$A = \begin{bmatrix} 1.00 & 2.25 & 1.29 \\ 0.44 & 1.00 & 0.57 \\ 0.78 & 1.75 & 1.00 \end{bmatrix}.$$

The next step is to normalise each column of a matrix using equation 2.

This yield

$$A' = \begin{bmatrix} 0.45 & 0.45 & 0.45 \\ 0.20 & 0.20 & 0.20 \\ 0.35 & 0.35 & 0.35 \end{bmatrix}.$$

One notices that the columns are now identical and that each column is indeed the weight vector in equation 5.

This symmetry arises because the comparison matrix elements have been calculated exactly in terms of the numerical values of the masses. For example, given a_{12} and a_{13}, a_{23} can be calculated as $a_{23} = \frac{a_{13}}{a_{12}}$.

However, the AHP is designed to be used in cases where the comparison a_{23} must also be assigned by the analyst, and not calculated using $a_{23} = \frac{a_{13}}{a_{12}}$.

One, therefore, needs to sum the rows and normalise the resulting vector to obtain the weight vector.

To continue with the above example, the sum of matrix A' across the rows yields

$$\begin{bmatrix} 1.35 \\ 0.6 \\ 1.05 \end{bmatrix}.$$

When this vector is normalised, the weight vector given in equation 5 is obtained.

The final ranking of the options is given by applying equation 1.

Each column of matrix $\boldsymbol{A}$ is a list of the relative ranking of all the options with a specific criterion (if the criterion does not have sub-criteria) or sub-criterion. Vector $\vec{d}$ is the relative ranking of all the sub-criteria and the criteria that do not have sub-criteria.

As one moves across a row of matrix $\boldsymbol{A}$, one obtains the ranking of all the criteria (those without sub-criteria) and sub-criteria in terms of a specific option.

The multiplication, given by equation 1, therefore results in the ranking of all options.

A numerical justification such as that given using the example of masses above is not possible using the current formalism of the AHP. For example, comparing radiological safety with system flexibility using an exact numerical scale, as was done for comparing masses, is not currently possible.

2.1.6 The consistency index

The pair comparison matrix and the weight vector can be written as an eigenvalue equation (R.W. Saaty, 1987): $\boldsymbol{A}\vec{d} = \lambda\vec{d}$ where λ is the eigenvalue. This equation has a slightly different form compared to equation 1.

For an $n \times n$ matrix, there will be n eigenvalues, $\lambda_1, \lambda_2, \dots, \lambda_n$ with $\lambda_1 = \lambda_{max}$, the maximum eigenvalue.

A matrix such as that constructed above for the mass example is termed consistent, since if a_{12} and a_{23} are given, then a_{13} can be calculated using the equation $a_{13} = a_{12} \times a_{23}$.

In such a case, one gets $\lambda_{max} = n$

i.e.

$$\begin{bmatrix} 1.00 & 2.25 & 1.29 \\ 0.44 & 1.00 & 0.57 \\ 0.78 & 1.75 & 1.00 \end{bmatrix} \begin{bmatrix} 0.45 \\ 0.2 \\ 0.35 \end{bmatrix} = 3 \begin{bmatrix} 0.45 \\ 0.2 \\ 0.35 \end{bmatrix}.$$

However, when a_{13} cannot be determined using $a_{13} = a_{12} \times a_{23}$, but needs to be estimated by the analyst, then it is found that λ_{max} is greater than n. A consistency index can then be defined in terms of $\lambda_{max} - n$.

R.W. Saaty (1987) defines the consistency index as

$CI = \lambda_{max} - \frac{n}{n-1}$.

The consistency index (CI) is then compared with a random consistency index (RI). To do this, the consistency ratio (CR) is defined as $CR = \frac{CI}{RI}$

As guided by Saaty R.W. (1987), if the ratio is less than 0.1, then the judgements used to construct the pairwise comparison matrices are accepted, else the judgements must be revised until a ratio of less than 0.1 is obtained.

RI is given as a function of N, the number of criteria, sub-criteria or options used to construct the pairwise comparison matrices. It is derived from a sample size of 500, of a randomly generated reciprocal matrix using the scale 1/9, 1/8, …., 1, …., 8, 9 (Saaty, R.W., 1987) and is shown in Table 2-2.

Saaty R.W. (1987) also gives an approximation to calculate λ_{max}:

A row vector $\vec{r}$, with elements r_j, where $j = 1, \ldots J$, is calculated from matrix $\boldsymbol{A}$ using the following equation.

$$r_j = \sum_{i=1}^{I} a_{ij}. \qquad (6)$$

The eigenvalue λ_{max} is then calculated from vectors $\vec{r}$ and $\vec{d}$ using the formula $\lambda_{max} = \sum_{j=1}^{J} r_j d_j$.

To state what is discussed in this section in another way, consistency of the pairwise matrices means the following: Assume that criterion one is more important than criterion two, and criterion one is even more strongly important than criterion three. Then criterion two must be stronger than criterion three. If the analyst finds that criterion three has been assigned to be stronger than criterion two, then the decision-making for the three comparisons is inconsistent, and the decisions must be reviewed. To aid the analyst with deciding whether the pairwise comparison matrix is consistent, the consistency ratio is calculated and should be less than 0.1.

Table 2-2: Random consistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

2.1.7 Dependence

Dependence can be described as the relationship between the criteria, sub-criteria and options. Saaty T.L makes a distinction between two types of dependencies namely functional dependence and structural dependence.

Structural dependence is the dependence of elements from the lower level on the elements on the level above them. The hierarchical structure of the AHP represents structural dependence.

Functional dependence is the dependence of elements on other elements on the same level in performing their function.

The AHP tool assumes there are no functional dependencies between or within the levels of the hierarchical structure, which it is not always the case.

To deal with functional dependence, Saaty T.L developed another tool. The tool is called the analytic network process (ANP) and it extends the AHP tool to accommodate functional dependence. Functional dependence is further broken down into inner and outer dependencies between criteria/sub-criteria and feedback (Ziemba, 2019).

An overview of the ANP is illustrated in Figure 2-2. The details of the method are presented in the publications of Ziemba (2019) and Saaty, T.L & Vargas (2006).

However, in the current study, to remain within the scope of the study, it is assumed that there are no functional dependencies between or within the levels. Intuitive judgement is used wherever possible in an attempt to satisfy this assumption. It is therefore recommended that a future study must look into the functional dependence of the elements in which the ANP must be used.

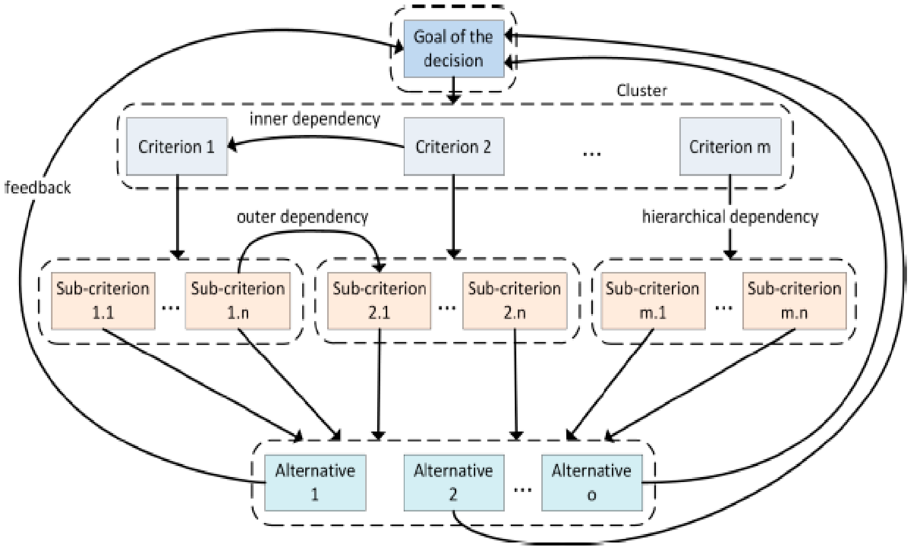

Figure 2-2: Network structure in the ANP tool (Ziemba, 2019)

2.2 Selection criteria

2.2.1 Basis for the establishment of criteria and sub-criteria to facilitate the selection of the dry storage option

The fundamental concern in establishing criteria and sub-criteria for the selection of a dry storage system is ensuring the safety of the workers, public and environment from any radiation hazard posed by the SNF during storage. Therefore, the main safety requirements of a dry storage system are as follows:

- Risk of radiation exposure to workers and members of the public is avoided or eliminated during normal operation or if accidents occur (HITACHI, 2014).
- Radioactive material and radioactive waste remain adequately controlled or contained so that it cannot leak or otherwise escape from such control or containment (HITACHI, 2014).
- The rate of production and total quantities of radioactive waste are minimised during the storage and decommissioning period (HITACHI, 2014).
- Passive heat removal is maintained at all times during the storage period (IAEA, 2007).
- The SNF is maintained in a sub-criticality condition at all times during the storage period (IAEA, 2007).

The criteria and sub-criteria have been chosen for the selection of the dry storage system to satisfy these safety requirements, i.e. the chosen criteria and sub-criteria should not compromise any of the safety requirements highlighted above.

The following sources outline broad criteria that can be used in the selection of dry storage system options:

- IAEA Guidebook for the Selection of Away-from-Reactor facilities for SNF (IAEA, 2007);
- Evaluation of Spent Nuclear Fuel Management Options for South Africa (Twala, 2007);
- UK ABWR Generic Design Safety Assessment Preliminary Safety Report on Spent Fuel Interim Storage (HITACHI, 2014).

From these, one can obtain specific relevant criteria and sub-criteria for the selection of a dry storage system. These criteria and sub-criteria are specified next. For each criterion and sub-criterion obtained, the description and justification are given. The criteria and sub-criteria are also listed in Table 2-3.

Table 2-3: Criteria and sub-criteria

No.	Main criteria	Sub-criteria
1.	Radiological safety	No sub-criteria identified
2.	System flexibility	Localisation
		Modularity
		Possibility of changing vendors
3.	Operation and maintenance	No sub-criteria identified
4.	Retrievability	No sub-criteria identified
5.	Decommissioning	No sub-criteria identified
6.	Cost	Capital cost
		Operational and maintenance cost
		Decommissioning cost

2.2.2 Criterion: Radiological safety

When nuclear fuel is taken from a reactor, it contains a lot of radioactive isotopes, for example fission products such as Sr-90 (a strontium isotope) and Cs-137 (a caesium isotope) and minor actinides such as neptunium, americium and curium (Wagner, 2016). These isotopes produce a considerable amount of heat and radiation, which can be harmful to human life and the environment. The task of protecting human life and the environment against this heat and radiation is called radiological safety (University of Newcastle Australia, 2014) and actions are required to ensure this. Some of the actions would, for example, be to cool the spent fuel in the reactor fuel storage water pool for a period of five years or more before it can be transferred to a dry storage system (IAEA, 2007).

Radiological safety is considered a major factor in the management of SNF owing to the radiological hazard presented by SNF. The purpose of radiological safety is to maintain radiation doses to which workers and the public are exposed below regulatory limits and as low as reasonably achievable, to prevent unplanned or accidental exposure to ionizing radiation, and to prevent the release of radioactive material into the environment (SLAC, 2019). Therefore, "radiological safety" has been chosen as one of the criteria to evaluate dry storage systems. The criterion has therefore been established as follows:

> *The preferred dry storage system should have minimum handling activities to keep occupational exposure of workers as low as reasonably achievable and high protection against radionuclide releases to the environment and radiation doses to the members of the public during normal operation (*Twala, 2007*).*

No sub-criteria have been identified for this criterion.

2.2.3 Criterion: System flexibility

According to the International Atomic Energy Agency (IAEA, 2007), system flexibility refers to the ease with which the system can adapt or respond to internal or external changes in a time-bound and cost-effective manner. The processes for design, construction and fabrication directly affect the project expectations in terms of system flexibility. It is necessary to develop selection criteria to compare options on the basis of these expectations. Therefore, the following sub-criteria have been considered in the selection of a dry storage system:

(i) Modularity

Modularity refers to the ability to implement dry storage systems in separate units and has the following advantages:

- It enables one to start small, thus improving affordability by minimising the upfront cost outlay required to build the facility (IAEA, 2007).
- It provides flexibility for the expansion of the facility as the need arises by matching the spent fuel production and the amount of spent fuel intended to be stored in the facility (IAEA, 2007).
- It may also allow future improvements of dry storage systems based on the lessons learned from the storage operations.

The disadvantage of modularity will be the possibility of change in public perception of the facility and possible changes in regulations. This might pose a difficulty if further licensing and public acceptance are required during the extension of the facility.

The criterion has, therefore, been established as follows:

> *The preferred dry storage system should enable to start small thus improving affordability by minimizing the upfront cost outlay required to build the facility (IAEA, 2007).*

(ii) Localisation

Localisation refers to the manufacturing of a dry storage system compatible with local construction practices and experience that enables the utilisation of the local workforce and skills (IAEA, 2007). Localisation has the following advantages:

- It provides jobs to the local community, which will also enhance public acceptance.
- Most of the money will be invested within the country, which will help to grow the economy.
- It minimises the cost uncertainty due to currency exchange fluctuation or an unfavourable exchange rate.

- It minimises supply disruptions due to transportation logistics, political considerations or other international disruptions that could affect the delivery and cost of the dry storage systems (IAEA, 2009).

The disadvantage of localisation will only be evident when there is a need to establish a manufacturing or fabrication facility, which will increase the cost of establishment of dry storage systems.

The criterion is therefore as follows:

The preferred dry storage system should be compatible with local construction practices and experience, and enable utilization of local workforce and skills (IAEA, 2007).

(iii) Possibility of changing vendors

The possibility of changing vendors refers to the importance of allowing the participation of multiple vendors to avoid dependence on a single vendor in the implementation of a dry storage system (IAEA, 2007). The advantages of multiple vendors are:

- the competitive cost; and
- meeting supply constraints.

The foreseen disadvantage might be the difficulty in further licensing of the dry storage system supplied by different vendors, as well as compatibility with existing infrastructure. However, based on international experience in the implementation of dry storage systems, it can be assumed that the highlighted disadvantages can be addressed easily.

The criterion has been established as follows:

The preferred dry storage system should allow the participation of multiple vendors to avoid dependence on a single vendor in the implementation of the facility (IAEA, 2007).

2.2.4 Criterion: Operation and maintenance

The operability and maintainability of the dry storage system are important selection considerations (IAEA, 2007).

Operability refers to the ability of a dry storage system to be operated for a specified period of time without degradation and the need for repairs or maintenance (IAEA, 2007).

Maintainability refers to the ability of the dry storage system to be restored within a specified time to its full performance (IAEA, 2007).

The key aspects in terms of operation and maintenance are:

- simplicity of use; and
- ease of maintenance.

The criterion has been established as follows:

> *The preferred dry storage system should be easily operable without the need for elaborate systems and procedures and should be easily maintainable without the need for complicated maintenance requirements (IAEA, 2007).*

No sub-criteria have been identified for this criterion.

2.2.5 Criterion: Retrievability

Retrievability refers to the ease with which spent fuel can be recovered from the dry storage system. Since in South Africa no decision has yet been made on how the SNF will be disposed of, at the end of its storage lifetime, ultimately the SNF would have to be retrieved either to be sent for reprocessing or transmutation or to be directly disposed of, using systems designed and licensed for the disposal of SNF. Therefore, it is important that the dry storage system chosen should maintain the ability to retrieve or recover SNF for this purpose.
The criterion has been established as follows:

> *The preferred dry storage system should maintain the ability to retrieve or recover the SNF when the need arises.*

No sub-criteria have been identified for this criterion.

2.2.6 Criterion: Decommissioning

The current dry storage systems are not designed or licensed for use as disposal containers for SNF. Their licensed term for usage is country-dependent and is estimated to be between 40 to 50 years and in some countries, such as Spain and the Netherlands, it is 100 years (OECD, 2017). At the end of their life, they will need to be decommissioned. Decommissioning is referred to as the actions that will be taken at the end of the useful life of a nuclear facility or dry storage system to release it from regulatory control, and/or to reduce the levels of residual radionuclides in the materials and on the site of the facility so that the materials can be safely recycled, reused or directly disposed of in a low-level waste (LLW) disposal facility. This typically includes dismantling, decontamination, and rehabilitation activities (IAEA, 2016).

The advantages of decommissioning are the reduction of the materials needed to be disposed of and the rehabilitation of the site. However, if not properly planned, it could also result in an increased amount of waste being produced and unnecessary exposure of the workers.

The criterion has been established as follows:

> *The dry storage system shall be designed so that at the time it is to be decommissioned, the decontamination and dismantling of structures and equipment together with the removal of waste can be facilitated, the quantities of waste arising can be minimised and occupational exposure can be reduced to as low as reasonably achievable (IAEA, 2007).*

No sub-criteria have been identified for this criterion.

2.2.7 Cost

The Policy requires that the available systems for managing radioactive waste/SNF should be evaluated systematically and the identified option should be the best available technology not entailing excessive cost. Therefore, to find a dry storage system that will not impose any financial burden on the country; cost is chosen as one of the criteria for the selection of a dry storage system. To enable assessment of the cost for each dry storage system, the sub-criteria discussed below have been identified.

(i) Capital cost

Capital cost refers to the upfront cost required for the establishment of the dry storage facility, which among others includes design and engineering, purchase or manufacturing of the dry storage system, auxiliary equipment and infrastructure. The individual capital cost varies, depending on the dry storage system. This sub-criterion is included because the intended financial burden on the country needs to be taken into consideration as well. The criterion has been established as follows:

The dry cask storage system shall be modular in nature, enabling starting small, thus improving affordability by minimising the up-front cost outlay required to establish the facility (IAEA, 2007).

(ii) Operational and maintenance cost

Operational and maintenance cost can be defined as all expenses associated with the utilisation of the dry storage system or facility. Operational and maintenance cost includes among others labour, dry storage system handling activities, services (such as electricity, etc.), material and goods required for operation and maintenance, and inspection/monitoring. A more complex system will demand a lot more attention to keep it in working condition, which will, therefore, result in a high cost of operation and maintenance.

The criterion has been established as follows:

The preferred dry storage system shall be less complex, which will result in less cost for operation and maintenance (IAEA, 2007).

(iii) Decommissioning cost

The decommissioning cost can be defined as all expenses associated with the decontamination, dismantling and decommissioning of the storage system and site restoration subsequent to the removal of SNF from the facility (IAEA, 2007). The factors affecting decommissioning cost are (IAEA, 2007):

- Measures to be put in place to ensure dose limits are not exceeded during decommissioning. One example would be to rotate workers in order to reduce exposure, which could be reasonably achievable but may require more workers involved in the decommissioning. The dose limits are defined as the values of the effective dose or the equivalent dose to individuals in planned exposure situations that are not to be exceeded (IAEA, 2014). These limits are established by the regulatory body.
- Exemption of some actions during the decommissioning process. Some actions during decommissioning, such as cutting of removing some components from the facility or system, may not need to be subject to regulatory control after being decontaminated. The exemption means the

determination by a regulatory body that action need not be subject to some or all aspects of regulatory control on the basis that the exposure (or potential exposure) due to the action is too small to warrant the application of those aspects (South Africa, 2006). To reach these levels, a number of processes may need to be implemented, which would affect the decommissioning cost:

- Equipment required for dismantling;
- Development of methods required for decontamination;
- Size of the facility and the extent of contamination;
- The complexity of the dry storage, which may result in difficulty to decontaminate; and
- Establishment of radioactive waste management processes for the resultant waste and development of waste disposal packages.

The criterion has been established as follows:

The preferred dry cask storage system and the related facility should be designed so that at the end of their lifetime, decommissioning can be easily facilitated without excessive cost (IAEA, 2007).

2.2.8 Criteria and sub-criteria not considered

The list of criteria and sub-criteria discussed above is not necessarily exhaustive but is a sufficient sample to demonstrate the application of the AHP tool for selecting the best possible option for SNF dry storage for South Africa. Any other relevant criteria and/or sub-criteria not considered in this study can be used in the same manner to demonstrate the functioning of the AHP tool.

Examples of some of the criteria that were not studied are:

- Safeguards and security; and
- Environmental impact.

2.2.9 Dependencies between criteria, inclusive of sub-criteria

It was discussed in Section 2.1.7 that the consideration of dependencies between criteria, inclusive of sub-criteria, was beyond the scope of this study. However, it was considered important to list a few possible dependencies that should be considered as starting points in further studies.

When considering the criterion operation and maintenance, it is noted that there is benefit in choosing good operability conditions (for example, being able to operate for longer periods between maintenance times) in that there would be a reduction in the time the workers have to spend close to the dry storage system. This would reduce the exposure time to radiation and is therefore related to the criterion radiological safety.

Moreover, this criterion, operation and maintenance, would share dependency with the sub-criterion operational and maintenance cost of the criterion cost.

2.3 Dry Storage Options

2.3.1 Basic description of a dry storage system

When the SNF is discharged from a nuclear reactor core, it must be stored in the SNF pool or wet storage facility for at least five to 10 years to allow for initial cooling and radioactive decay. After this period, the SNF can be transferred to a dry storage system. The dry storage system normally uses concrete and/or steel, to shield from gamma radiation, and neutron shielding is provided by polyethylene, concrete and/or resins or boron-impregnated metal.

Two main different types of dry storage systems have been implemented aboveground worldwide. These are referred to as bare-fuel and canister-based dry storage systems. In bare-fuel dry storage systems, the SNF is placed directly into a basket that is integrated into the cask cavity. In a canister-based dry storage system, the SNF assemblies are placed in a basket that is integrated into a metal cylinder, which is referred to as the canister. The canister provides leak-tight containment of the SNF assemblies and is placed inside a thick-walled overpack to provide radiation shielding (Wang, 2015). The canister is filled with an inert gas (e.g. helium) to prevent oxidation of the SNF cladding and maintain the integrity of the SNF during storage.

2.3.2 Requirements

The dry storage system should have the following main features (Roland, *at. al.,* 2003; The National Academies of Sciences, 2006):

- A multiple containment barrier;

- Passive cooling, while fuel assemblies are stored in an inert atmosphere and under conditions of temperature preventing the degradation of rod cladding;
- Sub-criticality meeting ICRP 60 requirements, as well as all applicable regulations (including severe weather conditions and earthquake);
- Safe handling operations;
- Future decommissioning of the facility through design optimisation;
- Construction and operating cost-effectiveness; and
- Shielding of workers and the public from the radiation emitted by radioactive decay in the SNF and provision of a barrier for any releases of radioactivity.

2.3.3 Countries that use dry storage systems

As mentioned in Section 1.2, several dry storage options implemented aboveground are in use worldwide and dry storage systems are commercially available on the international market.

The study will focus on dry storage options that have been proven practical to store PWR fuel for a significant period to demonstrate dry storage option's technical adequacy (Hitachi, 2014).

Examples of countries that have already implemented dry storage of spent fuel and the different designs of dry storage systems used are given in Table 2-4. The table includes the following:

- Status of dry storage of SNF in each country;
- Design of dry storage system;
- Type of storage facility used for the dry storage system;
- Location of the dry storage facility, either away from the reactor or centralised;
- Vendor;
- The orientation of the dry storage system in storage; and
- Type of spent fuel stored.

Table 2-4: Dry storage systems implemented internationally

Country	***Status of the storage facilities***	***Type of storage facilities***	***Location of the storage facilities***	***Type of fuel stored***	**Type of dry storage systems**	**Orientation**	**Vendor**	**References**
France	Operational	Modular vault dry storage (MVDS)	Centralised storage	PWR, BWR	Vault	Vertical	SGN	Roland *et al.*, 2003
Germany	Operational	Concrete building	Centralised storage, on-site storage	PWR, BWR, and Triga research reactor	Metal cask	Vertical	GNS mbH, transnuclear	Thomauske, 2002
Switzerland	Operational	Concrete building	Centralised storage	PWR	Metal cask	Vertical	GNS mbH, transnuclear	Williams, 2015
Japan	Construction phase	Concrete building	Centralised storage	PWR, BWR	Metal cask	Vertical/ horizontal	Transnuclear, Toshiba, Hitachi Zosen, Hitachi GE	Fujimoto, 2010; Kumano, 2010; Takase & David Von Hippel, 2017
	Operational	Concrete building	On-site storage	BWR	Metal cask	Vertical/ horizontal		
USA	Operational	Open air concrete pad	On-site storage	PWR	Concrete cask, metal cask	Vertical	Transnuclear, GNS mbH, Holtec International, NAC International, USA, BNFL Fuel Solutions, USA	Jones Jr., 2015,
	Operational	Concrete module	On-site storage	PWR, BWR	Vault	Vertical/ horizontal		
	Operational	MVDS	On-site storage	Triga research reactor	Concrete modules	Horizontal	Foster Wheeler Environmental Corporation/ALSTEC, USA	

Ukraine	Construction phase	Concrete module	Centralised storage	VVER/RBMK	Concrete modules	Horizontal	Holtec International	Lisichenko, *et al.*, 2017
	Operational	Open-air concrete pad	On-site storage	VVER	Concrete cask	Vertical	Holtec International	
Spain	Planned	MVDS	Centralised storage	PWR	Vault	Vertical	The vendor could not be found in the literature	Enresa, 2015
	Operational	Concrete building	On-site storage	PWR	Metal cask	Vertical	ENSA	
	Operational	Open-air concrete pad	On-site storage	PWR	Concrete cask	Vertical	ENSA	
Belgium	Operational	Concrete building	On-site storage	PWR	Metal cask	Vertical	Transnuclear	Van Mierloo, 2014
United Kingdom	Operational	Steel-cladded enclosure	On-site storage	PWR	Metal cask	Vertical	Holtec International	Office for Nuclear Regulation, 2017
Czech Republic	Operational	Concrete building	On-site storage	VVER	Metal cask	Vertical	GNS mbH	National report, 2017
Hungary	Operational	MVDS	On-site storage	VVER	Vault	Vertical	Foster Wheeler Environmental Corporation	National report, 2017
Russia	Operational	Concrete building	Centralised storage	RBMK-1000, VVER-1000	Metal cask	Vertical	The vendor could not be found in the literature	National report, 2017

A dry storage system that has already been used and licensed in different countries could make the licensing process easier, since compliance with regulatory criteria tested by different regulatory systems would already have been established.

2.3.4 Detailed description of dry storage systems

The key dry storage system options are:

- Concrete cask with an inner metal canister stored on a reinforced concrete storage pad open to the environment;
- Metal cask with an integrated metal basket stored inside a reinforced concrete storage building;
- Metal cask with an integrated metal basket stored inside a steel-cladded enclosure;
- Metal cask with integrated metal basket stored on a reinforced concrete storage pad open to the environment;
- Concrete module with inner metal canister stored on a reinforced concrete storage pad open to the environment; and
- Concrete vault with an inner metal canister.

These will be discussed individually in Sections 2.3.5 to 2.3.10.

2.3.5 Concrete cask with inner canister stored on a concrete storage pad open to the environment

The concrete cask is a canister–based dry storage system made up of two systems. The first system, the overpack, is made from a reinforced concrete structure lined with a steel liner. The second system is the canister, which is stored inside the overpack. The canister is provided with a boron aluminium basket with a lattice structure that holds the SNF assemblies in individual compartments. Boron is a neutron-absorbing material that is used to prevent any possible nuclear chain reactions. This arrangement and the use of boron provide criticality control. The canister is welded shut to provide leak-tight containment of the SNF, preventing any release of radioactivity. An example of the canister is shown in Figure 2-3.

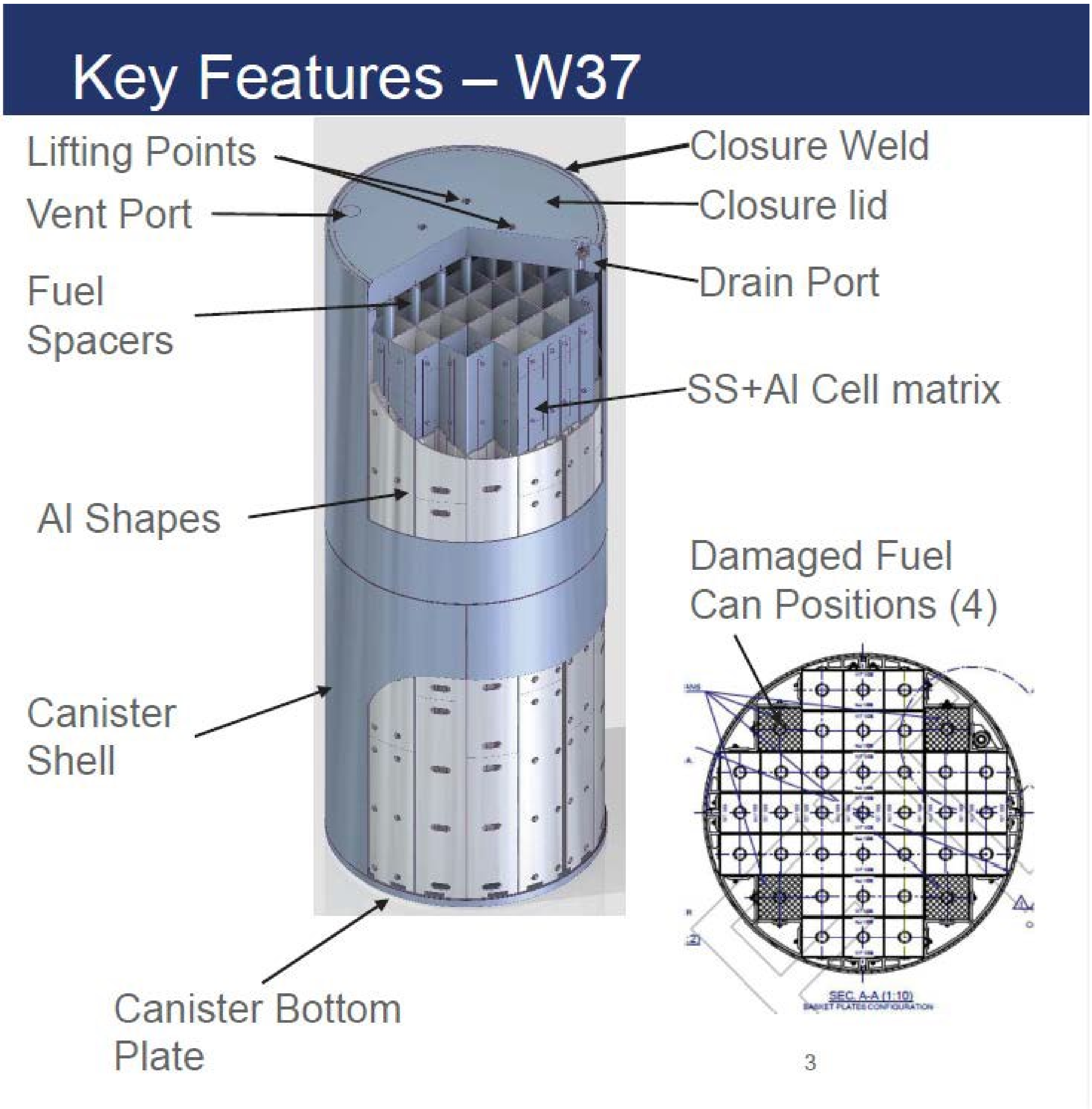

Figure 2-3: An example of concrete cask canister- Sentry W37 canister (Greene, 2020)

The reinforced concrete over-pack and the cask lid provide the overall containment of the sealed welded canister. It also provides structural strength, radiological shielding to the workers and the public and protection of the sealed welded canister from environmental conditions. The concrete cask is cooled by natural convection of air; air inlet vents are supplied at the bottom of the cask and outlet vents at the top. An example of this cask is shown in Figure 2-4.

These casks are stored vertically on a reinforced concrete storage pad open to the environment.

A variant of the reinforced concrete cask design is a design in which concrete is sandwiched between an outer steel shell and an inner steel shell connected by radial ribs and top and bottom plates (Gencturk *et.al.*, 2016). An example of this design is shown in Figure 2-5.

The designs are regarded as one option because of the similarities in their functioning, namely:

- Both cask designs consist of two systems, a concrete overpack and an inner canister.
- Concrete provides the main gamma and neutron shielding.
- The canister arrangement and the use of boron provide criticality control.
- Both cask designs are cooled by natural convection of air; air inlet vents are supplied at the bottom of the cask and outlet vents at the top, as shown in Figure 2-4 and Figure 2-5.
- These casks are stored vertically on a reinforced concrete storage pad open to the environment.

However, in terms of the AHP tool, these two cask designs should be regarded as two options and the process of the AHP would differentiate between these two designs. If indeed it does not matter which design is chosen, then both designs would have the same (or closely similar) scores. Since the aim of the study is to demonstrate the application of the AHP tool for the selection of the option that will best meet South Africa's needs, it has therefore been decided to consider both designs as one option. Consideration of these designs as individual options is reserved for future studies.

As mentioned above, these casks are stored vertically on a reinforced concrete storage pad open to the environment. The reinforced concrete storage pad is a free-standing reinforced concrete structure supported by a firm foundation open to the environment. The reinforced concrete storage pad has been designed to support casks for a minimum of 50 years (Dukes *et al.*, 2015). It has also been designed to handle site-specific seismic motion, lateral loading movements and heavy machinery or equipment used during the placement of the casks (United States Nuclear Waste Technical Review Board, 2010). In this type of dry storage facility, the cask dry storage system is stored in the open air, which allows the surface of the cask to be naturally cooled by ambient air. The reinforced concrete storage pad is not considered complicated to design and is economical to construct. This is because the cask dry storage system itself is designed to withstand man-made events due to handling accidents, and external natural events such as earthquakes, tornadoes and floods, without impairing its capability to perform its intended design functions (Shah *et al.,* 2003).

This type of dry storage facility is mostly used in the USA (on-site storage facilities). An example of this type of facility is shown in Figure 2-6, the Connecticut Yankee Dry Storage Facility located at the Connecticut Yankee reactor in the USA (Connecticut Yankee, 2019). The sizes of these facilities vary depending on the needs of the country or the nuclear power plant (NPP).

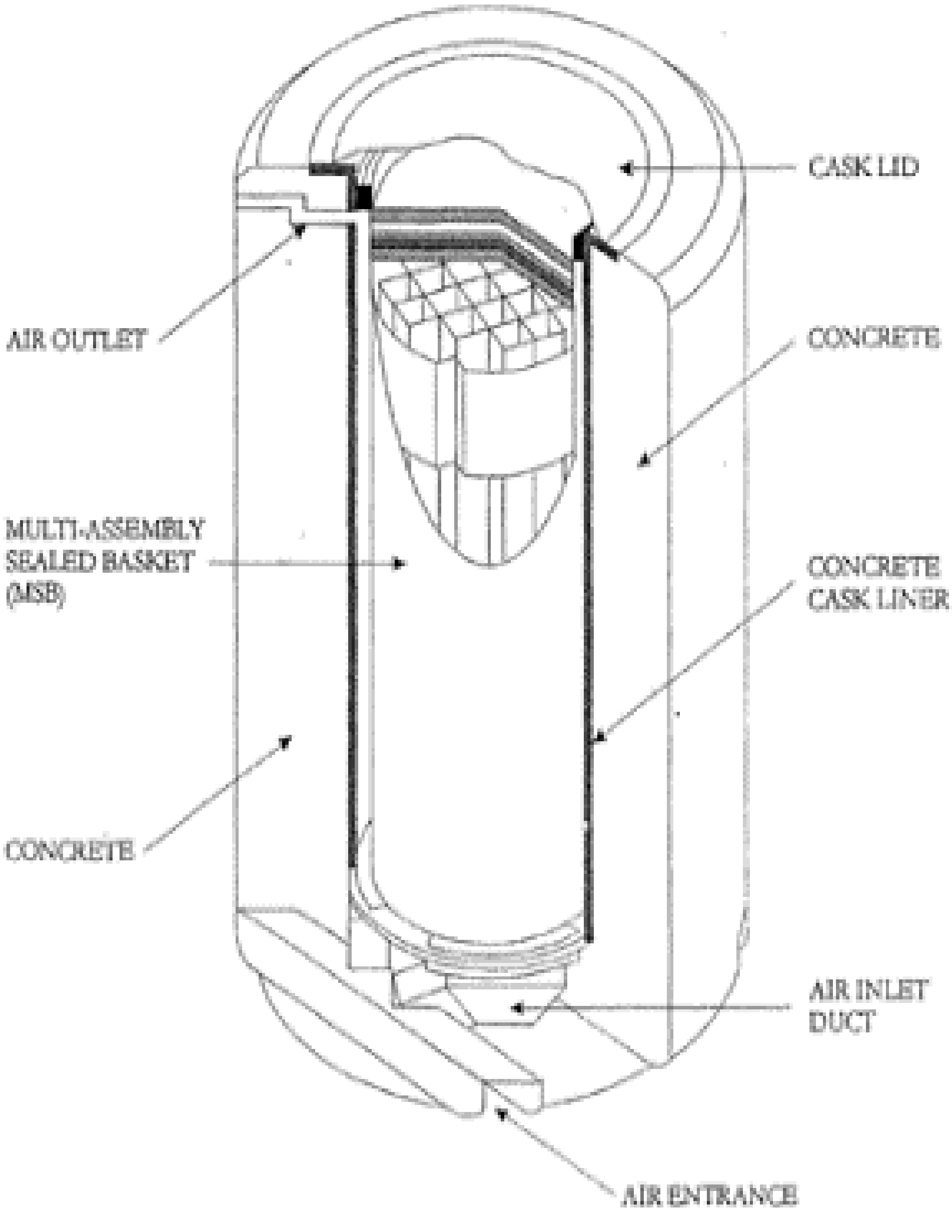

Figure 2-4: Transtor ventilated storage cask system (Bace, 1998)

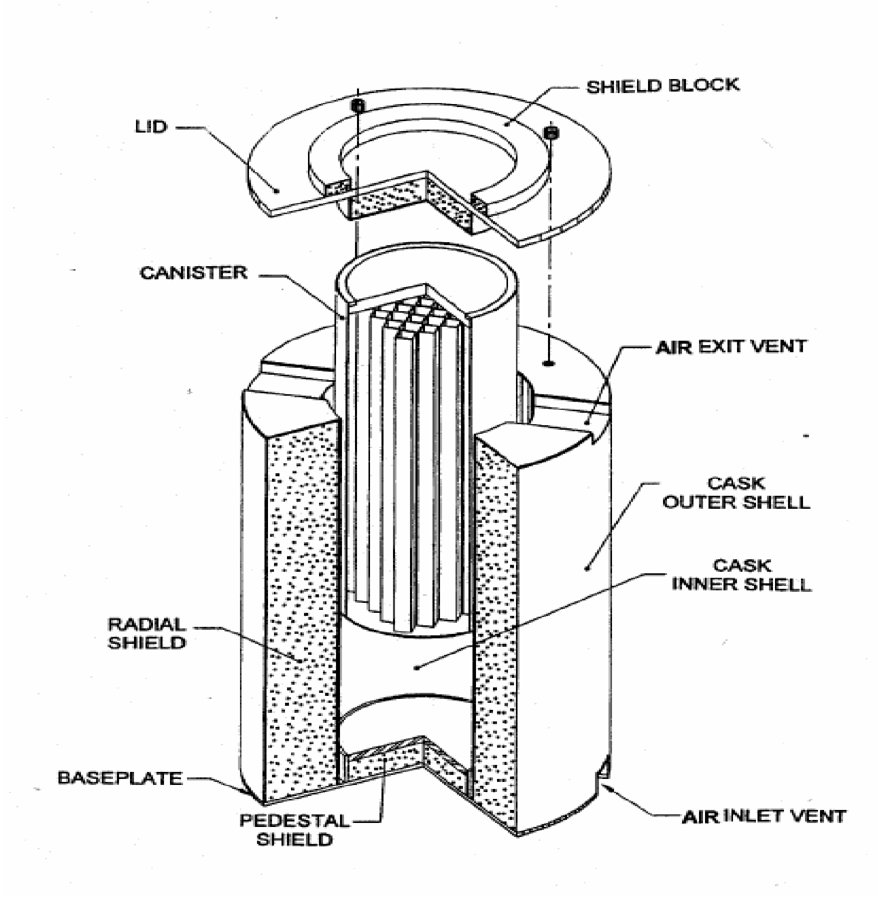

Figure 2-5: Holtec International HI-STORM 100 cask storage system (Petroski, 2005)

Figure 2-6: Connecticut Yankee dry cask storage facility (Connecticut Yankee, 2019)

2.3.6 Metal casks with integrated basket stored inside a reinforced concrete storage building

Metal casks are generally similar to concrete casks in shape (IAEA, 2007). However, the concrete cask is a canister–based dry storage system, while the metal cask is a bare fuel dry storage system. The outer structure of the metal cask is manufactured from a monolithic body made out of ductile cast iron. The cask is equipped with a double lid system (primary lid and secondary lid, one on top of the other, as shown in Figure 2-7) with metal gaskets bolted onto the cask to seal it. The interspace between the primary lid and secondary lid is filled with pressurised helium, allowing continuous monitoring to detect possible leaks from the fuel cavity. This structure makes up the containment. Inside this structure is a cylindrical cavity with an integrated basket. The basket is fixed to the inner cavity of the cask. In this design, instead of using boron aluminium as the material for the basket, boronated stainless steel has been used. Similar to the canister basket discussed in Section 2.3.5, this basket also has a lattice structure, which holds the SNF assemblies in individual compartments. This arrangement and the use of boron provide criticality control.

The thick wall of the cask (varies between 20 – 40 cm, depending on the size of the cask) provides the main gamma shielding. Neutron shielding is provided by the polyethylene moderator rods inserted in axial boreholes drilled into the cask wall (Skrzyppek & Kim, 2015).

The cask is not provided with inlet and outlet vents like the concrete cask described in Section 2.3.5. The cask is cooled by heat conduction through the cask body and the surface of the cask is cooled by natural convection of air. The outer surface of the cask has fins to improve heat removal further. Trunnions are fitted on the structure for handling the cask. An example of this cask is shown in Figure 2-7.

A variant to this cask design is a design in which the outer structure is made from thick steel cylindrical forging. The bottom of the cask is also made of forged steel, which is welded onto the cask body. As in the cask design described above, this cask is also closed with a double lid system (primary lid and secondary lid, one on top of the other, as shown in Figure 2-8) with metal gaskets bolted onto the cask body. The interspace between the primary lid and secondary lid is also filled with pressurised helium, allowing continuous monitoring to detect possible leaks from the fuel cavity. This structure makes up the containment. Inside, this structure is also a cylindrical cavity with an integrated basket. In this design, instead of using boronated stainless steel as in the design discussed above, boronated aluminium has been used as the material for the basket. This basket also has a lattice structure, which holds the SNF assemblies in individual compartments. As in the design discussed above, this arrangement and the use of boron provide criticality control.

As in the cask design discussed above, the thick wall of the cask also provides the main gamma shielding. Neutron shielding is provided by the resin layer enclosed between the cylindrical cavity and the steel outer shell (Roland *et.al.,* 2003).

Similar to the cask design described above, the cask is cooled by heat conduction through the cask body and the surface of the cask is cooled by natural convection of air. However, this cask is not provided with fins to improve heat removal like the design described above. Trunnions are also fitted on the structure for handling the cask. An example of this cask is shown in Figure 2-8.

Based on the reasoning in Section 2.3.5, these casks' design will also be considered as one option; consideration as individual options is reserved for future studies.

These casks are stored vertically or horizontally inside a reinforced concrete storage building. Countries such as Germany, Spain, Japan, Belgium, Switzerland and the Czech Republic are employing this strategy. Examples of storage buildings are shown in Figure 2-9 and Figure 2-10.

The reinforced concrete storage building comprises reinforced concrete walls and a reinforced concrete slab floor similar to the reinforced concrete storage pad that was discussed in Section 2.3.5. The building is designed in such a way that the cooling of the cask is performed passively by natural convection of air (Botch, 2013). The cooling air enters the building at the sides, flows around the casks and is released through the roof (Botch, 2013). The reinforced concrete storage building provides the following storage functions:

- Protection of the casks and handling equipment from environmental conditions;
- Reduction to a minimum of radiation exposure outside the building, well below the permitted values (Czech Republic National Report, 2017);
- Cooling of the stored casks and decay heat sink to the environment using convection of air (Czech Republic National Report, 2017);
- Creation of favourable working conditions for the personnel working in the facility;

- In conjunction with the physical protection system, prevention of unauthorised access (Czech Republic National Report, 2017); and
- Provision of a maintenance area where casks can be repaired.

The storage building is a conventional hall construction divided into a cask reception area, a storage area and a cask maintenance area. The storage building has a bridge crane that can reach over the entire length of the building to provide cask transportation from the reception area to every storage position, as well as the maintenance bay. These reinforced concrete storage buildings are of similar design but different in sizes, according to the needs of the country or NPP.

2.3.7 Metal cask with integrated basket stored inside a steel-cladded enclosure

In this design, the metal cask with the integrated basket is the same as that described in Section 2.3.6.

The steel-cladded enclosure comprises cladded steel-frame walls and a floor of reinforced concrete slab similar to the reinforced concrete storage pad that was discussed in Section 2.3.5. The steel structure is also ductile, which can resist large seismic loads without collapsing. This is due to metal’s ability to be deformed without losing toughness and pliability (and therefore is not brittle) (Hartnick, 2017).

Similar to the concrete building, the cladded enclosure is designed in such a way that the cooling of the cask is performed passively by natural convection of air. As in the reinforced concrete building, the cooling air enters the building at the sides, flows around the casks and is released through the roof.
The cask can be stored in either a vertical or horizontal orientation.

This facility is fairly quick and inexpensive to build and allows most of the structure to be manufactured off-site and erected on-site (Hartnick, 2017). An example of this facility is the Sizewell B dry storage facility located in the Sizewell B Nuclear Power Station site in the UK, shown in Figure 2-11.

2.3.8 Metal cask with integrated basket stored on the reinforced concrete storage pad open to the environment

In this design, the metal casks with integrated inner canisters are the same as those described in Section 2.3.6. These casks are stored on a reinforced concrete storage pad open to the environment, similar to that described in Section 2.3.5. This storage arrangement is currently implemented in the USA only. An example of this storage arrangement is shown in Figure 2-12.

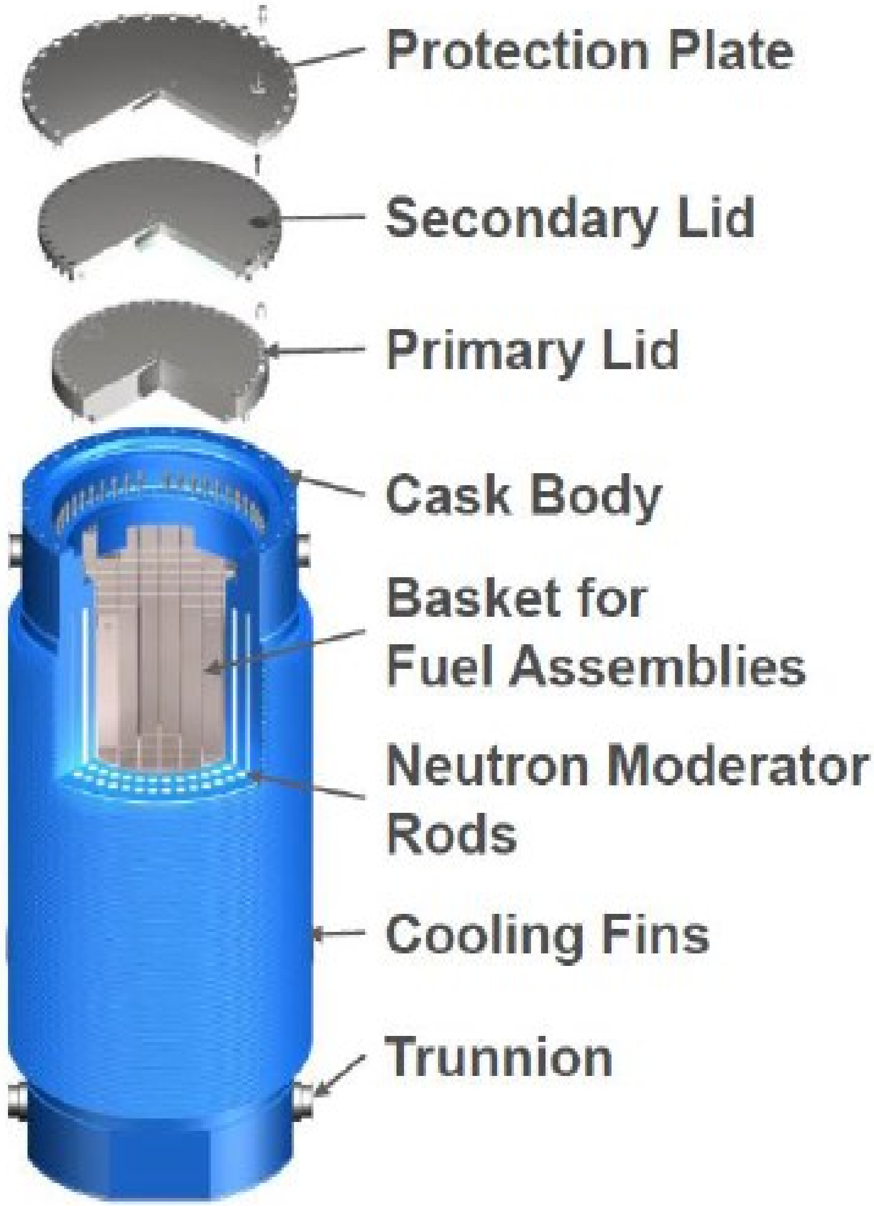

Figure 2-7: Castor cask (Sun & Li, 2019)

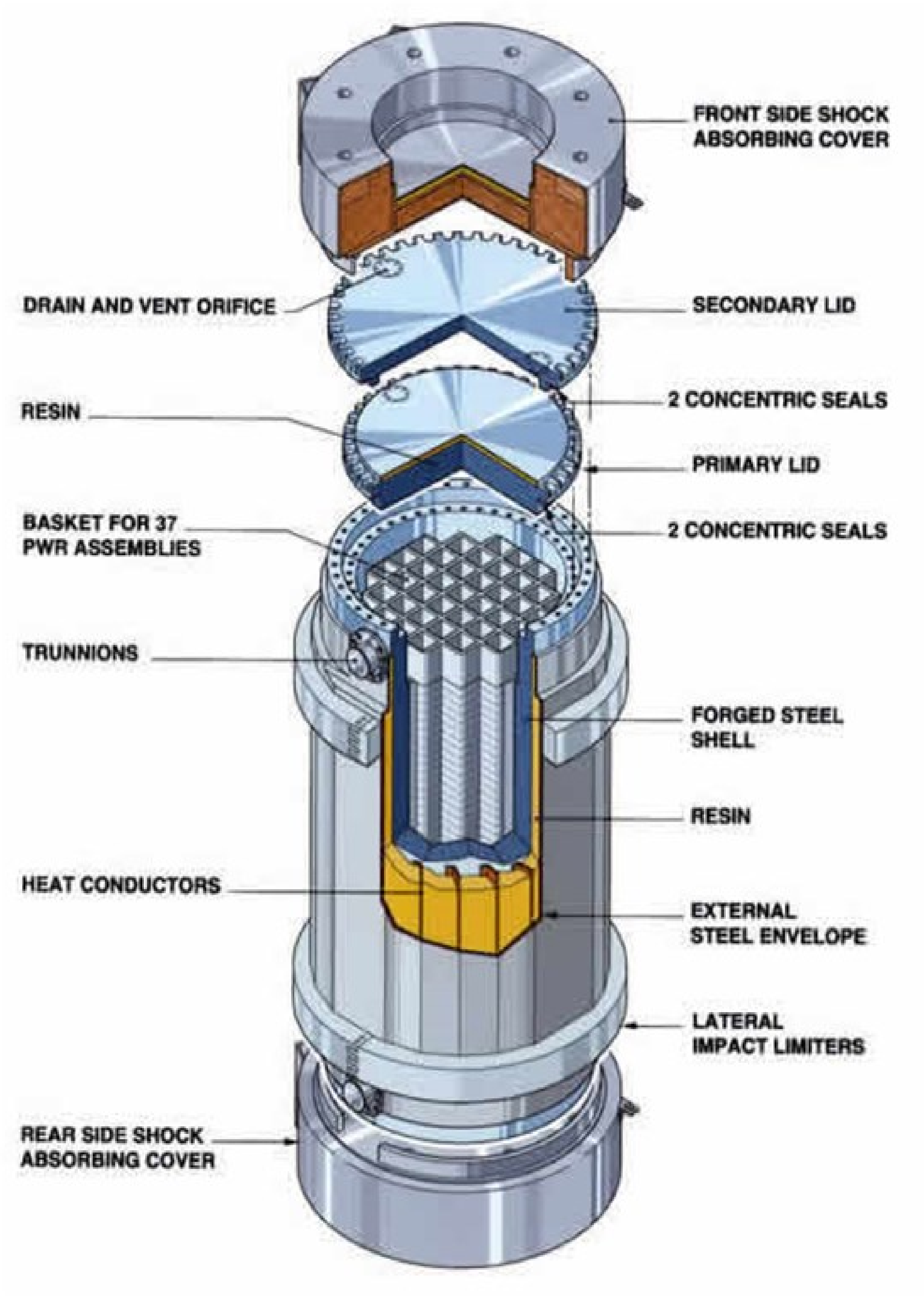

Figure 2-8: Transnuclear TN24G cask (Roland & Samson, 2011)

Figure 2-9: Interim storage facility at Temelin, Czech Republic (Skrzyppek & Kim, 2015)

Figure 2-10: Fukushima dry storage facility in Japan (Gilmore, 2018)

Figure 2-11: Sizewell B dry storage facility in UK (Department for Business, Energy and Industrial Strategy, 2017)

Figure 2-12: Example of metal cask stored on an open reinforced concrete storage pad open to the environment at Surry power station, Virginia USA (Skrzyppek & Kim, 2015):

2.3.9 Concrete module with inner canister stored on a reinforced concrete storage pad open to the environment

Concrete modules are reinforced concrete structures similar to concrete casks in that they are also canister-based dry storage systems. The difference is that the concrete module structure is rectangular and provides storage of the canister in a horizontal orientation. An example of a concrete module is the NUHOMS, which can be seen in Figure 2-13.

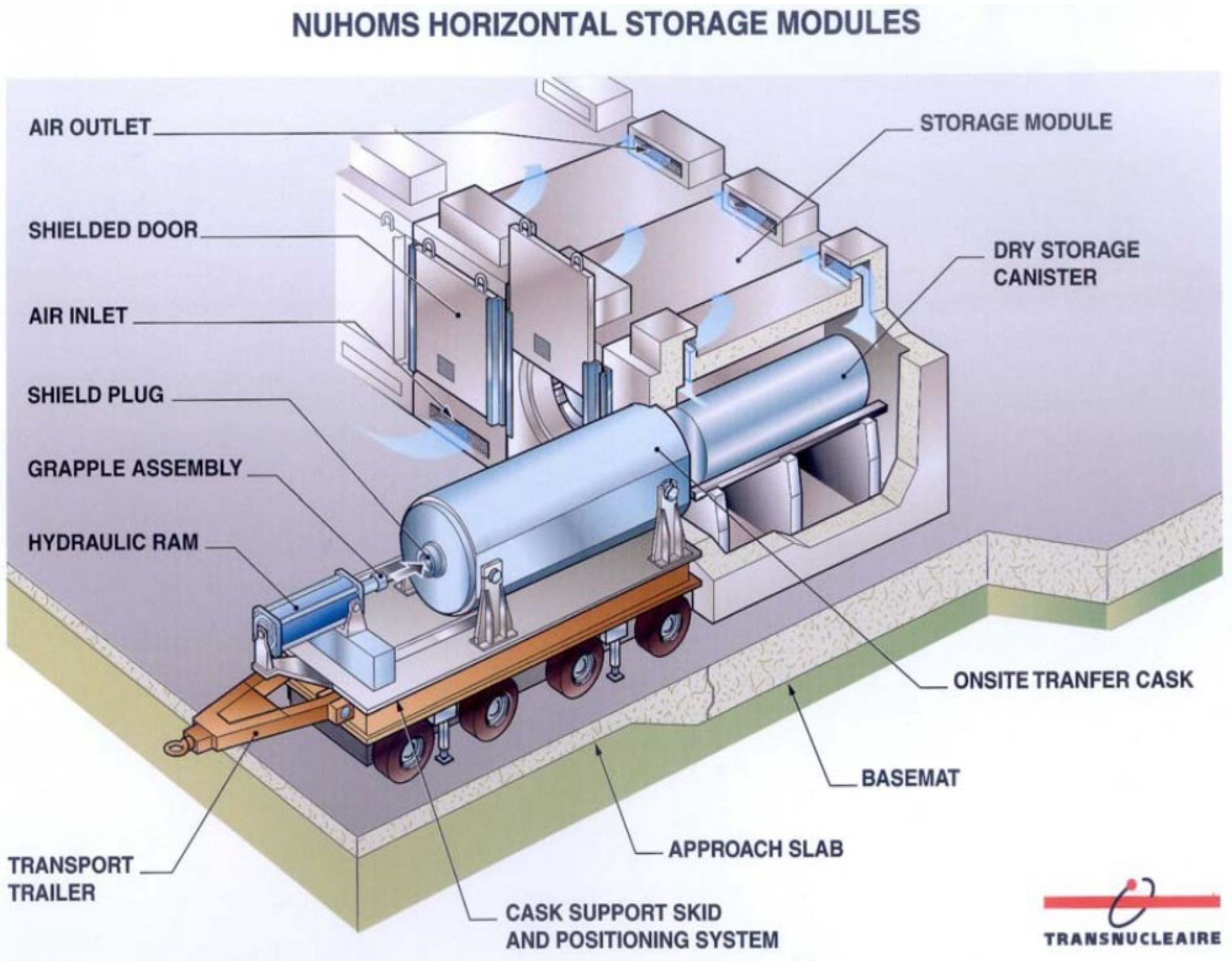

Figure 2-13: Example of horizontal dry storage modules with canister handling (Roland *et al.,* 2003)

An example of the NUHOM canister is shown in Figure 2-14, this canister is provided with a boron aluminium basket having a lattice structure, which holds the SNF assemblies in individual compartments. This arrangement and the use of boron provide criticality control.

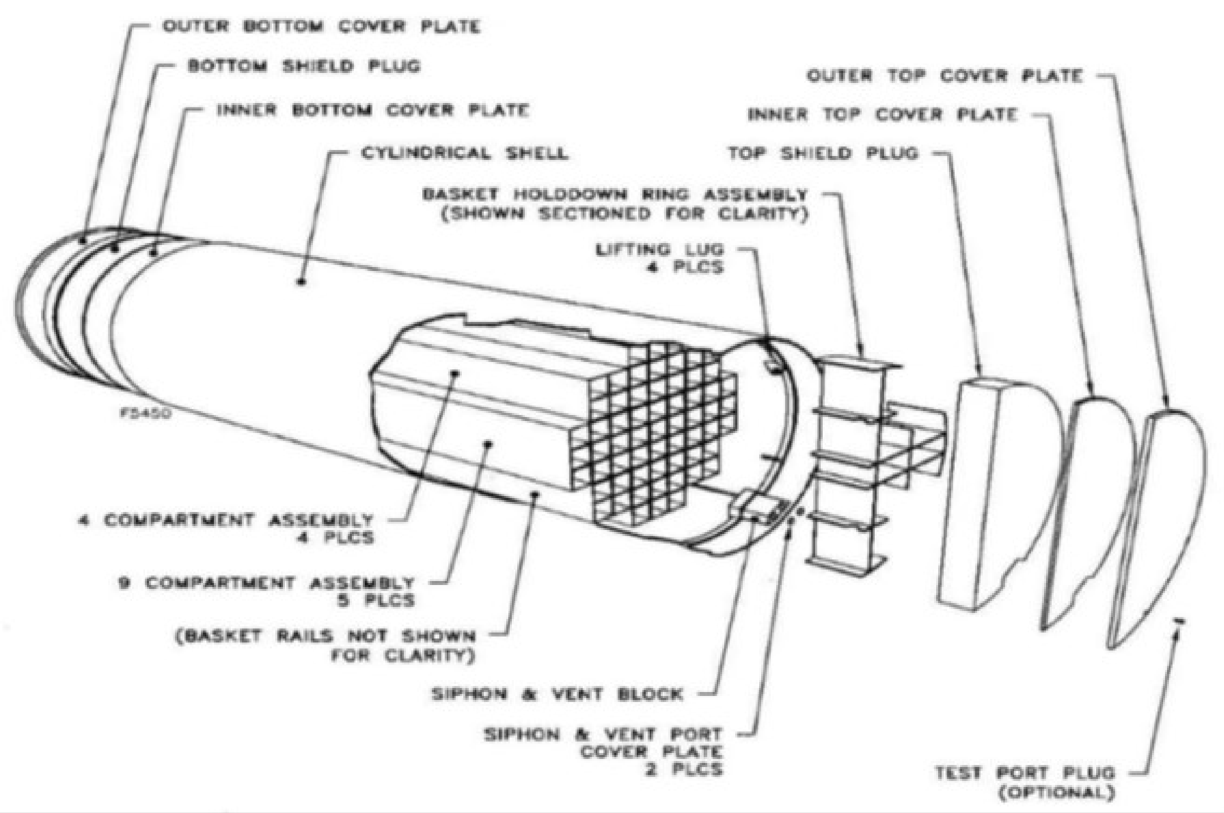

Figure 2-14: Cross-section of NUHOM 61 BTH canister (Bondre, 2015)

The reinforced concrete structure provides structural strength, radiological shielding to the workers and the public and protection of the sealed welded canister from environmental conditions.

The concrete modules are designed to store various sizes of canisters. Spacers are used for smaller canisters to minimise any possible movement.

The concrete module is equipped with air inlet vents at the bottom and exit vents at the top to allow natural convection of air through the space between the canister and the concrete structure, providing heat removal to the environment outside the concrete module.

The concrete modules are stored on a reinforced concrete storage pad open to the environment. This reinforced concrete storage pad is similar to the design discussed in Section 2.3.5. To provide structural stability, the concrete modules are anchored to the reinforced concrete pad.

2.3.10 Concrete vault with an inner canister

Similar to the concrete cask and concrete module, the concrete vault is a canister-based dry storage system. The concrete vault is a reinforced concrete building. It comprises a reinforced concrete slab, vault walls and the roof.

It houses an array of vertical concrete storage tubes, each lined with a steel liner. These tubes are housed on the reinforced concrete slab. These, in turn, contain canisters. The reinforced concrete building protects the concrete storage tubes from environmental conditions. Examples of the concrete vault are shown in Figure 2-15 and Figure 2-16.

The canisters hold one or more SNF. The canister is similar to that described in Section 2.3.5. Sub-criticality is maintained by the canister arrangement and the geometrical array of storage tubes within the reinforced concrete slab.

Containment is first ensured by a double barrier. The first barrier is formed by the sealed welded canister, in which the SNF is accommodated. The second barrier is made by the leak-tight storage tube into which the canisters are stored (Roland, *at. al.,* 2003). The third barrier is the reinforced concrete building.

As mentioned above, the reinforced concrete building comprises the reinforced concrete slab, vault walls and the roof. These provide similar functions as the reinforced concrete storage building discussed in Section 2.3.5:

- Protection of the storage tubes and the canister handling equipment from environmental conditions;
- Reduction to a minimum of the radiation exposure outside the building;
- Cooling of the stored canisters and decay heat sink to the environment using natural convection of air;
- Creation of conducive working conditions for the personnel working in the facility; and
- Prevention of unauthorised access in conjunction with the physical protection system.

Commercially available vault systems are located above ground and heat is generally transferred to the atmosphere by natural convection of air over the exterior of the storage tubes, as shown in Figure 2-16 (Hitachi, 2014).

Figure 2-15: Cascad dry vault storage facility (AREVA, 2010)

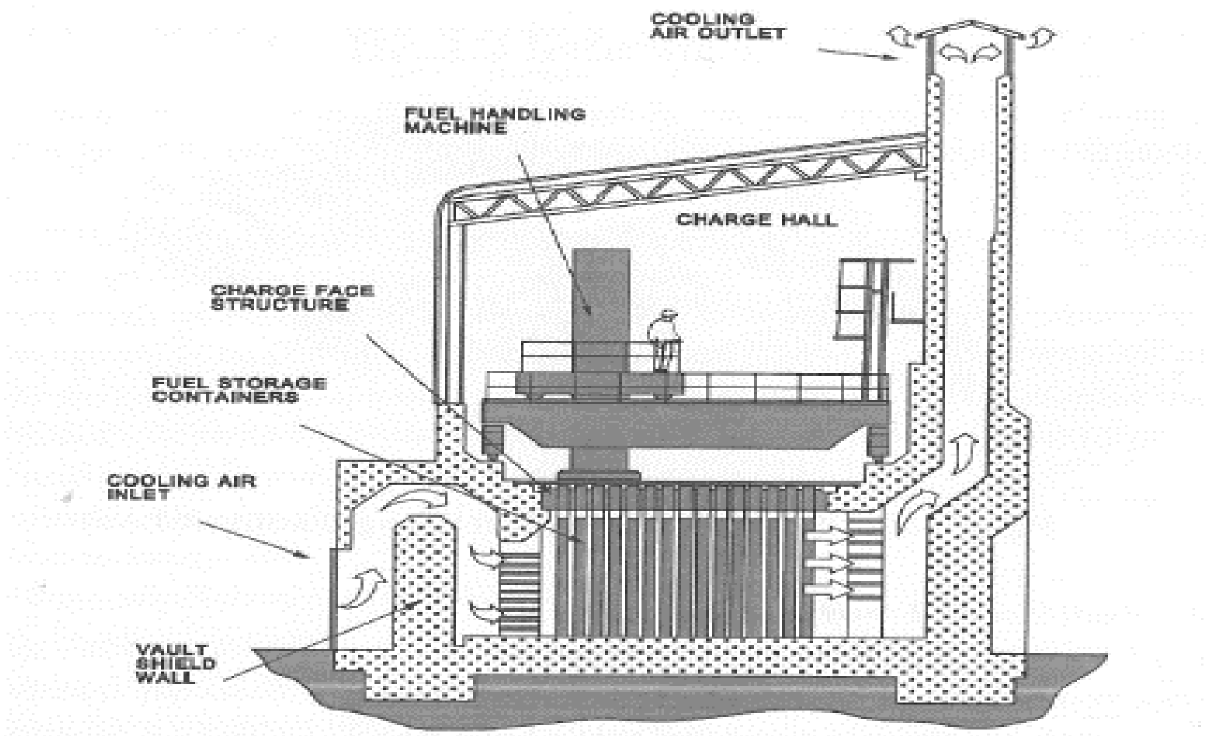

Figure 2-16: Schematic view of dry vault storage (MVDS) (Hitachi, 2014)

2.3.11 Summary of dry storage options

A summary of all the options considered is presented in Table 2-5.

In terms of the canister-based or bare fuel dry storage systems, rows A, E and F have inner canisters and rows B, C and D have integrated baskets.

In terms of the cask, module or vault, row A has a concrete cask, rows B, C and D have metal casks, row E has a concrete module and row F has a concrete vault.

In terms of the outermost structure, rows A, D and E have reinforced concrete pads, rows B and F have reinforced concrete buildings and row C has a cladded enclosure.

It is noted that the combinations are not easily ordered.

Table 2-5: Summary of dry storage system options

Row	Section in text	Canister-based/bare fuel dry storage system	Cask/module/vault	Concrete pad or enclosure
A	2.3.5	Inner canister	Concrete cask	Reinforced concrete pad
B	2.3.6	Integrated basket	Metal cask	Reinforced concrete storage building
C	2.3.7	Integrated basket	Metal cask	Cladded enclosure
D	2.3.8	Integrated basket	Metal	Reinforced concrete pad
E	2.3.9	Inner canister	Concrete module	Reinforced concrete pad
F	2.3.10	Inner canister	Concrete vault	Reinforced concrete building

3 METHODOLOGY

The current chapter presents the methodology followed to conduct the study. The methodology involves the following six steps:

1) Choose the criteria and sub-criteria;
2) Choose the options;
3) Carry out the pairwise comparisons;
4) Choose the cases for the AHP so that the study could be feasible given the time constraints;
5) Apply the APH tool; and
6) Verify the calculation of the Microsoft Excel program using a computer code.

The computer code was written to do the AHP calculation as part of the research group's effort. This code, however, was not written by the author of this work.

3.1 Choosing of Criteria and Sub-criteria

The criteria and sub-criteria were chosen from literature sources, which outline broad criteria that can be used in the selection of dry storage system options. The sub-criteria were chosen for criteria with attributes that contribute to the overall criteria, enabling clear discrimination between the dry storage system options. The sources are as follows:

- IAEA Guidebook for the Selection of Away-from-Reactor Facilities for SNF (IAEA, 2007);
- Evaluation of Spent Nuclear Fuel Management Options for South Africa (Twala, 2007); and
- UK ABWR Generic Design Safety Assessment Preliminary Safety Report on Spent Fuel Interim Storage (HITACHI, 2014).

From these sources, specific relevant criteria and sub-criteria were derived for the selection of the dry storage system option.

3.2 Choosing of Dry Storage Option

Dry storage systems are implemented in various countries around the world. To enable choosing dry storage systems currently in use around the world, the following literature was reviewed:

- Country reports on the management of spent fuel;
- Conference papers and presentations;
- Published papers and reports; and

- Official websites.

To gain insight into the implementation of the dry storage system in each country reviewed, the following information was considered:

- Status of dry storage of SNF in each country;
- Type of dry storage system;
- Type of storage facility used for the dry storage system;
- Location of the dry storage facility, either on the reactor site or off reactor site;
- Vendor used;
- Orientation (vertical/horizontal) of the dry storage system in storage; and
- Type of spent fuel stored.

This information was arranged in tabular form. From this table, the dry storage options considered were grouped into headings, making clear discrimination between the options. The description of each dry storage system was also entered.

3.3 Pairwise Comparisons

To carry out the pairwise comparisons, each possible pair for the criteria, the sub-criteria and the options were compared in terms of advantages and disadvantages. To enable comparison, a Saaty 9-point scale (Saaty, R.W., 1987) was used as the judgement score between the pairs. A table of items was constructed to present the pairwise comparisons.

In the tables, each pairwise comparison consists of two rows. In the first row, the first column is the number of the comparison, numbered sequentially without any preference and referred to as items. The second column contains the name of the pairwise comparison and the third column contains the score.

The second row contains a supporting discussion for the assignment of the score.

3.4 Choosing Cases for the AHP

Three cases were chosen for demonstrating the application of the AHP tool. Criteria, sub-criteria and options were chosen arbitrarily and used in the application.

The first case chosen involved two criteria with no sub-criteria and two options. This was a simple case that allowed the researcher to become familiar with the AHP tool.

The two criteria chosen were:

(i) radiological safety; and
(ii) cost.

The options chosen were:

(i) concrete modules with inner canisters stored on a reinforced concrete storage pad open to the environment; and
(ii) metal casks with integrated inner canisters stored inside a reinforced concrete storage building.

In the second case, three sub-criteria were added to the second criterion, and three options were used. This case allowed the researcher to establish the manner in which the sub-criteria should be treated. The two criteria, including the three sub-criteria for the second criterion and three options, were:

(i) radiological safety; and
(ii) cost:
    - capital cost;
    - operational and maintenance cost; and
    - decommissioning cost.

The options chosen were:

(i) concrete modules with inner canisters stored on a reinforced concrete storage pad open to the environment;
(ii) metal casks with integrated inner canisters stored inside a reinforced concrete storage building; and
(iii) concrete casks with inner canisters stored on a reinforced concrete storage pad open to the environment.

In the third case, two more criteria were added to the second case. One of these criteria had three sub-criteria. The number of options was kept to three. This was considered the most complicated case and it is expected that in larger cases, the level of complexity would not be deeper than the third case. The four criteria where two of the criteria had three sub-criteria each were:

(i) radiological safety;
(ii) system flexibility:
    - localisation;

- modularity; and
- possibility of changing the vendor;

(iii) retrievability; and

(iv) cost:

- capital cost;
- operational and maintenance cost; and
- decommissioning.

The options chosen (which were the same as for case two) were:

(i) concrete modules with inner canisters stored on a reinforced concrete storage pad open to the environment;

(ii) metal casks with integrated inner canisters stored inside a reinforced concrete storage building; and

(iii) concrete casks with inner canisters stored on a reinforced concrete storage pad open to the environment.

3.5 Application of the AHP

To apply the AHP, an Excel spreadsheet (Microsoft Excel, 2010) was constructed for each case. A table of items described in Section 3.3 was used to construct the pairwise comparison matrices for each case. The weight of each element, the consistency of judgement for each matrix and the ranking of the options were calculated using the equations developed in Section 2.1. These equations were implemented in the Excel spreadsheet.

3.6 Verification of Calculations

A code was developed and this code was used to verify the calculations performed on the Excel spreadsheet, i.e. that both the Excel results and the code results should give the same results. The code was developed using the computer language FORTRAN and named jun0219. It was made part of the North-West University Reactor Code Suite (NWURCS) (Naicker *et al.,* 2015).

4 RESULTS AND DISCUSSION

This chapter presents the implementation of the AHP tool for the selection of the option that will best meet South Africa's needs.

4.1 AHP Studies

In the literature reviewed in Chapter 2, available dry storage system options have been grouped into headings, discriminating clearly between the options. The criteria to evaluate these options have been formulated. The AHP tool will be implemented using the Microsoft Excel Program.

4.2 Selection of Criteria, Sub-criteria and Options

In Chapter 2, six criteria were identified. Two of these had three sub-criteria each.

Given this, the number of pair-wise comparisons would have been 21.

In terms of the options, there were six chosen. This, therefore, meant that for a given criterion, 15 pairwise comparisons would be required for each sub-criterion or criterion (when there is no sub-criterion for the criterion).

With the six criteria and six sub-criteria, there would be a total of 10 sub-criteria and criteria for which pairwise comparisons of the options were required, giving a total of 150 pairwise comparisons required for the options.

In total, 171 pairwise comparisons would have been required. This was considered to be too much for the present study, given the time constraint. It was therefore decided to use four criteria, two of which had three sub-criteria each, and three options.

The total number of pairwise comparisons would then be 37.

However, this then required the researcher to choose four criteria from the six criteria, two of which had three sub-criteria each, and three options from the six options.

The criteria chosen were radiological safety, system flexibility, retrievability and cost. The sub-criteria for the criterion system flexibility were localisation, modularity and the possibility of changing the vendor. For criterion cost, the sub-criteria were capital cost, operational and maintenance cost and decommissioning cost.

The options chosen were concrete modules with inner canisters stored on a reinforced concrete storage pad open to the environment, metal casks with integrated baskets stored inside a reinforced concrete storage building and concrete casks with inner canisters stored on a reinforced concrete storage pad open to the environment.

These choices were chosen arbitrarily. As mentioned earlier, the inclusion of all the criteria, sub-criteria and options will be carried out in later studies, once the implementation of the AHP has been demonstrated in this study. It is furthermore noted that the criteria, sub-criteria and options can be extended to include other criteria, sub-criteria and options not mentioned in Chapter 2, but deemed applicable.

4.3 Pairwise comparisons

The next step in the AHP is to determine the pairwise comparison matrices of the criteria and options. This is discussed in the next section. It is noted that all the cases will use the same set of pairwise comparisons.

In order to construct the pairwise matrices, pairwise comparisons must first be made. The pairwise comparisons are performed on each possible pair for the criteria, the sub-criteria and the options.

To facilitate the assignment, the results and discussion for all the matrices are presented in tabular form. However, a considerable amount of text presented in the tables is not repeated in the text body, since this would mean a large amount of duplication. Presentation in tabular form also allows one to access the score for any pairwise comparison relatively easily. To ensure consistency in the tables, the options have been abbreviated as per the following table:

Table 4-1: Summary of the options

Full name of the option	**Abbreviation**
Concrete modules with inner canister stored on a reinforced concrete storage pad open to the environment	ConMod
Metal casks with integrated inner canister stored inside a reinforced concrete storage building	MetCas
Concrete casks with inner canister stored on a reinforced concrete storage pad open to the environment	ConCas

In the tables, each pairwise comparison consists of two rows. In the first row, the first column is the number of the comparison, numbered sequentially and referred to as item 1, 2,…37. The second column contains the name of the pairwise comparison and the third column contains the score.

The second row contains supporting discussion for the assignment of the score. Note that the score judgement was used as given in Table 2-1.

Item 16 is required for case one but not for cases two and three.

Table 4-2: Pairwise comparison of criteria with respect to the goal

<table>
<tr><td>1</td><td>Radiological safety vs system flexibility</td><td>Score = 5</td></tr>
<tr><td colspan="3">Radiological safety is described in Section 2.2.2, and system flexibility is described in Section 2.2.3.

To state this again, radiological safety deals with the protection of workers, the public and the environment against radiological hazards.

System flexibility, on the other hand, assists the operator of the medium-term storage facility in terms of implementation and further expansion. It allows the operator to start with a small system and have the option of expansion if required.

Radiological protection deals with the immediate and future protection of human life and the environment, whereas system flexibility considers ease of implementation, including future needs. In this context, radiological protection is considered more important than system flexibility.

However, if due consideration is not given to system flexibility (for example, the system is chosen to be large from the start to avoid the issue of further expansion), then it is possible that the dry storage facility might take a longer time to implement because of delays in design, construction and licensing (of a big system). This will force the reactor operator to continue storing the spent fuel on site, thereby risking the continued operation of the reactor if the storage facilities on site become full. Furthermore, as the experience at Fukushima indicated (Maree & Carolissen, 2017), a risk to the public is also present if the fuel is stored on the reactor site rather than at a medium-term storage facility.</td></tr>
</table>

Given this, the criterion radiological safety is given a score of five, “Essential or strong importance”, according to Table 2-1, against criterion system flexibility. However, the possibility of delayed implementation of a medium-term storage facility (if the system is designed to be large from the start) can also be a potential risk to the public and a score higher than five was not considered.		
2	Radiological safety vs retrievability	Score = 7
Radiological safety is described in Section 2.2.2 and also discussed in item 2 above, and retrievability is described in Section 2.2.5. As discussed in item 1 above, radiological safety deals with the protection of workers, the public and the environment against radiological hazards. Retrievability, on the other hand, deals with the ease with which the spent fuel can be recovered from the dry storage system when this need arises. Radiological safety must be maintained throughout the storage lifetime of the dry storage system, while retrievability is regarded as a once-off activity, mainly at the end of the storage lifetime of the dry storage system or when the need arises. During actions involved with retrievability, the protection of workers, the public and the environment against radiological hazards will remain an important factor. In this context, radiological safety will receive more consideration than retrievability, i.e. if radiological safety is being comprised during the retrieval process, then it would be a better decision to obtain a system without the feature of retrievability. Given this, the criterion radiological safety is given a score of seven, “Very strong importance”, according to Table 2-1, against the criterion retrievability. However, a score higher than seven was not considered, since the current dry storage systems are not designed for disposal; failure to remove the spent fuel from these systems at the end of the storage life might pose a safety risk.		
3	Radiological safety vs cost	Score = 3
Radiological safety is described in Section 2.2.2 and discussed in item 1 and item 2 above, and the cost is described in Section 2.2.7. As discussed in item 1 and item 2 above, radiological safety deals with the protection of workers, the public and the environment against radiological hazards.		

Cost, on the other hand, deals with the affordability of implementing the medium-term storage. For the country to be able to implement medium-term storage, it is important that the cost of the dry storage system option chosen does not pose a financial burden to the country. However, the chosen dry storage system must demonstrate that all possible safety provisions intended to minimise the radiation hazard to the workers, public and environment to the greatest practical extent during operational activities of the facility and the storage lifetime have been considered (Twala, 2007). In this context, radiological safety is considered more important than cost. Given this, the criterion radiological safety is given a score of three, “Moderate importance”, according to Table 2-1, against the criterion cost. A score higher than three was not considered because non-implementation of medium-term storage due to cost will increase the risk posed by storing SNF on site.		
4	System flexibility vs retrievability	Score = 3
System flexibility is described in Section 2.2.3 and discussed in item 1 above and retrievability is described in Section 2.2.5 and discussed in item 2 above. As discussed in item 1, system flexibility assists the operator of the medium-term storage facility with implementation and further expansion. It allows the operator to start small and have the option of expansion if required. As discussed in item 2, retrievability, on the other hand, deals with the ease with which the spent fuel can be recovered from the dry storage system when this need arises. System flexibility is considered more important than retrievability in that it plays a major role in the continuous and safe operation of the NPP. Any delays in the implementation of the dry storage system will result in the reactor pools becoming full. This will result in cessation of reactor operation and the risk of having a considerable amount of SNF stored on site. Given this, the criterion system flexibility is given a score of three, “Moderate importance”, according to Table 2-1, against the criterion retrievability. However, since no decision has been made in South Africa on the final management option for SNF, retrievability remains an important factor; a score higher than three was therefore not considered.		

5	System flexibility vs cost	Score = 4
Cost is described in Section 2.2.7 and also discussed in item 3 and system flexibility is described in Section 2.2.3 and described in item 1 and item 4 above. As discussed in item 3 above, cost deals with the affordability of implementing medium-term storage. System flexibility allows the operator more security in the sense that if the installed capacity becomes inadequate, then the extension of the system would be easier if system flexibility was taken into account when choosing the system. For example, the site would already have been licensed and the process of licensing a new site, if needed, would not be required. Since an excessive cost of the system which cannot be met will prohibit the construction of a storage site, and inclusion or exclusion of considering system flexibility would not have such an effect, the cost is considered more important than system flexibility. Given this, the criterion cost is given a score of four, “Intermediate between moderate importance and essential or strong importance”, according to Table 2-1 against the criterion system flexibility. A score higher than four was not considered because of the contribution of system flexibility in reducing the cost, as will be discussed in the remainder of this section. System flexibility also encompasses some of the factors that contribute to reducing the cost of implementing the dry storage system. In this case, the cost is not a truly independent criterion compared to system flexibility. It was decided to reserve the study of dependencies in the follow-up studies. However, it would be appropriate to document some of the ideas concerning this for reference in subsequent studies. The factors are modularity, which plays an important role in the selection of a dry storage system by reducing the upfront cost; localisation, which among others minimises the cost uncertainty due to currency exchange fluctuation or an unfavourable exchange rate and the possibility of changing vendors, which among others allows the participation of multiple vendors in order to obtain competitive cost.		
6	Retrievability vs cost	Score = 5
Cost is described in Section 2.2.7 and discussed in item 3 and item 5 above and		

retrievability is described in Section 2.2.5 and discussed in item 2 and item 4 above. As discussed in item 4 above, since no decision has been made in South Africa on the final management option for SNF, retrievability remains an important factor. However, cost plays a major role in deciding whether the country can or cannot afford to implement medium-term storage for SNF, which has a direct impact on the continual and safe operation of the NPP. This was also discussed in item 5 above. In this context, cost is considered more important than retrievability. Given this, criterion cost is given a score of five, "Essential or strong importance", according to Table 2-1 against the criterion retrievability. A score higher than five was not considered. This was because the main concern with regard to retrievability is how easy or complex it would be to retrieve the SNF.

Table 4-3: Pairwise comparison of sub-criteria with respect to the parent criterion: Flexibility

7	System flexibility: Localisation vs modularity	Score = 3
Localisation is described in Section 2.2.3 (ii) and modularity is described in Section 2.2.3 (i). Section 2.2.3 gives the advantages and disadvantages of localisation and modularity. Considering the advantages, it can be concluded that both sub-criteria enable the country to afford the implementation of medium-term storage for SNF. However, localisation also addresses the current urgent need for the government to create jobs and grow the economy. In this context, localisation is considered more important than modularity. The disadvantages of both sub-criteria are not considered to have a major influence on decision-making. In terms of modularity, the increase in cost due to the need to establish the facility will be a once-off cost. This cost will still be spent in the country. If there are no changes in the system, it is not foreseen that further licensing will be required during the extension of the facility. Given this, the sub-criterion localisation is given a score of three, "Moderate importance", according to Table 2-1, against the sub-criterion modularity.		

8	System flexibility: Localisation vs possibility to change vendors	Score = 5

Localisation is described in Section 2.2.3 (ii) and the possibility of changing vendors is described in Section 2.2.3 (iii).

The possibility of changing vendors facilitates the participation of multiple vendors and it is important in getting a competitive price and prevents dependence on one supply in meeting the demand.

However, localisation, on the other hand, eliminates the cost uncertainty posed by international vendors due to currency fluctuations, supply disruption logistics and political instabilities.

Moreover, as mentioned in item 7, localisation enables the creation of jobs and the growing of the economy. In this context, localisation is considered more important than the possibility of changing vendors.

Given this, the sub-criterion localisation is given a score of five, "Essential or strong importance", according to Table 2-1, against the sub-criterion possibility of changing vendors. A score higher than five was not considered, since these multiple vendors may include sub-contracting of local vendors/contractors, which would then enable localisation.

9	System flexibility: Modularity vs the possibility of changing vendors	Score = 3

Modularity is described in Section 2.2.3 (i) and discussed in item 7. The possibility of changing vendors is described in Section 2.2.3 (iii).

As discussed in item 8 above, the possibility of changing vendors facilitates the participation of multiple vendors and it is important in determining a competitive price and in overcoming supply constraints.

Modularity, on the other hand, will help the country to alleviate storage space in the reactor pool directly and address the current concern of minimising the amount of SNF stored on the reactor site. In this context, modularity is considered more important than the possibility of changing vendors.

Given this, the sub-criterion modularity is given a score of three, "Moderate

importance", according to Table 2-1, against the sub-criterion possibility of changing vendors. However, if the participation of multiple vendors is implemented in the manufacturing modular system, it facilitates the alleviation of the storage space in the reactor pool; therefore, a score higher than three was not considered.

Table 4-4: Pairwise comparison of sub-criteria with respect to the parent criterion: Cost

10	Cost: Capital cost vs operational and maintenance cost	Score = 5
Capital cost is described in Section 2.2.7(i), and operational and maintenance cost is described in Section 2.2.7(ii) The actual capital cost and operational and maintenance cost could not be found in the literature. These could be obtained from the vendors when the country is ready to establish medium-term storage. Estimating the actual cost was beyond the scope of this study, since the aim of the study is to initiate the implementation of the AHP tool for the selection of a dry storage system. Capital cost, among others, includes the cost of the design of the dry storage system and related facilities, manufacturing and construction, as well as purchasing of the equipment needed for the operation. Operational and maintenance cost, among others, includes labour cost, the cost of the equipment required for inspections and maintenance and utility cost (such as electricity, etc.). The implementation of medium-term storage is dependent on the availability of finances for capital cost. This cost is defined by the complexity of the dry storage system. It is believed that a complex system will require higher capital cost. Given this, the criterion capital cost is given a score of five, "Essential or strong importance", according to Table 2-1, against operational and maintenance cost. A score higher than five was not considered because dry storage systems that are complex will demand much more attention to keep them in safe working condition, which will also relate to the high cost of operation and maintenance.		

11	Cost: Capital cost vs decommissioning cost	Score = 7

Capital cost is described in Section 2.2.7(i) and discussed in item 10 above, and decommissioning cost is described in Section 2.2.7(iii)

As discussed in item 11 above, capital cost, among others, includes the cost of the design of the dry storage system and related facilities, manufacturing and construction, as well as purchasing of the equipment needed for the operation.

Decommissioning costs include expenses associated with the decontamination, dismantling and decommissioning of the storage system and site restoration subsequent to the SNF removal from the facility (IAEA, 2007).

As mentioned in item 10, the actual capital cost could not be found in the literature. This could be obtained from the vendors when the country is ready to establish medium-term storage. Estimating the actual cost was beyond the scope of this study, since the aim of the study is to initiate the implementation of the AHP tool for the selection of a dry storage system.

The decommissioning cost can only be estimated when the actual capital cost is known; therefore the comparison could not be done using actual costs.

Decommissioning costs are often assumed to be 2 - 10% of the base capital cost, depending on the characteristics of the option/facility (IAEA, 2007). Given this, the criterion capital cost is given a score of seven, “Very strong importance”, according to Table 2-1, against the decommissioning cost.

12	Cost: Operational and maintenance cost vs decommissioning cost	Score = 3

Operational and maintenance cost is described in Section 2.2.7(ii) and also discussed in item 10 above and the decommissioning costs are described in Section 2.2.7(iii) and discussed in item 11 above.

During operation and maintenance, measures are put in place to ensure that no contamination occurs on the external surface of the dry storage system to avoid contamination of the related facility and handling equipment. This helps to reduce the decontamination activities required, the waste generated during the decommissioning

activities and the activities related to site restoration. This will, in turn, keep the cost of decommissioning minimal. Given this, the criterion operation and maintenance are given a score of three, "Moderate importance", according to Table 2-1, against the decommissioning cost. A score higher than three was not considered, although the measures put in place during operation and maintenance reduces the decommissioning cost. This is because the decommissioning cost is also dependent on the availability of the decommissioning fund. These funds are set aside by the country for the purpose of decommissioning.

Table 4-5: Pairwise comparison of options with respect to criterion: Radiological safety

13	Radiological safety: ConMod vs MetCas	Score = 3
The description of the concrete module is given in Section 2.3.9 and the description of the metal cask is given in Section 2.3.6. As discussed in item 1 above, radiological safety deals with the protection of workers, the public and the environment against radiological hazards. In metal cask storage, the intentionally thick-walled metal casks and the thick concrete walls of the storage building reduce the dose rate of gamma and neutron radiation outside the storage buildings effectively to acceptable levels where no further measures for the protection of the workers on site or the public outside need to be established (Botsch *et al.,* 2013). The storage building also protects the cask from harmful weather conditions, external effects or man-made hazards (Botsch *et al*., 2013). In the concrete module storage, the concrete module wall thickness can be increased or the concrete modules can be arranged in various configurations to minimise the dose rate associated with the site (Hanson, Chollet, 2003; Roland *et al.,* 2003). The dose rate to the public is also reduced by the distance between the storage pad and the boundaries of the facility, which is established based on the dose rate limits set by the regulator. The concrete modules are designed to withstand normal loads and design-based accident effects, such as earthquakes, tornados and floods (DOE, 1996).		

The general surface dose rates for the concrete module and metal cask could not be found in the literature. Dose rates are a specific vendor design, and could therefore not be included in this comparison. It is consequently assumed that both designs meet the required limit for the allowed dose rate. Both the concrete module and metal cask are considered to provide acceptable radiation measures to reduce radiation exposure of the public and workers during normal operations.

It is assumed that in beyond design basis accident conditions or man-made hazards such as aircraft crashes and missile strikes, the reinforced concrete building and the reinforced concrete module will provide similar protection of the SNF.

However, the concrete module is given a score of three, "Moderate importance", according to Table 2-1, against the metal cask, because a concrete module does not require lifting for the transfer of the canister into the storage module, while the metal cask relies on lifting using a crane for all handling activities, which poses the risk of a drop accident and possible collision with another cask when placing it into a storage position. A score higher than three was not considered because of the use of a single failure-proof crane, which minimises the risk of a drop accident. The single failure-proof crane is equipped in such a way that a single failure will not result in a crane dropping a load or causing a system failure during a critical lift (Hubbard and Zukley, 2019).

14	Radiological safety: ConMod vs ConCas	Score = 5

The concrete module is described in Section 2.3.9 and also discussed in item 13 above. The concrete cask is described in Section 2.3.5.

As discussed in item 1 above, radiological safety deals with the protection of workers, the public and the environment against radiological hazards.

Similar to the concrete module discussed in item 13 above, the concrete wall thickness of the cask provides radiation shielding. The general surface dose rates for the concrete cask could not be found in the literature. Dose rates are a specific vendor design and could therefore not be considered for this comparison.

Accordingly, the concrete cask is also assumed to be designed adequately to provide acceptable radiation protection measures to reduce radiation exposure of the public and workers during normal operations. As in the concrete module, the dose rate to which the public is exposed to is also reduced by the distance between the storage pad and the boundaries of the facility, which is established based on the dose rate limits set by the regulator. The level of SNF protection in beyond design basis accident conditions or man-made hazards such as aircraft crashes and missile strikes is considered similar to that of the reinforced concrete module and concrete building described in item 13 above.

However, compared to the concrete module discussed above, the transfer of the canister into the concrete cask overpack requires a transfer facility where the canister is removed from the transport cask into the transfer cask and from the transfer cask into the concrete cask. This additional step increases the exposure time of the workers to radiation and these actions require lifting, which poses a risk of drop accidents, which could result in the public being exposed to radiation.

Given this, the concrete module is given a score of five, “Essential or strong importance”, according to Table 2-1, against the concrete cask. However, a score higher than five was not considered, since the transfer is conducted in a controlled environment.

15	Radiological safety: MetCas vs ConCas	Score = 2

The concrete cask and metal cask were discussed in item 13 and item 14.

In the discussion in items 13 and 14 above, both casks provide acceptable radiation measures to reduce radiation exposure of the public and workers during normal operations.

Both the concrete and metal casks require lifting during the storage process, which poses a risk of casks being dropped accidentally. However, because of the additional activities during transfer of the canister in the concrete cask storage process that could result in workers being exposed to additional doses of radiation, the metal casks are given a score of two, “Intermediate between equal importance and moderate importance”, according to Table 2-1, against the concrete cask.

Table 4-6: Comparison of options with respect to criterion: Cost

<table>
<tr><td>16</td><td>Cost:

ConMod vs MetCas</td><td>Score = 4</td></tr>
<tr><td colspan="3">The description of the concrete module is given in Section 2.3.9 and the description of the metal cask is given in Section 2.3.6.

The actual cost of the concrete module and the metal cask could not be found in the literature and could consequently not be considered for this comparison.

However, metal casks are believed to cost more than concrete modules. Among the reasons is that metal is generally more expensive than concrete. Furthermore, the fabrication of the metal cask requires advanced facilities and skills; establishing such facilities and skills locally will increase the cost of fabricating the cask significantly. Furthermore, the material for the fabrication of the cask will have to be imported, which could also result in a high cost due to currency fluctuation. The fact that the metal cask is stored in a reinforced concrete building designed to withstand natural phenomena, such as earthquakes, and man-made events, such as missile attacks, would have a significant further impact on the cost of establishing the facility.

The concrete modules, on the other hand, are manufactured from standard concrete technology using normal construction methods and do not require advanced facilities. The material can be sourced locally and the skills required are available locally, which makes the concrete module less expensive compared to the metal cask, which would facilitate local production. Furthermore, these casks are stored on reinforced concrete storage pads open to the environment, which is not considered difficult to design and construct.

Given this, the concrete module is given a score of four, “Intermediate between moderate importance and essential or strong importance”, according to Table 2-1, against the metal cask. Because the actual cost was not used in the comparison, a score higher than four could not be justified adequately.</td></tr>
</table>

Table 4-7: Pairwise comparison of options with respect to sub-criterion of flexibility: Localisation

17	Localisation:	Score = 5

	ConMod vs MetCas	
The description of the concrete module is given in Section 2.3.9 and the description of the metal cask is given in Section 2.3.6. In localisation, it should be possible to manufacture the dry storage system in South Africa, using local skills, and material could be sourced locally. Concrete modules and the reinforced concrete storage pad are constructed using standard concrete technology that facilitates the utilisation of local skills and material sourced locally. The canisters can also easily be fabricated locally (Roland *et al.,* 2003). On the other hand, it might be difficult to localise the fabrication of metal casks, in view of the availability and cost of the material in South Africa, the facilities and skills required to fabricate these casks. Given this, the concrete module is given a score of five, “Essential or strong importance”, according to Table 2-1, against the metal cask. However, because the concrete storage building housing the metal cask facilitates localisation in that it can be designed locally and constructed using local skills with material sourced locally, a score higher than five was not considered.		
18	Localisation: ConMod vs ConCas	Score = 1
The description of the concrete module is given in Section 2.3.9 and the description of the concrete cask is given in Section 2.3.6. Both concrete modules and concrete casks are produced using similar material in similar facilities and can easily be localised. Given this, both concrete modules and concrete cask are given a score of one, “Equal importance”, according to Table 2-1.		
19	Localisation: MetCas vs ConCas	Score = 5
On the basis of the reason given in item 17 and item 18, the concrete casks are given a score of five, “Essential or strong importance”, according to Table 2-1, against the metal cask.		

Table 4-8: Pairwise comparison of option with respect to sub-criterion of flexibility: Modularity

20	Modularity: ConMod vs MetCas	Score = 5
As mentioned in the above items, concrete modules and metal casks are described in Sections 2.3.9 and 2.3.6 respectively. As mentioned in section 2.2.3, modularity makes it possible to start small, thus improving affordability by minimising the upfront cost outlay required to build the facility (IAEA, 2007). Both concrete modules and metal casks are standalone units, which can easily be added as required. This will require extending the open reinforced concrete pad for concrete modules and the reinforced concrete building for metal casks. However, the open reinforced concrete pad is not considered difficult to design and construct, while metal casks are considered difficult to design and construct, as they need to withstand natural phenomena, such as earthquakes, and man-made events, such as missile attacks. For this reason, the modularity of the metal casks and that of the concrete modules are not considered to be on equal footing. Given this, the concrete modules are given a score of five, "Moderate importance" according to Table 2-1, against the metal casks.		
21	Modularity: ConMod vs ConCas	Score = 1
As mentioned in the above items, concrete modules and concrete casks are described in Sections 2.3.9 and 2.3.5 respectively. The concrete casks are also standalone units. Similar to the concrete modules, concrete casks are stored on an open reinforced concrete pad, which is not considered difficult to design and construct. Given this, the concrete modules are given a score of one, "Equal importance" according to Table 2-1, against the concrete casks.		

22	Modularity: MetCas vs ConCas	Score = 5
On the basis of the reasoning given in item 20 and item 21, the concrete casks are given a score of five, “Moderate importance”, according to Table 2-1, against metal casks.		

Table 4-9: Pairwise comparison of options with respect to sub-criterion of flexibility: Possibility of changing vendors

23	Possibility of changing vendors: ConMod vs MetCas	Score = 5
As mentioned in the above items, concrete modules and metal casks are described in Sections 2.3.9 and 2.3.5 respectively. Since the concrete modules are of standard design and are manufactured using standard construction practices, it is possible to subcontract multiple vendors to meet logistics and supply constraints. Because of this standard design, it is not believed that the use of multiple vendors will complicate the licensing of the facility. However, in the case of metal casks, the method of fabrication and the material are specific to the vendor design and fabrication requires advanced facilities and skills. Different vendors would most probably use different designs. This will complicate the licensing of the facility, should the vendor be changed. These reasons limit the participation of multiple vendors in terms of metal casks. Given this, the concrete modules are given a score of five, “Essential or strong importance”, according to Table 2-1, against the metal casks.		
24	Possibility of changing vendors: ConMod vs ConCas	Score = 1
The concrete modules and concrete casks make use of similar material and standard construction practices. Given this, the concrete modules are given a score of one, “Equal importance”, according to Table 2-1, against the concrete casks.		
25	Possibility of changing vendors:	Score = 5

	MetCas vs ConCas	
Based on the same reasoning given in item 23 and item 24, the concrete casks are given a score of five, “Essential or strong importance”, according to Table 2-1, against the metal casks.		

Table 4-10: Pairwise comparison of options with respect to criterion: Retrievability

26	Retrievability: MetCas vs ConMod	Score = 3
As mentioned in the previous items, concrete modules and metal casks are described in Sections 2.3.9 and 2.3.5 respectively. In the concrete modules, the SNF is stored in sealed welded canisters. These canisters will require special equipment to be cut open to enable the retrieval of the SNF. The metal casks make use of a basket integrated into the cask cavity to store the SNF. The cask is closed with two bolted lids, which can easily be opened for the retrieval of spent fuel. Therefore, it is considered that it will be more difficult to retrieve the SNF from the concrete modules compared to the concrete casks because of the risk posed by cutting a canister containing SNF compared to removing the bolts on the metal cask lids. Given this, the metal casks are given a score of three, “Moderate importance”, according to Table 2-1, against the concrete modules. Since the decision on retrieval is dependent on a final management option, a score higher the three was not considered.		
27	Retrievability: ConMod vs ConCas	Score = 1
Concrete casks are similar to concrete modules, which are canister-based systems. The SNF is stored in sealed welded canisters (as was explained in Sections 2.3.5 and 2.3.9 respectively). Therefore the concrete modules are given a score of one, “Equal importance”, according to Table 2-1, against the concrete casks.		

28	Retrievability: MetCas vs ConCas	Score = 3
Based on the same reasoning given in item 27 and item 28, metal casks are given a score of three, “Moderate importance”, according to Table 2-1, against the concrete casks.		

Table 4-11: Pairwise comparison of options with respect to sub-criterion of cost: Capital cost

29	Capital cost: ConMod vs MetCas	Score = 7
As mentioned in the previous items, concrete modules and metal casks are described in Sections 2.3.9 and 2.3.6 respectively. Capital cost is mainly the cost to establish the medium-term storage facility. Among others, it includes the fabrication of the dry storage system, purchase of the handling equipment and the construction of related facilities. The concrete modules are fabricated using standard concrete technology, which facilitates local manufacturing using local resources and labour. Since the concrete modules are standalone systems, they can easily be added as required, which reduces capital cost. As mentioned in Section 2.3.5, these concrete modules are stored on an open reinforced concrete storage pad, which is constructed from the standard concrete technology. The open reinforced concrete storage pad is not considered expensive to construct and can easily be extended when required. Metal casks, on the other hand, are considered expensive to fabricate owing to the high cost of the metal. Localisation of fabrication is not guaranteed in view of the availability of the material, skills and facilities required for manufacturing in the country. This will result in foreign expenditure if the required materials and skills are not available locally. Moreover, these casks are stored inside a reinforced concrete building that is designed to be robust enough to withstand natural external events such as earthquakes and man-made events such as aircraft crashes, which would increase		

the cost of the design and construction of the building. Given this, the concrete modules are given a score of seven, “Very strong importance”, according to Table 2-1, against the metal casks.		
30	Capital cost: ConMod vs ConCas	Score = 2
As mentioned in item 29 above, the capital cost is mainly the cost of establishing the medium-term storage facility. Among others, it includes the fabrication of the dry storage system, purchase of the handling equipment and the construction of related facilities. Concrete casks are similar to concrete modules; both are fabricated using standard concrete technology, which facilitates local manufacturing using local resources and labour. These concrete casks are stored on an open reinforced concrete storage pad and are standalone units, which can easily be added as required. However, concrete casks require a transfer building for the transfer of the canister into the concrete storage cask/overpack, compared to concrete modules, where the canister is directly transferred from the transport cask into the concrete module. This will increase the capital cost of the concrete cask slightly. Given this, the concrete module is given a score of two, “Intermediate between equal importance and moderate importance”, according to Table 2-1, against the concrete cask.		
31	Capital cost: MetCas vs ConCas	Score = 6
As mentioned in item 29 and 30 above, the capital cost is mainly the cost of establishing the medium-term storage facility. Among others, it includes the fabrication of the dry storage system, purchase of the handling equipment and the construction of related facilities. As discussed in item 30, concrete casks share similarities with concrete modules, except that the concrete casks require a transfer building for the transfer of casks into the concrete cask/overpack, which is believed to cost slightly more than the concrete		

module. However, it is not believed that the level of design and engineering required for this building will be the same as that of the storage building required for metal casks, since this facility is used for transfer only. Given this, the concrete module is given a score of six, "Intermediate between essential or strong importance and very strong importance", according to Table 2-1, against metal casks. It is ranked one point less than that of item 29 owing to the requirement of the transfer building.

Table 4-12: Pairwise comparison of options with respect to sub-criterion of cost: Operational and maintenance cost

32	Operational and maintenance cost: MetCas vs ConMod	Score = 2
Both concrete modules and metal casks will require periodic inspection and maintenance to ensure that they are functioning as intended. However, since the concrete modules are stored open to the environment, a daily visual inspection of the airflow inlet vents and outlet vents to ensure they are not blocked will be required. Therefore, the metal casks are given a score of two, "Intermediate between equal importance and moderate importance", according to Table 2-1, against the concrete modules.		
33	Operational and maintenance cost: ConMod vs ConCas	Score = 1
Similar to the concrete modules, the concrete casks are stored open to the environment and require daily inspection of the airflow inlet vents and outlet vents to ensure they are not blocked. Therefore, concrete modules are given a score of one, "Equal importance", according to Table 2-1, against the concrete casks.		
34	Operational and maintenance cost: MetCas vs ConCas	Score = 2
Based on the reasons given in item 32 and item 33, metal casks are given a score of two, "Intermediate between equal importance and moderate importance", according to Table 2-1, against concrete casks.		

Table 4-13: Pairwise comparison of options with respect to sub-criterion of cost: Decommissioning cost

35	Decommissioning cost: ConMod vs MetCas	Score = 4

In concrete modules, the SNF assemblies are contained within the canister, which is sealed by welding at the originating reactor site. Measures to ensure that the external surface is maintained in a clean condition are implemented during the canister loading operations at the originating reactor site, to prevent contaminated spent fuel pool water from coming into contact with the external surfaces of the canister. A canister is not permitted to be transported with contamination levels exceeding the defined limits (IAEA, 2009).

Under normal conditions of canister transfer and storage operations, it is not expected that the interior and exterior of the concrete module will be contaminated. Therefore during decommissioning only the canister needs to be decontaminated.

The neutron flux originating from the canister containing SNF assemblies is approximately 10 orders of magnitude lower than neutron flux levels at an operating nuclear power plant (10^3 versus 10^{13} n/sec-cm^2). It consists of fast neutrons with energies around 1 MeV. The concrete module and the pad will be only very slightly activated (less than 0.05 µSv/h above background) as a result of their long-term exposure to the relatively small neutron flux emanating from SNF, which will allow the general release of the concrete module as non-controlled material (IAEA, 2009). This will significantly reduce the amount of decommissioning radioactive waste to be disposed of, which will, in turn, reduce the overall decommissioning cost.

In metal casks, the basket containing the SNF is integrated into the cavity of the cask. During SNF loading, the whole cask is placed inside the pool. To facilitate the decontamination of the cask after SNF loading, the cask surfaces are kept smooth by using non-corrosive surfaces, for example by painting the surfaces with an epoxy-based paint (IAEA, 1999). The casks are decontaminated using techniques prescribed by the vendor or operator to contamination levels complying with transport and storage. Under normal conditions of cask transfer and storage operations, it is not expected that the exterior of the cask will be contaminated.

The cask cavity and the basket in contact with SNF assemblies (and the pool water

during SNF loading) will have to be decontaminated sufficiently to be disposed of in the LLW disposal facility. The neutron activation of the metal cask is regarded as very small and within LLW disposal requirements. Similar to concrete modules, metal casks are placed on a reinforced concrete slab inside a reinforced concrete building. The slab is expected to be only very slightly activated and can generally be released as non-controlled material. The building is also not expected to be activated. However, the decommissioning of a reinforced concrete building will make the decommissioning of metal cask storage more labour-intensive compared to the decommissioning of a concrete module. Given this, the concrete modules are given a score of four, “Essential or strong importance”, according to Table 2-1, against the metal casks. A score of three is not given, since the concrete modules must have stronger importance than the concrete casks, as discussed in item 36 below.		
36	Decommissioning cost: ConMod vs ConCas	Score = 3
Similar decommissioning approaches are implemented for both concrete modules and concrete casks. However, owing to the additional transfer facility, the decommissioning of concrete casks is slightly more labour-intensive compared to concrete modules; therefore, concrete modules are given a score of three, “Moderate importance”, according to Table 2-1, against concrete casks.		
37	Decommissioning cost: ConCas vs MetCas	Score = 2
In item 35 it has been shown that the decommissioning of metal casks will cost more than the decommissioning of concrete modules. In item 36 it has been shown that the decommissioning of concrete modules and that of concrete casks are similar, but the concrete casks have additional decommissioning cost owing to the additional transfer facility. However, it is not believed that the decommissioning of the transfer facility		

would be as labour-intensive as decommissioning of the reinforced concrete building housing the metal casks. It is a small facility and is not designed to meet the same requirements. Given this, the concrete casks are given a score of two, "Moderate importance", according to Table 2-1, against the metal casks.

4.4 Case 1

In this case, there are only two criteria and two options, as outlined in Section 4.3.

4.4.1 Pairwise matrix for the criteria

The pairwise matrix for the criteria is shown in Table 4-14. For brevity, this matrix is called $\boldsymbol{C}$ with elements c_{11}, c_{12}, c_{21} and c_{22}. Elements c_{11} and c_{22} are equal to 1.0, since these are the diagonal terms of the pairwise matrix. Element c_{12} is the comparison between the criteria radiological safety and cost, and is listed as item 3 in Table 4-2. It has a value of 3. The rationale for this score is given in the second row of item 3 of Table 4-2. Element c_{21} is calculated as $c_{21} = 1/c_{12,}$ which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.3333.

Table 4-14: Matrix of criteria radiological safety and cost with respect to the goal

Matrix of the criteria with respect to the goal	Radiological safety	Cost
Radiological safety	1.0000	3.0000
Cost	0.3333	1.0000

The next step was to calculate the weight vector. To calculate this vector, the matrix was normalised to the matrix $\boldsymbol{C2}$ in terms of the columns of matrix C, using equation 2 for each column of matrix $\boldsymbol{C2}$. This matrix is shown in Table 4-15 as the cells shaded light blue.

Table 4-15: Normalised matrix of criteria radiological safety and cost with respect to the goal

Normalised matrix of criteria	Radiological safety	Cost	Sum of rows	Weight/ Eigenvector
Radiological safety	0.7500	0.7500	1.5000	0.7500
Cost	0.2500	0.2500	0.5000	0.2500

From this matrix a column vector $\vec{c}$ with elements c_i, where $i = 1, 2$ is calculated using equation 3. The values are shown in the cells shaded light green in Table 4-15.

Finally, this vector was normalised to a vector $\vec{e}$ with elements e_i, where $i = 1, 2$ using equation 4. This is shown in the cells shaded yellow in Table 4-15. This vector $\vec{e}$ was then the weighted vector derived from the pairwise comparison matrix shown in Table 4-14. Since there are only two criteria for case one, no consistency check is required.

4.4.2 Pairwise matrix for the options

There are two criteria without any sub-criteria; therefore there will be two pairwise comparison matrices, one for each criterion. There are two options, therefore each pairwise matrix will have dimension 2×2.

The pairwise matrix for the criterion radiological safety is shown in Table 4-16.

Table 4-16: Matrix of options with respect to criterion radiological safety

Matrix of criterion: Radiological safety	ConMod	MetCas
ConMod	1	3
MetCas	0.3333	1

For brevity, this matrix is called $\boldsymbol{O}$, with elements O_{11}, O_{12}, O_{21} and O_{22}. As was the case for the criteria pairwise comparisons discussed in Section 4.5.1, elements O_{11} and O_{22} are equal to 1.0, since these are the diagonal terms of the pairwise matrix. Element O_{12} is the comparison between options ConMod and MetCas, and is listed as item 13 in Table 4-5. It has a value of 3. The rationale for this score is given in the second row of item 13 of Table 4-5. Element O_{21} is calculated as $O_{21} = \frac{1}{O_{12}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.3333.

The procedure used to obtain the weights is the same as that for the matrix $\boldsymbol{C}$ discussed in Section 4.5.1, and the final result is shown in Table 4-17, where the colour coding is the same as that for matrix $\boldsymbol{C2}$.

Table 4-17: Normalised matrix of options with respect to criterion radiological safety

Normalised matrix of sub-criteria of radiological safety	ConMod	MetCas	Sum of rows	Weight/ Eigenvector
ConMod	0.75	0.75	1.5	0.75
MetCas	0.25	0.25	0.5	0.25

A similar process was used for the pairwise comparison of the options with respect to the criterion cost.

Using the data from

Table **4-6**, item 16, the following pairwise matrix, shown in Table 4-18, was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight eigenvector is shown in Table 4-19.

Table 4-18: Pairwise matrix of options with respect to criterion cost

Matrix of criterion cost	ConMod	MetCas
ConMod	1	4
MetCas	0.25	1

Table 4-19: Normalised matrix of options with respect to criterion cost

Normalised matrix of criterion cost	ConMod	MetCas	Sum of rows	Weight/ Eigenvector
ConMod	0.8	0.8	1.6	0.8000
MetCas	0.2	0.2	0.4	0.2000

4.4.3 Calculating the ranking

To calculate the ranking, equation 1 must be used. This requires the construction of matrix $\boldsymbol{A}$ and vector $\vec{d}$. The matrix $\boldsymbol{A}$ is shown in Table 4-20.

Table 4-20: Matrix for the ranking of the options

	Radiological safety	Cost	Vector $\vec{d}$
ConMod	0.75	0.8000	0.75
MetCas	0.25	0.2000	0.25

In this matrix, the second column is populated using the 5th column of Table 4-17, and the third column is populated using the 5th column of Table 4-19. The explanation for these assignments was given in Section 2.1.3.

Vector $\vec{d}$ is shown in Table 4-20 and is populated using the 5th column of Table 4-15. The explanation for this assignment was also explained in Section 2.1.3.

Using this, equation 1 can then be constructed as shown in equation 7, with the ranking shown as the column vector in the right-hand side of this equation

$$\begin{bmatrix} 0.75 & .8000 \\ 0.25 & .2000 \end{bmatrix} \begin{bmatrix} 0.75 \\ 0.25 \end{bmatrix} = \begin{bmatrix} 0.7625 \\ 0.2375 \end{bmatrix}. \qquad (7)$$

This, therefore, shows that the first option has a higher ranking of 0.7625 compared to the second, which has a ranking of 0.2375. The first ranking was ConMod and MetCas.

4.5 Case 2

In this case, there are two criteria and three options, as outlined in Section 4.3. Criterion two (cost) has three sub-criteria.

4.5.1 Pairwise matrix for the criteria

The pairwise matrix for the criteria is the same as that discussed in case one above.

4.5.2 Pairwise matrix of sub-criteria of cost

The pairwise matrix for the sub-criteria is shown in Table 4-21.
For brevity, this matrix is called $\boldsymbol{S}$ with elements s_{11}, s_{12}, s_{13}, s_{22}, s_{23} and s_{33}. Elements s_{11}, s_{22}, and s_{33} are equal to 1.0, since these are the diagonal terms of the pairwise matrix.

Element s_{12} is the comparison between the criteria capital cost and operational and maintenance cost, and is listed as item 10 in Table 4-4. It has a value of 5. The rationale for this score is given in the second row of item 10 of Table 4-4.

Element s_{13} is the comparison between capital cost and decommissioning cost and listed as item 11 in Table 4-4. It has a value of 7. The rationale for this score is given in the second row of item 11 of Table 4-4.

Element s_{23} is the comparison between operational and maintenance cost and decommissioning cost and listed as item 12 in Table 4-4. It has a value of 3. The rationale for this score is given in the second row of item 12 of Table 4-4.

The elements s_{21}, s_{31}, s_{32} are calculated as $s_{21} = 1/s_{12}$, $s_{31} = 1/s_{13}$ and $s_{32} = 1/s_{23,}$ which are the definitions of the AHP tool, as stated in Section 2.1.2. The values are 0.2000, 0.1429 and 0.3333 respectively.

Table 4-21: Matrix of sub-criteria capital cost, operational and maintenance cost and decommissioning cost with respect to parent criterion cost

Matrix for the sub-criteria of criterion cost	Capital cost	Operational and maintenance cost	Decommissioning cost
Capital cost	1.0000	5.0000	7.0000
Operational and maintenance cost	0.2000	1.0000	3.0000
Decommissioning cost	0.1429	0.3333	1.0000

The next step was to calculate the weight vector. To calculate this vector the matrix was normalised to the matrix $\boldsymbol{S2}$ in terms of columns of matrix $\boldsymbol{S}$ using equation 2 for each column of matrix $\boldsymbol{S2}$. This matrix is shown in Table 4-22 as the cells shaded light blue.

Table 4-22: Normalised matrix of sub-criteria capital cost, operational and maintenance cost and decommissioning cost with respect to parent criterion cost

Normalised matrix of sub-criteria of cost	Capital cost	Operational and maintenance cost	Decommissioning cost	Sum of rows	Weight/ Eigenvector
Capital cost	0.7447	0.7895	0.6364	2.1705	0.7235
Operational and maintenance cost	0.1489	0.1579	0.2727	0.5796	0.1932
Decommissioning cost	0.1064	0.0526	0.0909	0.2499	0.0833

From this matrix a column vector $\vec{s}$ with elements s_i, where $i = 1, 2 \text{ and } 3$ is calculated using equation 3. The values are shown in the cells shaded light green in Table 4-22.

Finally, this vector was normalised to a vector $\vec{e}$ with elements e_i, where $i = 1, 2 \text{ and } 3$, using equation 4. This is shown in the cells shaded yellow in Table 4-22. This vector $\vec{e}$ was then the weighted vector derived from the pairwise comparison matrix shown in Table 4-21.

4.5.3 Consistency of the judgement

Since there are three sub-criteria, the consistency of the judgement is checked. As discussed in Section 2.1.6, the consistency of the judgement is measured by a consistency ratio (CR) and the consistency index (CI) is then compared with a random consistency index (RI) defined as the ratio $CR = \frac{CI}{RI}$. If the ratio is less than 0.1, then the judgements used to construct the pair-wise comparison matrices are accepted, else the judgements must be revised until a ratio of less than 0.1 is obtained.

The *RI* is also described in Section 2.1.6 and is given in Table 2-2. The *CI* is calculated using the following equation $CI = \lambda_{max} - \frac{n}{n-1}$ where λ_{max} is the maximum eigenvalue of the comparison matrix calculated as described in Section 2.1.6 and n is the number of evaluations.

The *CI* was calculated and had a value of 0.0557. Then the *CR* was calculated and had a value of 0.0961. Based on the *CR* obtained, the judgement was consistent (it was less than 0.1).

4.5.4 Pairwise matrix for the options with respect to sub-criteria or criteria when there are no sub-criteria

There are two criteria with one criterion having three sub-criteria; therefore there will be four pair-wise comparison matrices, one for each sub-criterion or criterion when there is no sub-criterion. There are three options, therefore each pairwise comparison matrix will have dimension 3×3.

The pairwise comparison matrix of options for the criterion radiological safety is shown in Table 4-23 .

Table 4-23: Matrix of options with respect to criterion radiological safety

Matrix of radiological safety	ConMod	MetCas	ConCas
ConMod	1	3	5
MetCas	0.3333	1	2
ConCas	0.2	0.5	1

For brevity, this matrix is called $\boldsymbol{O}$ with elements O_{11}, O_{12}, O_{13}, O_{22}, O_{23}, O_{33}, O_{21}, $O_{31}$and O_{32}.

As was the case for the criteria pairwise discussed in Section 4.5.1, Elements O_{11}, O_{22} and O_{33} are equal to 1.0, since these are the diagonal terms of the pairwise matrix.

Element O_{12} is the comparison between options ConMod and MetCas, and is listed as item 13 in Table 4-5. It has a value of 3. The rationale for this score is given in the second row of item 13 of Table 4-5. Element O_{21} is calculated as $O_{21} = \frac{1}{O_{12}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.3333.

Element O_{13} is the comparison between options ConMod and ConCas, and is listed as item 14 in Table 4-5. It has a value of 5. The rationale for this score is given in the second row of item 14 of Table 4-5. Element O_{21} is calculated as $O_{21} = \frac{1}{O_{12}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.2.

Element O_{23} is the comparison between options MetCas and ConCas, and is listed as item 15 in Table 4-5. It has a value of 2. The rationale for this score is given in the second row of item 15 of Table 4-5. Element O_{21} is calculated as $O_{21} = 1/O_{12}$ which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.5.

The procedure used to obtain the weights is the same as that for the matrix $\boldsymbol{C}$ discussed in Section 4.5.1, and the final result is shown in Table 4-24, where the colour coding is the same as that for matrix $\boldsymbol{C2}$.

Table 4-24: Normalised matrix of options with respect to criterion radiological safety

Normalised matrix of radiological safety	ConMod	MetCas	ConCas	Sum of rows	Weight/ Eigenvector
ConMod	0.6522	0.6667	0.6250	1.9438	0.6479
MetCas	0.2174	0.2222	0.2500	0.6896	0.2299
ConCas	0.1304	0.1111	0.1250	0.3665	0.1222

A similar process was used for the pairwise comparison of the options with respect to the sub-criteria capital cost, operational and maintenance cost, and decommissioning cost.

Using the data from Table 4-11, item 29, 30 and 31, the pairwise matrix for the capital cost shown in Table 4-25 was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight is shown in Table 4-26.

Using the data from Table 4-12, item 32, 33 and 34, the pairwise matrix for the operational and maintenance cost shown in Table 4-27 was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight is shown in Table 4-28.

Using the data from Table 4-13, item 35, 36 and 37, the pairwise matrix for the capital cost shown in Table 4-29 was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight is shown in Table 4-30.

Table 4-25: Pairwise matrix of options with respect to sub-criterion capital cost

Criterion capital cost	ConMod	MetCas	ConCas
ConMod	1	7	2.
MetCas	0.1429	1	0.1667
ConCas	0.5000	6.	1

Table 4-26: Normalised matrix of options with respect to sub-criteria cost

Normalised matrix of criterion capital cost	ConMod	MetCas	ConCas	Sum of rows	Weight/ Eigenvector
ConMod	0.6087	0.5000	0.6316	1.7403	0.5801
MetCas	0.0870	0.0714	0.0526	0.2110	0.0703
ConCas	0.3043	0.4286	0.3158	1.0487	0.3496

Table 4-27: Pairwise matrix for options with respect to sub-criterion operational and maintenance cost

Sub-criterion operational and maintenance cost	ConMod	MetCas	ConCas
ConMod	1	0.5	1
MetCas	2	1	2
ConCas	1	0.5	1

Table 4-28: Normalised matrix of options with respect to sub-criterion operational and maintenance cost

Normalised matrix of sub-criterion operational and maintenance cost	ConMod	MetCas	ConCas	Sum of rows	Weight/ Eigenvector
ConMod	0.2500	0.2500	0.2500	0.7500	0.2500
MetCas	0.5000	0.5000	0.5000	1.5000	0.5000
ConCas	0.2500	0.2500	0.2500	0.7500	0.2500

Table 4-29: Pairwise matrix of options with respect to sub-criterion decommissioning cost

Sub-criterion decommissioning cost	ConMod	MetCas	ConCas
ConMod	1	4	3
MetCas	0.2	1	0.5
ConCas	0.3333	2	1

Table 4-30: Normalised matrix of options with respect to sub-criterion decommissioning cost

Normalised matrix of sub-criterion decommissioning cost	ConMod	MetCas	ConCas	Sum of rows	Weight/ Eigenvector
ConMod	0.6316	0.5714	0.6667	1.8697	0.6232
MetCas	0.1579	0.1429	0.1111	0.4119	0.1373
ConCas	0.2105	0.2857	0.2222	0.7185	0.2395

4.5.5 Consistency of the judgement

The procedure used to check the consistency of the judgement is the same as that for the sub-criteria discussed in Section 4.5.4, and the consistency index CI and consistency ratio CR values are shown in Table 4-31.

Table 4-31: $\boldsymbol{CI}$ and $\boldsymbol{CR}$ of the judgement matrices for options with respect to sub-criteria or criteria where there are no sub-criteria

Judgement matrix	**Consistency Index ($\boldsymbol{CI}$)**	**Consistency Ratio ($\boldsymbol{RI}$)**
Options with respect to criteria: Radiological safety	0.0027	0.0047
Options with respect to sub-criteria: Capital cost	0.0224	0.0386
Options with respect to sub-criteria: Operation and maintenance	0.0000	0.0000
Options with respect to sub-criteria: Decommissioning cost	0.0127	0.0220

Based on the consistency ratio obtained, the judgement was consistent and is shown in column three of Table 4-31.

4.5.6 Calculating the ranking option

To calculate the ranking, equation 1 must be used. This requires the construction of matrix $\boldsymbol{A}$ and vector $\vec{d}$. Matrix $\boldsymbol{A}$ is shown in Table 4-33. To calculate the vector $\vec{d}$, each sub-criterion weight is multiplied by the parent criterion weight to obtain the overall weight of each sub-criterion, which is the vector $\vec{d}$ used in the matrix $\boldsymbol{A}$. This calculation is shown in Table 4-32.

Table 4-32: Vector $\vec{\boldsymbol{d}}$ calculation for case two

Criteria	Criteria weight	Sub-criteria	Sub-criteria weight	Overall weight/ Vector d
Cost	0.25	capital cost	0.7235	0.1809
		Operational and maintenance cost	0.1932	0.0483
		Decommissioning cost	0.0833	0.0208
Radiological safety of the public and workers	0.75	No sub-criteria	Not applicable	0.75

Table 4-33: Matrix for the ranking of the options

Options	Radiological safety	Capital cost	Operational and maintenance cost	Decommissioning cost
Vector $\vec{\boldsymbol{d}}$	0.75	0.1809	0.0483	0.0208
ConMod	0.6479	0.5801	0.2500	0.6232
MetCas	0.2299	0.0703	0.5000	0.1373
ConCas	0.1222	0.3496	0.2500	0.2395

In this matrix, vector $\vec{d}$ is shown in row two underneath each corresponding criterion or sub-criterion. The second column is populated using the sixth column of Table 4-24; the third column is populated using the sixth column of Table 4-26; the fourth column is populated using the sixth column of Table 4-28 and the fifth column is populated using the sixth column of Table 4-30. The explanation for these assignments was given in Section 2.1.3.

Vector $\vec{d}$ is shown in Table 4-33 in row two underneath each corresponding criterion or sub-criterion and is populated using the fifth column of Table 4-32. This assignment was also explained in Section 2.1.3.

Using this, equation 1 can then be constructed as shown in equation 8, with the ranking shown as the column vector in the right-hand side of this equation.

$$\begin{bmatrix} 0.6479 & 0.5801 & 0.2500 & 0.6232 \\ 0.2299 & 0.0703 & 0.5000 & 0.1373 \\ 0.1222 & 0.3496 & 0.2500 & 0.2395 \end{bmatrix} \begin{bmatrix} 0.75 \\ 0.1809 \\ 0.0483 \\ 0.0208 \end{bmatrix} = \begin{bmatrix} 0.6159 \\ 0.2121 \\ 0.1719 \end{bmatrix} \quad (8)$$

This, therefore, shows that the first option has a higher ranking of 0.6159 compared to the second option, which has a ranking of 0.2121, and the third option, which has a ranking of 0.1719. The first ranking was the ConMod, the second-ranking was the MetCas and the third-ranking was the ConCas.

4.6 Case 3

In this case, there are four criteria and three options, as outlined in Section 4.3. Two of the criteria have three sub-criteria each.

4.6.1 Pairwise matrix of the criteria

The pairwise matrix for the criteria is shown in Table 4-34. Similar to the matrix discussed in case one, Section 4.5.1, this matrix is also called $\boldsymbol{C}$ with elements c_{11}, c_{12}, c_{13}, c_{14}, c_{22}, c_{23}, c_{24}, c_{33}, c_{34}, c_{44}, c_{21}, c_{31}, c_{41}, c_{32}, c_{42} and c_{43}. Elements c_{11}, c_{22}, c_{33} and c_{44} are equal to 1.0, since these are the diagonal terms of the pairwise matrix. Element c_{12} is a comparison between the criteria radiological safety and system flexibility, and is listed as item 1 in Table 4-2. It has a value of 5. The rationale for this score is given in the second row of item 1 of Table 4-2. Element c_{21} is calculated as $c_{21} = \frac{1}{c_{12}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.2.

Element c_{13} is a comparison between the criteria radiological safety and retrievability, and is listed as item 2 in Table 4-2. It has a value of 7. The rationale for this score is given in the second row of item 2 of Table 4-2. Element c_{31} is calculated as $c_{31} = \frac{1}{c_{13}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.1429.

Element c_{14} is a comparison between the criteria radiological safety and cost, and is listed as item 3 in Table 4-2. It has a value of 3. The rationale for this score is given in the second row of item 3 of Table 4-2. Element c_{41} is calculated as $c_{41} = 1/c_{14}$ which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.3333.

Element c_{23} is a comparison between the criteria system flexibility and retrievability, and is listed as item 4 in Table 4-2. It has a value of 3. The rationale for this score is given in the second row of item 4 of Table 4-2. Element c_{32} is calculated as $c_{32} = \frac{1}{c_{23}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.3333.

Element c_{24} is a comparison between the criteria system flexibility and cost, and is listed as item 5 in Table 4-2. It has a value of 4. The rationale for this score is given in the second row of item 5 of Table 4-2. Element c_{42} is calculated as $c_{42} = \frac{1}{c_{24}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.25.

Element c_{34} is a comparison between the criteria retrievability and cost, and is listed as item 6 in Table 4-2. It has a value of 5. The rationale for this score is given in the second row of item 6 of Table 4-2. Element c_{43} is calculated as $c_{43} = 1/c_{34},$ which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.2.

Table 4-34: Pairwise matrix of the criteria

Matrix of criteria	Radiological safety	Flexibility	Retrievability	Cost
Radiological safety	1.0000	5.0000	7.0000	3.0000
Flexibility	0.2000	1.0000	3.0000	0.2500
Retrievability	0.1429	0.3333	1.0000	0.2000
Cost	0.3333	4.0000	5.0000	1.0000

The next step was to calculate the weight vector. To calculate this vector, the matrix was normalised to the matrix $\boldsymbol{C2}$ in terms of columns of matrix C using equation 2 for each column of matrix $\boldsymbol{C2}$. This matrix is shown in Table 4-35 as the cells shaded light blue.

Table 4-35: Normalised matrix of the criteria

Normalised matrix of criteria	Radiological safety	System flexibility	Retrievability	Cost	Sum of rows	Weight/ Eigenvector
Radiological safety	0.5966	0.4839	0.4375	0.6742	2.1921	0.5480
Flexibility	0.1193	0.0968	0.1875	0.0562	0.4598	0.1149
Retrievability	0.0852	0.0323	0.0625	0.0449	0.2249	0.0562
Cost	0.1989	0.3871	0.3125	0.2247	1.1232	0.2808

From this matrix a column vector $\vec{c}$ with elements c_i, where $i = 1, 2, 3, 4$ is calculated using equation 3. The values are shown in the cells shaded light green in Table 4-35.
Finally, this vector was normalised to a vector $\vec{e}$ with elements e_i, where $i = 1, 2, 3, 4$ using equation 4. This is shown in the cells shaded yellow in Table 4-35. This vector $\vec{e}$ was then a weighted vector derived from the pairwise comparison matrix shown in Table 4-34.

4.6.2 Consistency of the judgement

The procedure used to check the consistency of the judgement is the same as that for the sub-criteria discussed in Section 4.5.4. The CI was calculated and had a value of 0.0852. Then the CR was calculated and had a value of 0.0947. Based on the consistency ratio obtained, the judgement was consistent.

4.6.3 Pairwise comparison of the sub-criteria of system flexibility

The pairwise matrix for the sub-criteria is shown in Table 4-36.

Similar to the matrix discussed in case two, Section 4.6.2, this matrix is also called $\boldsymbol{S1}$, with elements $s1_{11}$, $s1_{12}, s1_{13}, s1_{22}, s1_{23}$ and $s1_{33}$. Elements $s1_{11}$, $s1_{22}$, and $s1_{33}$ are equal to 1.0, since these are the diagonal terms of the pairwise matrix.

Element s_{12} is a comparison between the sub-criteria localisation and modularity, and listed as item 7 in Table 4-3. It has a value of 3. The rationale for this score is given in the second row of item 7 of Table 4-4. The element $s1_{21}$ is calculated as $s1_{21} = 1/s1_{12}$ which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.3333.

Element $s1_{13}$ is a comparison between the sub-criterion localisation and the sub-criterion possibility of changing vendor, and listed as item 8 in Table 4-3. It has a value of 5. The rationale for this score is given in the second row of item 8 of Table 4-3. The element $s1_{31}$ is calculated as $s1_{31} = \frac{1}{s1_{13}}$, which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.2.

Element s_{23} is a comparison of sub-criteria between modularity and the possibility of changing the vendor and listed as item 9 in Table 4-3. It has a value of 3. The rationale for this score is given in the second row of item 9 of Table 4-3. The element $s1_{32}$ is calculated as $s1_{32} = 1/s1_{23,}$ which is a definition of the AHP tool, as stated in Section 2.1.2. The value is 0.3333.

Table 4-36: Matrix of the sub-criteria of system flexibility

Matrix of sub-criteria of flexibility	Localisation	Modularity	Possibility of changing vendor
Localisation	1.0000	3.0000	5.0000
Modularity	0.3333	1.0000	3.0000
Possibility of changing vendor	0.2000	0.3333	1.0000

The next step was to calculate the weight vector. To calculate this vector, the matrix was normalised to the matrix $\boldsymbol{S3}$ in terms of the columns of matrix $\boldsymbol{S1}$ using equation 2 for each column of matrix $\boldsymbol{S3}$. This matrix is shown in Table 4-37 as the cells shaded light blue.

Table 4-37: Normalised matrix of the sub-criteria of system flexibility

Normalised matrix of sub-criteria of flexibility	Localisation	Modularity	Possibility of changing vendor	Sum of rows	Weight/ Eigenvector
Localisation	0.6522	0.6923	0.5556	1.9000	0.6333
Modularity	0.2174	0.2308	0.3333	0.7815	0.2605
Possibility of changing vendor	0.1304	0.0769	0.1111	0.3185	0.1062

From this matrix a column vector $\vec{s}$ with elements s_i, where $i = 1, 2, 3$ is calculated using equation 3. The values are shown in the cells shaded light green in Table 4-37.
Finally, this vector was normalised to a vector $\vec{e}$ with elements e_i, where $i = 1, 2, 3$ using equation 4. This is shown in the cells shaded yellow in Table 4-37. This vector $\vec{e}$ was then a weighted vector derived from the pairwise comparison matrix shown in Table 4-36.

4.6.4 Consistency of the judgement for the sub-criteria of system flexibility comparison

The procedure used to check the consistency of the judgement is the same as that for the sub-criteria discussed in Section 4.5.4. The CI was calculated and had a value of 0.0277. Then the CR was calculated and had a value of 0.0477. Based on the CR obtained the judgement was consistent.

4.6.5 Pairwise comparison of the sub-criteria of cost

The pairwise comparison of the sub-criteria of cost is the same as that of case two in Section 4.6.2 and will not be repeated in this section.

4.6.6 Pairwise comparison of the option with respect to sub-criteria or criteria where there are no sub-criteria

There are four criteria and two of these have three sub-criteria each; therefore, there will be eight pairwise comparison matrices, one for each sub-criterion or criterion where there is no sub-criterion. There are three options, therefore each pairwise matrix will have dimension 3×3.

A similar process was used for the pairwise comparison of the options with respect to sub-criteria or criteria where there are no sub-criteria in Section 4.6.4 of case two.

The matrix for the options with respect to the criterion radiological safety is the same as that in Section 4.6.4 of case two and will not be repeated in this section.

Using the data from

Table 4-7, item 17, 18 and 19, the pairwise matrix for the options with respect to sub-criterion localisation shown in Table 4-38 was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight is shown in Table 4-39.

Using the data from Table 4-8, items 20, 21 and 22, the pairwise matrix for the options with respect to the sub-criterion modularity shown in Table 4-40 was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight is shown in Table 4-41.

Using the data from Table 4-8, items 23, 24 and 25, the pairwise matrix for the options with respect to the sub-criterion possibility of changing vendor shown in Table 4-42 was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight is shown in Table 4-43.

Using the data from Table 4-8, items 26, 27 and 28, the pairwise matrix for the options with respect to criterion retrievability shown in Table 4-44 was constructed using the method outlined above for the first criterion shown in this section, and the resulting weight is shown in Table 4-45.

The matrices of the options with respect to the sub-criteria of cost, capital cost, operational and maintenance cost and decommissioning cost are the same in Section 4.6.4 of case two and will not be repeated in this section.

Table 4-38: Pairwise matrix of options with respect to sub-criterion localisation

Matrix of options with respect to sub-criterion localisation	ConMod	MetCas	ConCas
ConMod	1.0000	5.0000	1.0000
MetCas	0.2000	1.0000	0.2000
ConCas	1.0000	5.0000	1.0000

Table 4-39: Normalised matrix of options with respect to sub-criterion localisation

Normalised matrix of options with respect to localisation	ConMod	MetCas	ConCas	Sum of rows	Weight / Eigenvector
ConMod	0.4545	0.4545	0.4545	1.3636	0.4545
MetCas	0.0909	0.0909	0.0909	0.2727	0.0909
ConCas	0.4545	0.4545	0.4545	1.3636	0.4545

Table 4-40: Pairwise matrix of options with respect to sub-criterion modularity

Matrix of options with respect to sub-criterion modularity	ConMod	MetCas	ConCas
ConMod	1.0000	5.0000	1.0000
MetCas	0.2000	1.0000	0.2000
ConCas	1.0000	5.0000	1.0000

Table 4-41: Normalised matrix of options with respect to sub-criterion modularity

Normalised matrix of options with respect to criterion modularity	ConMod	MetCas	ConCas	Sum of rows	Weight/ Eigenvector
ConMod	0.4545	0.4545	0.4545	1.3636	0.4545
MetCas	0.0909	0.0909	0.0909	0.2727	0.0909
ConCas	0.4545	0.4545	0.4545	1.3636	0.4545

Table 4-42: Pairwise matrix of options with respect to the sub-criterion possibility of changing vendors

Matrix of options with respect to the sub-criterion possibility of changing vendor	ConMod	MetCas	ConCas
ConMod	1.0000	5.0000	1.0000
MetCas	0.2000	1.0000	0.2000
ConCas	1.0000	5.0000	1.0000

Table 4-43: Pairwise matrix for options with respect to the sub-criterion possibility of changing vendors

Normalised matrix of options with respect to the sub-criterion possibility of changing vendor	ConMod	MetCas	ConCas	Sum of rows	Weight/ Eigenvector
ConMod	0.4545	0.4545	0.4545	1.3636	0.4545
MetCas	0.0909	0.0909	0.0909	0.2727	0.0909
ConCas	0.4545	0.4545	0.4545	1.3636	0.4545

Table 4-44: Pairwise matrix of options with respect to criterion retrievability

Matrix of options with respect to criterion retrievability	ConMod	MetCas	ConCas
ConMod	1.0000	0.3333	1.0000
MetCas	3.0000	1.0000	3.0000
ConCas	1.0000	0.3333	1.0000

Table 4-45: Normalised matrix of options with respect to criterion retrievability

Normalised matrix of options with respect to criterion retrievability	ConMod	MetCas	ConCas	Sum of rows	Weight/ Eigenvector
ConMod	0.2000	0.2000	0.2000	0.6000	0.2000
MetCas	0.6000	0.6000	0.6000	1.8000	0.6000
ConCas	0.2000	0.2000	0.2000	0.6000	0.2000

4.6.7 Consistency of judgement for the options

The procedure used to check the consistency of judgement is the same as that for the sub-criteria of cost discussed in Section 4.5.4, and the consistency index CI and consistency ratio CR values are shown in Table 4-31. Based on the consistency ratio obtained, the judgement was consistent and is shown in column three of Table 4-46.

Table 4-46: $\boldsymbol{CI}$ and $\boldsymbol{CR}$ of the judgement matrices for the option with respect to sub-criteria or criteria where there are no sub-criteria

Judgement matrix	**Consistency index**	**Consistency ratio**
Options with respect to sub-criterion: localisation	0.0000	0.0000
Options with respect to sub-criterion: Modularity	0.0000	0.0000
Options with respect to sub-criterion: Possibility of changing vendor	0.0000	0.0000
Options with respect to criterion: retrievability	0.0000	0.0000

4.6.8 Calculations of the ranking for Case 3

To calculate the ranking, equation 1 must be used. This requires the construction of matrix A and vector $\vec{d}$. Matrix A is shown in Table 4-48. To calculate the vector $\vec{d}$, each sub-criterion weight is multiplied by the parent criterion weight to obtain the overall weight of each sub-criterion, which is the vector $\vec{d}$ used in matrix A. This calculation is shown in Table 4-47.

Table 4-47: Vector $\vec{d}$ calculation for case three

Criteria	Criteria weight	Sub-criteria	Sub-criteria weight	Overall weight
Radiological safety	0.5480		None	0.5480
Flexibility	0.1149	Localisation	0.6333	0.0728
		Modularity	0.2605	0.0299
		Possibility of changing vendors	0.1062	0.0122
Retrievability	0.0562		None	0.0562
Cost	0.2808	Capital cost	0.7235	0.2032
		Operational and maintenance cost	0.1932	0.0542
		Decommissioning cost	0.0833	0.0234

Table 4-48: Matrix for the ranking of the options for case three

Option	Radiological safety	Localisation	Modularity	Possibility of changing vendors	Retrievability	Capital cost	Operational and maintenance cost	Decommissioning cost
Vector $\vec{d}$	0.5480	0.0728	0.0299	0.0122	0.0562	0.2032	0.0542	0.0234
ConMod	0.6479	0.4545	0.4545	0.4545	0.2000	0.5801	0.2500	0.6232
MetCas	0.2299	0.0909	0.0909	0.0909	0.6000	0.0703	0.5000	0.1373
ConCas	0.1222	0.4545	0.4545	0.4545	0.2000	0.3496	0.2500	0.2395

In this matrix, vector $\vec{d}$ is shown in row two underneath each corresponding sub-criterion or criterion when there are no sub-criteria. The second column is populated using the sixth column of Table 4-24; the third column is populated using the sixth column of Table 4-39; the fourth column is populated using the sixth column of Table 4-41; the fifth column is populated using the sixth column of Table 4-43; the sixth column is populated using the sixth column of Table 4-45; the seventh column is populated using the sixth column of

Table 4-26; the eighth column is populated using the sixth column of Table 4-28, and the ninth column is populated using the sixth column of Table 4-30. The explanation of these assignments was given in Section 2.1.3.

Vector $\vec{d}$ is shown in Table 4-48 in row two underneath each corresponding criterion or sub-criterion and is populated using the fifth column of Table 4-48. This assignment was also explained in Section 2.1.3.

Using this, equation 1 can then be constructed as shown in equation 9, with the ranking shown as the column vector in the right-hand side of this equation.

$$\begin{bmatrix} 0.6479 & 0.4545 & 0.4545 & 0.4545 & 0.2000 & 0.5801 & 0.2500 & 0.6232 \\ 0.2299 & 0.0909 & 0.0909 & 0.0909 & 0.6000 & 0.0703 & 0.5000 & 0.1373 \\ 0.1222 & 0.4545 & 0.4545 & 0.4545 & 0.2000 & 0.3496 & 0.2500 & 0.2395 \end{bmatrix} \begin{bmatrix} 0.5480 \\ 0.0728 \\ 0.0299 \\ 0.0122 \\ 0.0562 \\ 0.2032 \\ 0.0542 \\ 0.0234 \end{bmatrix} = \begin{bmatrix} 0.5646 \\ 0.2148 \\ 0.2206 \end{bmatrix} \quad (9)$$

This, therefore, shows that the first option has a higher ranking of 0.5646 compared to the second option, which has a ranking of 0.2206, and the third option, which has a ranking of 0.2148. The first ranking was the ConMod, the second ranking was the ConCas and the third ranking was the MetCas.

4.7 Verification of calculation

The procedure to calculate the weight for criteria, sub-criteria, options, the ranking of the options and the consistency ratios was implemented using the Microsoft Excel program discussed in Chapter 3 Section 3.

An alternative approach was used through which the procedure was coded using a Fortran compiler, thus producing an executable; the code was named jun0219 and is part of the NWURCS code suite (Naicker *et al.,* 2015). The code was not written by the author of this study and was therefore considered to be an independent implementation of the AHP.

The first verification check was to ensure that the calculation of the comparison matrices for the criteria, sub-criteria and options were correct, and it found that both sets of results were consistent.

The next verification check was to establish that the final ranking and the consistency ratios were the same.

The results were identical to four significant figures after the decimal point. The results for all three cases as calculated with the code are included in Appendix 1.

4.8 Summary and Comments

The following ranking was obtained in the three cases chosen for this study:
In case one, the first ranking was the ConMod (0.76) and the second ranking (0.24) was the MetCas.
In case two, the first ranking was the ConMod (0.62), the second ranking was the MetCas (0.21) and the third ranking was the ConCas (0.17). In case three, the first ranking was the ConMod (0.56), the second ranking was the ConCas (0.22) and the third ranking was the MetCas (0.21). It is noted that in comparing case two and case three the order of second and third-ranked options changed. However, in both cases, the second-ranked option had the same ranking of 0.21. The strength of the first and third ranking changed. Since the third case was the most general case, it is important to realise that all the criteria, sub-criteria and options must be considered as far as possible, since the rankings are sensitive to this selection.

The results show that ConMod (concrete modules with an inner canister stored on a reinforced concrete storage pad open to the environment) is the best option to meet South Africa's needs within the constraints of this study. These results will most probably change when more detailed studies are carried out later. One could have guessed intuitively that these results would be obtained, i.e. without the implementation of the AHP. This is because intuition is built on experience and knowledge without formal (mostly based on scientific reasoning) assimilation. However, the difference between the concrete cask and the concrete module might have required more than an intuitive judgement.

In order to achieve the ranking shown above, pairwise comparisons were performed on each possible pair for the criteria, sub-criteria and options. None of the criteria, sub-criteria or options could be compared numerically, as was shown in the example in Chapter 2, where items were compared based on their mass. Therefore, all the comparisons performed were based on the judgement of the writer. These judgements were based on the experience that the writer has had in this field of study, which included information obtained from the literature that was reviewed.

It is noted that these judgements are biased since only a single person was involved in the decision process. The judgements made must, therefore, be extended to include other workers in the field. The terminology normally used is that "expert judgement" should be obtained. However, since such work will increase the scope significantly, this is reserved for further studies. Nevertheless, since the present study was intended to introduce the methodology, it was deemed acceptable to use only the judgements of a single person.

In addition to the above-mentioned involvement of other workers in the field in conducting the pairwise comparison, further information needs to be obtained to make the comparison more numerical or easier; for example:

- The cost of each dry storage system and the related facilities or support systems is required. This cost includes the purchase cost or design and construction cost, operational and maintenance cost and the expected decommissioning cost.
- An expected dose rate of each dry storage system is required.
- The total number of SNF assemblies that can be stored in each dry storage system must be determined.

The expected dose rate is required to ensure that the country's regulatory dose rate limit will not be exceeded.

The total number of SNF assemblies that can be stored in each dry storage system is vital to determine the required number of dry storage systems and the size of the space needed for storage.

In essence, it has been demonstrated in this study that the AHP tool has the potential to be used as a selection tool to decide which is the best available option from the subset of options that will best meet South Africa's needs. It has the advantages of robustness and a clear concept. The use of the AHP tool becomes more important when elements of the decision-making process are difficult to quantify or compare equally. The procedure is simple to implement once one is familiar with the process. However, if many criteria, sub-criteria and options are considered, it takes time to implement. It has also been noted that when new criteria, sub-criteria and options are introduced, the results change. As mentioned above, it would also be important for the next study to consider all the criteria and sub-criteria and options identified to identify the best options.

A potential weakness of the AHP tool is that it assumes independence between criteria or sub-criteria on the same level, which can lead to bias in the judgement, as some criteria or sub-criteria are implicit in others. For example, in this study, it has been noted that cost is implicit in other criteria. It is expected that in more detailed studies following this study, careful attention will have to be paid to this question of independence. However, for the purposes of this study, these matters are considered independent of one another. This question of dependencies has been highlighted in the text.

Regarding the criteria, sub-criteria and options, it is possible that not all the elements were identified in this study. It would, therefore, be of value to reconsider this aspect of the study and to include the input from other experts in the field in the assignment of possible criteria, sub-criteria and options in follow-up studies.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study was intended to demonstrate the application of the AHP tool to compare dry storage options currently in use worldwide to decide which of the available options will best meet South Africa’s needs.

To achieve the purpose, a number of objectives were set and specific relevant criteria and sub-criteria were derived from literature sources for use in the selection of dry storage system options.

A computer code was used to verify the calculation of the comparison matrices for the criteria, sub-criteria and options and the final ranking and the consistency ratios. This gave confidence in the correctness of the implementation of the AHP tool.

This study has shown that the AHP is a good tool to use in the selection of a dry storage system in that the concept is clear and robust, as well as easy to implement when one is familiar with it. More importantly, it enables decision-making when the elements of the decision-making process are difficult to quantify or compare equally. These characteristics make the AHP a potential tool that can be used in the selection of a dry storage system that will best meet South Africa’s needs.

5.2 Recommendations

Based on this study, the following recommendations are made:

- To address the dependencies discussed above, it is recommended that the next study must first look into the dependencies in which the ANP must be used.
- Only a subset of criteria, sub-criteria and options identified was used to make this study feasible; it is therefore recommended that future studies should include all the criteria, sub-criteria and options.
- Since the aim of the study was to initiate the implementation of the AHP tool, it was decided to consider the two variant designs for metal casks as one option and the two variant designs for concrete casks as one option. It is recommended that future studies should consider these designs as individual options.
- As mentioned, in this study only one person was involved in decision-making. It is recommended that the next study be extended to include other workers in the field.
- Ethical considerations when working with people in such a research study must also be taken into account.

REFERENCES

[1] Ababio, K. A. & Mwamba, J. M. 2015. Expert Subjective Ranking of Listed Banks in Ghana: Use of Analytical Hierarchy Process. Biennial Conference of the Economic Society of South Africa (ESSA) at University of Cape Town, Cape Town.

[2] Amorocho-Daza, H., Cabras, S., Santos, R. & Saldarriaga, J. 2019. A New Multi-Criteria Decision Analysis Methodology for the Selection of New Water Supply Infrastructure. Bogota, Colombia.

[3] Areva NP (UKEPR). 2008. Solid Waste Strategy Report (SRWSR). UK.

[4] Bace, M. Jecmenica, R. & Trontl, K. 1998. Concrete spent fuel storage cask dose rates. Terme Catez.

[5] Baldwin, C. Y. 2015. Modularity and Organizations. (In: James D. Wright ed. International Encyclopaedia of the Social & Behavioural Sciences (Second Edition). Orlando FL, USA: University of Central Florida. pp. 718-723)

[6] Bhushan, N. & Rai, K. 2004. Strategic Decision Making Applying the Analytic Hierarchy Process: The Analytic Hierarchy Process. http://www.springer.com/978-1-85233-756-8 Date of access: 19 Feb. 2019.

[7] Bondre, J. 2015. MP19HB; First Licensed Transportation Package with Canistered High Burnup Fuel after Dry Storage, AREVA TH, 7135 Minstrel Way, Colombia, MD 20145.

[8] Botsch, W., Smalian, S., Hinterding, P., Volzke, H., Wolff, D. & Kasparek, E. 2013. Safety Aspects of Dry Spent Fuel Storage and Spent Fuel Management-13559. WM2013 Conference. Phoenix, Arizona, USA.

[9] Brewer, J. D., Amico, P. J., Copper S. E. & Hendrickson, S. M. L. 2012. Preliminary, Qualitative Human Reliability Analysis for Spent Fuel Handling. Sadia National Laboratories, U.S.

[10] Bunn, M., Holdren J. P., Macfarlane, A., Pickett, S. E., Suzuki, A., Suzuki, T., & Weeks, J. 2001. Interim Storage of Spent Nuclear Fuel: A Safe and Cost-Effective Near-Term Approach to Spent Fuel Management, United States of America.

[11] Connecticut Yankee. 2019. Fuel Storage & Removal. http://www.connyankee.com/html/fuel_storage.html Date of access: 12 Oct. 2019.

[12] Cumo, M. 2004. Principles of Nuclear Safety: Spent Fuel Management. Trieste, Italy, the Abdus Salam International Centre for Theoretical Physics.

[13] Czech Republic. State Office for Nuclear Safety. 2017. National Report under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Czech Republic.

[14] Department for Business, Energy & Industrial Strategy. 2017. The United Kingdom's Sixth National Report on the Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel and Radioactive Waste Management. UK.

[15] Department for Communities and Local Government in London. 2009. Multi-criteria analysis: Manual. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/191506/Mult-crisis_analysis_a_manual.pdf Date of access: 29 Sept. 2019.

[16] DME (Department of Mineral and Energy). 2005. Radioactive Waste Management Policy and Strategy for the Republic of South Africa. Pretoria.

[17] Dukes, H., Ebert, J., Meess. D., Chilson L., Kurach D., Dayton, C. & Sullivan, D. 2015. High-level Waste Relocation Requires Use of New Technology in Aging Nuclear Facility-15269. WM2015 Conference, March 15-19, 2015, Phoenix, Arizona, USA.

[18] Enresa. 2015. Presentation: Spanish strategy for the management of Spent Nuclear Fuel-ATC Project. Vienna, Austria.

[19] EPRI. 2010. Industry Spent Fuel Storage Handbook. EPIR, Pao Alto, CA: 2010. 102048.

[20] Fujimoto, T. 2010. Presentation: Inspection of Fuel Cladding and Metal Gasket in Metallic Dry Cask at Tokai No .2 Power Station. Japan.

[21] Gencturk, B., William, K., Padgett, J. & Uddin, R. 2016. Project No. 12-3730: Probabilistic Multi-Hazard Assessment of Dry Cask Structures. US Department of Energy.

[22] Generowicz, A., 2013. Multi-Criteria Analysis of Waste Management in Szczecin.

[23] Greene, C. 2020. Presentation: Global Spent Fuel Overview. Georgia. Krakow University of Technology, Poland.

[24] Hambley, D., Laferrere, A., Walters, W. S., Hodgson, Z., Wickham, S. & Richardson, P. 2016. Lessons Learned from a Review of International Approaches to Spent Fuel Management. UK. *EPJ Nuclear Sci. Technol. 2(26)*.

[25] Hanson, A. S. & Chollet, P. 2003. Storage of Spent Fuel from Nuclear Power Reactors International conference: International experience of storing spent fuel in NUHOMS systems, IAEA-CN-102/56. Vienna, Austria.

[26] Hartnick, M. D. 2017. Evaluation of Nuclear Spent Fuel Dry Storage Casks and Storage Facility Designs. Cape Town: University of Cape Town. (Dissertation – MEng).

[27] Hitachi-GE Nuclear Energy, Ltd. 2014. UK ABWR Generic Design Assessment: Preliminary Safety Report on Spent Fuel Interim Storage. UK.

[28] Holtec International. 2016. Final Safety Analysis Report for the HI-STROM 100 Cask System Revision 13. Holtec Center, USA.

[29] Hubbard, B. & Zukley, D. 2019. Crane Safety: Lessons from the Nuclear Industry. Perdue University. U.S.A. https://www.irbnet.de/daten/iconda/CIB_DC27542.pdf Date of access: 11 Nov. 2019.

[30] Hungary. Atomic Energy Authority. 2017. National Report: Sixth Report Prepared within the Framework of the Joint Convention on the Safety of the Spent Fuel Management and on the Safety of Radioactive Waste Management. Budapest, Hungary.

[31] IAEA (International Atomic Energy Agency). 1999. Survey of Wet and Dry Spent Fuel Storage. Vienna, Austria.

[32] IAEA (International Atomic Energy Agency). 2005. Technical Report Series No. 425: Country Nuclear Fuel Cycle Profile, second edition. Vienna, Austria.

[33] IAEA (International Atomic Energy Agency). 2006. No.SF-1: Fundamental Safety Principles. Vienna, Austria.

[34] IAEA (International Atomic Energy Agency). 2007. IAEA-TECDOC-1558: Selection of Away-from-Reactor Facilities for Spent Fuel Storage. Vienna, Austria.

[35] IAEA (International Atomic Energy Agency). 2009. No. NF-T-3.5: Costing of Spent Nuclear Fuel Storage. Vienna, Austria.

[36] IAEA (International Atomic Energy Agency). 2014. Radiation Protection and Safety of Radiation Sources: International Basic Standards. Vienna, Austria.

[37] Jones Jr, R. H. 2015. Fuel Cycle Research and Development: Dry Storage Cask Inventory Assessment. US Department of Energy.

[38] Kumano, Y. 2010. Presentation: Integrity Inspection of Dry Storage Casks and Spent Fuels at Fukushima Daiichi Nuclear Power Station, Session 6. Japan.

[39] Lisichenko, G., Shteingerg, M., Chumak D., Prokip, A., Shutyak, S., Maskalevich, I. & Vasilkivskiy, B. 2017. The Ukrainian Nuclear Industry: Expert review. Bellona, Norway.

[40] Maree, V. & Carolissen, A. 2017. The Management of Used (Spent) Fuel and High Level Waste in South Africa. *Universal Journal of Management*, 5(2):53-57.

[41] Microsoft Excel. (2010). Microsoft.

[42] Naicker, V.V., Du-Toit, M.H. & Nyalunga, G.P. 2015. NWURCS User Guide. Potchefstroom: North-West University. (User Guide).

[43] NNR (National Nuclear Regulator). 2017. South African National Report on the Compliance to Obligations under the Joint Convention on Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management: Fourth Report. http://www.nnr.co.za/nnr-library/south-african-nuclear-safety-conventions-reports/ Date of access: 3 Jun. 2019.

[44] NRWDI (National Radioactive Waste Disposal Institute). 2018. Central Interim Storage. https://www.nrwdi.org.za Date of access: 5 November 2018.

[45] OECD (Organisation for Economic Co-operation and Development) Nuclear Energy Agency (NEA). 2017. The Safety of Long-Term Interim Storage Facilities in NEA Member Countries. https://www.oecd-nea.org/nsd/docs/2017/csni-r2017-4.pdf Date of access: 29 Sept. 2019

[46] Office for Nuclear Regulation. 2017. Step 4 Assessment of Spent Fuel Interim Storage for the UK Advanced Boiling Water Reactor. Office for Nuclear Regulation, UK.

[47] Petroski, R. 2005. Centralized Interim Storage of Nuclear Waste and a National Interim Storage Strategy. Berkeley: University of California.

[48] Rao, M. & Hardy D. 2003. Status of Centralized Storage Systems for Used Nuclear Fuel. Toronto, Canada.

[49] Roland, V. & Samson, P. 1999, Rationalizing Transport Operations: The TN24 Transport Storage Cask approach, IAEA Symposium held in Taejon, Republic of Korea, 30 August – 3 September 1999.

[50] Romanato, L. S. 2011. Advantages of Dry Hardened Cask Storage over Wet Storage for Spent Nuclear Fuel. Sao Paulo, Brazil, 2011 International Nuclear Atlantic Conference, ISBN: 978-85-99141-04-5.

[51] Russian Federation. State Atomic Energy Corporation Rosatom, Federal Environmental, Industrial & Nuclear Supervision Service. 2017. The Fifth National

Report of the Russian Federation on Compliance with Obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management. Moscow.

[52] Saaty R.W. 1987. The Analytic Hierarchy Process - What it is and how it is used. Great Britain. *Mathi Modelling. 9(3-5):161-176.*

[53] Saaty, T.L. & Vargas, L.G. 2006. Decision Making with the Analytic Network Process: Economic, Political, Social and Technological Applications with Benefits, Opportunities, Cost and Risks. University of Pittsburgh, PA, USA.

[54] Saaty, T.L. 2008. Decision Making with the Analytic Hierarchy Process. University of Pittsburg, USA. *Int. J. Services Sciences, Vol. No. 1*.

[55] Shah, M. J., Cox, P.A. & Chowdhury, A.H. 2003. Tip-Over Analysis of the HI-STORM Dry Storage Cask System. Transactions of the 17th International Conference on Structural Mechanics in the Reactor Technology (SMiRT 17). Prague, Czech Republic.

[56] Shevchenko, G., Ustinovichius, L. & Andruskevicius, A., 2008. Multi-Attribute Analysis of Investments Risk alternatives in Construction. *Technological and Economic Development of Economy, 14:3, 428-443.*

[57] Skrzyppek J. & Kim, J. Du-III. 2015. A Well Established System for the Dry Storage of Spent Fuel. Transactions of the Korean Nuclear Society Spring Meeting. Jeju, Korea.

[58] SLAC (Standford Linear Accelerator Center) National Accelerator Laboratory. 2019. Chapter 9: Radiation Safety. https://www-group.slac.stanford.edu/esh/eshmanual/pdfs/ESHch09.pdf Date of access: 29 Sept. 2019.

[59] South Africa. Department of Minerals and Energy. 2006. National Nuclear Regulatory Act 1999 (Act No. 47 of 1999): Regulations in terms of section 36, read with section 47 of the National Regulator Act, 1999 (Act No. 47 of 1999), on Safety Standards and Regulatory Practices. (Government notice no. R388). *Government Gazette*, 28755, 28 Apr.

[60] Sun, H. & Li, G. 2019. International Status of Dual Purpose Cask Designed for both Transport and Storage of Spent Fuel. IOP *Conf.: Earth Environ. Sci.* 227 02005.

[61] Takase, K. & Von Hippel, D. F. 2017. NAPSENET Special Report: Options for remote Interim Storage of Nuclear Spent Fuels in Japan. Tokyo, Japan.

[62] The National Academies of Sciences. 2006. Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report, Washington, D.C.

[63] Thomas, F. 2010. Presentation: GNS Activities - Solutions for Russian Spent Fuel. Bulgarian Nuclear Energy - National, Regional and World Energy Safety, June 09-11, 2010. Varna, Bulgaria.

[64] Thomauske, B. R. 2002. Interim Storage of Spent Nuclear Fuel in Germany - Situation, state of licensing procedures, prospects. WM'02 Conference, February 24-28, 2002, Tuscon, AZ.

[65] Twala, V.G. 2007. Evaluation of Nuclear Fuel Management Options for South Africa. Johannesburg: UJ. (Thesis – PhD).

[66] United States Nuclear Waste Review Board. 2010. Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Fuel

[67] University of Newcastle Australia, 2014. Radiation Safety Manual. Australia.

[68] Van Mierloo, X. 2014. Presentation: Experience Dry Storage of Spent Fuel - Belgium NPP Doel, Workshop IAEA. Vienna, Austria.

[69] Wagner, J. C. 2016. Spent Nuclear Fuel Disposition. Idaho National Laboratory, US.

[70] Wang, L. 2015. Project No.10-961: Evaluation of Aluminium-Boron Carbide Neutron Absorbing Material for Interim Storage of Used Nuclear Fuel. University of Michigan.

[71] Williams, T. 2015. Presentation: Management and Transportation of Spent Nuclear Fuel in Switzerland - US NWTRB Summer Board Meeting. US.

[72] WNA (World Nuclear Association). 2018. World Nuclear Performance Report: Report No. 2018/004. England and Wales.

[73] Zakariya, N. I. 2016. Development of Nuclear – Radiological Facility Monitoring System. Cape Town: Cape Peninsula University of Technology. (Thesis – PhD).

[74] Ziemba, P, 2019. Inter-Criteria Dependencies-Based Decision Support in the Sustainable Wind Energy Management. *Journal: Energies 2019, 12, 749.*

6 APPENDIX

Verification of the correctness of the Excel spreadsheet calculations using a code named jun0219.

The outputs from the code for the various cases are shown in the sub-sections below. The final ranking of the options is given in the last column of the output under the heading “Pref”.

6.1 Case 1

```
--------------------------------------------------------------------------
Paired Comparisons Matrix for level: 1

Paired Comparisons Matrix
       RadSaf Cost
RadSaf 1.0000 3.0000
Cost   0.3333 1.0000

Weights
 0.7500 0.2500

lamda max    C.I    C.R   %C.R
   2.0000 0.0000 0.0000  0.000
--------------------------------------------------------------------------
Criteria reduced to level 3
 1 0.7500 1 0 0 RadSaf
 2 0.2500 2 0 0 Cost
--------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  RadSaf

Paired Comparisons Matrix
       ConMod MetCas
ConMod 1.0000 3.0000
MetCas 0.3333 1.0000

Weights
 0.7500 0.2500

lamda max    C.I    C.R   %C.R
   2.0000 0.0000 0.0000  0.000
--------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Cost

Paired Comparisons Matrix
       ConMod MetCas
ConMod 1.0000 4.0000
MetCas 0.2500 1.0000

Weights
 0.8000 0.2000

lamda max    C.I    C.R   %C.R
   2.0000 0.0000 0.0000  0.000
--------------------------------------------------------------------------
A.w = y

        RadSaf  Cost

                        |    C.wgt       |     Pref

ConMod  0.7500  0.8000  |    0.7500      |    0.7625
MetCas  0.2500  0.2000  |    0.2500      |    0.2375
```

6.2 Case 2

```
---------------------------------------------------------------------------
Paired Comparisons Matrix for level: 1

Paired Comparisons Matrix
       RadSaf Cost
RadSaf 1.0000 3.0000
Cost   0.3333 1.0000

Weights
 0.7500 0.2500

lamda max    C.I    C.R   %C.R
   2.0000 0.0000 0.0000  0.000
---------------------------------------------------------------------------
Paired Comparisons Matrix for level: 2 Cost

Paired Comparisons Matrix
       CaCost OMCost DeCost
CaCost 1.0000 5.0000 7.0000
OMCost 0.2000 1.0000 3.0000
DeCost 0.1429 0.3333 1.0000

Weights
 0.7235 0.1932 0.0833

lamda max    C.I    C.R   %C.R
   3.1115 0.0557 0.0961  9.609
---------------------------------------------------------------------------
Criteria reduced to level 3
 1 0.7500 1 0 0 RadSaf
 2 0.1809 2 1 0 Cost   CaCost
 3 0.0483 2 2 0 Cost   OMCost
 4 0.0208 2 3 0 Cost   DeCost
---------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  RadSaf

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 3.0000 5.0000
MetCas 0.3333 1.0000 2.0000
ConCas 0.2000 0.5000 1.0000

Weights
 0.6479 0.2299 0.1222

lamda max    C.I    C.R   %C.R
   3.0054 0.0027 0.0047  0.465
```

```
--------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Cost   CaCost

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 7.0000 2.0000
MetCas 0.1429 1.0000 0.1667
ConCas 0.5000 6.0000 1.0000

Weights
 0.5801 0.0703 0.3496

lamda max    C.I    C.R   %C.R
   3.0447 0.0224 0.0386  3.855
--------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Cost   OMCost

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 0.5000 1.0000
MetCas 2.0000 1.0000 2.0000
ConCas 1.0000 0.5000 1.0000

Weights
 0.2500 0.5000 0.2500

lamda max    C.I    C.R   %C.R
   3.0000 0.0000 0.0000  0.000
--------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Cost   DeCost

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 4.0000 3.0000
MetCas 0.2500 1.0000 0.5000
ConCas 0.3333 2.0000 1.0000

Weights
 0.6232 0.1373 0.2395

lamda max    C.I    C.R   %C.R
   3.0255 0.0127 0.0220  2.197
--------------------------------------------------------------------------
A.w = y

        RadSaf  Cost    Cost    Cost
                CaCost  OMCost  DeCost
                                          |    C.wgt      |     Pref

ConMod  0.6479  0.5801  0.2500  0.6232    |    0.7500     |    0.6159
MetCas  0.2299  0.0703  0.5000  0.1373    |    0.1809     |    0.2121
ConCas  0.1222  0.3496  0.2500  0.2395    |    0.0483     |    0.1719
                                          |    0.0208     |
```

6.3 Case 3

```
------------------------------------------------------------------------
Paired Comparisons Matrix for level: 1

Paired Comparisons Matrix
       RadSaf SysFle Retrie Cost
RadSaf 1.0000 5.0000 7.0000 3.0000
SysFle 0.2000 1.0000 3.0000 0.2500
Retrie 0.1429 0.3333 1.0000 0.2000
Cost   0.3333 4.0000 5.0000 1.0000

Weights
 0.5480 0.1149 0.0562 0.2808

lamda max    C.I    C.R   %C.R
   4.2556 0.0852 0.0947  9.467
------------------------------------------------------------------------
Paired Comparisons Matrix for level: 2 SysFle

Paired Comparisons Matrix
       Locali Modula ChaVen
Locali 1.0000 3.0000 5.0000
Modula 0.3333 1.0000 3.0000
ChaVen 0.2000 0.3333 1.0000

Weights
 0.6333 0.2605 0.1062

lamda max    C.I    C.R   %C.R
   3.0554 0.0277 0.0477  4.773
------------------------------------------------------------------------
Paired Comparisons Matrix for level: 2 Cost

Paired Comparisons Matrix
       CaCost OMCost DeCost
CaCost 1.0000 5.0000 7.0000
OMCost 0.2000 1.0000 3.0000
DeCost 0.1429 0.3333 1.0000

Weights
 0.7235 0.1932 0.0833

lamda max    C.I    C.R   %C.R
   3.1115 0.0557 0.0961  9.609
------------------------------------------------------------------------
Criteria reduced to level 3
 1 0.5480 1 0 0 RadSaf
 2 0.0728 2 1 0 SysFle Locali
 3 0.0299 2 2 0 SysFle Modula
 4 0.0122 2 3 0 SysFle ChaVen
 5 0.0562 3 0 0 Retrie
 6 0.2032 4 1 0 Cost   CaCost
 7 0.0542 4 2 0 Cost   OMCost
 8 0.0234 4 3 0 Cost   DeCost
```

```
---------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  RadSaf

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 3.0000 5.0000
MetCas 0.3333 1.0000 2.0000
ConCas 0.2000 0.5000 1.0000

Weights
 0.6479 0.2299 0.1222

lamda max    C.I    C.R   %C.R
   3.0054 0.0027 0.0047  0.465
---------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  SysFle Locali

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 5.0000 1.0000
MetCas 0.2000 1.0000 0.2000
ConCas 1.0000 5.0000 1.0000

Weights
 0.4545 0.0909 0.4545

lamda max    C.I    C.R   %C.R
   3.0000 0.0000 0.0000  0.000
---------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  SysFle Modula

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 5.0000 1.0000
MetCas 0.2000 1.0000 0.2000
ConCas 1.0000 5.0000 1.0000

Weights
 0.4545 0.0909 0.4545

lamda max    C.I    C.R   %C.R
   3.0000 0.0000 0.0000  0.000
---------------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  SysFle ChaVen

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 5.0000 1.0000
MetCas 0.2000 1.0000 0.2000
ConCas 1.0000 5.0000 1.0000

Weights
 0.4545 0.0909 0.4545

lamda max    C.I    C.R   %C.R
   3.0000 0.0000 0.0000  0.000
```

```
-----------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Retrie

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 0.3333 1.0000
MetCas 3.0000 1.0000 3.0000
ConCas 1.0000 0.3333 1.0000

Weights
 0.2000 0.6000 0.2000

lamda max    C.I    C.R   %C.R
   3.0000 0.0000 0.0000  0.000
-----------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Cost   CaCost

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 7.0000 2.0000
MetCas 0.1429 1.0000 0.1667
ConCas 0.5000 6.0000 1.0000

Weights
 0.5801 0.0703 0.3496

lamda max    C.I    C.R   %C.R
   3.0447 0.0224 0.0386  3.855
-----------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Cost   OMCost

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 0.5000 1.0000
MetCas 2.0000 1.0000 2.0000
ConCas 1.0000 0.5000 1.0000

Weights
 0.2500 0.5000 0.2500

lamda max    C.I    C.R   %C.R
   3.0000 0.0000 0.0000  0.000
-----------------------------------------------------------------------
Paired Comparisons Matrix of Alternatives for Criteria  Cost   DeCost

Paired Comparisons Matrix
       ConMod MetCas ConCas
ConMod 1.0000 4.0000 3.0000
MetCas 0.2500 1.0000 0.5000
ConCas 0.3333 2.0000 1.0000

Weights
 0.6232 0.1373 0.2395

lamda max    C.I    C.R   %C.R
   3.0255 0.0127 0.0220  2.197
```

A.w = y

	RadSaf	SysFle Locali	SysFle Modula	SysFle ChaVen	Retrie	Cost CaCost	Cost OMCost	Cost DeCost	C.wgt	Pref
ConMod	0.6479	0.4545	0.4545	0.4545	0.2000	0.5801	0.2500	0.6232	0.5480	0.5646
MetCas	0.2299	0.0909	0.0909	0.0909	0.6000	0.0703	0.5000	0.1373	0.0728	0.2148
ConCas	0.1222	0.4545	0.4545	0.4545	0.2000	0.3496	0.2500	0.2395	0.0299	0.2206
									0.0122	
									0.0562	
									0.2032	
									0.0542	
									0.0234	