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INTERNATIONAL STATUS OF DRY STORAGE OF SPENT FUELS

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INTRODUCTION

Spent fuel from the world's nuclear power reactors, or the high-level radioactive wastes from reprocessing of the spent fuels, are planned to be disposed of in national deep geological repositories in the respective countries of origin. The plans for most countries with nuclear power call for spent fuel or high-level waste disposal to start between 2010 and about 2050. Although storage in water pools is the primary method for management of spent nuclear fuels for the first few years after discharge from the reactor, dry storage has been implemented in several countries and is being considered in others. Dry storage is generally planned for an interim period (from 10 to as long as 100 years) until the spent fuel is disposed of or until a final decision is made on reprocessing. Dry storage is also being used to supplement wet storage capacity at some nuclear power stations.

This paper summarizes the world-wide status of dry spent fuel storage and information on the expected long-term integrity of the dry-stored spent fuel based on experience, particularly for Zircaloy-clad fuels. The paper also addresses briefly the dry storage of solidified high-level radioactive wastes. This paper is based on work carried out for the U.S. Department of Energy (DOE) by the Pacific Northwest Laboratory.

DRY STORAGE CONCEPTS

Several concepts have been considered for dry storage of spent nuclear fuel, and some concepts have been implemented in selected countries. The U.S. DOE's initial research and development needs report for a Monitored Retrievable Storage Facility (MRS) identified eight dry storage concepts that could be placed in three general categories: casks, vaults, or dry wells (DOE 1983). These concepts are summarized in Table 1.

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TABLE 1. Concepts for Dry Storage of Spent Fuels (DOE 1983)

A. Casks (or shielded canisters)
   1. Metal storage casks
   2. Concrete casks (or silos)
   3. Concrete casks in a trench or berm

B. Vaults
   1. Surface, open-cycle vaults
   2. Surface, closed-cycle vaults
   3. Subsurface, open-cycle vaults (or tunnel racks)

C. Drywells
   1. Surface field drywells
   2. Tunnel drywells

In most dry storage concepts the spent fuel assemblies are oriented vertically, although some horizontal orientations have been used. The differences among the concepts within any category generally have little effect on the long-term integrity of the spent fuel that they contain. For example, spent fuel integrity in casks is independent of the structural material or whether the cask exterior is exposed to the air or is buried; rather, integrity is determined by other factors (e.g., storage temperature, storage gas composition [i.e., inert gas such as He or Ne or Ar or N_2, or oxidizing gases such as air or CO_2], failure of the storage system integrity). Because of the significant effect of dry storage temperature on spent fuel integrity, heat transfer from the storage system is important. Dry storage concepts can use mechanical draft systems for improved heat transfer. However, existing installations typically use only natural passive external air cooling, which generally limits the spent fuels that can be stored to those that have cooled for several years since discharge from the reactor (Johnson et al. 1983; Gilbert et al. 1990b).

Industrial-scale storage has been implemented in several types of metal casks, in concrete casks (above grade), and open-cycle surface vaults. All of these concepts transfer the decay heat within the spent fuel to air in passive, natural convection systems. Subsurface dry storage (i.e., storage concepts A-3, B-3, and C-1 and C-2, listed above) have only been used for test purposes or for small amounts of materials (IAEA 1987; IAEA 1988; IAEA 1990).

MECHANISMS FOR DEGRADATION OF SPENT FUEL CLADDING IN DRY STORAGE

The potential degradation mechanisms for spent fuel cladding during dry storage are: stress rupture if internal gas pressures creates high hoop stresses in the cladding wall; stress corrosion cracking due to cladding interactions with fission products contents such as iodine, cesium, and cadmium; oxidation of the cladding material that could weaken its mechanical characteristics; fatigue of the cladding from thermal cycling; and hydriding of the cladding material if sufficient to cause its embrittlement. For storage in an inert gas, the most likely mechanism for cladding failure is creep rupture. For storage in air, the most likely mechanisms for fuel cladding failure are cladding oxidation or splitting due to oxidation of the fuel materials exposed at cladding defects if temperatures are sufficiently high. The other mechanisms are less likely to cause failures (Johnson et al. 1983; IAEA 1985; IAEA 1987; EPRI 1989).

Maintenance of the integrity of spent fuel depends on the storage conditions rather than directly on the storage concept. Potential deleterious effects of dry storage on the integrity of spent fuel are generally limited by time-at-temperature. Controlled tests under various conditions have established design limits for extended storage in inert gas. For LWR fuels clad in Zircaloy, the maximum storage temperature limit in an inert gas is accepted internationally to be in the range of 300 to 400°C. The acceptable temperature limit with oxidizing cover gases for Zircaloy-clad LWR fuels is not yet well defined, but is probably up to about 160°C (Kawasaki and Nakamura 1991). A simplified summary of the effects of various factors on the integrity of dry-stored spent fuel is given in Table 2 (IAEA 1988).

TABLE 2. Overview of Effects of Conditions on Integrity of Spent Fuel in Dry Storage (based on IAEA 1988)

Factors Affecting Spent Fuel During Dry Storage	Effects Using Inert Gas	Effects Using Oxidizing Gas
Pre-storage in a water pool	None if temps. remain below design limit	Same as with inert gas, but design temp. limit is lower
Condition of fuel assem's		
- Fuel type	None	None
- Clad type: e.g., Zr-2, Zr-1Nb, Zr-4, Zr-2.5Nb	None	None
- Pressurization	Minor effect	None
- Operational defects	None	Guiding criterion
- Crud	Only affects retrievability	Only affects retrievability
Dry storage conditions		
- Temperature/time	Guiding criterion	Limited by defect behavior
- Atmospheric impurities	Minor (if water)	Possible synergistic effect with water
- Storage-induced defects	Seldom	Less limiting than operational defects
- Packaging	None	None
Retrievability		
- Time <10 yrs	Easily retrievable	Easily retrievable if opn'l defects are excluded or if low freq. of UO_2 oxid'n
- 10 to 40 yrs	Easily retrievable	
- Time >40 yrs	Easily retrievable	

The most limiting degradation phenomenon for dry storage of spent LWR fuels in inert gases has been shown by testing and modeling to be creep rupture resulting from high temperatures and internal fuel rod pressures. The temperature criteria in the U.S. for extended storage without cladding failure due to creep rupture vary with the initial dry storage temperature, the long-term dry storage temperatures, and the out-of-reactor age of the fuel. The older the fuel when it is placed in dry storage, the lower the maximum allowable temperature during dry storage should be to assure constant stress with time and to eliminate creep rupture within a given period of time. For a dry storage life of 40 years for 5-year-old fuel in inert gases, the allowable initial dry storage temperature, as determined by U.S. testing, is about 380°C; for 15-year-old fuel, the allowable initial dry storage temperature is about 350°C (Gilbert et al. 1990a).

A study carried out by the Electric Power Research Institute (EPRI 1989) assessed the probability of LWR fuel rod cladding failure versus dry storage temperature by several mechanisms. The study concludes that failure of the cladding in some small amount of the spent fuel rods (i.e., one percent in 100 years) can be expected during dry storage under generally acceptable conditions (EPRI 1989). In another study, the probability for failure of Zircaloy cladding due to creep rupture at 380°C in inert gas is estimated to be less than 0.005 rod failures per rod over a 40-year storage period (Cunningham et al. 1987). Under generally acceptable storage conditions, the cladding defects that develop are generally small (about 1 μm) (Johnson et al. 1987) and the amounts of radioactive gases released to the storage chamber atmosphere are not sufficient to interfere with fuel retrieval operations.

Dry storage of spent LWR fuel in air has not been approved in the U.S. because the database on the effects of air on spent fuel integrity is not yet adequate to establish specific allowable temperature limits. The temperature limit in the U.S. may eventually be supported in the range of 135 to 150°C (with the air dew point no higher than about 40°C) for 40-year storage, and somewhat lower for longer storage periods. The concern with storage in air is oxidation (and possibly hydration) of the UO_2 fuel through cladding defects to a less dense oxide (e.g., U_3O_8) that will increase the local fuel volume, resulting in growth of the cladding defect and potential release of fuel particles. (Gilbert et al. 1990; Cunningham et al. 1991).

INTEGRITY OF SPENT FUEL PACKAGINGS AND OTHER STORAGE SYSTEM COMPONENTS

The integrity of system components is an important consideration in projecting the extended application of dry storage. This aspect of the technology has been subjected to some investigation (Johnson et al. 1983; Johnson et al. 1987), suggesting that the behavior of several types of packagings and other storage system components has been satisfactory through experience in time frames of 7 to 27 years.

DRY STORAGE EXPERIENCE IN SELECTED COUNTRIES

Dry storage of spent fuel from nuclear power stations has been carried out for small quantities of fuel and for testing since about 1960. Dry storage on an industrial basis has been used since 1972. This first industrial use was at the Wylfa nuclear power station in the United Kingdom for storage of Magnox fuels (metallic uranium rods clad in a magnesium-aluminum alloy) is with a carbon dioxide cover gas, in a vault that was cooled passively by air. Two more vaults that use air as a cover gas have operated at Wylfa since 1979-1980 (IAEA 1988; IAEA 1990).

The highlights of the information obtained about dry spent fuel storage in each of the countries surveyed are summarized in Tables 3 and 4. Thirteen foreign countries were reviewed that were known to have some activities in dry storage of spent fuel. Eight of the 14 countries (including the U.S.) that have had the more active programs are identified in Table 3. Highlights from countries with less active programs or whose activities are planned for the future are given in Table 4.

Ten countries have at least small amounts of spent nuclear fuels in dry storage in vaults or in casks (i.e., Canada, Germany, France, India, Italy, Japan, Switzerland, U.K., USSR, and the U.S.). However, only Canada, the United Kingdom, and the United States have implemented dry storage on an industrial scale. By the end of 1991, Canada will have about 600 MTU of CANDU fuels stored in dry concrete casks at several sites. The Canadian fuel (Zircaloy-clad natural UO_2) is stored in air at cladding temperatures below 150°C. The United Kingdom (U.K.) has stored hundreds of MTU of spent fuel from their Magnox reactors at a central vault storage facility at one nuclear power station. The U.K. stores the Magnox fuels for only a few years (in CO_2 for 150 days with a maximum temperature of 365°C, then in air at a maximum temperature of 150°C) before the fuels are sent to reprocessing.

In the U.S., two dry storage concepts have been licensed and demonstrated by utilities: metal casks and horizontal storage modules (NUHOMS). License requests for a modular concrete vault (which has been constructed and is undergoing testing) for HTGR fuel and for vertical concrete storage casks (VSCs) have been approved by the NRC. The total inventory of US commercial fuel in dry storage was 340 MTU in November 1991.

Dry storage has been utilized beginning in 1964 for spent fuel management at the Idaho National Engineering Laboratory (INEL) in the U.S. for LWBR, HTGR, and LMFBR fuels. Facilities include vaults and dry wells. The inventory now in dry storage at INEL is about 40 MTHM (Johnson, et al., 1983).

India is the only other country known to dry-store light-water reactor (LWR) fuels beyond R and D activities: India has about 21 MTU of boiling-water reactor (BWR) fuel stored in four indigenous metal storage/transportation casks. All the other countries in Table 3 currently store only small quantities of specialty spent fuels (IAEA 1988; IAEA 1990).

Five of the six countries in Table 4 currently have no spent fuel in dry storage other than for R and D activities. The USSR has a few MTU of VVER (Soviet designation for their pressurized-water reactors, PWR) fuel in demonstrations in two storage casks, and some RBMK (Soviet designation for their water-cooled graphite-moderated reactors) fuel in demonstration storage in a hot cell. These fuels are both UO_2 clad in zirconium alloys. Italy has stored fuel from their Magnox reactor in sealed canisters in a storage pool, in air for a few years, then in nitrogen. This fuel has recently been shipped to the U.K. for reprocessing. Italy also has a small amount of specialty fuels stored in a hot cell (IAEA 1988; IAEA 1990).

TABLE 3. Summary of Dry Spent Fuel Storage Experience in Eight Countries with Active Programs

Country	Current Dry Storage	Future Dry Storage	Research & Development	Longevity of Dry Storage Experience	Expected Duration of Fuel Integrity
Canada	600 MTU of CANDU fuel (natural UO_2 clad in Zircaloy) in concrete casks in air in 1991; T is <100°C to 150°C.	Hundreds of MTU/yr to be loaded into casks in next few years. Technology is licensed.	Since 1975, & to continue past 2000. Exam. of clad & fuel degradation in air, 100-150°C. Heat transfer work. Developing concrete casks for storage & tranportation.	Test storage since 1980. Examinations after 8.3 yr to date.	General: 50 to 100 yr Cladding: 100 to 1000 yr at 100°C in air Defected: >8 yr at 150°C in air.
Federal Republic of Germany	0.62 MTHM of HTGR fuel (from HTGR/AVR) in cans in hot cells in He at 40°C-170°C. 6.9 MTHM in HTGR/THTR fuel (UO_2 + ThO_2 spheres) in cans in A-R vault in He at 320°C.	Two 1500-MTU AFRs to use Castor casks are built for LWR fuel but not yet operating. Technology is licensed.	From 1979 to 1986, tested 3000 LWR rods in metal casks. Tested durability of cladding in inert gases at 250-430°C & did heat transfer studies. Developing cask for stg./transp./disp.	Tests on LWR assemblies lasted up to to 2 yr.	General: Up to ~100 yr for LWR fuels Cladding: Up to ~100 yr at initial maximum temp. of 420°C in inert gas for LWR fuels Defected: TBD.
France	Concrete vault started up in 1990 for experimental fuels (GCR) using He-filled canisters at <180°C. A second concrete vault for 9.5 MTHM for FBR fuel (UO_2 + PuO_2 in ss. clad) at <640°C.	Continue storage for 200 MTU experimental fuels for decades, with possible future expansion.	None found.	Experimental fuels in storage started in 1990. FBR fuel stored since 1985.	General: ~50 yr for experimental fuels Cladding: No information found Defected: No information found.
India	Four indigenous storage/transportation casks store 20.6 MTU of fuel from BWRs. Cover gas & temp. are unknown.	No information on any more planned.	Heat transfer work.	Casks loaded in 1987.	No information found.
Japan	15 MTU of research reactor fuel (natural U clad in Al) in cans in He in below-grade dry-well vault. Temp is not known.	Space for 15 MTU more research fuel.	Oxidation tests in air and Ar on Zircaloy & UO_2. Cladding creep tests & designs of cast iron casks.	Started dry storage of research reactor fuel in 1982. Exams after 5 yr.	General: 30 yr or more for LWR fuels Cladding: At least 30 yr for LWR fuels in inert gas at 328°C Defected: About 30 yr for LWR fuels in air at 160°C.
Switzerland	2.5 MTU of research reactor fuel (U clad in Zircaloy) in Castor cask in 1983 in He at 180°C.	AFR planned for up to 1550 MTU of fuel and/or HLW in Castor casks. Technology is licensed.	None found.	Research reactor fuel loaded into cask in 1983. No exams. of fuel.	No information found. Apparently use FRG data.
United Kingdom	Hundreds of MTU of Magnox fuel (U in Mg-Al alloy) in one vault in CO_2, followed by storage in 2 other vaults in air. Initial storage temp. is up to 365°C in CO_2 and 150°C in air.	Continued use of existing vaults for Magnox fuel. Considering vault for AGR fuels. Technology is licensed.	Design/development of vault storage for Magnox and AGR fuels. Fuel and cladding oxidation tests in air at 250 to 450°C, starting R&D for AGR fuels.	Storage started in CO_2 in 1972 & in air in 1979. Fuel is usually stored 1 to 4 yr before reprocessing. Some exams. after 4-5 yr.	General: Few years to several decades for Magnox fuel in CO_2 then air under U.K. vault conditions. Cladding: No information found. Defected: No information found.
United States	340 MTU of LWR fuel in metal casks & NUHOMS modules in inert gas, at 3 power plants. 40 MTHM of LWBR, HTGR, & LMFBR fuels in vaults and dry wells (in air & inert gas) at INEL. 20 MTU of consol. PWR fuel & 20 MTU PWR assemblies in metal & concrete casks at INEL.	Continued use of metal casks & NUHOMS modules, and use of concrete casks for LWR fuels. Use of vault for HTGR fuels. Continued dry storage of special fuels at INEL. National MRS planned but no final decision.	Since 1964. Tested irradiated clad & declad fuel specimens, fuel rods, fuel assemblies, and consolidated fuel assemblies in inert gas (temperatures 325 to 570°C) & in air (temperatures up to 230°C). Performed heat transfer studies & numerous demo's.	Some LMFBR fuels have been dry-stored since 1964. PWR fuels in demo. storage in inert gas since 1979. First licensed dry storage in inert gas in 1986. Monitoring of demonstration cask storage continues at INEL.	General: At least 40 years for LWR fuel in inert gas at initial maximum temp. of about 380°C, or lower, depending on prior spent fuel history. Cladding: Same as above for LWR fuel in inert gas. Defected: Same as above for LWR fuel in inert gas. Prelim. indications are tens of years for LWR in

TABLE 4. Summary of Dry Spent Fuel Storage Activities in Five Countries with Modest Programs

Country	Current Dry Storage	Future Dry Storage	Research & Development	Longevity of Dry Storage Experience	Expected Duration of Fuel Integrity
Argentina	No storage to date.	Plan to start use of Canadian concrete casks for CANDU fuel in 1992. Plan for 10 yr of fuel production.	Started development of dry well, but status is unknown. Did heat transfer studies.	No experience to date.	No information found. Apparently using Canadian data.
Former German Democratic Republic	No storage to date.	No plans were identified.	Heat transfer studies for storage casks.	No experience to date.	No information found.
Italy	Fuel from Magnox reactor stored 15 to 20 yr in air & nitrogen in sealed cans in a pool. ~2 MTU from specialty fuels stored in a hot cell.	Dry storage of Magnox fuel was discontinued when fuel shipped for reprocessing. Dry storage of specialty fuel to continue. No other plans.	None found.	Magnox fuel stored 15 to 20 yr. Recent exam of Magnox fuel showed much cladding corrosion.	Much cladding failure after 15-20 yr, but fuel mostly intact.
South Korea	No storage to date.	Canadian concrete casks ordered for 700 MTU of CANDU fuel.	Starting generic dry storage R&D. Heat transfer studies for vault storage.	No experience to date.	No information found. Apparently using Canadian data.
Spain	No storage to date.	Plan for ≥500 MTU storage in NAC transport/storage casks for LWR fuel.	Discontinued development & heat transfer studies on metal transport/storage casks. Formerly used maximum fuel clad temp. of 250°C.	No experience to date.	Expect to store until at least 2020.
USSR	Demonstration of VVER fuel both in Castor-V cask since 1984, and in a USSR transport cask since 1990, both inert gas. Demonstration of RBMK fuel (UO_2 with Zr clad) in hot cell.	Considering some dry storage, especially for RBMK fuel, in transportation/storage casks.	Demonstrations of VVER fuel in Castor cask & in Soviet cask, & RBMK fuel tests in hot cell. Tests on degradation at various temperatures in air & inert gas.	VVER fuel in Castor-V cask since 1984, and in Soviet cask since 1990. Date unknown for RBMK fuel in hot cell.	No time period identified, but limiting temp. in air is 125°C & in inert gas is 350°C.

In Table 3, Canada, the Federal Republic of Germany (FRG), Switzerland, the U.K. and the U.S. plan to continue or start industrial-scale dry storage of spent nuclear fuels in the near future. The other three countries (France, India, and Japan) plan no such activities. Canada is planning to continue adding concrete cask storage of their CANDU fuels at a significant rate. The U.K. plans to continue their existing short-time (e.g., few years) vault storage of Magnox fuels, and is considering future vault storage of fuels from their advanced gas-cooled reactors (AGR). The FRG and Switzerland have or are building away-from-reactor (AFR) storage facilities for dry storage of up to several thousand MTU of LWR fuels in Castor casks. In the U.S., two more nuclear power stations are planning for future storage in recently-licensed vaults or concrete casks, and others are considering supplemental dry storage. A national central dry storage facility has been planned, and initiation of design has started. Vault storage and/or dry cask storage is licensed technology in those countries that are using or plan to use dry storage in the near future (IAEA 1988; IAEA 1990).

Argentina, South Korea, and Spain plan for near-future dry storage of hundreds of MTU of spent fuel in storage casks. Argentina and South Korea are preparing to use Canadian concrete casks for dry storage of their CANDU fuel in air. Spain is planning to use transportation/storage casks for extended interim storage of their LWR fuel in inert gas, pending licensing of the casks in the U.S. The USSR is considering the possible future use of dry storage casks, particularly for their RBMK fuel. The U.K. is considering the possible future industrial-scale vault storage of fuels (uranium dioxide clad in stainless steel) from its AGRs (IAEA 1988; IAEA 1990).

An important related application is dry storage storage of solidified high-level wastes (HLW). Significant amounts of vitrified HLW in stainless steel canisters have been stored in air-cooled vaults in France at Marcoule (since 1978) and La Hague (since 1989), in the United Kingdom at Sellafield (since 1990), in India at Tarapur, and in the USSR (since 1988), and in a hot cell in Belgium at Mol (since 1985). In addition, granular HLW calcine has been stored in bins in the U.S. at INEL since 1963.

Research on dry storage of spent LWR fuels in inert atmospheres is considered to be basically completed in most of the countries, now that the technologies are licensed. The FRG conducted significant extensive research and development on dry storage of LWR fuels in inert atmospheres in the early 1980s, and this work was satisfactorily concluded to the point of licensing the technology. Canada is continuing periodic long-term examination of CANDU fuels stored in air, Japan is carrying out high-temperature oxidation tests of LWR fuels, the U.K. is starting research and development on dry storage of their AGR fuels, and the USSR is continuing their three demonstrations and are starting research and development testing on degradation of their VVER and RBMK fuels under various dry storage conditions. Dry storage R&D activities are essentially completed in the U.S., but dry storage demonstrations are continuing at the INEL involving four metal casks and a ventilated concrete storage cask (VSC), and a cooperative demonstration effort with LWR fuels at one nuclear power plant involving six metal casks. The other countries are generally not carrying out further R and D except perhaps for design-development work (such as heat transfer studies) for their specific cases. Canada is developing a concrete storage cask that is intended to be licensed for transportation. The FRG is developing their "Pollux" cask for potential use for storage, transportation and disposal of spent fuels that are considered undesirable to reprocess.

Some examinations of the dry-stored Magnox spent fuels in the U.K. have been carried out after about five years of storage, with favorable observations. (Some Magnox fuel with failed cladding was discovered in 1990 in their storage vault; the cause of the failures has been determined to be contact by rain water leaking through a roof joint.) In addition, a small amount of Magnox fuel that was dry-stored in Italy for more than 15 years had significant cladding damage.) In Canada, test storage in air using their concrete cask concept was started in 1980, and examinations have been made after 8.3 years of storage, with no cladding degradation noted. The major R and D activities and extrapolations for the long-term storage of LWR fuels in the FRG in the early 1980s was done with fuel dry-stored for up to two years in metal casks with inert cover gas. Japan has examined some of their dry-stored research reactor fuel after five years, with favorable observations. No other foreign observations of long-term dry storage are known.

In the U.S., the duration of integrity of LWR fuels in inert gas storage is projected to be at least 40 years at the specified temperature limits, which range from about 325 to 380°C, depending on the history of the spent fuel. The temperature limits are based on modeling from experimental data from German and U.S. work. Direct observations from storage experience have indicated one unexplained rod failure out of 3500 fuel rods in PWR assemblies stored for four years (Cunningham et al. 1987). In a demonstration of storage of 9800 consolidated PWR spent fuel rods, up to 11 rod failures were detected by storage cask gas monitoring within a few months after rod consolidation (Gilbert et al. 1990b).

In the FRG, the duration of the integrity of LWR fuels in dry storage in inert gas is projected to be in the order of 100 years, based on tests and predictions done in the FRG, the U.S., and elsewhere. This view is apparently shared by all the surveyed countries with interest in dry storage of LWR fuels. The duration of the integrity of defected LWR fuels stored in air is less well defined: the Germans propose that oxidation testing is needed to define conditions and their effects on defected LWR fuel integrity in air storage of 40 to 100 years; the Japanese believe defected LWR fuel can be stored for about 30 years in air at 160°C (Kawasaki and Nakamura 1991). The Canadians estimate that their cask dry-storage concept can reliably store CANDU fuels for the 50 to 100 years that they may use dry storage, and that technical predictions indicate safe storage for 100 to 1000 years. Defected CANDU fuels have been stored without loss of integrity in air at 150°C for eight years so far. The British indicate that they can store Magnox fuels in their vault concept for up to several decades. Preliminary indications in the U.S. are that storage times of 30 to 40 years for fuels in air at temperatures up to about 150°C may be possible.

CONCLUSIONS

Based on the findings in this survey, the general conclusions that can be drawn for extended dry storage of spent fuels from nuclear power reactors are given below.

1. Foreign experience in long-term (i.e., decades) dry storage of LWR fuels has been limited mostly to tests and demonstrations for about two to ten

years. U.S. experience started in 1979, and demonstrations with periodic monitoring are continuing.

2. Based on past and current data developed in foreign countries and the U.S., inert gas storage of LWR fuels is considered in the countries surveyed to be well developed, it is licensed for industrial application, and is being implemented in the market place by industry (principally concrete casks, metal casks, and vaults).

3. Because of the developed status of dry storage, relatively little R and D is in progress now in the countries surveyed, with most efforts on development/design for specific applications. Active R and D efforts appear to be in progress in the USSR for possible dry storage of their VVER and RBMK fuels; Canada is continuing long-term testing and fuel examinations for dry storage of their CANDU fuels in air; the U.S. is continuing some dry storage demonstrations, but R and D is essentially completed.

4. The duration of LWR fuel integrity stored in inert gases at initial temperatures of about 350 to 400°C is generally considered to be proven in the countries surveyed for the needed storage time periods of up to 50 to 100 years.

5. Storage times with acceptably low fuel degradation of LWR fuels in air are shorter and at much lower temperatures than in inert gases, and there are relatively few results on long-term air-storage effects on defected spent fuels. Canadian tests have been carried out for 8.3 years on defected CANDU fuels in air at 150°C, with favorable results. The In Germany and the U.S., more studies would be needed for air storage for 40 to 100 years.

6. The U.K. was the country that first implemented industrial-scale dry storage (in 1972). Their storage is for Magnox fuels and is for short time periods. Their experience has generally been favorable. Canada was the second country to implement industrial-scale dry storage (in 1980); their storage is at low temperatures in air for CANDU fuels. Their experience has also been favorable.

7. Canada, the U.K., and the U.S. are currently the only countries with industrial-scale experience, and are the most active in implementing dry storage technologies. Germany is also planning to actively implement dry storage on an industrial scale as soon as the litigation on their away-from-reactor storage facilities is satisfactorily concluded. In addition to at-reactor dry storage in the U.S., a central away-from-reactor dry storage facility is planned.

8. Casks (concrete and metal) and vaults are the most common dry storage concepts in use in the countries surveyed. All casks and most vault concepts in use utilize natural, convective air flow for cooling.

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