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ABSTRACT

Most countries with nuclear power are planning for spent nuclear fuel (or high-level waste from reprocessing of spent fuel) to be disposed of in national deep geological repositories starting in the time period of about 2010 to 2050. While spent fuel has been stored in water basins for the early years after discharge from the reactors, interim dry storage for extended periods (i.e., several tens of years) is being implemented or considered in an increasing number of countries. Dry storage technology is generally considered to be developed on a world-wide basis, and is being initiated and/or expanded in a number of countries. This paper presents a summary of status and experience in dry storage of spent fuel in other countries, with emphasis on zirconium-clad fuels. Past activities, current status, future plans, research and development, and experience in dry storage are summarized for Argentina, Canada, France, former West Germany, former East Germany, India, Italy, Japan, South Korea, Spain, Switzerland, United Kingdom, and the former Soviet Union. Conclusions from their experience are presented. Their experience to date supports the expectations that proper dry storage should provide for safe extended dry storage of spent fuel.

INTRODUCTION

Spent fuel from the world's nuclear power reactors and high-level radioactive wastes (HLW) from reprocessing the spent fuel 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 HLW disposal to start between 2010 and 2050. Although storage in water pools is the primary method for managing spent nuclear fuels for the first few years after discharge from the reactors, dry storage has been implemented in several countries and is being considered by others. Dry storage is generally planned for an interim period (from 10 to 100 years) until the spent fuel is disposed of or a final decision is made on reprocessing. At some nuclear power stations, dry storage is also being used to supplement wet storage capacity.

This paper summarizes the status of dry spent fuel storage in other countries and the expected long-term integrity of the dry-stored spent fuel, based on experience. This paper is based on work carried out for the U.S. Department of Energy (DOE), Office of Civilian Radioactive Waste Management, by the Pacific Northwest Laboratory.[1]

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DRY STORAGE CONCEPTS

A number of 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 (MRS) facility identified eight dry storage concepts that could be placed in three general categories: casks, vaults, or drywells.[2] These concepts are summarized below.

- Casks (or shielded canisters)
  - Metal storage casks
  - Concrete casks (or silos)
  - Concrete casks in a trench or berm
- Vaults
  - Surface, open-cycle vaults
  - Surface, closed-cycle vaults
  - Subsurface, open-cycle vaults (or tunnel racks)
- Drywells
  - Surface field drywells
  - 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, as long as the dry storage containment remains intact. Spent fuel integrity is determined by factors such as storage temperature and time, and 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). 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.[2,4]

Industrial-scale storage has been implemented in several types of metal casks, 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., concrete casks in a trench or berm; subsurface, open-cycle vaults; and surface field drywells) have only been used for test purposes or for small amounts of materials.[5,6,7]

MECHANISMS FOR DEGRADATION OF SPENT FUEL CLADDING IN DRY STORAGE

The potential degradation mechanisms for spent fuel cladding during dry storage are: stress or creep rupture if internal gas pressure creates high hoop stresses in the cladding wall; stress corrosion cracking due to cladding interactions with fission products 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 resulting from high temperature and internal fuel rod pressures. 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.[3,8,5,9]

Potentially deleterious effects of dry storage on the integrity of spent fuel are generally controlled by time-at-temperature. Controlled tests under various conditions have established design limits for extended storage in inert gas. For light water reactor (LWR) fuels clad in Zircaloy, the maximum storage temperature 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 in the range of 135 to 160°C.[10] A simplified summary of the effects of various factors on the integrity of dry-stored spent fuel is given in Table 1.[6]

The temperature criteria in the U.S. for extended storage without cladding failure due to creep rupture vary with temperatures, which are a function of fuel burnup. These controlling conditions are 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 ensure 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.[11]

A study carried out by the Electric Power Research Institute[9] assessed the probability of LWR fuel-rod cladding failure by several mechanisms at various dry storage temperatures. The study concludes that failure of the cladding in some small number of spent fuel rods (i.e., 1% in 100 years) can be expected during dry storage under generally acceptable conditions.[9] 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.[11] Under generally acceptable storage conditions, the cladding defects that develop are usually small (about 1 μm),[12] 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_4O_9) that will increase the local fuel volume, resulting in growth of the cladding defect and potential release of fuel particles.[11,14]

DRY STORAGE EXPERIENCE IN SELECTED COUNTRIES

Dry storage of small quantities of spent fuel from nuclear power stations has been carried out for testing since about 1960. Dry storage on an industrial basis has been used since 1972. The first industrial use was at the Wylfa nuclear power station in the U.K. for storage of Magnox fuels (metallic uranium rods clad in a magnesium-aluminum alloy), 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.[6,7]

Table 1. Overview of Effects of Conditions on Integrity of Spent Fuel in Dry Storage[6]

Factors Affecting Spent Fuel During Dry Storage	Effects Using Inert Gas	Effects Using Oxidizing Gas
Pre-storage in a water pool	None if temperatures remain below design limit	Same as with inert gas, but design temperature limit is lower
Condition of fuel assembly		
- Fuel type	None	None
- Clad type: e.g., Zr-2, Zr-1Nb, Zr-4, Zr-2.5Nb	None	None
- Pressurization	Minor effect	Minor effect
- 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 <10 yr to >40 yr	Easily retrievable	Easily retrievable if w/o operational defects or if low UO_2 oxidation

Current Dry Storage Activities

The highlights of dry spent fuel storage activities in each of the countries surveyed are summarized in Tables 2 and 3. Data were reviewed from thirteen foreign countries that were known to have some activities in dry storage of spent fuel. Seven of the 13 countries that have had the more active programs are identified in Table 2. Highlights from countries with less active programs or whose activities are planned for the future are given in Table 3.

Nine foreign 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., and the former USSR). However, only Canada and U.K. (and the U.S.) have implemented dry storage on an industrial scale. By the end of 1991, Canada had 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 U.K. has stored hundreds of MTU of spent fuel from its 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.

Table 2. Summary of Dry Spent Fuel Storage Experience in Seven 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. AECL is planning on using ventilated vaults, CANSTOR.	Since 1974, and to continue past 2000. Exam. of clad and fuel degradation in air, 100°C to 150°C. Heat transfer work. Developing concrete casks for storage and transportation.	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 dry air and in moist, limited air.
Federal Republic of Germany	0.62 MTHM of HTGR fuel (from HTGR/ AVR) in cans in hot cells in He at 40°C to 170°C. 6.9 MTHM in HTGR/THTR fuel (UO_2 + ThO_2 spheres) in cans in at-reactor vault in He at up to 320°C.	Two 1500-MTU AFRs for Castor and TN casks are built for LWR fuel (and pebble-bed fuel and vitrified HLW) but not yet operating. Technology is licensed.	From 1979 to 1986, tested 3000 LWR rods. Tested durability of cladding in inert gases at 250°C to 430°C and did heat transfer work. Developing cask for stg./transp./disp.	Tests on LWR rods lasted up 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	A concrete vault for 9.5 MTHM for FBR fuel (UO_2 + PuO_2 in S.S. clad) at <640°C. A Second concrete vault started up in 1990 for experimental fuels (GCR) using He-filled canisters at <180°C.	Continue storage for up to 200 MTU experimental fuels for decades, with possible future expansion. Vault design is available for LWR fuels.	From 1987 to 1991, heat transfer and facility safety and containment studies.	Experimental fuels storage started in 1990. FBR fuel stored since 1985.	General: ~50 yr for experimental fuels in inert gas Cladding: No information found Defected: No information found.
India	Four indigenous storage/ transportation casks store 20.6 MTU of fuel from BWRs in air since 1987. Temp. is unknown.	No information on any more planned. Vault planned for vitrified HLW.	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 drywell vault since 1982. No temp. information found.	Space for 15 MTU more research fuel.	Oxidation tests in air and Ar on Zircaloy and UO_2. Cladding creep tests and designs of cast iron casks. Durability tests of metallic seals.	Started dry storage of research reactor fuel in 1982. Examinations after 5 yr.	General: 30 yr or more for LWR fuels Cladding: At least 30 yr for LWR fuels in air at 328°C; in inert gas at 350-430°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 examinations 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. Vault planned for ~2000 MTU of AGR fuels by Scottish Nuclear. Technology is licensed.	Design/development of vault storage for Magnox and AGR fuels. Fuel and cladding oxidation tests in air at 250°C to 450°C, R&D in progress for AGR fuels.	Storage started in CO_2 in 1972 and in air in 1979. Fuel is usually stored 1 to 4 yr before reprocessing. Some examinations after 4-5 yr.	General: Few years to several decades for Magnox fuel in CO_2, then in air under U.K. vault conditions. Cladding: No information found. Defected: No information found.

Table 3. Summary of Dry Spent Fuel Storage Activities in Six 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 1993. Plan for 5 to 33 yr of fuel production.	Started development of drywell, 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 before unification with FRG. Recent indications are for an AFR holding 300 to 700 MTU using dry storage casks.	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 and 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 Magnox cladding failure after 15-20 yr, but fuel mostly intact. Failures probably due to high-temp. storage in oxidizing gas.
South Korea	No storage to date.	Canadian concrete casks ordered for 700 MTU of CANDU fuel, starting in 1997.	Started 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 in inert atmosphere. Central AFR planned for ca. yr 2000, and could be repository sites.	Discontinued development and 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.
Former USSR	Demonstration of VVER fuel in Castor-V cask since 1984 and in a USSR transport cask since 1990, both in 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 in vaults, or in concrete casks.	Demonstrations of VVER fuel in Castor cask and in Soviet cask, and RBMK fuel tests in hot cell. Tests on degradation at various temperatures in air and 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 and in inert gas is 350°C.

India is the only other country known to dry-store LWR fuels beyond R&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 2 currently dry-store only small quantities of specialty spent fuels.[6,7]

Five of the six countries in Table 3 currently have no spent fuel in dry storage other than for R&D activities. The former 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. Both fuels are UO_2 clad in Zirconium alloys. Italy has stored fuel from its 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.[6,7]

Planned Dry Storage Activities

Canada, the Federal Republic of Germany (FRG), Switzerland, and the U.K. plan to continue or start industrial-scale dry storage of spent nuclear fuels in the near future. France, India, and Japan plan no such activities. Canada is planning to continue adding concrete cask storage of its CANDU fuels at a significant rate. The U.K. plans to continue its existing short-time (e.g., a few years) vault storage of Magnox fuels, and one utility is planning for future vault storage of fuels from its advanced gas-cooled reactors (AGR, with UO_2 fuel clad in stainless steel). The FRG has completed building away-from-reactor (AFR) storage facilities for dry storage of up to 3,000 MTU of LWR fuels in transport/storage casks. Switzerland is building an AFR storage facility that will use transportable storage casks. 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.[6,7]

Argentina, South Korea, and Spain each plan for near-future dry storage of hundreds of MTU of spent fuel in storage casks. Argentina (starting in 1993) and South Korea (starting in 1997) 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 its LWR fuel in inert gas, pending licensing of the casks in the U.S. The former USSR is considering the possible future use of dry storage casks or vaults, particularly for its RBMK fuel. Dry cask storage is now expected to be implemented for fuel from some of the shutdown reactors in the former German Democratic Republic, and some Eastern European countries (e.g., Czechoslovakia, Hungary) are now planning for dry spent fuel storage.

Research and Development

Research and development 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 R&D on dry storage of LWR fuels (primarily in inert atmospheres) in the early 1980s, and this work resulted in licensing the technology. Canada is continuing periodic long-term examination of CANDU fuels stored in air, and is continuing to develop its dry storage technology. Japan is carrying out high-temperature oxidation tests of LWR fuels in air, the U.K. is carrying out R&D on air storage of its AGR fuels, and the former USSR is continuing its three demonstrations and is starting R&D testing on degradation of its VVER and RBMK fuels under various dry storage conditions. The other countries are generally not carrying out further R&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, and is also developing dry storage vaults. The FRG is developing its "Pollux" cask for potential storage, transportation, and disposal of spent fuels that may not be reprocessed.

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. (However, some Magnox fuel with failed cladding was discovered in 1990 in a U.K. storage vault; the cause of the failure was determined to be corrosion from 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 the 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&D activities and extrapolations for long-term storage of LWR fuels in the FRG in the early 1980s were done with fuel dry-stored for up to two years. Japan has examined some of its dry-stored research reactor fuel after five years, with favorable observations. No other foreign observations of long-term dry storage are known.

Expected Duration of Dry-Stored Spent Fuel Integrity

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 and experimental data from German and U.S. work.[4]

In the FRG, the duration of the integrity of LWR fuels in dry storage in inert gas is projected to be about 100 years, based on tests and predictions done there, in 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 estimate that undefected LWR fuel can be stored for about 30 years at 350 to 430°C in inert gas, depending on fuel conditions and history, and undefected fuel can be stored for about 30 years in air at up to 160°C.[10] 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 (at 100 to 150°C), 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.

CONCLUSIONS

Based on 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 to determine long-term (i.e., decades) integrity of dry stored LWR fuels has been limited mostly to tests and demonstrations for about two to ten years.

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 it is being implemented in the marketplace by industry.

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

4. The duration of LWR fuel integrity stored in inert gases at initial temperatures of about 320 to 400°C is generally considered to be proven in the countries surveyed for the needed storage times of 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. In Germany and the U.S., more studies would be needed for air storage for 40 to 100 years. Studies to date in the U.S. and Japan indicate allowable temperature for air storage of LWR fuels is in the range of 135 to 160°C.

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

7. Canada and U.K. are currently the only foreign countries with industrial-scale experience and are the most active in implementing dry storage technologies. The FRG is planning to actively implement dry storage on an

industrial scale as soon as the litigation on its away-from-reactor storage facilities is satisfactorily concluded.

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

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