BG9600385

VVER Spent Fuel Storage

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1 Introduction

Each type of nuclear fuel is unique, initially by virtue of its physical size, material, and enrichment, and subsequently because of its operating history and burn-up.

If the fuel is to be stored after irradiation, then the storage system itself introduces its factors on to the fuel to add to the complexity. Such aspects as the fuel storage temperature and the geographical location all contribute.

All of these aspects need attention if the integrity of the fuel at the end of its storage is to be ensured, particularly as interim storage periods of 100 years may be required.

GEC ALSTHOM, has recently completed such an evaluation of VVER 440 fuel for the Paks NPP in Hungary. GEC ALSTHOM signed a contract with Paks NPP to provide a design and safety case for a Modular Vault Dry Store (MVDS) to accommodate 10 years of fuel arisings from their four -VVER 440 reactors. This amounted to a total of 5000 irradiated fuel assemblies (IFAs) which need to be stored.

This paper outlines the selection criteria used by Paks with specific reference to some of the more important technical, licensing and technology transfer issues.

2 Paks Dry Storage System Selection Criteria

Paks NPP having decided on a dry fuel storage system, had to determine which system was best suited to their situation. Selection is complicated by the fact that there are several dry storage concepts commercially available, with an even greater number of vendors.

To assist in the evaluation process Paks drew up a list of technical criteria which they considered to be important to ensure safety, reliability, flexibility and economy throughout the loading and storage period. Weightings were given to the more important criteria with rankings between 1 and 5.

Amongst the more heavily weighted criteria were:

- temperature of fuel in storage;
- sub-criticality assurance, (avoidance of criticality for fuel in the unirradiated condition without having to take credit for burn-up);
- assurance of decay heat removal;
- dose uptake to the operators and public;
- protection of the environment;
- volume of waste produced during operation and decommissioning;
- physical protection of stored irradiated fuel assemblies;
- IAEA safeguards assurance;
- storage system should not prejudice final disposal route;
- cost of construction and extent of technology transfer to Hungarian industry.

Some of the factors which affect the dry storage system's ability to satisfy the selection criteria are outlined below.

(a) Temperature of the Fuel in Storage

A major concern of Paks was that the storage system must not prejudice the final disposal route by permitting degradation of the spent fuel while it is stored. One of the most important factors is the temperature of the fuel whilst in storage. Virtually all of the mechanisms which cause degradation of the fuel are temperature dependent. There are published values giving maximum storage temperatures for different fuels.

For VVER fuel a recommended maximum value of 350°C in an inert atmosphere has been suggested. Paks adopted the policy that the lower the storage temperature for the fuel, the higher the resistance the stored fuel has to degradation during storage.

The MVDS offers the lowest storage temperature of any of the dry storage technologies.

(b) Sub-criticality Assurance

Some dry store systems take credit for fuel burn-up, in order to offer low capital costs for the facility. Such systems are open to scrutiny on account of the potential hazards associated with storing the wrong specification of fuel. A system which takes no credit for burn-up is inherently safer.

(c) Dose Uptake to the Operators and Public

Statutory requirements regarding permitted offsite radiation emission levels and dose uptake are likely to become more restrictive in the future. Any new on-site facility such as a dry store will contribute to the off-site dose and when the reactor was built, maybe 10 or 15 years ago, the allowable radiation emission levels were much higher. With the reduction in the allowable doses, the reactors contribution to the site boundary dose becomes an increasingly larger percentage of the allowable boundary dose. The result is that any new facility will require extremely efficient shielding.

In the UK where GEC ALSTHOM are building MVDSs for Scottish Nuclear at Torness and Hunterston, the MVDS contribution to the site

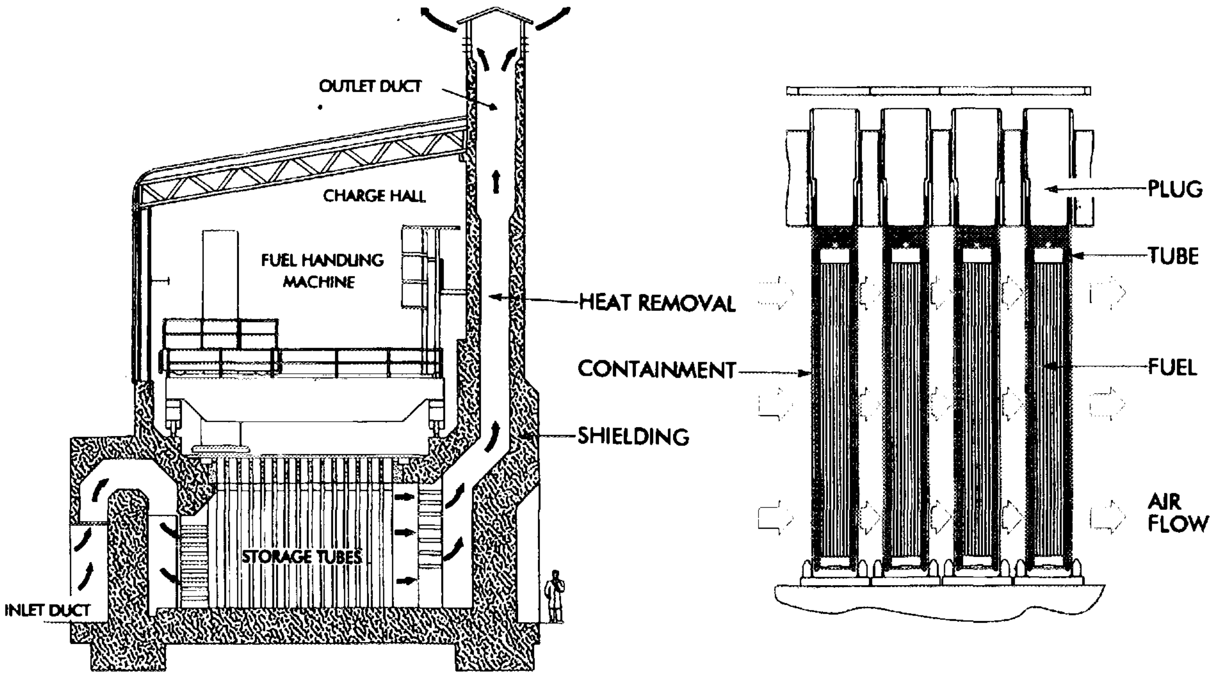

Figure 1 Modular vault dry store - cooling system

boundary dose is just 10% of the site allowable boundary dose. This is also the case at Paks.

It is axiomatic therefore that a system with very low radiation levels is required. Consideration must also be given to future extension and its contribution to the site boundary dose.

(d) Physical Protection

The facility must be able to withstand all the natural events, such as flood, very high winds, and earthquakes. Paks specified a seismic ground acceleration 0.35 *g*. Cognisance must also be given to national requirements, which might require such events as terrorist attack, aircraft crash, or explosive vapour clouds to be considered.

(e) Fuel Storage Attitude

VVER fuel assemblies are designed for producing thermal power inside a nuclear reactor. During that process the fuel assemblies are designed to be located and operated in a vertical attitude. When irradiated fuel assemblies are put into a dry store the attitude of the assembly over a long period of time can exert additional stresses and strains on the fuel pins. The condition of the fuel can be better justified if it is stored in the same attitude as it was designed to operate in the reactor.

Paks applied these criteria together with a number of others in their evaluation of the competing technologies, with a weighting against some of the criteria. As a result of this evaluation the GEC ALSTHOM MVDS system was selected. This does not mean that the GEC ALSTHOM MVDS scored the highest points in all categories, but against the Paks criteria, it was perceived as the system which most nearly satisfied their requirements.

3 The Paks Modular Vault Dry Store

3.1 Modular Vault Dry Store Concept

The MVDS is a passively cooled dry storage facility comprising three main areas: the Cask Reception Facility, used for the receipt of the transfer cask and transporter (and, if necessary, the drying of spent fuel if carried in wet casks); the Modular Storage Vault; and the Fuel Handling Machine. The three areas allow the MVDS to operate independently from the reactor facilities, even after these facilities have been decommissioned.

In the MVDS, spent fuel is contained in individual vertical sealed fuel storage tubes retained within a concrete vault, which can be constructed in a phased manner. The storage tube provides a high integrity mechanical barrier between the fuel and the cooling air. Cooling air is drawn by natural convection through a protective bird mesh and labyrinth, before entering the vault through concrete distribution louvres. The cooling air circulates around the storage tubes before discharging through the vault's exit louvres, up a concrete duct and out to the atmosphere after passing through a second bird mesh and a weather-protected duct top. The cooling air does not come into contact with the spent fuel and therefore does not become contaminated.

The concrete inner surfaces of the vaults are not exposed to contaminated air and remain clean structures throughout the life of the store. The cooling arrangement is illustrated in Figure 1.

The cooling system, which is passive, self-regulating and driven by the natural buoyancy of warm air, maintains a wide margin on acceptable fuel and structural concrete temperatures for all site specific environmental conditions.

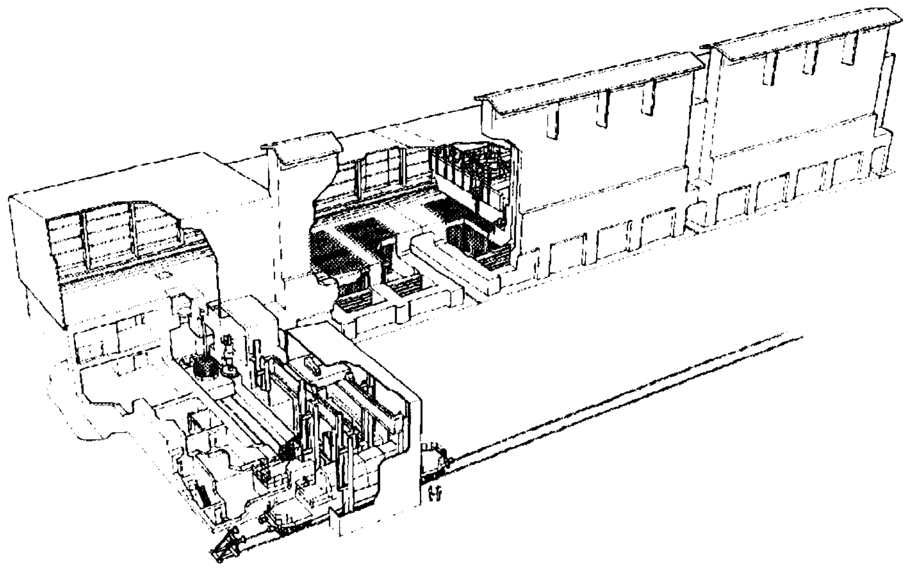

Figure 3 Paks NPP - Modular vault dry store

3.2 Description of the Paks MVDS

Paks has four - VVER 440 reactors and in each reactor are 312 fuel assemblies and 37 control assemblies. Annually about 120 spent fuel assemblies are removed from each reactor, giving a total arising of 480 fuel assemblies. In addition to the annual arising Paks wish to create some empty space within their storage pools and therefore require the on site dry store to receive spent fuel at twice the annual rate of arising (960 assemblies/year).

Paks are planning for an initial storage capacity of 4950 fuel assemblies equivalent to 10 years of operation of the reactors. The store will be built in 3 phases, the first phase will accommodate 1350 fuel assemblies (3 vaults) followed by two further phases of 1800 positions (4 vaults) each.

Provision has been made in the design for the store to be eventually extended to 14850 positions representing 30 years of reactor operation.

The Paks MVDS facility with three phases of construction is illustrated in Fig. 2. The VVER 440 fuel assembly is illustrated in Fig. 3.

The spent fuel arrives at the MVDS Transfer Cask Receipt Bay (TCRB) from the reactor building on a flat bed rail truck. The cask is the normal C30 cask used for off-site shipment so that no modifications are required to the reactor building storage pools. The cask is water filled and contains 30 assemblies. On arrival at the TCRB it is lifted off the rail truck by the overhead crane in the TCRB and lowered onto the Transfer Trolley, from where it is transferred into the inner area of the TCRB where the cask is off-gassed and the lid unbolted. On completion of this operation it is transferred onwards to the lid lift position and finally to the load/unload position, where the trolley is locked in place by means of a seismic lock.

The Fuel Handling Machine (FHM) is positioned over the cask at the load/unload port, where the load/unload port shield plug is removed into the

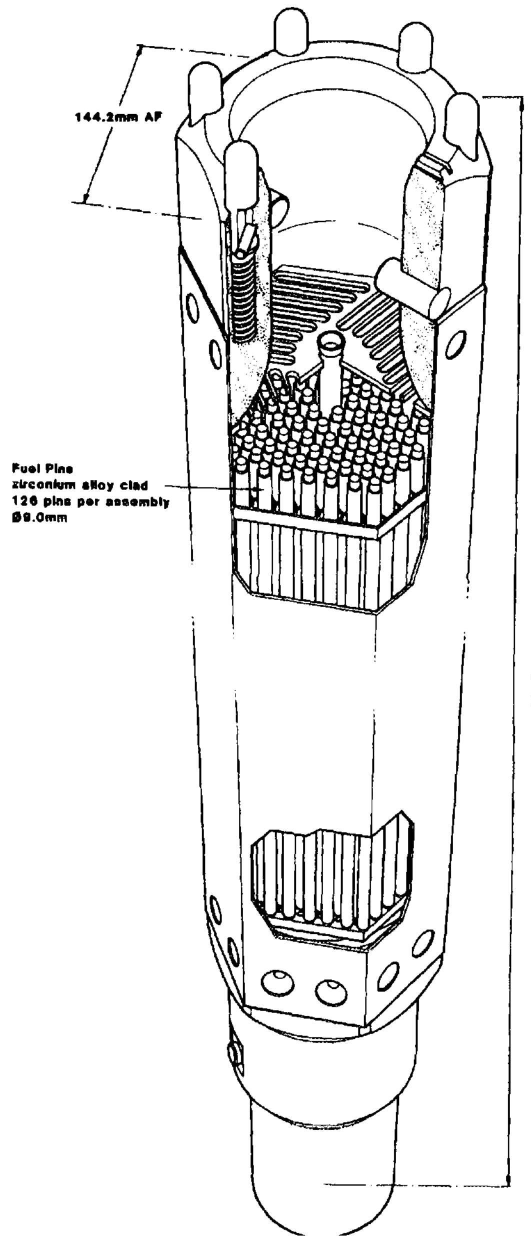

Figure 2 VVER-440 fuel assembly

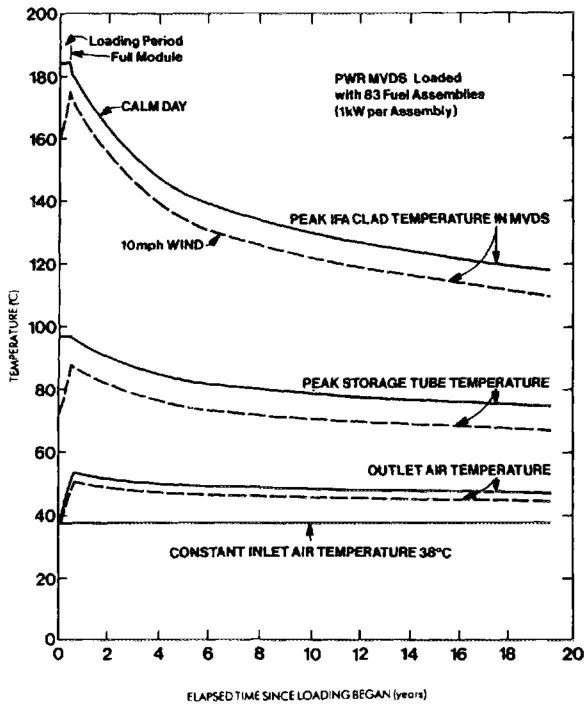

Figure 4 PWR MDVS - results of DADS assessment

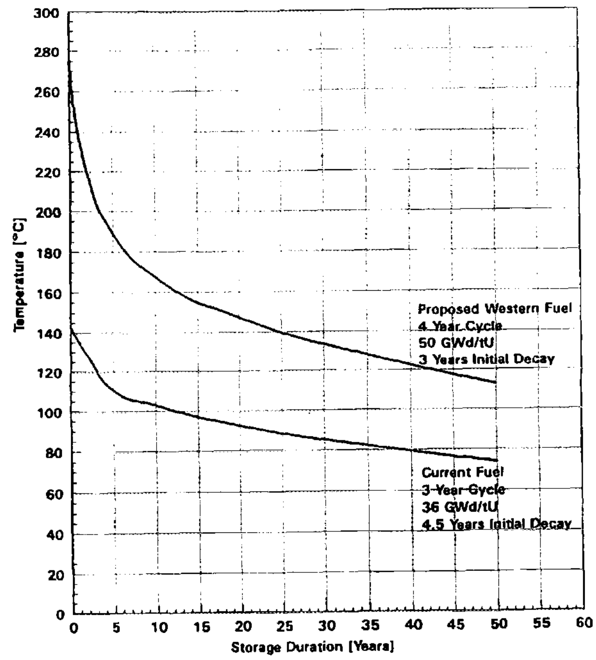

Figure 5 The peak local fuel clad temperature for maximum irradiated VVER-440 assembly during term dry storage in MVDS

FHM magazine. The FHM grab is lowered through the port to engage the fuel assembly in the cask and raise it into the drying tube. After dwelling in the drying tube for the requisite period with hot gas circulating around the fuel, it is raised into the FHM for transfer to the selected Fuel Storage Tube (FST).

At the FST the FHM removes the shield plug and lowers the fuel assembly into the tube. The plug is replaced and the FHM returns to the TCRB load/unload port to repeat the process. At the FST a service trolley is attached to the valve connection on the shield plug. The FST is drawn down to vacuum and back-filled with nitrogen. This operation is repeated a second time to ensure the required gas purity has been achieved. Finally the valve on the gas monitoring pipework to the FST is opened to allow the continuous monitoring of the integrity of the FST.

As described above a single VVER-440 fuel is stored in each storage tube. Because the storage tube radiates heat directly to the cooling airflow this gives an excellent heat removal capability, as shown in Fig. 4. The peak pin fuel clad temperatures, even for the most conservative case and the higher burn up fuels, are well below the 350°C temperature limit.

3.3 Safety Case

The MVDS system was licensed in America in 1988 by the US NRC for LWR fuel and this was accepted by Paks as the basis for their safety case, but with additional requirements to satisfy the various ministries and authorities within Hungary.

In the safety case the differences between PWR and VVER fuel and the site specifics of the Paks location had to be addressed. Some of the aspects addressed in the safety case are:

- Wind tunnel testing;
- Fuel temperatures;
- Criticality;
- Duct blockage;
- Fuel monitoring.

(a) Wind Tunnel Testing

As part of the assurance of cooling flow through the vault the effects of wind on the cooling flow have been investigated to ensure there is no cooling flow stagnation. This is not amenable to analysis and the only practical way it to model the store and the surrounding buildings and take measurements of pressure distribution across the store inside a wind tunnel.

The wind tunnel test where carried out with two models of the Paks MVDS having capacities of 4,950 storage positions and 14,850 positions respectively.

With the wind blowing from any direction, it must be demonstrated that a positive pressure differential always exists between the air inlet and the discharge.

In previous work GEC ALSTHOM investigated wind effects on the fuel storage temperatures. Figure 4 shows the effect of a modest breeze on the fuel temperature, the fuel storage tube temperature and the cooling air temperature. The MVDS design basis is the still-air condition.

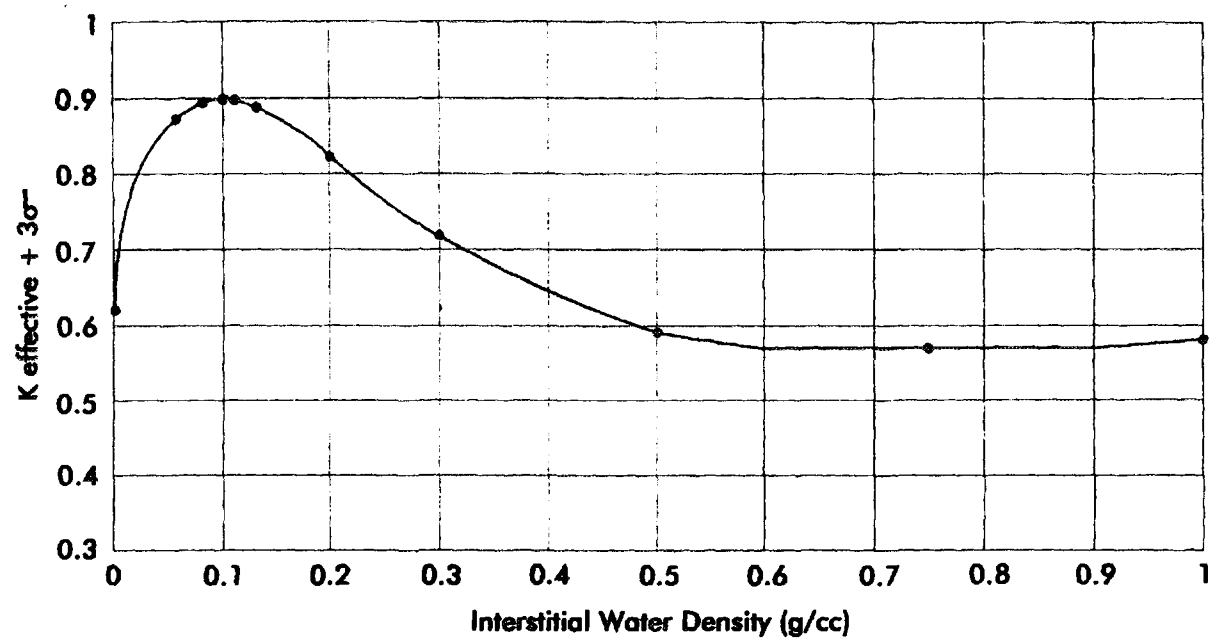

Figure 6 Variation in K effective with interstitial water density

(b) Fuel Storage Temperature

The graph shown in Figure 5 is taken from the Paks safety report and shows two normal cases for the VVER fuel.

Case 1 is based on the present operating cycle with fuel enrichment of 3.6%, 3 year cycle, 36 *GWd/tU* burn-up and 4.5 year initial decay before loading into the MVDS.The temperature shown of 140°C is the hottest point on the hottest pin.

Case 2 is the proposed future reactor operating cycle which is still based on fuel with 3.6% enrichment, but with a 4 year cycle, 50 *GWd/tU* and 3 years initial decay.

The peak temperature is 270°C, which is still well below the recommended peak temperature of 350°C for VVER fuel.

It is important when specifying the requirements of a storage system, that the future operating cycle of the reactor should be considered. As Figure 5 shows, it would take 25 years for the decay heat from the higher burn-up fuel to decrease to the level of the present operating cycle fuel.

(c) Criticality Analysis

Under US NRC regulation, when calculating criticality, all conceivable fault situations within the design basis must be considered. For the Paks safety case, this was extended to include two coincident faults. The first fault is the vault fully flooded, and the second fault is a fuel storage tube also flooded. Paks specified a sub-criticality value (K_{eff}) of < 0.95 for any condition, Figure 6 shows the results of the analysis.

It should be noted that no credit is taken for burn-up. The highest K_{eff} is with a vault flooded with a water density of 0.1. Even in this situation the K_{eff} is well below the Paks specified maximum.

(d) Duct Blockage

As part of the fault analysis, the effect of the cooling air duct blockage must be considered. This is an extremely unlikely event, as the inlet is 3 и high and runs the length of the store and an interconnecting passageway behind the inlet screen connects the vaults.

Figure 7 shows the effect of varying percentage blockage of the inlet duct, on the fuel pin temperature, the fuel storage tube temperature, and the outlet air temperature. It is not until blockage around 95% occurs that there is a significant temperature increase.

In fact if total blockage of the inlet duct did occur, then the condition shown on Figure 8 would be the result, thus maintaining a cooling airflow across the vault and allowing sufficient time for remedial action to be taken.

(e) Fuel Condition & Monitoring during Storage

The potential for consequential fuel degradation mechanisms in storage are increased if storage temperatures are high, moisture is present and there is an oxidising atmosphere. The low fuel temperature in storage achievable with the MVDS design will reduce if not eliminate completely, the potential corrosion mechanisms. Further loading operation for an MVDS storage tube requires evacuation of the enclosed air before back filling with nitrogen. This provides an inherent check on the dryness of each individual fuel assembly before storage giving additional protection against the presence of moisture.

Finally the ability to sample the gas within the storage tube enables the condition of the fuel throughout its storage lifetime to be monitored, giving confidence about the end of life condition.

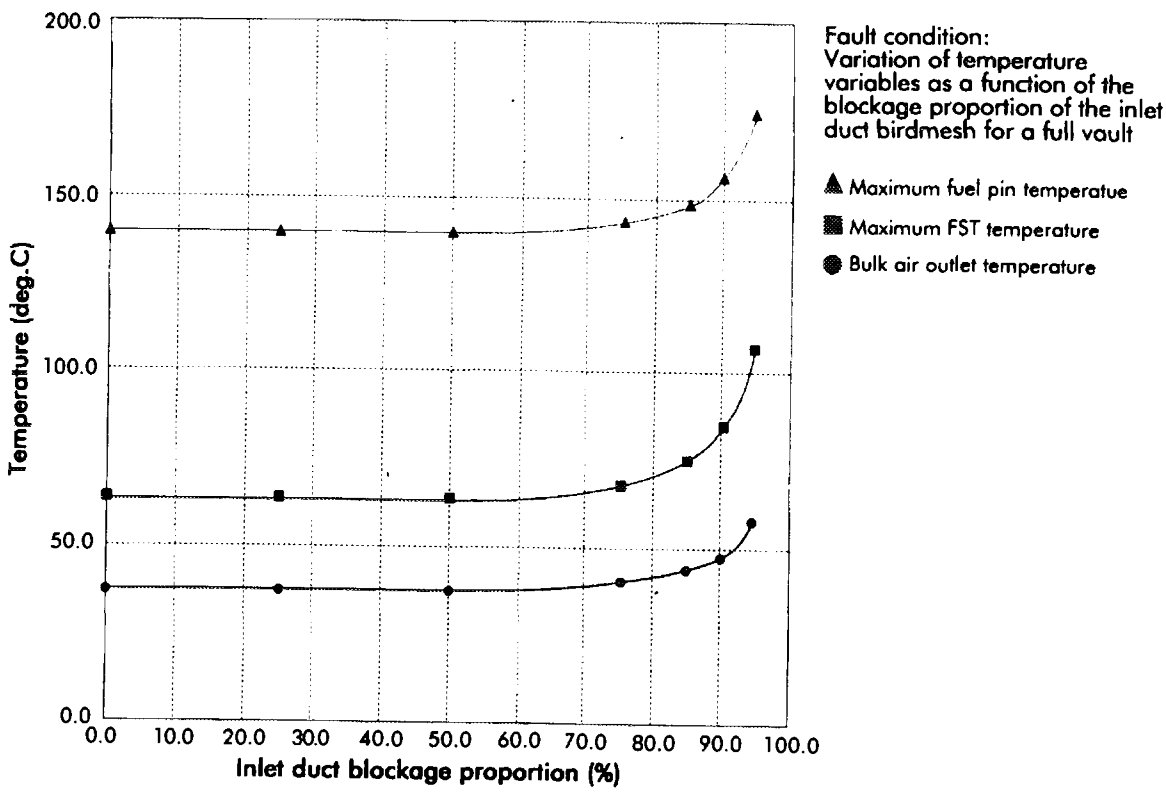

Figure 7 Effects of partial air blockage on fuel pin temperature

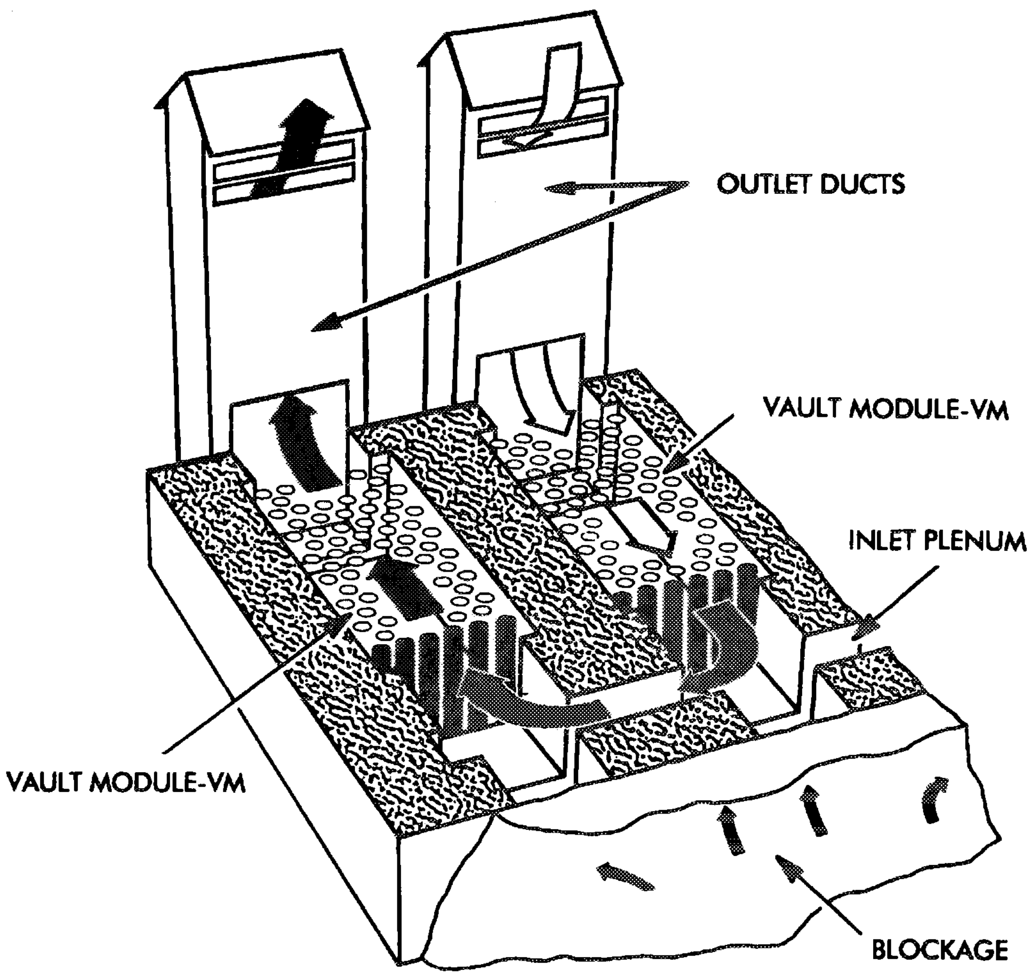

Figure 8 Cooling regime as result of duct blockage

Additional visual monitoring of the fuel cladding condition on entry to the store and subsequently during its storage, is provided by the Fuel Handling Machine. TV systems can be located in the machine to permit direct visual inspection of the fuel. The machine is fully shielded, dissipates the fuel assembly heat output naturally and allows direct manual recovery of defective fuel.

3.4 Licensing of Paks MVDS

GEC ALSTHOM proposed that the American Licensing and Safety Standards be adopted in Hungary for the licensing process of the MVDS. A non site specific design for the storage of LWR fuels had already been given US - NRC (Nuclear Regulatory Commission) licensing approval in 1988 and a site specific MVDS licensing procedure had been successfully completed in 1991 by the US Utility, Public Services of Colorado. This recommendation was accepted by Paks but with additional requirements imposed by various Hungarian Ministries and Institutions.

The safety and licensing standards which have been applied to the Paks MVDS are:

- American NRC Guide Lines - Licensing requirement for the independent storage of spent nuclear fuel - 10 CFR72;
- American Nuclear Standards - Design criteria for an independent spent fuel installation - ANS 57.9;
- Allowable doses in accordance with recommendations of the International Commission on Radiological Protection - ICRP 60;
- The standard format and content for the Safety Analysis Report for an independent spent fuel storage installation - US Reg. Guide 3.48;
- Additional requirements identified by the Hungarian Government departments of safety, health, ecology etc.

The completed PCSR was initially reviewed by a Paks appointed international review committee. This was followed by a Paks Jury made up of experts from the universities, the various ministries, design consultants and the institutions. The final stage is the submission of the documents to the Hungarian Licensing Authority. In parallel with this, the application for the site construction licence is being prepared.

3.5 Technology Transfer

The initial contract for the Paks MVDS was placed in September 1992 with GEC ALSTHOM Engineering Systems for the preparation of the Licensing Design, the Construction Design and the Pre-Construction Safety Report (PCSR), with support in presenting the Final Safety Case to the various Hungarian Committees. This was total technology transfer with Paks NPP operating as the Project Manager throughout and with the option to have all manufacture and construction work carried out by Hungarian industry.

In mid 1993 Paks took the decision to proceed with the implementation phase of the dry store project with a target completion in 1995. As the Project Manager Paks are now moving towards gaining approval of the PCSR, having selected the civil constructor and have commenced the procurement of long delivery items of equipment. GEC ALSTHOM's continuing role is to provide assistance and advice as required by Paks.

The Technology Transfer process has ensured the involvement of the Hungarian designers in the Paks MVDS detailed design. Manufacture and construction is being carried out by Hungarian Industry. Nonetheless, the procurement programme has provided GEC ALSTHOM with the opportunity to bid competitively against Hungarian Industry and successfully against Hungarian Industry for hardware supply. The manufacturing contract for the Fuel Handling Machine was placed with GEC ALSTHOM in 1993 for delivery in early 1995.

4 East European Perspective

Looking at Eastern Europe in general the selection of which spent fuel storage system is best for the reactor operator is complex and is invariably a compromise. No one system will fulfil all the requirements imposed by a utility and its licensing authority, so it is a question of establishing which system provides the optimum. The Paks approach, where a list of criteria was drawn up with a weighting against the more important parameters, is a very satisfactory method of sorting the increasing number of available dry storage technologies. To help clarify what is important, in addition to the priorities identified by Paks, some other key questions for consideration are discussed below.

a) Most Utilities are considering going to the higher burn-up fuels at some time in the future. The consequence of this is that the fuel will stay hotter longer and also emit an increased radiation level. The question to be asked here is whether the dry storage system will be able to accept the higher burn-up fuel or whether a considerably extended storage period in the fuel storage pool will be required? Will the intended system give adequate shielding to the higher radiation levels associated with higher burn-up fuels? The self-compensating, efficient, passive cooling system and the massive, low-cost concrete shield walls of an MVDS design provide considerable tolerance to higher burn-up fuels.

b) For the end of reactor life has consideration been given to the period of time that the fuel must remain in the storage pool prior to discharge into dry storage and the cost associated with this decay time? If the system can accept more recently decayed fuel,then significant savings can be made by the earlier withdrawal of the nuclear licence for the reactor buildings.

c) How self-contained is the system? If the storage period is 50 to 100 years, is the security and integrity of the system such that no matter what problem arises, the resolution of that problem is within the storage system control?
d) At the end of the storage period, if it were decided to directly dispose of the fuel to a deep repository, how easy would it be to remove the fuel from its present storage system and repack it into the final disposal container and how much would these transfer facilities cost?

5 Conclusion

Paks went through an extremely comprehensive evaluation of the available systems, selected the MVDS, and are making good progress towards licensing and construction of the system. They are now approaching their goal of a secure and safe route for the discharge of their fuel from the reactor pools and will have the next 50 years to consider its eventual disposal route.