Dry Storage of Spent Nuclear Fuel:
The Safer Alternative to Reprocessing

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Abstract

The international situation and developments in the storage of spent fuel are examined. Reprocessing is a minority activity in world terms: most (>70%) spent fuel arisings are stored. Wet and dry storage systems are described and compared. The advantages of dry storage, types of dry stores and technical aspects of dry storage are discussed. The estimated costs of storage are compared with reprocessing costs, from the perspectives of the complete fuel path and of a single stage of the fuel path.

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Executive Summary

La Hague reprocessing discharges, along with Sellafield reprocessing discharges, are among the largest sources of civil radioactive pollution in the world. A less polluting alternative to reprocessing is the storage of spent nuclear fuel. The Cogema Dossiers to the La Hague Public Inquiry in January 2000 do not discuss alternatives to reprocessing, and are silent on dry storage issues.

In mid 1999, 140,000 tonnes of spent nuclear fuel were in storage throughout the world, with 100,000 tonnes in reactor pools, 34,000 tonnes in wet stores away from reactors, and 6,000 tonnes in dry stores. About 10,500 tonnes of spent fuel arise annually, of which 2,000 to 3,000 tonnes are reprocessed. In other words, most (70% to 80%) fuel arisings throughout the world are stored not reprocessed. Many utilities and governments with nuclear programmes are moving to storing rather than reprocessing their spent fuels, including utilities in Germany, Netherlands, Spain and recently the UK. Almost all new developments in fuel storage concern dry rather than wet storage.

An important issue is the degree to which dry storage may be considered a viable medium or long-term option for managing spent fuel. After reviewing national experiences of dry storage, the IAEA has concluded it is an acceptable waste management option for the storage of spent fuel for periods of 50 to 100 years by which time heat rates have declined by two orders of magnitude. The anticipated longevity of dry stores (50 to 100 years) is expected to exceed that of wet stores. It is concluded that dry storage in inert gas presents relatively few theoretical or practical difficulties over this time frame.

The report describes and compares wet and dry storage methods including their operating characteristics and long-term safety capabilities. At present, most fuel is stored in water pools which are expensive to construct and operate in comparison to dry stores. In addition, dry systems, which require neither energy nor human inputs, are inherently safer and more reliable than wet stores. Current dry storage technologies are described, with emphases on technical methods, costs, experience, and licensing requirements. The longevity of spent fuel, including defective fuel, in dry stores is discussed.

Predicted costs of the reprocessing path and dry storage path are examined in US, German, UK and NEA/OECD studies. Costs of storage path are lower by factors of 0.5 to 0.7 than the reprocessing pathway. Disputes within the committee which prepared the most recent NEA/OECD report may indicate attempts to mask the higher costs of the reprocessing route compared to storage. More reliable German studies confirmed higher costs.

The NEA/OECD insistence on comparing costs of fuel paths instead of more relevant fuel stages is shown to be unrealistic. Viewed as a single stage, estimated costs of European dry stores per tonne are 2 to 3 times lower than reprocessing costs. Estimated costs of US dry stores are much lower - 8-20 times less expensive per tonne. Canadian system costs are even lower - an estimated 30-50 times less expensive than reprocessing per tonne, although these are for low burnup fuels.

Due to the paucity of data, it is difficult to make exact comparisons of costs e.g. using the same currency years, and discount rates. Nevertheless it is clear that the dry storage systems examined have lower marginal costs than reprocessing: depending on the system chosen, dry storage costs can be considerably lower than reprocessing costs.

Taking into account the technical and cost advantages of dry storage and the fact that environmental and local groups in a number of countries including the US and the UK have not opposed dry storage developments, it is concluded that dry storage should be investigated as a medium-term method of dealing with spent nuclear fuel.

However in UK and France, despite apparent advantages of dry storage over reprocessing, it is expected that the large resources, political commitments and institutional investments in reprocessing will continue to hinder consideration of dry storage issues in the immediate future.

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CHAPTER 1. INTERNATIONAL SITUATION RE: FUEL STORAGE

Present Inventories

1. In 1999, 140,000 tonnes of spent nuclear fuel were in storage throughout the world. About 100,000 tonnes were stored in reactor pools, 34,000 tonnes in storage pools away from reactors, and another 6,000 tonnes in dry stores (Dyck, 1999). To put this into perspective, in the French nuclear programme, a 900 MW PWR reactor discharges about 40 tonnes of fuel per year at 35,000 MWdays/tonne burnup in a four year cycle. This inventory is increasing at the rate of 10,000 tonnes per year (IAEA, 1999; Dyck, 1999). In addition, about 2,500 to 3,000 tonnes of fuel are reprocessed annually at the large commercial reprocessing centres at La Hague, France and Sellafield, UK. Approximately 25% - 30% of annual global spent fuel arisings are currently reprocessed. In other words, reprocessing is a minority activity in comparison with storage, in world-wide terms.

Two Approaches to Spent Fuel

2. Until about the early 1990s, the world was divided into two camps as regards policies and preferences for dealing with spent fuel discharged from nuclear reactors. On the one hand, many Governments and utilities were committed to reprocessing their spent fuel ostensibly for reusing the Pu thus obtained for fast breeders and/or MOX fuel. These included France, UK and Russia. This camp included utilities in a number of Western European countries (Germany, Switzerland, Netherlands, Belgium, and Spain) plus Japan which contracted most of their fuel to be reprocessed at La Hague or Sellafield. It also included state utilities in many Eastern European countries which contracted their spent fuel to be reprocessed in Russian facilities.

3. On the other hand, a number of Western Countries including Canada, the US, Sweden and Finland were committed to storing their fuels, in the case of the latter two countries at least since the late 1980s. This was partly due to proliferation concerns, partly due to technical difficulties with early reprocessing facilities, and partly due to environmental concerns over the large scale of nuclide discharges resulting from reprocessing operations (see Fairlie, 1997).

4. Since the early 1990s, interest in reprocessing has waned in most nuclear countries, as a result of a number of factors. These include
    - declines in the original rationales for reprocessing (military and fast breeders)
    - increased awareness of large cost differentials between reprocessing and storage
    - increased competitive pressures on nuclear utilities to reduce costs
    - declining enthusiasm for relatively expensive MOX fuel in the late 1990s
    - increased reliance by utilities on higher burnup fuels rather than MOX
    - increased awareness that spent fuel is an acceptable waste form for final disposal, and
    - increased environmental pressures, including OSPAR decisions, to find ways of reducing or stopping reprocessing discharges

5. These tendencies have been countered by other developments such as the lack of storage space in reactor pools especially at European and US utilities. In 1995, this forced some German utilities

not to cancel their reprocessing contracts over concern about the return of spent fuel and/or separated Pu.

Changing National Policies

6. Since the mid 1990s, utilities in a number of countries have declined to commit future fuel arisings to be reprocessed, including Germany, Switzerland, Netherlands, Belgium, and Spain. As a result, since 1995, there have been no contracts for additional fuel tonnages to be reprocessed at la Hague or Sellafield. In at least one country, Germany, utilities cancelled reprocessing contracts in 1995 although others did not as mentioned above. In 1999, the German government attempted to cancel reprocessing contracts between German utilities and BNFL. It was dissuaded from doing so by threats of legal action and threats of the immediate return of spent fuel and separated Pu. Instead, many utilities and governments are investigating, planning, or constructing fuel storage facilities as set out in table 1.1 below.

Table 1.1 National And Utility Policies On Nuclear Waste

Countries/Utilities Using Only Storage (wet and dry)	Countries/Utilities Constructing Dry Stores	Countries/Utilities with plans for Dry Storage	Countries Presently Committed to Reprocessing Fuel
Canada Finland Sweden US	Armenia Bulgaria Czech Rep Germany Hungary Lithuania Russia Slovakia Spain Ukraine	Argentina Belgium Brazil Czech Rep Japan South Korea Netherlands Switzerland Ukraine	France United Kingdom China Japan

6. The table reveals that countries and utilities formerly committed only to reprocessing are now exploring dry storage options. These include utilities in countries such as Switzerland, Netherlands, Belgium, Germany, Czech Republic and Spain. The above table is a simplification of a mixed and changing situation: many countries may have old reprocessing contracts for small amounts of fuel, but may in addition be planning increased storage facilities. In addition, many countries are adopting a wait-and-see approach. Overall, from a world-wide perspective, there is a clear movement to dry storage.

7. The next 3 tables from a recent IAEA report on fuel storage (IAEA,1999) indicate national capacities and inventories for the storage of spent fuel. First, table 1.2 reveals that about 100,000 tonnes of spent fuel are stored temporarily at reactor pools throughout the world. The table adds up to only 92,000 tonnes in 1997 but is states to be 100,000 tonnes as of 2000 by the IAEA (Dyck,1999.) Table 1.3 shows 34,000 tonnes of fuel are wet stored in dedicated pools remote from reactors. Table 1.4 shows 6,000 tonnes are dry stored. Table 1.5 tables compares world-wide capacities and inventories as of 1999. At Reactor pools are defined as storage pools directly connected with reactors (i.e. pool space needs to be reserved for full core discharges).

Table 1.2 At Reactor Wet Storage as of 1998

COUNTRY	REACTOR TYPE	No of Pools	Capacity tonnes HM	Inventory tonnes HM
Argentina	PHWR	2	1450	120
Bulgaria	WWER-440	4	480	121
	WWER-1000	2	520	266
Canada	CANDU	10	31407	22555
China	PWR	3	177	0
Czech Rep.	WWER	4	480	306
Finland	BWR/WWER	4	666	251
France	**900 MW PWR**	**34**	**5870**	**4187**
	1300 MW PWR	**20**	**5420**	**1608**
Germany	operating PWR	13	3176	2011
	operating BWR	6	1385	821
	Shut down	8	526	0
Hungary	WWER	4	480	350
Italy	LWR	3	253	253
Japan	PWR	20	6460	2070
	BWR	23	8410	3050
	Others	2	280	120
Korea, Rep.	PWR/PHWR	12	5875	3072
Lithuania	RBMK	2	209	1380
Mexico	BWR	2	984	80
Romania	CANDU	1	940	100
Russian Fed	WWER-440	6	480	320
	WWER-1000	7	1200	460
	RBMK	11	3560	2700
Slovakia	WWER	4	480	150
Slovenia	PWR	1	410	205
South Africa	PWR	2	670	392
Spain	PWR/BWR	9	3820	2000
Sweden	PWR/BWR	12	1500	730
Switzerland	PWRIBWR	5	705	150
Ukraine	WWER-440	2	240	92
	WWER-1000	11	2170	1156
	RBMK	3	600	380
UK	Magnox	20	1500	330
	AGR	14	230	154
	PWR	1	936	30
USA	operating LWR	110	59000	38343
	shutdown LWR	8	1700	957
TOTALS		405	154,649	91,270

Table 1.3 Summary Of Away-From-Reactor Wet Spent Fuel Storage

tonnes Heavy Metal (as of 1997)

Member State	Number of facilities	Design capacity	Current inventory
Argentina	1	1100	766
Belgium	1	1000	35
Bulgaria	1	600	356
Finland	2	1450	700
France	**4**	**14400**	**9159**
Germany	1	560	526
India	1	27	27
Japan	3	4300	3500
Russian Federation	6	12960	6046
Slovakia	1	600	523
Sweden	1	5000	2703
Ukraine	1	2000	1695
United Kingdom	4	10350	7031
United States	1	780	700
TOTAL	**28**	**55,127**	**33,767**

Table 1.4 Summary of Worldwide Dry Spent Fuel Storage

As of 1998 tonnes Heavy Metal

State	Number of facilities	Design capacity	Current inventory
Argentina	1	200	64
Belgium	1	800	142
Canada			
Operating	7	8567	1930
Under Construction	1	14500	0
Czech Republic	1	600	232
France	**1**	**180**	**180**
Germany			
Operating	3	7768	58
Under Construction	1	585	0
Hungary	1	162	54
Japan	1	73	73
Republic Of Korea			
Operating	1	609	609
Under Construction	1	812	0
Lithuania	1	419	0
Ukraine	1	50	0
United Kingdom	1	958	680
USA			
Operating	10	4,700	1,270
Under Construction	6	2,155	0
Total	**39**	**43,138**	**5,292**

Table 1.5 Total Worldwide Storage (Wet And Dry) In 1998

tonnes Heavy Metal

	Number of facilities	Design capacity t HM	Current inventory t HM
Reactor Pools	405	154,472	91,447
Storage Ponds	28	55,127	33,767
Dry Stores	39	43,138	5,292
GRAND TOTAL	**472**	**252,737**	**130,506**

The global totals of design capacity mask considerable shortages of storage capacity especially at utilities in Germany and the US.

FRANCE

11. As revealed in the above IAEA tables, the capacity and inventory of spent fuel in France are as indicated in table 1.6 below.

Table 1.6 Fuel Stores In France

tonnes HM in 1998

	Number	Capacity	Current Inventory
Reactor Pools	54	11,290	5,795
AFR Pools	4	14,400	9,159
Dry Store	1	180	180
Totals	59	25,870	15,134

11. France has 6 AFR pools operated by COGEMA at La Hague in support of reprocessing activities, as listed in Table 1.7.

Table 1.7 French AFR Storage Facilities At La Hague (1998)

Plant	Storage Pools	Nominal Capacity t HM	Current Inventory t HM	Commissioning Date
UP2-800	Storage HAO	400	184	1976
	NPH	2000	1133	1981
	Pool C	3600	2417	1984
UP3	Pool D	3500	2196	1986
	Pool E	4900	3256	1988
Totals		**14,400**	**9,159**	

8. The single French dry store CASCAD at Cadarache is small (180 tonnes) and is full. It is a vault type store and used to store spent research fuel or experimental fuel (Bonnet and Ducroux, 1994). In 1993, nuclear industry managers (NuclearFuel, 1993c) proposed an expansion in the construction of dry stores in France: this was never implemented.

CHAPTER 2 WET AND DRY STORAGE OF SPENT FUEL

Recent trends in fuel storage

1. Due to the fact that many ponds are being filled to capacity, and that dates for the introduction of permanent repositories are receding throughout the world[1], acute shortages of capacity for spent nuclear fuel exist in a number of countries particularly the US and Germany. (Blowers et al, 1991; Lenssen, 1991; Fairlie, 1997a, Blowers et al, 1999). These pressures have resulted in a number of developments in the storage of nuclear fuel. First is increased fuel residence times, so that the storage of 30 year-old fuel in the US is not uncommon. Second is the intensive development of reracking, consolidation and double-decking techniques in reactor pools particularly in the US, but also in other countries in recent years. Third, newer nuclear stations have incorporated progressively larger pools: for example, Sizewell B in the UK has storage space for over 34 years' of fuel discharges, i.e. its expected lifetime (British Energy, 1996). Fourth, some utilities in Canada, Spain and Japan have constructed additional storage ponds at station sites. Sweden has constructed a large national underground pool, CLAB, for spent fuel. A fifth development is the partial appropriation of reprocessing storage ponds for the lengthy storage of fuel. This includes ponds at the defunct Allied General reprocessing plant at Barnwell, South Carolina, US; completed ponds at the unfinished Rokkashu reprocessing plant in Japan; and ponds at Sellafield and Cap La Hague. Extensive storage capacities exist at Cap La Hague (14,400 tonnes) and at Sellafield (10,400 tonnes).

Wet Storage

2. In 1998, about 86 % of spent fuel stored at AFR facilities throughout the world was stored under water. Commercial fuel storage ponds have existed since the 1960s. Storage ponds have operated with a few major incidents[2] in most nuclear power programmes throughout the world. The majority of the world's spent fuel is from LWR or HWR reactors which use water at high temperatures and pressures as coolant. Storing HWR and PWR fuel in water at lower temperatures and pressures is not expected to result in fuel difficulties, and this has been borne out in operating experiences so far (IAEA 1994b).

3. Used fuel contains fissile material albeit at lower concentrations than fresh fuel. A main danger of pond storage is the possibility of criticality, as water is an excellent moderator. The possibility of criticality requires adherence to strict geometry in storage configurations and the use of borated water to provide adequate safety margins. Another main danger is that if there were a major accident at a reactor pond, it could be difficult, if not impossible, to service the reactor pools to ensure the spent fuels remained covered with water. Exposure of spent PWR fuel rods could lead to the fuels heating to past 800 degrees C at which point the zirconium cladding of PWR fuel may spontaneously ignite in air.

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[1] No nuclear waste repository exists. The earliest planned date for a repository is 2015 in Sweden.

[2] in 1984, the pneumatic seal of the main pond at Connecticut Yankee station in the US ruptured with the loss of 200,000 gallons of water. This could have resulted in the exposure of personnel to high levels of direct radiation.

4. Wet stores require continuous operation of cooling, filtration, cleaning and sampling systems, which depend upon mechanical components such as pumps, valves, and filters. The chemical and temperature control of cooling water requires continuous monitoring and sampling. These operations result in appreciable quantities of radioactive Low Level Wastes. Such operational requirements increase with the amount of fuel in the pond and are particularly high when pools are near to capacity. Pond systems and mechanical components also require large maintenance inputs, rendering them inherently less reliable than passive dry storage systems. These factors result in relatively high operating costs for pools. These high costs resulted in many utilities and national nuclear agencies carrying out R&D and feasibility studies into dry storage facilities which tend not to suffer from the above disadvantages.

Dry Storage

5. The world's first dry store for spent fuel was constructed in 1970 as an integral part of the Wylfa reactor, in north Wales in the UK, as a buffer[3] store for spent Magnox fuel prior to its removal to Sellafield for reprocessing. The store originally had a capacity of 250 tonnes, later expanded to 950 tonnes. Since 1971, High Temperature Gas Reactor fuel from the Peach Bottom reactor in Pennsylvania US has been stored in dry wells at the Idaho National Engineering Laboratory. In 1975, in Manitoba, Canada, fuel from a PWHR demonstration reactor was placed in sealed concrete storage casks. This was followed by other experimental dry storage systems so that now Canada currently has about 900 tonnes of fuel from research and small-scale reactors in long-term dry storage.

6. After the mid 1970s, interest in dry stores waned, apart from in Canada, mainly because of the adoption of inexpensive reracking and double-decking technologies at ponds. Since the early 1990s, interest in dry storage has grown. Dry stores are presently being commissioned or are under construction in Argentina, Belgium, Canada, the Czech Republic, Germany, Hungary, Japan, South Korea, Lithuania, Russia, Ukraine and the US (IAEA, 1996; 1999). In 1992, Scottish Nuclear, in evidence to the 1992/3 public inquiry into its dry store plans, added Mexico, Italy, India, South Africa, and Taiwan to this list (Hickman, 1993). Currently about 14% of stored fuel at AFRs is kept in the dry form (IAEA, 1999). See table 1.4 above.

Costs Of Wet And Dry Storage

7. Siemens engineers (Peehs and Banck, 1993) have stated that dry store construction costs are considerably lower per tonne of fuel stored than wet stores, particularly in the case of small stores. In addition, the multiple operating systems and hardware maintenance requirements of pool storage result in higher operating costs for pools. Bowser *et al.* (1994) estimated that the annual running costs of wet ponds to store fuel from the closed Rancho Seco reactor in California to be $10.6 million per year and for dry stores -$2.6 million per year, a saving of about $8 million per year.

8. Since most pool costs have been paid for and dry stores have yet to be constructed, a useful comparison is the amortised cost of constructing a dry store plus annual operating costs, compared

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[3] originally for<100 days.

with the annual operating costs of an existing pool. In the above Rancho Seco study, the costs of constructing a transportation plus dry storage system to store spent fuel were estimated at $12.4 million. The study amortised this figure over a 10-year depreciation period using a 5% interest rate. This plus annual running costs resulted in an estimated total annual cost of $4.2 million for dry storage compared with annual operating costs of $10.6 million for wet storage. In other words, considerable savings accrued from constructing dry stores and transferring fuel from pools to them. Table 2.1 compares estimated costs of wet and dry storage systems in more detail. It reveals that the cost of dry storing fuel is 2.5 times lower than wet storing it.

Table 2.1 Cost of Wet and Dry Storage Options

Management Option For Spent LWR Fuel	Estimated Cost For 500 Tonnes Over 20 Years	Estimated Cost Per Tonne Over 20 Years
Dry Storage At Closed Reactor	$148 million	$180,000
Wet Storage At Closed Reactor	$230 million	$460,000

estimated from Bowser *et al* (1994)

9. Supko (1995) predicted dry storage costs of an operating nuclear utility where storage costs were permitted by its Public Utility Commission to be an operating overhead and be charged to electricity ratepayers (NuclearFuel, 1993a). The result was that store operating costs and insurance costs were significantly lower than those at the closed site studied by Bowser. Estimated representative life-cycle costs over a 20 year period for a 500 tonne dry store were $34 to $50 million, i.e. $68,000 to $100,000 per tonne. These studies indicate that costs allocation is important in examining back end costs.

Description of Dry Stores

6. The distinctive characteristic of dry storage systems is their passive cooling by radiation and air convection. Convection results from the natural thermosyphon effect of hot spent fuel which ranges in temperature from ~200° to ~360° C. Unlike wet stores, dry stores require virtually no electrical, water, or maintenance inputs, apart from that required for monitoring and surveillance. This results in enhanced reliability and safe operational running for long periods. The nominal life of the former planned Scottish Nuclear dry store was 100 years, including a 35 year loading period, 50 year storage period and 15 year period for fuel unloading and encapsulation, prior to disposal (Ealing, 1993). It is expected that dry stores may be able to operate for periods longer than 100 years (Schneider and Mitchell. 1992b).

7. A second important characteristic of dry storage systems is their heavy radiation shielding. Spent fuel, even after 10 years' preliminary cooling, remains highly radioactive; radiation dose rates from unshielded PWR canisters range from 1 to 100 Gy per hour. Dry stores are therefore exercises in heavy engineering involving massive shielding, commonly 60 to 100 cm of heavy density

concrete, ductile iron, steel or steel/lead combinations. This reduces surface dose rates of shielded casks to between 200 and 800 μGy per hour[4].

8. Dry stores have been in operation since 1970 with relatively few reports of accidents or failure. In 1990, a leak[5] from a flat roof at the UK Wylfa dry store permitted rainwater ingress over a lengthy period. Although this failure required the prolonged drying and refurbishing of stored fuel tubes over a number of years, the mistake did not concern the failure of fuel or essential elements of dry storage. In May 1996, a fire occurred inside a BNFL Corporation VSC 24 cask at Point Beach in Wisconsin, US, during remote welding of the cask lid. (NuclearFuel, 1996). This was due to H_2 gas released from interaction between the zinc coating of the inner container and borated water adhering from wet storage.

9. For most high burnup fuel types[6], it is necessary to store discharged fuel in cooling ponds to permit nuclide decay before the fuel can be transferred to dry storage. The required duration of the initial cooling period depends on fuel burnup and the heat-handling capacity of the store. For high burnup (45,000 MWday/tonne) LWR fuel, about 3 years' cooling is required before it may be placed in a vault, and 10 years’ cooling before it may be placed in a cask, as casks have much smaller heat-handling capacities than vaults. In all cases, spent fuel assemblies are first dried, in some cases dismantled and reconfigured, sealed within stainless steel canisters, and placed in the outer cask or vault. Casks or modules are placed on concrete pads in the open air or within hangar-type buildings with open sides.

Functions and Regulatory Criteria of Storage

10. The main functions of spent fuel storage systems are heat removal, subcriticality, and radiation shielding. Accordingly, the key criteria for many national regulators (Ealing, 1993) (IAEA, 1994b) are, in order of importance

    - low temperature of stored fuel,
    - subcriticality,
    - assurance of heat removal,
    - low doses to operators and public,
    - environmental protection,
    - low volume of waste produced,
    - physical protection,
    - safeguards against diversion, and
    - storage not to prejudice final disposal route.

11. Currently, there are no UK regulatory criteria for the storage and disposal of spent fuel or vitrified HLW (Griffin, 1994), and it would appear that the same is the case for French spent fuel. Criticality is an important consideration. Fuel in dry stores which is kept in the same geometrical configuration as in wet stores is inherently subcritical (Pacific-Sierra, 1991) due to the absence of

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[4] about 2 to 8 Gy per year.

[5] due to the flooding of the inner roof resulting from a cracked drainpipe.

[6] But not for low burnup fuels e.g. Magnox and Candu fuel

moderating water. At least in theory, no burnup credit is allowed by US regulators (US NRC, 1996) in deciding criticality criteria, i.e., the geometric configuration of spent fuel in dry storage must be the same as that for fresh fuel. This means that, although spent fuel contains lower concentrations of fissile isotopes than fresh fuel, US spent fuel may not be consolidated to save space in dry storage containers. Regulators in other countries allow burnup credit however.

12. Another prime consideration for most nuclear regulators is that spent fuel should be maintained in the best possible condition, in order to facilitate retrieval and final disposal in the future (Carter and Bower, 1995). This requires fuel to be kept at low a temperature as possible. Fuel temperatures are important as most mechanisms promoting the degradation of fuel cladding are temperature dependent (Manektela, 1993). In Hungary, the maximum allowed temperature is 250° C for Russian VVER fuel. In the US and Germany, which use GE/Siemens BWR or Westinghouse PWR fuels, higher maximum temperatures of 340° to 360° C (US NRC, 1996) are allowed, due to the higher resistance of zirconium-clad fuels to oxidation (Pacific-Sierra, 1991). In practice, temperature control is the main operating criterion of dry stores.

Performance of Fuel Cladding in Dry Stores

13. The performance of fuel cladding in dry stores is an important consideration. The cladding integrity of LWR fuel is not affected in wet storage because water temperatures of ~50°C are too low for significant fuel oxidation (Gilbert et al, 1990). Indeed, most countries store defective oxide fuel in the same conditions in pools as intact fuel. (IAEA, 1987). The much higher temperatures (200° to 370°C) in dry stores require that considerable attention be paid to cladding corrosion in dry stores. Therefore the main technical concern with dry storage is the degradation of fuel cladding over time. Degraded cladding may lead to accelerated oxidation of UO_2 in oxide fuel to the less dense U_3O_8 which causes fuel rods to split, and can result in possible serious rod damage.

14. To ensure absence of cladding degradation and ease of retrieval, dry storage R&D has focused on potential degradation mechanisms in spent fuel cladding in order to determine maximum permissible temperatures and time lengths of spent fuel in storage (Manektela, 1993). Cladding integrity depends on storage conditions, i.e. temperature, presence of oxygen, time stored, and absence of water. The critical factor is temperature: see table 2.2 for maximum cladding temperatures in various cask types at their maximum heat capacities.

Table 2.2 Maximum Permissible Temperatures Of Casks

Type	VSC-24	NUHOMS-24P	TN-24	TN-40	NAC-128	Castor V-21
Manufacturer	BNFL Inc	Vectra	Trans-Nuclear	Trans-nuclear Inc.	Nuclear Assurance	GNS
Country of Manufacture	US	US	Ger-Bel-Neth	Ger-Bel-Neth	US	German
Max Cladding Temperature	364°C	364°C	332°C	332°C	230°C	<250°C

source: Wisconsin PSC (1994)

15. The US Nuclear Regulatory Commission limits the maximum permissible LWR fuel temperature for dry storage purposes to 370°C (Schneider and Mitchell, 1992a) depending on fuel type and

burnup. In practice, this means that normal burnup PWR fuel must be cooled in ponds for 5 years, and higher burnup fuel cooled for up to 10 years before transfer to dry stores. These storage temperatures are close to the normal PWR operating temperatures of 370° - 380° C.

16. Computer simulations by the US Electrical Power Research Institute (1989) on the probability of LWR fuel cladding failure estimated a failure rate in 1% of fuel rods per 100 years under dry storage conditions. EPRI stated this was a "relatively high probability of failure". The cladding failures consisted of small defects less than 1 micrometer in diameter, and the amount of radioactive gas leaked into the storage chamber was estimated to be insufficient to interfere with fuel retrieval. Gilbert *et al.* (1990) cite US studies predicting fuel failure rates of less than 10^{-4} per year per PWR rod in dry storage at maximum allowed temperatures. Gilbert *et al.* (1990) also cite studies indicating that LWR spent fuel is expected to retain its integrity in inert gas for greater than 50 and up to 100 years. Technical projections using Arrhenius plots for CANDU fuel UO_2 oxidation predict spent fuel integrity for between 100 to 1,000 years (Frost, 1988; Stevens-Guille, 1991).

Reduction in Heat Loads

17. An important property of storage is the reduction in heat loads over time to permit easier management of spent fuel after cooling. For example, the heat output from PWR spent fuel after 10 years' cooling is about 3% of that one month after the fuel's removal from reactor. Table 2.3 sets out the heat loads for various fuel types after varying storage periods, following removal from reactor.

Table 2.3 Decay Heats After Varying Storage Periods

kW per tonne fuel

FUEL TYPE (exit burnup)	3×10^6 seconds ≈ 35 days	3×10^7 seconds ≈ 1 year	3×10^8 seconds ≈ 10 years	3×10^9 seconds ≈ 100 years
MAGNOX 4 GWday per tonne	3	0.74	0.14	0.035
AGR 18 GWday per tonne	14	3.5	0.58	0.15
PWR 33 GWday per tonne	33.5	8.7	1.12	0.28

source: Kempe *et al.,* 1981

18. Nuclear regulators and/or nuclear industry engineers from different countries have adopted different rankings for the licensing criteria of dry storage systems. For example, in Germany, greater weight is accorded to meeting the requirements of stringent transport regulations and to physical protection against external incidents, including aircraft crash, gas cloud explosion, fire, temporary burial, earthquake, transport crashes, and drop (Weh, 1993). German regulators also prohibit ventilated casks due to concerns over genetic mutations to insects, bacteria and viruses which may enter ventilation spaces[7] (Janberg, 1994). For these reasons, German CASTOR casks

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[7] screening against bacteria etc. would provide too great an impediment to passive airflows.

are built to resist physical insult and are sealed i.e. unventilated. This means that cooling is by direct radiation and air convection of outer surfaces, and not by inner air convection. The result is that unventilated German casks for LWR fuels are made from metal rather than concrete, as metals have higher heat conductivities than concrete. This results, inter alia, in unventilated German metal casks being more expensive than ventilated concrete casks.

19. Overall, national regulatory and licence requirements have a strong influence on, and indeed limit utility choices between dry store systems. Different countries have emphasised different criteria, placing national restrictions on storage choices. The process of drawing up regulatory or licence conditions for dry fuel storage has not been completed in many countries, and has not been started in France.

Types of Dry Stores

20. Three main types of dry storage are currently in use, as follows

- vaults or silos, which are large ventilated buildings, holding between ~600 to ~2,000 tonnes;
- metal casks, which are unventilated metal cylinders holding ~10 to ~17 tonnes; and
- ventilated[8] concrete casks or modules holding ~5 to ~15 tonnes.

21. Table 2.4 sets out indicative characteristics of the three main types of stores.

Table 2.4 Examples of Main Types of Dry Stores

	VAULT or SILO	CONCRETE CASK	METAL CASK
Manufacturer	GEC Alsthom	BNFL Inc	GNS
Country	UK	US	Germany
Model	MVDS	VSC-24	V/21
Fuel Capacity (tonnes)	variable, up to 1,200	17	15
Size metres HxWxD	50x30x60 metres approximately	5.6 x 3.5 x 3.5	5.2 x 2.5 x 2.5
Heat Capacity kW per tonne when full	17	1.4	1.4
Weight Full (tonnes)	-	132	117
Construction	Steel Reinforced Concrete	Steel Reinforced Concrete	Ductile Iron
Maximum radiation dose rate at surface	0.8 nSv/hour (at perimeter fence)	600 µSv/hour (at cask surface)	500µSv/hour (at cask surface)
Shielding dimension	60 -100 cm	80 cm	44 cm

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[8] Most concrete casks are ventilated with the exception of Canadian DSC casks

Vaults

22. According to Scottish Nuclear’s former plans for dry storage (Scottish Nuclear, 1992a), the maximum heat load in each 60 tonne vault was 1 MW, with 20 vaults planned. This is an extremely large heat output, and indicates the scale of the heat-handling capacities of vaults which are considerably larger than those of casks. Cooling in vaults occurred by natural air convection with temperature differences of about 15°C between ingress and egress air. Airflow rates for vaults are very large and range between 50-80 cubic metres per second (Scottish Nuclear, 1992b).

23. The Modular Vault Dry Store system in Hungary handles loads of up to 17 kW per tonne of fuel when fully loaded compared with about 1.4 to 2 kW per tonne for concrete casks. Vaults have sufficient heat removal capacity to keep fuel cladding temperatures of 5 year-cooled PWR assemblies below 200°C (Carter and Bower, 1995). Maximum fuel cladding temperature of Scottish Nuclear's planned store was 250°C (Scottish Nuclear, 1992b). On the other hand, concrete and metal casks hold their fuel temperatures near the maxima of 340°C to 360°C allowed by the US Nuclear Regulatory Commission (US NRC, 1996).

24. Gamma and neutron shielding is afforded by 60-100 cm concrete walls (Scottish Nuclear, 1992b). The maximum public dose rate at the perimeter fence 100 metres from the vault was estimated to be 0.8 nSv/hour from the side wall, or 2.1 μSv/year assuming a 30% occupancy rate (Scottish Nuclear, 1992a). A small part of the radiation dose from dry stores to operators and the public was due to skyshine radiation. In addition, doses from gaseous and liquid effluents, mostly from drying operations, were estimated at 2.3 μSv/a, giving a total of about 4 μSv/a (Sumner, 1993). This is low compared to the ICRP recommended limit to a member of the public of 1000 μSv/a from all radiological sources.

25. Table 2.5 compares the main advantages and disadvantages of vaults and casks.

Table 2.5 Advantages of Vaults, Advantages of Casks

CAPABILITY/PROPERTY	VAULTS	CASKS
Large Initial Loading	yes	no
Full Core Discharges	yes	no
High Heat-handling Capacity	yes	no
Keeps Fuel at Lower Temperature	yes	no
Low Marginal costs after 350 tonnes	yes	no
Can Include Transport	no	yes
Good For Small Loads	no	yes
May Meet Disposal Encapsulation Requirements	no	yes
Lower Initial Capital Costs	no	yes
Small Visual Impact	no	yes
Low Marginal Costs below ~350 tonnes	no	yes

Concrete Casks

26. Maximum heat loads in concrete casks are 22 to 24 kW when fully loaded depending on model (Wisconsin Public Service Commission, 1994). Maximum fuel temperatures are 340° to 360°C, depending on fuel type and burnup. Cooling in concrete casks occurs primarily by air ventilation between inner container and outer concrete shield. The maximum volume of air flowing through a BNFL VSC-24 cask is 0.38 cubic metres per second or 825 cubic feet per minute. This air is heated 20° to 32°C above ambient temperatures, depending on the ambient temperature. Some cooling is also provided by radiation and air convection from the outer cask surface. Temperatures of the cask surfaces are a few degrees C above ambient temperatures.

27. Shielding from gamma radiation and neutrons is effected by borated concrete alone, as hydrogen and boron atoms in concrete thermalise neutrons. Maximum calculated dose rates at the side of concrete casks vary from 480 μSv per hour for Vectra Associates' NUHOMS 24P cask to about 600 μSv per hour for BNFL VSC-24 flasks. Maximum calculated dose rates to the public at site boundaries vary with site, ranging between 10 to 60 μSv/a. (All data: Wisconsin PSC, 1994)

Metal Casks

28. Maximum heat loads in metal casks vary between 17 and 27 kW, depending on model. Cooling in metal casks is afforded solely by radiation and convection from outer finned surfaces: inner cores in metal casks are unventilated. Cask surface temperatures are 10 to 20°C above ambient temperatures. Gamma shielding is afforded by the various metals used including steel, iron, and lead. Hydrogen-rich polyethylene inserts in outer shielding provide neutron shielding. Maximum surface dose rates of metal casks are higher than with concrete casks and vary between 800 μSv per hour for Nuclear Assurance Corporation NAC-128 casks to 500 μSv per hour from the German GNS Castor V/21 flask. (All data Wisconsin PSC, 1994).

29. The main operational difference between the two types of casks is that steel casks have no convection cooling and are hotter to touch. The irradiation of insects and airborne bacteria and viruses which enter the ventilation ducts of concrete casks is a health aspect which is rarely considered but which governs German attitudes against ventilated casks as mentioned above (Fairlie, 1995).

Collective Doses Compared

30. Few studies have compared the likely levels of collective doses from reprocessing with that from dry storage systems. This is likely due to the intuition that doses from dry store operations are likely to be considerably lower than reprocessing. The few studies which have been carried out (Sumner, 1993; Fairlie, 1997) verify that this is indeed the case, by a considerable margin. Another study examined individual doses to members of critical groups and found larger doses from reprocessing (Papp and Loser, 1986).

CHAPTER 3. COST COMPARISON OF STORAGE AND REPROCESSING PATHS

Introduction

1. This chapter compares the costs of reprocessing and storage of spent nuclear fuel. Two methods of cost assessment widely used in accountancy - investment appraisal and financial appraisal - will be examined. The former examines all costs of a project through time and discounts these to a base date in order to obtain unit costs, e.g. mills ($0.001) per kWh. Such appraisals are carried out for projected plant, and involve predictions for some time into the future. The discount rate normally used is the required rate of return on the capital used, which is often above the prevailing base interest rate, as the initial capital outlay is usually borrowed. The UK government has used a return rate of 8% during the 1995 Nuclear Review, but higher figures are often used in the private sector. For example, the former Nuclear Electric used 11% for new investment in the Nuclear Review (Nuclear Electric, 1994) and 25% has been used for new nuclear plant in the US (MIT, 1990). Since these discount rates are normally higher than those used for assessing liabilities in financial appraisals, the unit costs arrived at are higher than those calculated using financial assessments.

2. Financial appraisal on the other hand is concerned with existing plant at the present time, and considers annual charges from incurred costs and future liabilities in order to obtain unit costs. Commonly, annual Profit and Loss Accounts of utilities reflect a financial appraisal of their operations. The costs of future liabilities, e.g. reprocessing, decommissioning and disposal, are usually discounted when brought forward to a base date using an appropriate discount rate. The questions of which rate should be used, and indeed whether to discount at all remain unresolved and subject to a wide variety of interpretations[9]. (see McKerron and Sadnicki, 1995) The UK nuclear industry has used a range of discount rates for liabilities from 2% (Nuclear Electric, 1994b) to 8% (BNFL, 1993). The OECD/NEA has used a discount rate of 5% in its analyses but this has been the subject of controversy, i.e. as being too high, within the OECD itself. (NuclearFuel, 1995a).

Discount Rates

3. The questions of whether to use a discount rate and at which rate are important in cost assessments of radioactive wastes. The once-through approach to waste management results in high encapsulation costs which will occur 50 -100 years hence because of the need for spent fuel to be cooled before final disposal, whereas the closed cycle approach has high reprocessing costs which are incurred now. Therefore the use of a relatively high discount rate of 5% to 8% results in the storage route having significantly lower unit costs than the reprocessing route when the costs of the back end of the fuel cycle are compared. This point is illustrated in BNFL's report setting out its economic case for reprocessing (BNFL, 1993) which stated that using a 2% discount rate the cost of abandoning reprocessing would be £430 million, but using an 8% rate there would be a benefit of £180 million.

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[9] in strict accounting procedures, independent financial provision should be made each year so that the amassed capital and assumed interest will cover estimated future liabilities when these arise, i.e. the discount rate would be the market interest rate used. In such cases, unit costs would be the same whether financial or investment appraisal was used. However, in the past most utilities have used such funds as sources of cheap internal finance, thus negating the simple accounting approach.

Differences in views on discount rates have led to differences of view within the OECD/NEA over the correct costs of storage compared with reprocessing (see NuclearFuel, 1995a).

4. A number of studies (MacKerron and Sadnicki, 1995; Neuberger, 1993; and COLA, 1994) have examined the complex issue of which, if any, discount rate should be used in assessing nuclear liabilities. The following points emerge from these studies:-

    - the distinction between discount rates for investment and liabilities should be observed
    - for new investment, the discount rate should reflect the expected rate of return
    - for liabilities, particularly nuclear liabilities, any discount rate should take into account the length of time over which discounting is performed, the share of risk assumed, and the ownership of the assets (i.e. degree to which in public control)
    - any discount rate for nuclear liabilities should reflect political and social wishes, i.e. the desire to ensure that nuclear wastes are properly financed, (i.e. zero or low discount rates should be used), and
    - for reasons of intergenerational equity, it has been proposed (MacKerron and Sadnicki, 1995) that there should be no discounting beyond the present generation, i.e. 30 years.

5. None of the studies examined below, with the exception of the OECD studies, employs discount rates in their analyses. Indeed some of the German studies employ relatively simple ‘snapshot’ examinations of all the backend costs of the fuel cycle. While these examine costs in some detail, chronological differences in fuel flows and expected costs are ignored. The study by the Energiewirtschaftliches Institut at Koln University presents a sophisticated analysis over time, although it too refrains from employing a discount rate. Both kinds of studies have advantages and disadvantages, but for comparison purposes either type is acceptable.

Cost Comparison of Routes

6. Comparative studies of storage and reprocessing routes conventionally require examination of the costs of all stages of the fuel path from reactor discharge through to final disposal in a permanent repository. Final repositories, encapsulation plant and disposal technologies are at the early stages of research or development throughout the world. Therefore many assumptions must be made about these technologies and their timings in the future. Assumptions also have to be made about methods of transport, future regulatory requirements, and interim storage methods. All these assumptions may have strong effects on costs. For example, the smaller and more compact an underground repository, the less expensive it is per unit volume of waste. This means, other things being equal, that the longer the storage period before emplacement, the less expensive the repository, as less heat has to be dissipated, thus requiring less volume to be excavated. The choice of geological medium is also important, as clay tunnels require expensive lining. The choice of barrier system and the use or non-use of separate disposal containers also significantly affects costs. Different studies use different assumptions, and in some studies, these assumptions are not made clear.

7. In addition to technical and timing assumptions, cost estimates depend crucially upon the views taken on the following matters:-

- values (whether positive or negative) of plutonium and uranium separated during reprocessing
- on the view taken of the commercial viability of MOX fuels
- on whether MOX fabrication costs should be included in reprocessing costs.
- or on whether reprocessing costs should be included in MOX costs (at present they are not, which is perhaps surprising), and
- discount rates to be applied.

8. In many studies, these matters are not treated explicitly, but it can usually be gleaned what view is taken on some of the above matters. In other studies, it is impossible to ascertain what views are taken. For these reasons, this examination will concentrate on three major studies in which the above matters are considered in some detail. These are the German utilities studies, the OECD/NEA study and the EWI study at the University of Koln.

German Utilities Studies

9. After the 1994 amendment to the German Atomic Act which permitted nuclear utilities to store as well as reprocess spent fuel, German utilities re-examined their previous commitments to post-2000 reprocessing contracts with Cogema and BNFL. In December 1994, two German utilities cancelled their reprocessing contracts with BNFL (NuclearFuel, 1995d). In addition, 1994 German utility contracts with Cogema are mainly for the storage of spent fuel, rather than its reprocessing (NuclearFuel, 1994a).

10. The tables below list studies carried out by three German institutes, the Rhine-Westfalische Energie (RWE) utility, the Vereinigung Deutscher Elektrizitatswerke (VDEW) the German Fuel Industry Association, and Projekt Andere Entsorgung at the Kernforschungszentrum Karlsruhe (PAE-KfK) a government-funded research agency. These predict that direct disposal is approximately 50% to 70% less expensive than reprocessing. German utilities' cost estimates will have been carefully carried out, as back end costs of the fuel cycle have a strong influence on anticipated profit and loss margins. Strictly speaking, these studies are not directly comparable because of the slightly different assumptions employed and different values in the currencies at various times. However their ratios in the final column may be usefully compared. The VDEW study on storage cost estimates was published by the VDEW but carried out by economists from VDEW and RWE. Therefore the RWE estimates <u>for storage</u> are the same as the VDEW estimates.

Table 3.1 Costs of Reprocessing Route

US$ Per Kg Heavy Metal

	RWE	VDEW	KfK- PAE
YEAR	1994	1993	1993
Spent Fuel Transport Germany to France	117	125	78-96
Reprocessing Incl. financing	1090	1175	1600 (1979) 970 (1989)
Return of residues, internal transport and interim storage	260	590	240
Final disposal	500	590	500
Uranium Utilisation: (conversion, interim storage and processing	117	117	-
Plutonium: transport and 5 years `storage	117	117	-
Additional MOX costs	300	-	-
TOTAL COSTS	~2500	~2900	~1800 (1989)

Table 3.2 Estimated Costs Of Direct Disposal Route Us $ Per Kg HM

	RWE (same as VDEW)	VDEW	KfK- PAE
Transport to Condition Plant	30	30	78-96
Interim Storage in CASTOR	300	300	220
Conditioning and POLLUX costs	470	470	300-425
Storage and PKA waste costs	117	117	-
Final Disposal costs	590	590	500
TOTAL COSTS	~1700	~1700	~1200

discount rate = zero

Table 3.3 RATIO OF REPROCESSING COSTS TO DIRECT DISPOSAL COSTS

	RWE	VDEW	KfK- PAE
Ratio	1.5	1.7	1.5

sources: KfK PAE. Paper presented to the Bundestag, November 5, 1993. See NuclearFuel (1993b). Rhine-Westfalische Energie. Report ON2-TSSA. 1994. VDEW. As reported in NuclearFuel (1994d).

11. Other national studies agree with these studies. A report by the German Federal Rechshoffhaus (BRH, 1993), the German parliamentary audit office stated that reprocessing had become twice as expensive as storage, and that reprocessing was no longer feasible. In a report prepared for the Irish government on THORP, Berkhout (1993d) estimated, using conservative assumptions, that dry storage/disposal costs were approximately half reprocessing/disposal costs.

OECD/NEA Study

12. In 1994, the OECD/NEA published the report of an expert group which examined levelised lifetime fuel cycle costs using investment appraisal methodology (OECD/NEA,1994). Costs were derived for fuel cycles based on both reprocessing and storage followed by direct disposal. The report, unlike the

other studies in this chapter, was concerned to develop fuel costs averaged over the whole fuel cycle, rather than the back end of the cycle. The consequence is that the relevant costs are calculated on a lifetime cost basis, and are not discounted to a commencement date. This resulted in the report's main conclusion that reprocessing and once through costs were about equal.

13. However the then chairman[10] of the OECD Expert Group which drafted the report repudiated the report's presentation and its main conclusion (NuclearFuel, 1995a). The chairman stated that, in practice, back end costs were not spread over the whole fuel cycle, and that reprocessing costs were incurred immediately. On the other hand, most storage, and all encapsulation and disposal costs would occur many years hence and could be discounted at 5% over decades. Cogema, whose directing manager was then chairman of OECD's Steering Committee for Nuclear Power, replied stating that discounting to this extent was inappropriate (NuclearFuel, 1995d). The OECD did not resolve this issue.[11]

14. The figures in tables 3.4 and 3.5 below reflect the view taken by the Chairman of the Expert Group. This approach is preferred as it reflects more accurately the present position of utilities and governments faced with the decision between storage and reprocessing. The figures indicate that in the reference case the predicted costs of the storage route were less than half the predicted costs of the reprocessing route.

Table 3.4 OECD Predicted Costs of Reprocessing

1991 US $ per Kg HM. Costs Discounted at 5% to year 2006.

	REFERENCE CASE	RANGE
Transport within Europe	50	20-80
Reprocessing (include all costs except vitrified HLW disposal)	720	540-720
Vitrified HLW Disposal	5	5-30
TOTAL COSTS	775	565-830

source: OECD, 1994

Table 3.5 OECD Predicted Costs of Direct Disposal

in 1991 US $ per Kg HM

	REFERENCE CASE	RANGE
Transport/Storage	230	60-290
Encapsulation/Disposal	110	25-120
TOTAL COSTS	340	85-410

source: OECD/NEA (1994)

Note: these costs are as reported in the OECD Report's executive summary, as amended by the chairman of the OECD Expert Group in his letter to NuclearFuel (NuclearFuel, 1995a).

15. The main conclusion as reported by the chairman of the OECD Expert Group is that storage is predicted to be half the cost of reprocessing. This agrees with the German studies above. However in

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[10] Dr. David Groom of Nuclear Electric

[11] this is a rare example of the surfacing of the very deep conflicts between pro and anti reprocessing proponents in the nuclear industry

absolute terms, predicted OECD costs are considerably lower than the German predicted costs, mainly due to the OECD's use of a discount rate. The OECD report was criticised by the authors of the EWI report (Hensing and Schulz, 1995), see next paragraph, for the use of unrealistic assumptions which substantially reduced the estimated costs of reprocessing. These assumptions included

- postponement of reprocessing to the year 2006,
- unrealistically high uranium prices,
- new reprocessing plant being built,
- a low price for reprocessing services ($720/kg c.f. the price quoted by EWI for German utilities for reprocessing at Cogema of $1560/kg in March 1994),
- a low price for MOX fuel fabrication ($1100/kg c.f. current price quoted by EWI for German utilities of $2600/kg).
- a positive value for plutonium ($5,000/kg) and uranium ($33-$135/kg) extracted from reprocessing.

16. These assumptions are, to say the least, not widely followed. BNFL (1993), for example, uses a zero value for its stock of recovered plutonium and uranium and Berkhout (1993a) uses a negative value for recovered Pu. These assumptions have the cumulative effect of decreasing the costs of reprocessing and increasing that of the storage route. For these reasons, the OECD report's estimates of reprocessing costs have limited applicability.

EWI Report

17. The Energiewirtschaftliches Institut (EWI) at the University of Koln evaluated various waste disposal options from the viewpoint of a nuclear utility (Hensing and Schultz, 1995). The EWI Institute is highly regarded by, and has close working contacts with, the German nuclear industry. The study carried out a comprehensive financial appraisal of both the storage and reprocessing routes using a zero discount rate. It concluded that direct disposal had a clear cost advantage over the reprocessing option with the disposal option cost (0.718 pf /kWh) being 33% lower than that of the median case for reprocessing (1.064 pf/kWh). Calculated over the German nuclear industry, the cost advantage amounted to 31.5 million DM, or $20 million, per year. The report stated that its estimates of disposal costs were lower than those calculated by the German Fuel Industry Association due to the higher fuel burnups assumed in the EWI scenario.

18. The study carried out sensitivity analyses to ascertain which factors exerted important effects over final costs. For both options, the most important attribute was the operating cost of the final repository. Price variations in various stages of the back end of the fuel cycle, with the significant exception of reprocessing, did not affect the overall result. The report concluded that, with its cost disadvantages, reprocessing could only be justified if nuclear energy were to be maintained in the long term, well after 2040.

Comparison of costs per kWh

19. Table 3.6 sets out the results of various studies (including the above three studies) comparing costs per kWh of storage/disposal and reprocessing options. Strictly speaking, these studies are not directly comparable because of different assumptions employed and different values in currencies at various

times, however the ratios in the final column may be usefully compared. It is apparent that storage/direct disposal is consistently less expensive than reprocessing, whatever method, part of the fuel cycle, or discount rate is used.

Table 3.6 Fuel Cycle Costs

Pfennig/kWh 1994

STUDY	Costs Compared	Discount Rate	A.Reprocessing	B.Direct Disposal	Ratio A/B
KfK/EWI (1984)	Back-end	0%	0.56	0.38	1.47
OECD/NEA (1985)	Complete fuel cycle	5%	>2.17	1.97	<1.1
Fichtner (1991)	Back-end	0%	0.97	0.63	1.54
VDEW (1993)	Back-end	0%	1.53	0.91	1.68
OECD/NEA (1994) (reference case) Lifetime levelised+	Complete fuel cycle	5%	1.25	1.09	1.15
OECD/NEA (1994) (reference case) Discounted++	Back-end	5%	0.36	0.15	2.4
EWI (1995)	Back-end	0%	1.064	0.718	1.48

current prices in year of study, except OECD- in 1991 $.

+ reported as "lifetime levelised fuel cycle costs"

++ reported in tables 5.7 and 5.8 (pages 59 and 64) of the report as sub-totals for the back-end of the fuel cycle. The OECD calculated these by discounting to the year 2006 using a 5% discount rate. These figures were explicitly referred to by the chairman of the OECD study group in his intervention (NuclearFuel, 1995a) following the publication's report. The disjunction between discounted and lifetime levelised estimates is not discussed in the OECD report.

sources: - as referenced. VDEW- as reported in NuclearFuel (1994d).

CHAPTER 4. COST COMPARISON OF SINGLE STAGES

1. As stated above, cost comparisons of complete fuel paths are dependent on assumptions about future repositories, future regulatory requirements, and their timings. They also depend on views taken about future discount rates, and currency values. These matters are difficult to predict and cost accurately, as in most cases these developments will occur many decades in the future. Such pathway studies also are predicated on the view that spent fuel is not a suitable waste form for final disposal and that extensive encapsulation may be required. Recent studies (Boyle et al, 1993; Wuschke, 1996) indicate that this is not the case, and that ceramic fuel is more resistant to leaching than vitrified wastes. In other words, estimations of the costs of future elaborate encapsulation strategies which may never occur are at least questionable and probably irrelevant.

2. On the other hand, single stage cost comparisons are considered more practicable, relevant and useful to utilities faced with the choice of deciding on future waste policies. Accordingly, this section collates estimates for the single stages of reprocessing and of storage and compares them. In contrast to the costs of complete paths, single stage costs do not include estimates for encapsulation and disposal repositories in the distant future.

3. However there are difficulties as well with single stage cost comparisons. It is often difficult to distinguish which waste management services are included or excluded in a given reprocessing price. Also, it is often difficult to ascertain the time periods for how long the storage, or post-reprocessing services are to last, as these details are usually excluded from public accounts. This may not be important in the case of dry storage costs as these are mostly the construction costs. Once cask storage systems have been built and casks loaded, maintenance and running costs are minimal.

Estimated Costs of Dry Storage

4. Cost estimates of dry storage from various studies are listed in table 4.1. The data in this table are not directly comparable because different assumptions, financial conventions, years for currencies, and exchange rates are used in their calculation. Also, estimates of storage costs which are expressed simply in $ per tonne should be treated as approximate, as costs also will depend on the length of time that fuel is expected to be retained. This is often not stated in industry estimates or is indeterminate, as in the SN-BNFL 1995 agreement. A more precise indication of estimated costs would be expressed in costs per tonne per year, but this is rarely stated. Nevertheless the data in the table report the figures from a number of studies which can be used to give an approximate indication of estimated dry store costs in various situations.

Table 4.1 Estimated Dry Storage Costs

STUDY	LWR FUEL $,000/tonne
KfK-PAE (NuclearFuel (1993b)*	220
OECD-NEA (1994)++	225
IAEA (1990)	82-165
Supko (1995)+	50-100
Wisconsin PSC (1994)#	35-68
Ontario Hydro (Stevens-Guille, 1994; Nash, 1997)	15-20

+representative life cycle costs
++levelised fuel cycle costs
#constant $ analysis
* undiscounted

5. From table 4.1 above, it is seen that German institutions give undiscounted estimates of about $225,000 per tonne of LWR fuel over indeterminate periods. Relatively expensive Castor casks were used in these calculations. Estimated costs of US and Canadian dry storage systems are significantly lower than European systems. These systems and the reasons for their lower costs are discussed further in Chapter 5.

Estimated Reprocessing Costs

6. Costs of the single reprocessing stage were estimated by the OECD/NEA (see table 3.4 above) to range between $540,000 to $720,000 per tonne of fuel, using 1991 $ discounted at 5% pa to year 2006. There are few other available studies which discuss reprocessing costs. These costs are compared to dry storage costs in table 4.2 below.

Table 4.2 Estimated Costs of Reprocessing and Dry Storage

$,000 per tonne of fuel

	OECD Reprocessing costs	European Costs of Dry Storage	US Costs of Dry Storage	Canadian Costs of Dry Storage
Year of Currency	1991	1993-1994	1994-1995	1996
Cost	540-720	220	35-68	15-20
x less expensive		~ 2-3	~ 8-20	~ 30-50

7. The data above relate to different time periods re: currency, and use different assumptions and conventions, but it can still be seen that reprocessing costs are roughly about 2 to 3 times higher than European dry storage costs which use the expensive Castor systems. If US or Canadian systems are included, the differences widen considerably to at least ~8 and ~30 times less expensive respectively. It is stressed that this table should only be used to make a broad comparison of costs. Given the paucity of available cost comparisons, this study at least provides some information for approximate comparisons.

8. It will be recalled that the estimated cost of the overall reprocessing path was a factor of 0.5 to 0.7 greater than the estimated cost of the overall storage path. The cost difference between paths and stages is due to the extremely high encapsulation and final disposal costs (similar for both paths) which dominate matters. In the stage comparison these costs are eliminated and differences between the individual stages become much clearer.

CHAPTER 5 COSTS OF DRY STORE TYPES

1. An older study (IAEA,1990) compared the costs of casks and vaults: the main finding is that after about 350 tonnes, the marginal cost of storing fuel was lower in vaults. This represents approximately 14 years' fuel output from a 1,000 MW PWR reactor at 35-40,000 MW days/tonne.

2. A major difference between vault and cask systems is that vaults provide only storage, whereas casks may also satisfy transport regulations and be suitable for final disposal in a repository, depending upon future regulatory criteria. Marginal costs of dual-purpose casks designed to observe the tighter safety criteria in transport regulations are higher than vault systems costs. This means that comparison studies of estimated costs should examine fuel handling and transport costs as well as vault/cask costs. In European practice, this means that vaults, other things being equal, will be more cost effective for at-site storage and casks will probably be more cost effective for fuel to be transported to a central site. Castor and NAC casks, for example, are designed for transportation.

3. The upshot is that cost comparisons of cask systems involve uncertainties, as costs may include estimates of transport and encapsulation costs. These require predictions or assumptions of transportation standards which are likely to be improved over time, and predictions of future repository standards. A further refinement is the choice between steel and concrete casks. The US Electrical Power Research Institute has concluded that concrete casks had incremental total system savings of 10% to 20% over metal casks (Lambert et al, 1993). This was primarily due to the less expensive material costs of concrete casks. In terms of immediate storage, i.e. ignoring future transportation and encapsulation stages, concrete casks offered utility operators 58% savings over the cost of steel casks.

4. In Chapter 4, it was stated that US and Canadian dry storage systems were much less expensive, per tonne of fuel stored, than their European counterparts. This is partly due to lower US/Canadian finance costs, land charges, construction costs and raw material costs. It is also due to the greater R&D and faster development of dry storage technologies in the US because of the strong pressures on many US utilities to come up with solutions to their shortage of wet store capacities. A final factor has been the continuing competition between the half dozen cask vendors in the US. Canadian costs are considerably lower due to the low burnups of Candu fuels which typically exit at 6,000 MWdays per tonne, i.e. about 6 to 8 times lower than the current range of exit burnups for French PWR fuels, - 35,000 to 45,000 MW days per tonne.

5. All of these factors have led to significantly lower costs of US/Canadian concrete casks than European steel/iron casks (Wisconsin PSC, 1994), as seen in table 5.1 below. Cask costs account for about two thirds of total storage costs over a 20 year period (Supko, 1995), with the remaining costs due to construction of operating, drying and loading facilities.

6. In 1994, the Sacramento Municipal Utility District constructed a dry store for fuel from its closed reactor at Rancho Seco in California. The utility predicted (Bowser et al, 1994) annual operating costs for the proposed dry store of $2.6 million, with planning and construction costs of $12.4 million for the transportation and dry storage system. Over a 20 year period, total undiscounted costs would be $64 million, or approximately $280,000 per tonne.

7. Supko (1995) predicted dry storage costs of an operating nuclear utility whose storage costs were permitted by its Public Utility Commission as an operating overhead and thus charged to electricity ratepayers (NuclearFuel, 1993a). As a result, operating and insurance costs were significantly lower than those at a closed site. Estimated representative life-cycle costs over a 20 year period for a 500 tonne dry store were $34 to $50 million, or $68,000 to $100,000 per tonne. These are considerably lower than the costs at a closed reactor. This indicates that the allocation of costs to ratepayers is an important matter in examining back end costs.

8. The Wisconsin PSC study (1994) compared total costs of a range of cask dry storage systems, using the following assumptions:
   - reactors operated until 2015,
   - storage costs would be charged to ratepayers,
   - storage would be for 15 years between 1995 and 2010 when the US DOE would begin accepting spent fuel,
   - 42 casks holding 714 tonnes would be needed, and
   - using a constant 1994 $ analysis.

The study calculated total costs ranging from $35,000 to $68,000 per tonne, as set out in table 5.1 below.

Table 5.1 Comparison of Dry Store Casks

Type	VSC-24	NUHOMS-24P	TN-24	TN-40	NAC-128	Castor V-21
Manufacturer	BNFL Inc	Vectra	Trans-nuclear	Trans-nuclear	Nuclear Assurance	GNS
Country of Manufacture	US	US	Ger-Bel-Neth	Ger-Bel-Neth	US	German
Air Ventilated	Yes	Yes	No	No	No	No
Cask Material	Steel-reinforced Concrete	Steel-reinforced Concrete	Pressure Vessel Steel	Pressure Vessel Steel	Stainless Steel, Lead	Ductile Cast Iron
Max No PWR Assemblies	24	24	24	40	26-31	21-28
Cost per cask	$300,000	$380,000	$900,000	$700,000	$1,040,000	$800,000
Estimated Cost per tonne	$35,000	$38,000	$62,000	$40,000	$68,000	$57,000

source: Wisconsin PSC (1994)

9. Clearly, major differences exist between the costs of casks. These are due to their differing performance characteristics required by their national regulatory criteria. Casks designed to withstand high operating heat loads, and high impact stresses (e.g. from missiles or aircraft) are more expensive than those that are not. In addition, casks designed with future transport and/or disposal requirements in mind, are more expensive than those designed solely for storage. A major factor is whether casks are cooled by air ventilation or not. Such casks are less expensive than sealed containers, as they dissipate heat by inner convection as well as radiation, thereby eliminating the need for expensive machined metal containers. However such casks are limited in their performance capabilities in that they are generally not able to be used for transport or

disposal, and have lower impact capabilities. Nevertheless their high heat-handling capacity combined with low cost are attractive features for US utilities.

10. Even lower estimated costs of $15,000 to $20,000 per tonne have been cited by Ontario Hydro[12] (Stevens-Guille and Pare, 1994; Nash, 1997) for its planned 40,000 tonne dry storage facility. This will eventually employ more than 6,000 steel and concrete containers which are unventilated. These low estimated marginal costs are due to a number of factors including
    - simple design reflecting straightforward regulatory requirements,
    - economies of scale from standardised design/production
    - avoidance of high capital costs as canisters are constructed when required and stored in the open on a concrete pad,
    - access to low cost finance by the Government-owned corporation,
    - ability to charge costs to electricity tariffs, and
    - less shielding and lower heat capacity required for low burnup CANDU fuels (~6,000 MWdays/tonne).

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[12] Now named Ontario Power Generation Ltd

CHAPTER 6 CONCLUSIONS

1. This report has examined world-wide trends and developments in the management of spent fuel. It has revealed that most (>75%) fuel arisings are stored and that most countries are moving towards storage as a medium-term strategy for spent fuel. Almost all new developments in spent fuel storage concern dry rather than wet storage.

2. In view of these developments, this report has examined dry and wet storage systems in detail, in particular their operating characteristics and long term safety capabilities. For waste management policy, an important issue is the degree to which dry storage may be considered a viable long-term option for managing spent fuel. It is concluded that dry storage in inert gas presents relatively few theoretical or practical difficulties. The IAEA has concluded after reviewing national experiences of dry storage that it is an acceptable waste management option for the storage of spent fuel for periods of 50 to 100 years (IAEA, 1994) by which time heat rates have declined by two orders of magnitude. The anticipated longevity of dry stores (50 to 100 years) is expected to exceed that of wet stores (Schneider and Mitchell, 1992a). It is concluded that passive dry storage systems appear to be an acceptable means of dealing with spent nuclear fuel in the medium term.

3. The report then compared costs of the reprocessing path with the storage path, and revealed differences within the NEA/OECD concerning attempts to mask higher costs of the reprocessing route compared to storage. More reliable German studies confirmed these higher costs.

4. Moreover, the insistence by the NEA/OECD on comparing fuel path costs instead of the more relevant fuel stage costs is considered unhelpful. When the latter are compared, large differences in costs become apparent: reprocessing costs are clearly greater than storage costs. And if US and Canadian systems are compared, the cost differentials become greater still. US dry storage systems for PWR fuel are estimated to be 8 to 20 times less expensive per tonne than reprocessing. Although, due to the paucity of data, it is difficult to make exact comparisons (e.g. using the same currency years, and discount rates), it is still clear that dry storage systems have lower per tonne costs than reprocessing. Depending on the system chosen, dry storage costs can be considerably lower than reprocessing costs.

5. Environmental and local groups in some countries have not opposed dry storage developments. This was evidenced by the 1987 agreement among major UK environmental groups, supported by over 40 regional and local groups, to a collective strategy of long-term on-site storage. Under this plan, waste would be stored where the waste was generated in facilities designed to optimise monitorability and retrievability (CORE, 1987). A US anti-nuclear research organisation concluded that on site dry storage was needed to resolve capacity problems of reactor operators, to reduce the temperature of spent fuel thus reducing degradation risks, and to reduce transportation risks (IEER, 1989). During the 1992-1994 UK public inquiry into Scottish Nuclear's dry storage plans, no environmental group made representations against the plans.

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6. In France, as in the UK, the obstacles to the adoption of dry storage technology are the political, industrial and financial interests[13] committed to reprocessing. This results in the philosophical unwillingness of senior managers within industry and Government departments to even consider the issue of dry storage. Dry storage is apparently not in their frame of reference. The overall conclusion is that, despite considerable apparent advantages of dry storage over reprocessing, the exceptionally large resources, political commitments and institutional investments in reprocessing in France are expected to continue to hinder dry storage developments in France in the immediate future.

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[13] However, at least one French company, Alsthom Automation, has extensive experience and business interests in dry storage.

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