ES7800223

INIS-mf--4471

COMPARISON OF CONCEPTS FOR INDEPENDENT SPENT FUEL STORAGE FACILITIES

Ch. Held, H.P. Hintermayer
Kernkraftwerk Planungsgesellschaft m.b.H. (KKWP)
Vienna, Austria

The design and the construction costs of independent spent fuel storage facilities show significant differences, reflecting the fuel receiving rate (during the lifetime of the power plant or within a very short period), the individual national policies and the design requirements in those countries. Major incremental construction expenditures for storage facilities originate from the capacity and the type of the facilities (casks or buildings), the method of fuel cooling (water or air), from the different design of buildings, the redundancy of equipment, an elaborate quality assurance program, and a single or multipurpose design (i.e. interim or long-term storage of spent fuel, interim storage of high level waste after fuel storage). The specific costs of different designs vary by a factor of 30 to 60 which might in the high case increase the nuclear generating costs remarkably. The paper also discusses the effect of spent fuel storage on fuel cycle alternatives with reprocessing or disposal of spent fuel.

1. INTRODUCTION

In view of the delays in irradiated fuel reprocessing it became obvious for different reasons that various spent fuel management alternatives will be of importance as more power reactors discharge fuel and the quantity of spent fuel to be stored before reprocessing or before final disposal becomes greater and can not be stored any more in the storage pools at the power plants. The shortage of spent fuel storage capacity envisioned for the upcoming decades causes wide interest in the technology, expenditures, and construction of an independent spent fuel storage facility. Consequently, different types of independent storage facilities have been designed in various countries. These facilities show considerable difference in design and associated costs making it an obvious task to analyse the reasons for significant peculiarities.

The paper also discusses some general design considerations concerning the objectives, the cooling principle, the arrangement of components, the location and the siting of such a facility. Special consideration will be given to a storage plant designed to requirements in Central Europe.

Emphasis must be placed also on the cost of a storage facility relative to countries with a limited nuclear power program and to the favoured fuel cycle alternative with or without reprocessing.

2. DISCUSSION OF VARIOUS BASIC FACILITY ARRANGEMENTS, FUEL COOLING PRINCIPLES, LOCATIONS, AND SITES

2.1 Basic Facility Arrangements and Fuel Cooling Principles

One of the basic decisions affecting the selection of the fuel cooling principle will be the storage period the facility must be designed for. If reprocessing of the stored fuel is expected within a few decades then storage in water pools should be an appropriate solution readily available. The wet storage principle is based on proven technology which allows for the immediate construction of a facility.

However, if long storage periods are anticipated it might be useful to consider the dry cooling of the fuel. Since any dry cooling principle requires the encapsulation of the fuel assemblies the dry storage mode will adversely affect the accessibility of the fuel if reprocessing of the stored fuel once will commence. The reduced accessibility of the encapsulated fuel may be offset by a reduced corrosion rate of the fuel canister and minimum construction and operating cost of the storage plant.

The fuel cooling principle also is closely related with the possible basic arrangement i.e. buildings or casks of the facility which is most significant for the construction and operating cost of the storage plant. Wet storage of spent LWR fuel requires the construction of a closed building or the construction of a storage vault as for the storage of HWR fuel. Dry fuel cooling may be effected also in a storage vault but additional alternatives like single or multiple fuel assembly sealed storage casks are considered also.

The fuel cooling principle will also be related to the construction site of a facility where in the case of independence of a parent plant or non-availability of water as a heat sink provide additional advantage of the air cooling.

Previous decay times of the fuel will be of importance to dry cooling but will not entail insurmountable design problems.

Estimates of the construction and operating expenditures of dry and wet storage plants indicate an incentive for further evaluation of air cooled arrangements. However, the relative cost advantage is not only dependent on the design of the dry storage facility. Any such comparison will be effected by the national requirements and site conditions the storage plant will be designed for.

In addition to storage buildings and vaults, much attention has been given to the design of sealed storage casks recently. Various design proposals and test results have been reported from Canada and the U.S.A. Preliminary studies indicate that the economics of this approach will depend strongly on the individual design of the cask e.g. the number of spent fuel assemblies emplaced in one cask will become a major parameter. The economic analyses of the surface storage cask concept show that this concept might become a promising future alternative. However, some specific problems have yet to be solved before this design will be ready to use. This design thus is not discussed in great detail.

2.2 Facility location

The location of a storage plant might be similar to those suggested for a high level waste storage facility located either above or below ground level. A location below ground level may be close to the surface, raising similar problems as those discussed for the underground location of a nuclear power plant.

The preferred arrangement of an underground facility might be to locate just the storage pools below ground level and to arrange all the other buildings and equipment which need not be protected above surface. This arrangement was suggested in Northern Europe where the subsoil properties favour the excavation of solid rock caverns.

To follow the various arrangements suggested for the storage of high level wastes, one also might consider to store fuel at the depth of some 100 meters, envisioned for the location of an ultimate repository for high level wastes. This suggestion might prove useful especially if a high level waste repository is required anyway which eliminates the need for separate installations above ground. In this arrangement, cooling would be effected by natural draft of the ambient air. The lengthy shafts of the repository will provide enough draft to overcome the flow resistance of HEPA filters. However, the fuel to be stored would have to be bottled previously to its emplacement.

An independent fuel storage facility would normally not be located in the deep ground because site selection would be restricted to particular geologic formations and the necessary drilling and evaluation of the subsoil would require excessive lead time before actual construction can start. The usual location of such a plant will normally be above ground and most of the present designs suggest a surface location.

2.3 Facility Site

A major parameter affecting the design and cost of a facility will be the construction site of the plant. Co-location of the storage pool at an existing reactor site will have several advantages: Site parameters will be available readily, site access of the power plant can be used and auxiliary services of the power plant like off-site and emergency power, water supply, waste water treatment, waste solidification, and others might be utilized to some extent. However, any additional release of radioactivity at the common site has to be considered. A reduction of the operating cost would also result if the operating personnel of the power plant will be involved in the operation of the storage facility.

If a particular construction site is not defined, hypothetical site parameters may be established which should envelop the site parameters of a variety of conceivable construction sites. The most limiting site parameters would result if a dry site without the availability of the minimum cooling water requirement is included in the scope of sites. This, however, will provide the flexibility to locate the storage facility at any site suitable for a medium industrial plant. Such a flexibility might prove useful if the co-location of the fuel storage facility and an ultimate repository for fuel or high level waste will become desirable.

The desired siting flexibility suggests also to reduce the estimated off-site dose rate of the storage facility to a number well below the off-site dose of a power plant. This also would reduce any siting problems.

The following paragraphs deal with the objectives and considerations which resulted in the design of a wet and a dry storage facility according to requirements in Central Europe.

3. THE DESIGN OF A WET STORAGE FACILITY ACCORDING TO REQUIREMENTS IN CENTRAL EUROPE

In some countries in Central Europe a few independent wet storage facilities were designed having a capacity from 500 t to 3000 t of uranium. These facilities are somewhat similar in design, each one having an aircraft crash-proof building and each one being designed to meet German standards and a design philosophy developed for standard nuclear power plants in Germany.

As an example for a storage facility satisfying a multitude of various requirements, the smallest of these plants having a capacity of 500 tons will be discussed in some detail.

Key objectives for the design of this plant were the assumption of unfavourable site conditions for a nuclear installation in Central Europe. In addition, a dry site remote from any appreciable water supply and a safe shutdown earthquake of 0.2 g was assumed. The facility is designed to receive spent fuel only from one power plant throughout its economic life of 20 years. Spent BWR core components i.e. control rods, fuel channels and incore instrumentation would also be accommodated in the storage facility.

Fig. 1 gives a plan view and sections of this plant. This building accommodates all safety related components and all equipment containing radioactivity. The main areas which are the area accommodating the storage pools, the shipping cask handling space and the section housing the auxiliary equipment, are arranged from the left to the right.

The outside dimensions of the building will be about 96 m length, 44 m height and 37 m width. The assumed need for protection against the impact of an aircraft limited the building width to less than 40 m. This limitation resulted from the detailed design of the reinforcements of the building's roof. The required wall thickness resulting from the aircraft crash-proof design is about 2 m of reinforced concrete. A second building shell is arranged inside the outer building. This second shell allows for the installation of the system components simultaneously with the construction of the outer building, which saves total construction time.

The desired flexibility for any possible extension or design modification suggested to arrange the pool area and the auxiliary equipment area at the periphery of the fuel building.

Transport containers enter the building by means of a special trolley being loaded in the cask receiving building. The fuel is unloaded from the cask after its content is cooled and cleaned by a special closed circuit system connected to the cask temporarily.

The pools are devided into four separable compartments, three of them providing a capacity of 500 tons. One of the pools is a spare only needed during conversion from wet to dry cooling to be discussed later. This spare pool would also be useful as a separate compartment where the cask would be unloaded and the fuel be sipped for leaks.

The pools will be equipped with racks of standard design which provide enough space for the storage of bottled fuel assemblies.

Two thirds of the building will be occupied by the auxiliary equipment area being an integral part of the aircraft crash-proof building.

The design of the plant is completely independent of any parent plant and includes all necessary equipment for a nuclear installation. The most spacy systems are those for the treatment of radioactive wastes, the emergency diesel generators, the control room, electric equipment and building ventilation.

The residual heat of the fuel is removed by three redundant cooling systems each at a capacity of 50 %. Fig. 2 shows the general arrangement of this system, its associated closed circuit, secondary and external portions.

Cooling would still be effected if only one cooling line remained operable. In this case, the pool temperature would rise from a normal 40°C to less than 60°C.

The system is rated at 2.4 MW. This small a capacity resulted from the relatively small fuel receiving rate of about 100 BWR fuel assemblies per year. The additional heat input of various other auxiliaries - the diesel generators and the air conditioning - requires a design capacity of the downstream equipment of 6 MW.

In case the supply of make-up water to the wet cooling towers is interrupted, continued cooling is provided by dry coolers arranged in parallel to the wet cooling towers. This not only provides adequate redundancy but also diversification of external cooling equipment.

External wet and dry coolers are separated from each other preventing simultaneous destruction of all cooling equipment in the case of an aircraft crash.

The plant is estimated to produce secondary waste at a rate of about 30 to 40 m^3 of solidified spent resins and miscellaneous wastes per year.

Concerning the release rate of radioactivity the objective was to limit the facility's off-site dose to much less than the off-site dose of a power plant. This was intended primarily in order to reduce any possible siting problems. With respect to lack of experience in the long term leakage rate of spent fuel a hypothetical leak rate of the fuel was established. A typical leak rate reported from reactor hot operation was assumed which resulted in a one year peak emission rate of about 50 Ci of the dominant Krypton-85 which equals about 0.02 mrem/yr.

Should at any time an indication exist of an accelerating fuel damage rate then fuel can be isolated in the sealed canister reducing the emission rate to below insignificant numbers.

Inside the fuel building space was also reserved for the installation of a separate system to absorb the Krypton by means of low temperature charcoal beds. This would eliminate the need for the encapsulation of leaking fuel but require the covering of the fuel pools and the installation of the retention system.

Waste water will be decontaminated by high efficiency evaporators and recycled to the maximum possible extent. Waste water to be released is cleaned to a concentration of 10^{-7} Ci/m^3 which - with respect to the dry site - does not require any further dilution with non-active water.

The plant originally was intended to store fuel for several decades before fuel reprocessing would become available. The uncertain further time schedule and the discussion about an indefinite deferral of reprocessing required to consider also the long term storage of unreprocessed spent fuel.

The assumption of very long storage periods of more than a few decades makes it evident that additional barriers for the safe isolation of the radioactivity stored will have to be included. The resulting measures amounted in the provision of a hot cell where fuel would be bottled, backfilled with lead and then sealed by welding. Additional consideration was given to long term storage of canned fuel when the pool water is drained and cooling is accomplished by natural circulation of the air inside the storage pools.

Fig. 3 gives a schematic sketch of the cooling principle and the associated equipment needed. This cooling mode can already be introduced after a previous cooling period of only a few decades. Longer cooling periods will allow for the heat to be removed solely by heat conduction of the building walls.

One of the further design objectives was the accommodation of high level wastes in the water pools of the facility once the pools would be emptied and fuel be taken to reprocessing. This double purpose of the plant could eliminate the need for a separate storage installation for high level waste for the case that these wastes will be returned from reprocessing before the residual heat has decayed to any desired minimum or before an ultimate repository becomes available.

4 A DRY STORAGE FACILITY DESIGNED TO REQUIREMENTS IN CENTRAL EUROPE

In addition to the wet storage plants, a dry storage facility was designed for a location in Central Europe. The purpose of this project was to show the general feasibility, the cost for construction and operation and to pinpoint particular problems yet to be solved. This storage project should serve as a further example how long term fuel storage could be accomplished.

The dry storage facility was designed to meet the same objectives as mentioned for the wet storage plant, i.e. to accommodate 500 tons of spent fuel and to meet the requirements originating from the hypothetical site conditions including the impact of an aircraft.

Concerning the cooling principle, the plant follows some basic conceptions which are: The application of convective cooling under natural draft, and the utilization of ambient air directly.

Alternate cooling principles, e.g. indirect cooling with heat transfer through conducting walls were ruled out because of anticipated construction problems.

The direct cooling of the fuel will require a reliable confinement of the radioactive material. Lead filled and welded canisters as described for the wet storage plant seemed also to be suitable for dry cooling.

The very low outside dose rate originates from the diffusion of tritium. A dose rate of 0.02 mrem/yr can be accomplished by an additional aluminum coating at the outside of the canister. This dose rate is governed by the leakage rate of the welding. Without the aluminum coating the offsite dose rate was conservatively estimated to be in the order of 2 mrem/yr.

The general building design is outlined in Fig. 4. The cooling air enters the building through intakes arranged closely to the top of the building. The air is then guided through building ducts to underneath of the storage racks. The air then heats up in the annular gap between the concrete storage racks and the fuel canister and leaves the building through ports on top of the building. Vacant rack positions would be blocked forcing the air through loaded positions and avoiding bypass losses. Some relevant temperatures of the cooling air and the fuel are indicated in Fig. 5.

The temperatures depend to a high degree on the age of the fuel in store. Typically, an air temperature of less than 50°C can be expected for fuel stored for 3 years previously. This low a temperature will not require particular measures for the protection of the building's concrete structure.

After several decades of decay the air inlets and outlets of the building could be closed and the residual heat removed by heat conduction of the building's walls.

Similar to the air cooled vault concept for storing high level reprocessing wastes it was concluded that some areas would need additional investigation such as the performance of the ventilation system at various atmospheric conditions, the entry of small life forms and airborne soil and the assurance of a continued integrity of the fuel canisters.

5. COMPARISON OF ECONOMICS

In order to demonstrate the effect of various design requirements and arrangements a direct comparison of different concepts was attempted.

Fig. 6 shows the outside dimensions of a storage plant of the same capacity if designed to various national conceptions.

Fairly small storage buildings would be required by the upper two concepts of North American origin relative to the voluminous facilities following the conceptions in Central Europe.

It certainly is a goal for the designer of a storage facility to arrive at a design which provides minimum expenditures for construction and operation. This task will be emphasized if the storage plant is to be built in countries with a limited nuclear power program. However, it should be noted that in some countries low cost was not the only design incentive but immediate licenceability was a primary objective. In Central Europe in some cases a licenceable storage project was required by local authorities in order to get a construction or operating permit of a nuclear power plant rather than needing the storage project for actual construction.

However, for storage plants already under construction or built like one in North America, remarkably low cost have been reported, reflecting the different objectives and requirements there.

This difference in objectives, requirements and design is reflected by comparison of the construction cost per kg of uranium in store.

Table I lists specific construction costs ranging from about 5 $/kg to as high as 250 $/kg. A major cost effect will be related to the capacity of the storage plant. This effect is indicated by the numbers of the center column which were taken from IAEA's regional fuel cycle center study. However, the effect of various capacities might not be the same for different design conceptions. A breakdown of the contributing construction expenditures of a 500 t wet storage plant designed to requirements in Central Europe is listed in Table II.

Buildings and structures as well as the mechanical equipment contribute each about one third to the total construction cost. The conversion from wet to dry storage will add about 20 % of the total construction cost. The cost of the encapsulation of 500 t or 2700 BWR fuel assemblies is estimated to be in the order of 5 %.

The right column gives the equivalent expenditures for a dry storage plant. Again the cost for buildings and structures amount to about one third.

Dominating contributions for the operating cost are attributed to expenditures for labour and maintenance.

The wide variation in the absolute annual operating costs originates from increased requirements anticipated during the fuel receiving period. After exhaustion of the storage capacity, the personnel and the operation of sub-systems can be reduced. In particular for a dry storage facility this would reduce annual operating costs to as low as 1 $/kg uranium.

6. CONCLUSIONS

An obvious conclusion emerging from above is that in some cases the specific storage cost of spent fuel might amount to a figure which can affect the optimum fuel cycle alternative. A throw-away fuel cycle which includes long-term fuel storage and final geological disposal of fuel assemblies is competitive with reprocessing and final disposal of high level waste only if the cost for long-term fuel storage are sufficiently low.

Fig. 7 indicates the incremental generating cost-percent of the throw-away fuel cycle relative to the cost of the fuel cycle with reprocessing.

This comparison is based on the assumption of equal cost for the conditioning and ultimate disposal of high level waste and spent fuel and the assumption of escalated costs of the various fuel cycle services and installations.

At storage costs of more than 100 $/kg the reprocessing option might be in advantage assuming equal cost for the disposal of spent fuel and waste respectively. At low storage costs, a long-term storage and an ultimate disposal of the fuel stored would result in the minimum fuel cycle cost. The highest cost would result if all fuel will be stored before reprocessing begins. In this case storage will simply be a dead load on fuel cycle cost.

One might also conclude that local policies, costs and safeguards will create an incentive for multinational storage projects. A large storage facility as might be appropriate for a multinational project would result in low specific storage costs which would alleviate the cost load in particular in countries with a limited nuclear power program. In those countries it might also prove beneficial to combine several storage projects in order to reduce the number of individual facilities needed.

Preliminary design analysis indicates that alternative conceptions like the sealed storage cask concept might become a viable approach providing a further reduction of storage costs.

Further evaluation of the alternative designs will clarify the availability, the advantages and the area of application of indicidual alternatives.

Table I: SPECIFIC CONSTRUCTION COST OF STORAGE FACILITIES OF VARIOUS ORIGIN (Costs in $/kg)

Capacity t U	North America HWR-fuel water basin	IAEA RFCC LWR fuel water basin	Central Europe LWR-fuel water basin	Central Europe LWR-fuel air cooled vault
350		57 - 114		
500			200 - 250	100 - 150
750		40 - 67		
1000		40 - 80	150 - 200	
2000		35 - 70	120 - 180	
3000		33 - 66	100 - 160	
3000	5 - 10			

Table II: BREAKDOWN OF CONSTRUCTION AND OPERATION EXPENDITURES FOR A 500 T WET AND DRY STORAGE FACILITY DESIGNED TO REQUIREMENTS IN CENTRAL EUROPE

	Wet Storage (%)	Dry Storage (%)
CONSTRUCTION COST		
Buildings	30 - 35	35 - 40
Mechanical Equipment	35 - 30	20
Electrical Equipment	15	10 - 5
Site, Commissioning, etc.	20	35
	100% = 250 $/kg U	100% = 125 $/kg U
OPERATING COST		
Labour	20 - 25	30 - 40
Service and Maintenance	30 - 33	20 - 30
Power	20 - 30	-
Taxes, Insurance, etc.	20 - 25	30 - 40
	100% = 5-8 $/kg yr	100% = 1-5 $/kg yr
COST OF MONEY	100 - 200 $/kg U	50 - 100 $/kg U
COST OF PERPETUAL CARE	200 - 300 $/kg U	50 - 200 $/kg U
TOTAL	400 - 750 $/kg U	250 - 425 $/kg U

Replacement Tables for the paper "Comparison of Concepts for Independent Spent Fuel Storage Facilities", Dr. H. Held, Mr. H.P. Hintermayer, KKWP, Austria

---

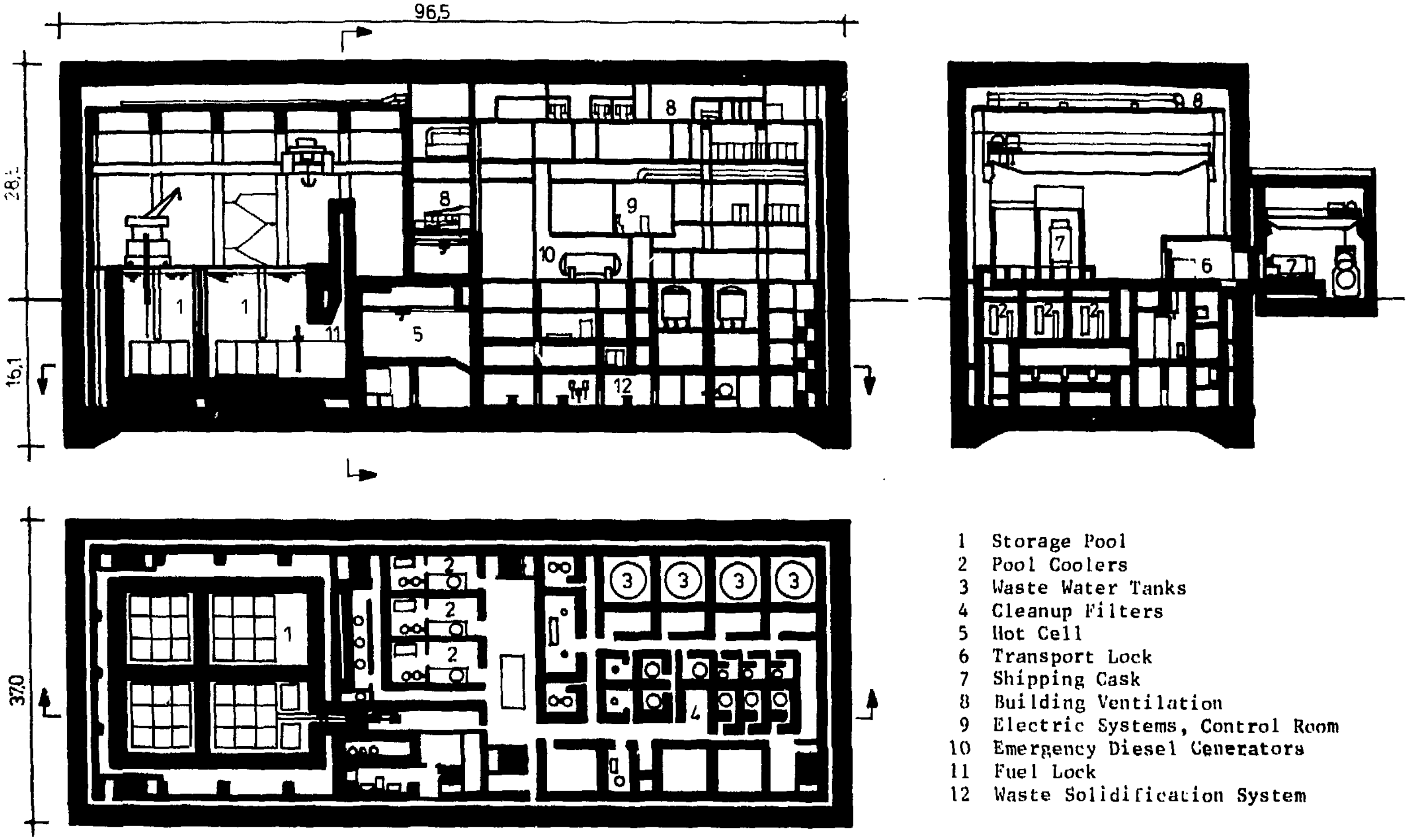
Table I: SPECIFIC CONSTRUCTION COST OF STORAGE FACILITIES OF VARIOUS ORIGIN (Costs in $/kg)

Capacity MTU	North America HWR-fuel Water Basin	IAEA RFCC LWR-fuel Water Basin	Central Europe LWR-fuel Water Basin	Central Europe LWR-fuel Air Cooled Vault
350		57 - 114		
500			200 - 250	100 - 150
750		40 - 67		
1000		40 - 80	150 - 200	
2000		35 - 70	120 - 180	
3000		33 - 66	100 - 160	
>3000	5 - 10			

Table II: BREAKDOWN OF CONSTRUCTION AND OPERATION EXPENDITURES FOR A 500 T WET AND DRY STORAGE FACILITY DESIGNED TO REQUIREMENTS IN CENTRAL EUROPE

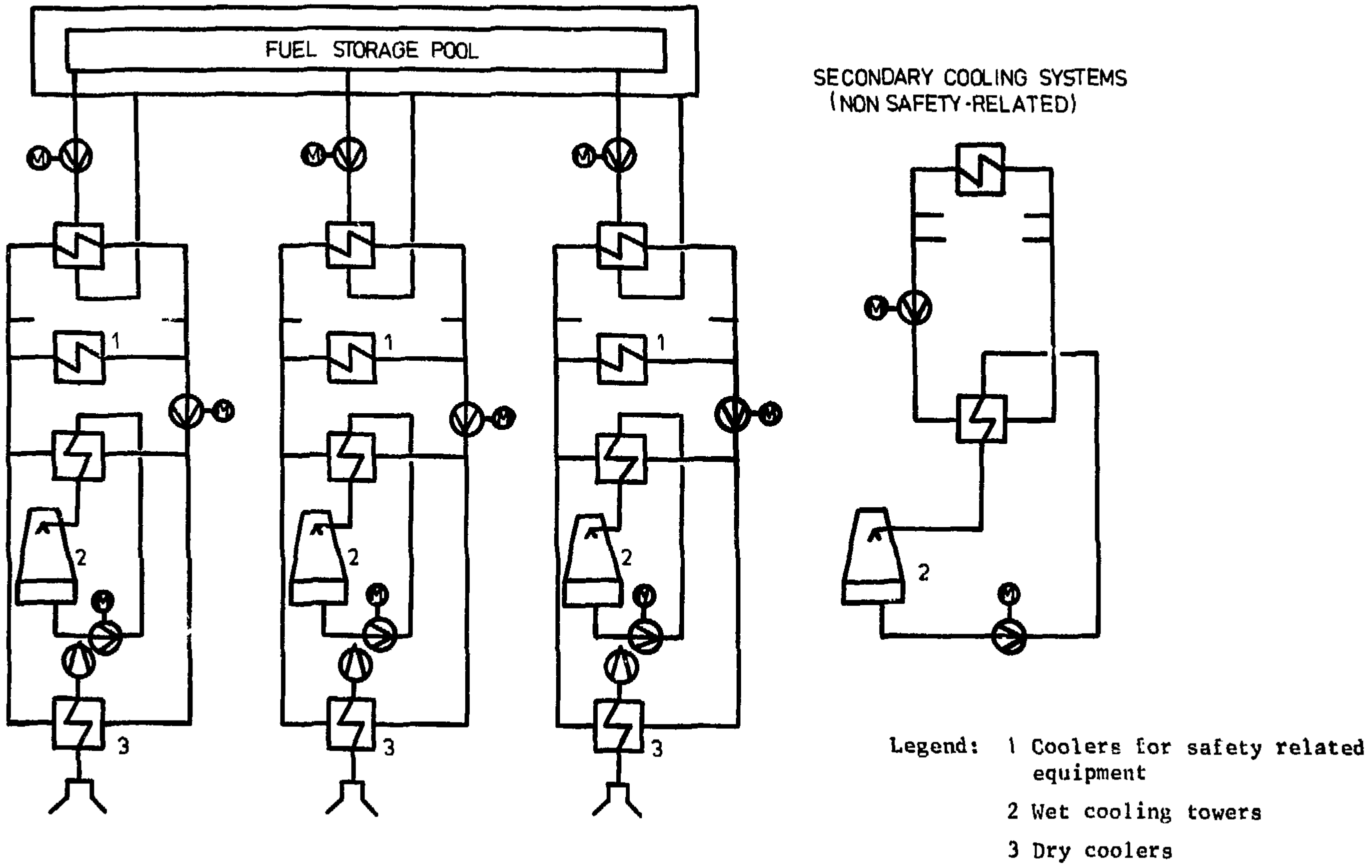
	Wet Storage (%)	Dry Storage (%)
CONSTRUCTION COST		
Buildings	30 - 35	30 - 35
Mechanical Equipment	30	20 - 15
Electrical Equipment	15	10 - 5
Site, Commissioning etc.	25 - 20	40 - 45
	100% = 200 - 250 $/kg U	100% = 100 - 150 $/kg U
OPERATING COST		
Labour	20 - 25	30 - 40
Service and Maintenance	35 - 30	30 - 20
Power	20 - 25	-
Taxes, Insurance etc.	25 - 20	40
	100% = 5-8 $/kg yr	100% = 1-5 $/kg yr x)
COST OF MONEY	100 - 200 $/kg U	50 - 100 $/kg U
COST OF PERPETUAL CARE	200 - 300 $/kg U	50 - 200 $/kg U
TOTAL	500 - 750 $/kg U	200 - 450 $/kg U

x) Based on total capacity of 500 MTU



1	Storage Pool
2	Pool Coolers
3	Waste Water Tanks
4	Cleanup Filters
5	Hot Cell
6	Transport Lock
7	Shipping Cask
8	Building Ventilation
9	Electric Systems, Control Room
10	Emergency Diesel Generators
11	Fuel Lock
12	Waste Solidification System

FIG. 1 PLAN VIEW AND SECTIONS OF AN INDEPENDENT SPENT FUEL STORAGE FACILITY FOR CENTRAL EUROPE (DESIGN: BBC-MANNHEIM)



Legend:
1 Coolers for safety related equipment
2 Wet cooling towers
3 Dry coolers

FIG. 2 GENERAL ARRANGEMENT OF COOLING SYSTEMS (DESIGN: BBC-MANNHEIM)

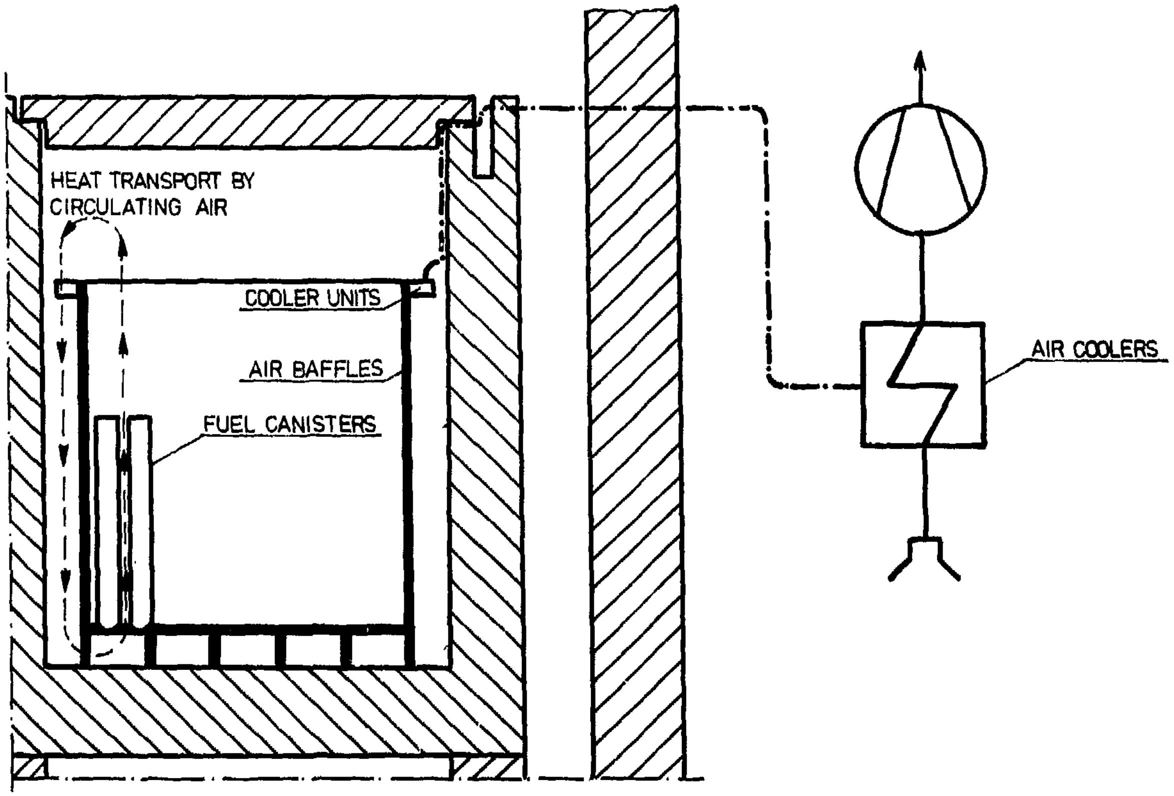


FIG. 3 CONVERSION FROM WET STORAGE TO DRY COOLING OF SPENT FUEL (DESIGN: BBC-MANNHEIM)

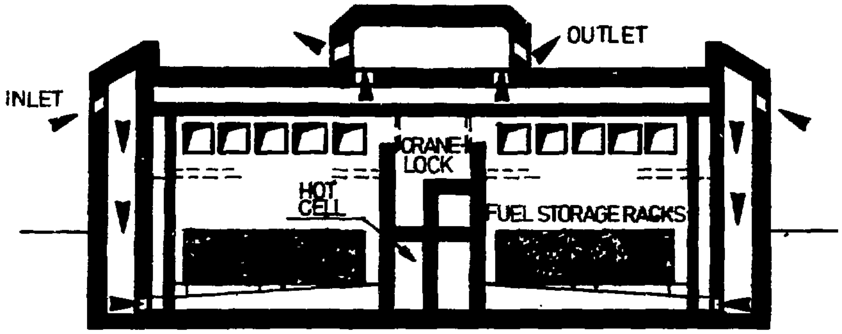


FIG. 4 GENERAL ARRANGEMENT OF A DRY STORAGE FACILITY (DESIGN: NUKEM-HANAU)

Direct Air Cooling:

Time after discharge - 3 years

Decay heat per fuel canister - 0,76 kW

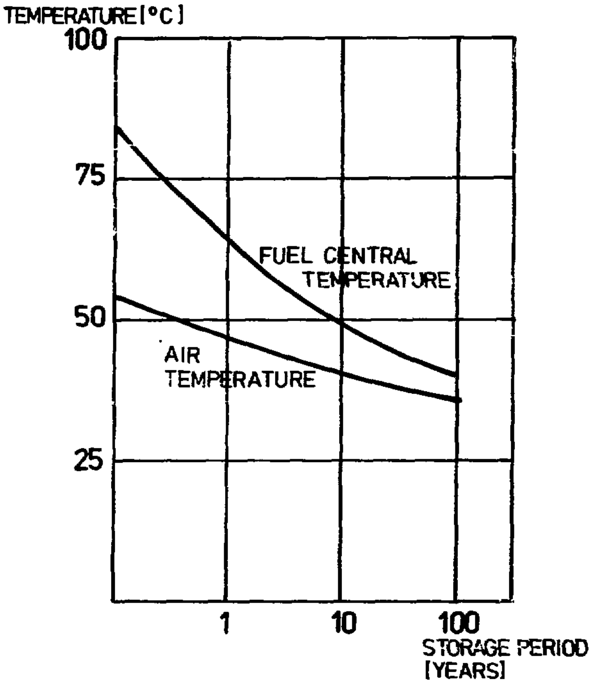
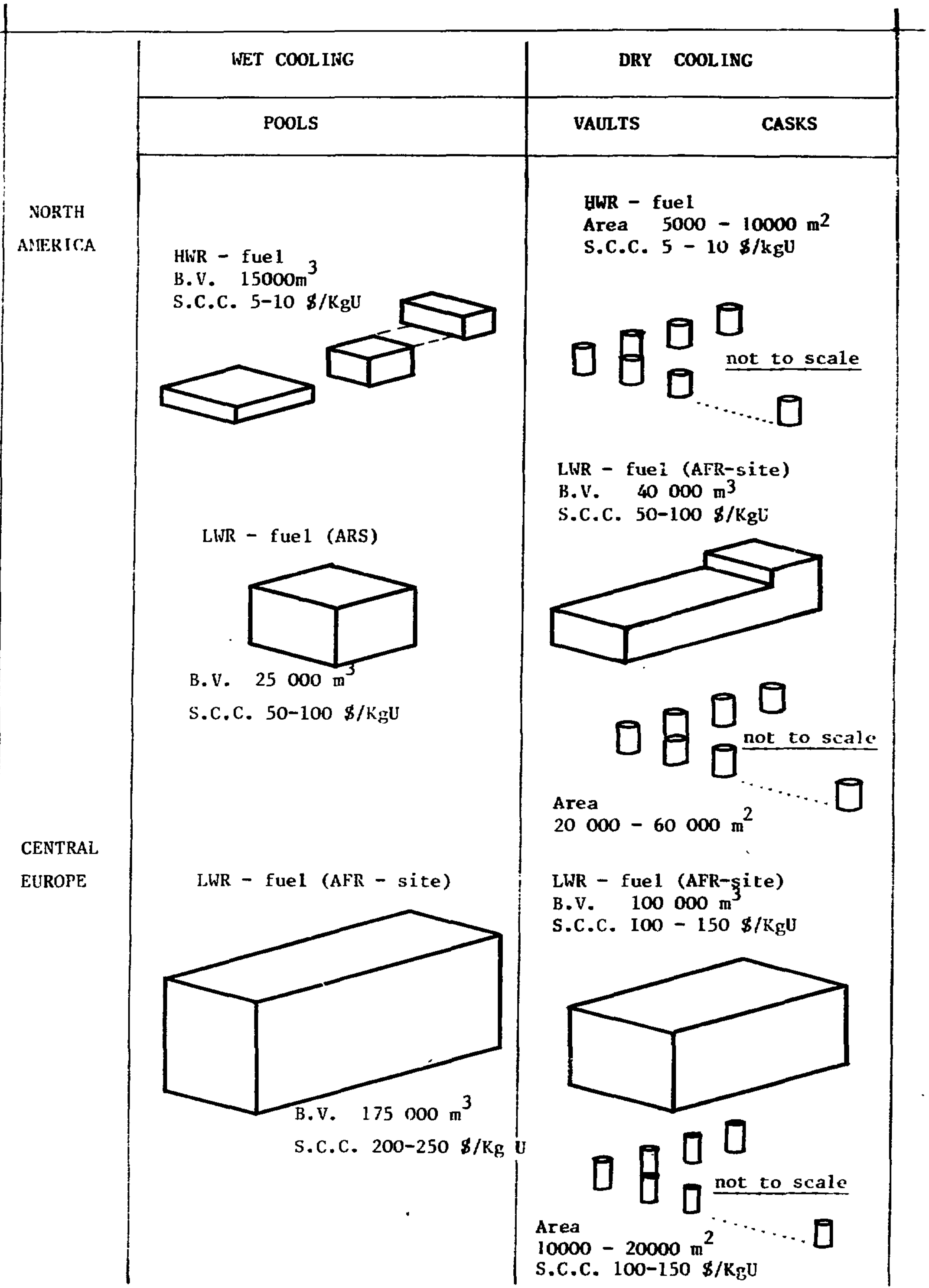
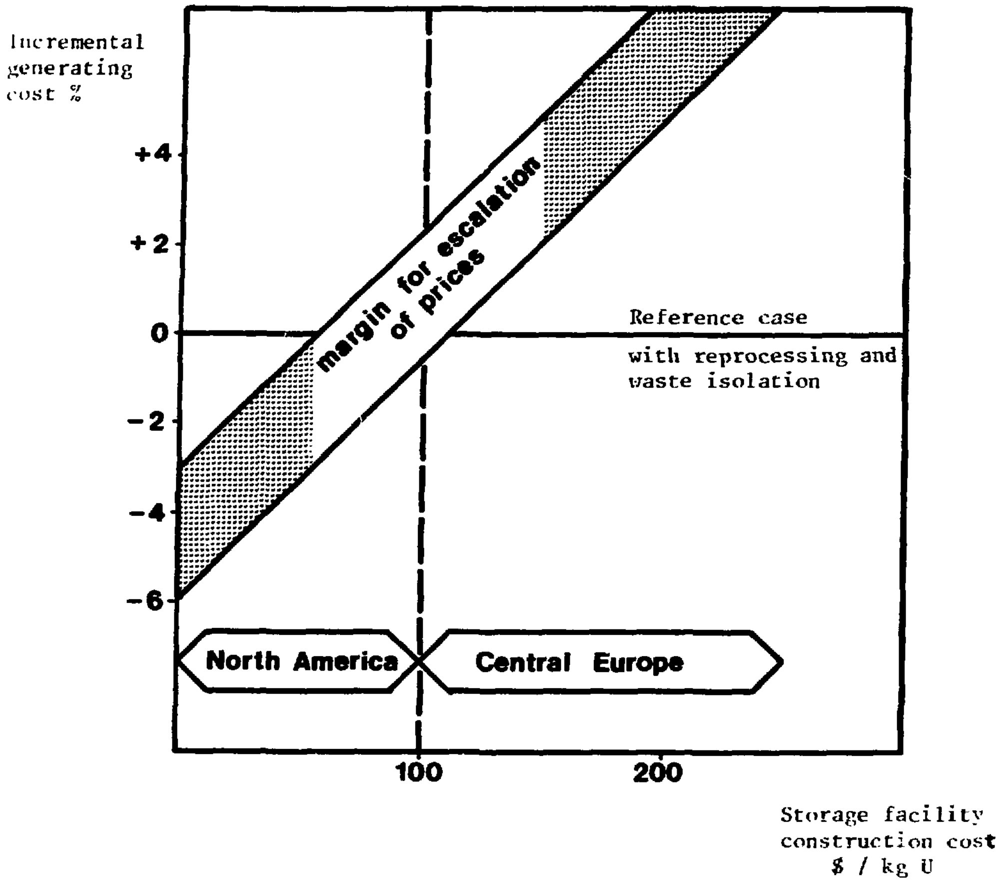


FIG. 5 AIR COOLED STORAGE FACILITY / TEMPERATURE VS. STORAGE TIME



B.V. ...... Building Volume
S.C.C. .... Specific Construction Cost

FIG. 6 COMPARISON OF VARIOUS STORAGE CONCEPTIONS
(relative dimensions indicate the storage of 500 t U in each case)



Assumptions:
- Disposal cost of reprocessing wastes equal disposal cost of spent fuel
- Cost of conditioning of reprocessing waste equal cost of conditioning of spent fuel
- Generating cost include cost of money and cost of sinking fund for a 40 year operating period of storage pool and a 20 year operating period of nuclear power plant

FIG. 7 EFFECT OF FUEL STORAGE COST ON THE OPTIMUM FUEL CYCLE ALTERNATIVE