HEAT EXCHANGER
(Typically SS)

FILTER AND ION
EXCHANGE

STAINLESS
STEEL PIPING

SKIMMERS

SPENT FUEL
ASSEMBLIES
IN STORAGE
RACKS

VACANT
RACK
POSITION

LINER (Typically SS)

REINFORCED CONCRETE
STRUCTURE

CASK SET-
OFF SHELF

FUEL POOL WATER DEPTH (8.5 - 17m)

ALUMINIUM OR STAINLESS
STEEL RACKS

CASK UNLOADING
BASIN

TECHNICAL REPORTS SERIES No. **218**

Storage of Water Reactor Spent Fuel in Water Pools

Survey of World Experience

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1982

STORAGE OF WATER REACTOR
SPENT FUEL IN WATER POOLS

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REPORT BASED ON A SURVEY
JOINTLY CONDUCTED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
AND THE
NUCLEAR ENERGY AGENCY OF THE OECD

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FOREWORD

Following discharge from a nuclear reactor, spent fuel has to be stored in water pools at the reactor site to allow for radioactive decay and cooling. After this initial storage period, the future treatment of spent fuel depends on the fuel cycle concept chosen. Spent fuel can either be treated by chemical processing or conditioning for final disposal at the relevant fuel cycle facilities, or be held in interim storage — at the reactor site or at a central storage facility.

Recent forecasts predict that, by the year 2000, more than 150 000 tonnes of heavy metal from spent LWR fuel will have been accumulated. Because of postponed commitments regarding spent fuel treatment, a significant amount of spent fuel will still be held in storage at that time. Although very positive experience with wet storage has been gained over the past 40 years, making wet storage a proven technology, it appears desirable to summarize all available data for the benefit of designers, storage pool operators, licensing agencies and the general public. Such data will be essential for assessing the viability of extended water pool storage of spent nuclear fuel.

In 1979, the International Atomic Energy Agency and the Nuclear Energy Agency of the OECD jointly issued a questionnaire dealing with all aspects of water pool storage. This report summarizes the information received from storage pool operators.

CONTENTS

SUMMARY AND CONCLUSIONS

The terms and abbreviations used in this publication
are defined in the Glossary (Appendix 1)

WATER STORAGE EXPERIENCE SURVEY — BASIS AND SCOPE

Water storage of irradiated nuclear fuel has been an important link in nuclear
fuel management since the first reactor discharged fuel in 1943. Since there
have been delays in decisions regarding the ultimate status of irradiated water
reactor fuel, water storage has emerged as the only licensed near-term fuel
management option in several International Atomic Energy Agency (IAEA)
Member States. Whatever decisions are reached, water storage will continue to
be an important factor in nuclear fuel management.

To expand the understanding of water storage technology, the IAEA and
the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation
and Development (OECD) agreed to conduct a survey on the storage experience
of water reactor fuel among countries with operating nuclear power programmes.
This publication summarizes the results of that survey. A brief overview of
water storage technology has also been included in order to provide a clearer
understanding of the survey results and the breadth of storage technology;
relevant literature references are cited.

The survey questionnaires were distributed to 22 countries through
established IAEA channels and through the NEA Committee on the Safety of
Nuclear Installations (CSNI). Nineteen states and one multi-national organization
(the Commission of the European Community) responded to the questionnaire.
The responses represented over 85% of the water-cooled power reactor[1] pools
and away-from-reactor (AFR)[2] pools that have operated for five years or more.
Seventeen research reactor pools and two facilities that store gas reactor fuel
also responded.

The first irradiated nuclear fuel was discharged to the X-10 reactor pool
(Oak Ridge, Tennessee, USA) in November 1943. Over the ensuing 37 years,
water storage technology has evolved to accommodate changing fuel designs and
storage requirements.

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[1] Responses came from both light water reactors (LWRs) and heavy water reactors
(HWRs).

[2] A similar terminology is 'independent spent fuel storage installation' (ISFSI), which
applies either to a fuel storage facility near to but independent of the reactor or to a facility
away from the reactor.

TABLE I. SUMMARY OF THE MOST SIGNIFICANT RESIDENCE TIMES OF SPENT FUEL AND
FUEL POOL COMPONENTS

Fuel or component	Environment	Date of first pool exposure	Storage status	Burn-ups and remarks
Longest spent fuel storage				
Zircaloy-2-clad fuel (Shippingport)	Deionized water	1959	Continuing	4 000 MW·d/t U
Zircaloy-4-clad fuel (H.B. Robinson)	Boric acid	1973	Continuing	17 500 MW·d/t U
Stainless-steel-clad fuel (Windscale)	Deionized water	1969	Continuing	32 600 MW·d/t U
Stainless-steel-clad fuel (Conn.Yankee)	Boric acid	1967	Continuing	18 800 MW·d/t U
Aluminium-clad fuel (JRR-3)	Deionized water	1970	Continuing	1 200 MW·d/t U
Highest burn-up of spent fuel				
Zircaloy-clad fuel (Shippingport)[a]	Deionized water	1974	Continuing	41 000 MW·d/t U
Zircaloy-clad fuel (Obrigheim)	Boric acid	1975	Continuing	39 000 MW·d/t U
Stainless-steel-clad fuel (BR-3)	Deionized water	1969	Continuing	32 000 MW·d/t U
Stainless-steel-clad fuel (Conn.Yankee)	Boric acid	1978	Continuing	37 000 MW·d/t U
Aluminium-clad fuel (HFR)	Deionized water	1978	Continuing	550 GW·d/t U
Longest residence time of pool components[b]				
Aluminium alloys (JEN)	Deionized water	1959	Continuing	Fuel storage rack
Aluminium alloys (Yankee Rowe)	Boric acid[c]	1962	Removed 1979	Fuel storage rack
Stainless steel (NRX)	Deionized water	1956	Continuing	Fuel handling equipment
Stainless steel (Yankee Rowe)	Boric acid[c]	1962	Continuing	Piping, fuel machine
Carbon steel (painted) (Halden)	Deionized water	1959	Continuing	Pool liner
Titanium (Studsvik)	Deionized water	1973	Continuing	Heat exchanger
Miscellaneous (X-10, ORNL)	Deionized water	1943	Continuing	

[a] In-reactor exposure from 1957 to 1974; 12.3 years were at reactor operating conditions.

[b] Some operating spent fuel pools have components that are older than those mentioned; however, material compositions are not available for components in some older pools.

[c] The maximum of boron in spent fuel pools during component residence was 800 ppm boron.

The survey deals principally with pools built since 1960. Generally, they are lined with stainless steel (SS) and have heat exchangers to dissipate residual fuel heat and equipment to control water purity. There are two principal types of water chemistry: deionized water and borated water. AFR pools, boiling water reactor (BWR) pools and HWR pools have deionized water; pressurized water reactor (PWR) pools have borated water. The PWR pools have borated water so that primary system and fuel pool waters will be compatible during refuelling. Research reactor pools generally have deionized water chemistry, and gas reactor pools have a special chemistry to control corrosion of the gas reactor fuel cladding.

Some spent fuel pools operate with unusual water chemistries. The Fuel Receiving and Storage Facility (FRSF) pool in Idaho, USA, has had chloride concentrations from ∼ 350 to 700 ppm over periods of several years resulting from algae control measures. Spent fuel pools that store Magnox (magnesium-clad) gas reactor fuel operate at pH ⩾ 11.5 to minimize Magnox corrosion. A spent fuel pool at the Test Area North (TAN), Idaho, USA, was on standby for about 12 years without clean-up procedures. When the pool water was sampled in 1979, the chloride level had risen to only 1.8 ppm over the 12-year period.

Control of water purities in spent fuel pools is a routine and effective procedure, using ion exchange, filters, skimmers and occasional vacuuming of pool floors.

STORAGE BEHAVIOUR OF IRRADIATED FUEL

An important goal of the survey was to determine how long and how well water reactor fuel and other materials have resided in spent fuel pools. Table I summarizes the highest nuclear fuel burn-ups and the longest fuel and component residence times for the principal pool types.

The survey questionnaire asked whether any degradation of spent fuel had been observed (Appendix A). Operators from approximately 115 pools that store fuel from water-cooled power reactors responded to this part of the questionnaire, including pools that store SS-clad and Zircaloy-clad fuel. All pool operators indicated that they have not seen any evidence that water reactor spent fuel is degrading during water storage. The pool operators have opportunities to observe fuel during handling and storage: discharge of hydrogen bubbles would signal substantial cladding corrosion rates; changes in fuel rod appearance might occur if corrosion were severe; and releases of helium/fission gas bubbles and increases in pool radioactivity levels would be potential consequences of fuel cladding perforation.

Pool operator observations are not the only basis for assessing fuel cladding behaviour. Several examinations of spent fuel have indicated that no detectable

3

degradation of water reactor fuel cladding has occurred during water storage; both SS-clad and Zircaloy-clad fuel have been examined.

Corrosion of Magnox-clad and SS-clad gas reactor fuel has been reported. However, the corrosion can be controlled by the use of appropriate measures (canning, water chemistry control, etc.).

Most research reactors operate with aluminium-clad fuel. All 17 research reactor operators who responded to the survey indicated that they have not seen evidence that the fuel degrades in storage.

BEHAVIOUR OF SPENT FUEL POOL COMPONENTS

The principal metallic components in spent fuel pools are fuel storage racks, fuel handling equipment, pool liners, piping, ion-exchange columns, and heat exchangers. Most water reactor and AFR pools built since 1960 have SS liners, and SS is also the predominant material for other spent fuel pool components. However, the fuel storage racks in numerous deionized water pools and in a few borated water pools are constructed from aluminium alloys.

The questionnaire responses suggest that malfunctions of spent fuel pool components have been both infrequent and not serious. The following types of malfunctions have been noted:

- Fuel assemblies dropped during handling (no major consequences occurred)
- Small leaks in SS liners
- Releases of mildly radioactive water due to failure of temporary couplings and freezing of heat-exchanger tubes
- Stress corrosion cracking (SCC) in stagnant legs of spent fuel pool piping (at only a few PWR pools)
- Swelling of fuel storage rack walls in designs where hydrogen could accumulate by corrosion or radiolytic decomposition
- Substantial corrosion of mild-steel components; minimal corrosion of SS and aluminium components (mild steel has essentially been eliminated as a spent fuel pool component material).

Malfunctions of components in U.S. pools are documented in the Docket literature and, therefore, can be reviewed by other spent fuel pool operators to minimize future malfunctions.

CONCLUSIONS

There is a strong basis from the survey to conclude that water storage of spent nuclear fuel is a mature, viable technology without major technological

4

difficulties. There is a substantial basis to conclude from pool operator observations and from specific fuel examinations that Zircaloy-clad water reactor spent fuel has not degraded appreciably in up to 20 years; SS-clad water reactor fuel has been examined after ∼ 5 years of storage and has resided in pools for up to ∼ 12 years without evidence of pool-induced degradation.

Operational problems with spent fuel pool components have been minor.

Spent fuel pool operations contribute small fractions to total radiation doses from nuclear reactor operations and make only minor contributions to volumes of low- and intermediate-level radioactive waste.

RECOMMENDATIONS

Evidence from pool operator experience and from specific fuel examinations provides a positive basis for regarding water storage of HWR and LWR spent fuel as a proven, viable technology.

As a conservative measure, it would seem prudent to continue some surveillance of spent fuel, as recommended by the International Nuclear Fuel Cycle Evaluation (INFCE) Working Group No.6, and to emphasize observation of fuel with higher burn-ups and fuel with extended pool residence. For individual pools, the surveillance needs to involve only normal observation during fuel handling and pool inspections. For national programmes, fuel examination should continue if spent fuel water storage for several decades continues to be a prospect. If decisions are reached that limit water storage to a few years or if the current favourable experience continues, a diminishing role for fuel surveillance would seem justified.

Pool operators should continue to be alert for improvements in pool design and operation. Although relatively few malfunctions have occurred, these should be reviewed to minimize recurrence.

1. INTRODUCTION

1.1. BACKGROUND

In many countries, delays in decisions related to spent fuel management have caused increasing requirements for the storage of spent fuel, and increased capacity requirements have been coupled with longer periods of storage. The member states have considerable experience in extended water storage of spent fuel that is potentially valuable to designers and operators of spent fuel pools, licensing agencies and the general public in assessing the viability of extended

water storage of spent nuclear fuel. This survey was organized to provide a major assessment of experience in the storage of spent water reactor fuel in water. The survey did not include an assessment of gas-cooled reactor fuel storage, but some comments are included where they are judged to be of interest.

Spent nuclear fuel assemblies require a minimum cooling period of 6 – 12 months after reactor discharge in the at-reactor (AR) storage pool before they are shipped to other fuel cycle facilities or to away-from-reactor (AFR) storage. Storage times may vary from several months to several decades, depending on the spent fuel management options chosen and the availability of relevant fuel cycle services (e.g. reprocessing, interim storage, final repository).

Placing spent fuel in AR and AFR water pools is the current world-wide method for interim storage of almost all spent fuel. The International Nuclear Fuel Cycle Evaluation Study (INFCE) [1] concluded that:

"Experience exists with wet storage of LWR (light water reactor) and HWR (heavy water reactor) spent fuel for periods up to 20 years with low burn-up fuel. No significant difficulties are expected in projecting spent fuel behaviour in wet storage for longer storage times and higher burn-ups. Nevertheless, observation and investigation should be continued to evaluate the behaviour of high burn-up spent fuel assemblies during prolonged storage periods and to confirm the present and positive experience...."

1.2. SCOPE OF THE INTERNATIONAL SURVEY

To evaluate the international water reactor spent fuel storage experience, a joint survey was initiated by the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD), in conjunction with a working group set up by the NEA Committee on the Safety of Nuclear Installations (CSNI) to assess the Behaviour of Spent Fuel Assemblies During Extended Storage (BEFAST). The objective of the survey was to characterize the scope of experience, to summarize specific problems and to identify possible areas for future research and development. The integrity of both the spent fuel and the components of the storage pool was investigated.

The joint IAEA/NEA questionnaire was sent to 22 countries with operating nuclear power reactors and to several multi-national organizations. Nineteen member states and one multi-national organization responded. Appendix A gives an example of the questionnaire and a list of states that contributed to it. Approximately 85% of water-cooled power reactors and AFR pool operators with more than five years of storage experience responded to the survey. Some responses were also received and evaluated from water-cooled research reactor

operators. Some information was received from gas-cooled reactor (GCR) operators storing spent fuel in water and is included in the assessment. Some pool operators did not respond because they did not have pool storage experience for more than five years.

Most of the responses arrived on schedule in 1979; clarifications and additional responses were received during 1980. All these data were standardized as of 1 January 1980.

Although the report focuses on information from the questionnaires, relevant information from published sources is also included. A six-member consultant group (see Appendix B) was organized by the IAEA to evaluate the questionnaire responses and other published data. An initial draft of the findings was prepared. The draft report was sent to all contributing states and to the members of the BEFAST Working Group for review. The comments received were evaluated by the consultant group and were incorporated where deemed appropriate.

FIG.1. X-10 research reactor fuel pool at Oak Ridge National Laboratory, TN, USA. The X-10 is the site of the world's first storage of irradiated nuclear fuel. The first fuel discharge was in November 1943 and the reactor operated until 1963. The spent fuel pool still stores irradiated materials (1980) and is also used for intermittent storage of fuel.

8

TABLE II. EARLY SPENT FUEL STORAGE POOLS WITH SPECIAL SIGNIFICANCE

Type of reactor	Reactor/location	Significant features	First fuel storage	Final operation	Pool water chemistry
Research	X-10/Oak Ridge, TN, USA	First reactor that stored irradiated fuel	1943	(a)	Culinary water until 1960; deionized water since 1960
Pu-production	Hanford B Reactor/ Richland, WA, USA	First production reactor spent fuel pool	1944	1965	Treated river water
LWGR[b]	Obninsk/USSR	First nuclear reactor used for commercial power generation	1954	(b)	Deionized water
Pressurized water	Shippingport/ Shippingport, PA, USA	First pressurized water reactor[c]	1959	(a)	Deionized water
Boiling water	Dresden I/Morris, IL, USA	First commercial boiling water reactor	1960	(a)	Deionized water
Pressurized heavy water	Nuclear Power Demonstration Reactor (NPD)/Rolphton, Ont., Canada	First pressurized heavy water reactor	1962	(a)	Deionized water
Pressurized water	Indian Point 1/ Indian Point, NY, USA	First spent fuel pool with borated water chemistry	1965	(d)	Borated water

(a) Still used to store radioactive materials in 1980.
(b) LWGR = light-water-cooled, graphite-moderated reactor; still used as a research reactor (1980).
(c) Operated with ammonia in the primary system coolant for pH control and deionized water in the pool.
(d) Reactor is shut down but still stores fuel (1980).
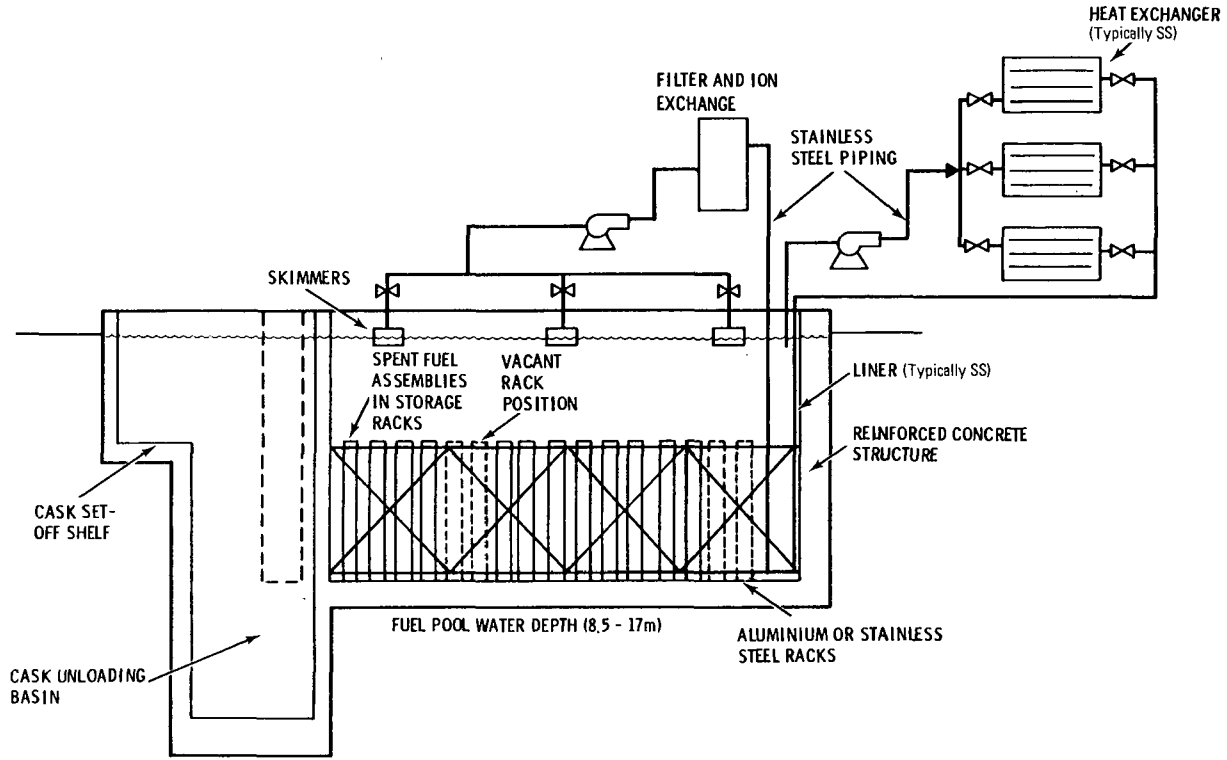
FIG.2. Schematic view of spent fuel pool and components.

2. SPENT FUEL POOL HISTORY

The main requirements for spent fuel storage after irradiation — removal of heat and shielding of personnel from radiation — are simultaneously solved by underwater storage of spent fuel. Water is an effective shield and coolant; it is readily available and is easily cooled and purified; and it provides a transparent medium to facilitate fuel handling and visual observation.

The technology to store irradiated fuel in water has been developing since the first nuclear reactor discharged fuel in November 1943 (see Fig.1). Table II summarizes historical data for various reactor types that have utilized water pools to handle, inspect and store spent fuel.

Early fuel from research reactors generally consisted of aluminium-clad elements, which were frequently reprocessed soon after discharge. Fuel handling and storage equipment was relatively simple. The need for water purity control was less stringent than at present; because of low thermal loads, heat exchangers generally were not required. The pool walls were reinforced concrete and were often unpainted and without metal liners.

The advent of power reactors brought major changes in fuel configuration and heat dissipation requirements. New fuel storage needs and concepts developed, including (see Fig.2):

— sophisticated fuel handling equipment
— heat exchangers and water purity control equipment
— stainless steel (SS) liners
— storage racks compatible with the new generation of fuel configurations.

The survey is principally directed at the characteristics and operation of spent fuel pools that have developed since about 1960 for AR or AFR storage.

3. EXTENT OF SPENT FUEL STORAGE EXPERIENCE

3.1. NUMBER OF SPENT FUEL POOLS

Approximately 240 commercial power reactors and 300 research reactors are currently operating, and several AFR pools are also in service. Almost all of these nuclear facilities store spent fuel in water, representing a wide base of experience. Figure 3 and Appendix C indicate the start-up dates for the storage facilities addressed in the survey. The first fuel storage generally occurs about one year after reactor start-up, but in some locations water is added to the pool before initial reactor operation.
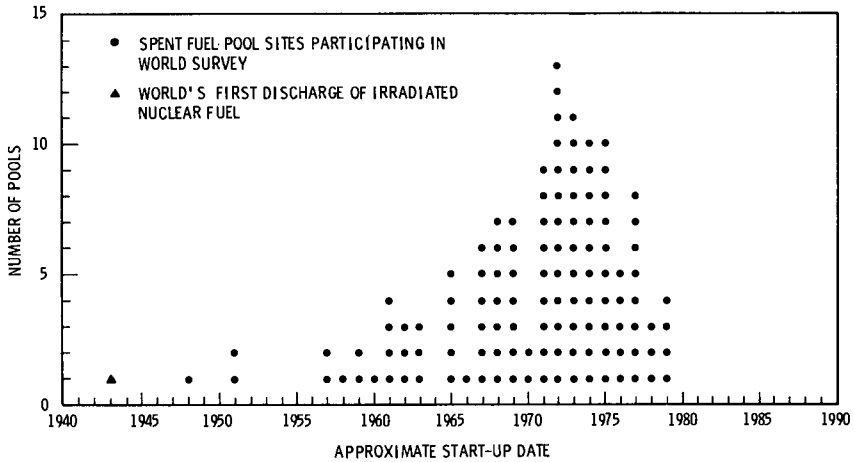
FIG.3. Approximate pool start-up dates.

Most of the questionnaire responses were received from AR or AFR facilities that store water-cooled power reactor fuel.

3.2. SPENT FUEL ARISINGS

The extent of water reactor fuel storage in 1980 was projected by the INFCE Working Group No.6 report [1] as follows:

Type of reactor	Spent fuel arisings (tonnes of heavy metal)
Light water[a]	12 600
Heavy water	3 100
Total	15 700

[a] Assumes 0.575 t per fuel assembly for PWRs and 0.195 t per fuel assembly for BWRs. Two-thirds of the LWR inventory is from pressurized water reactors (PWRs), the other third is from boiling water reactors (BWRs). Approximately 14 600 PWR and 21 540 BWR spent fuel assemblies are estimated to be in storage in 1980. The LWR figure includes < 300 t heavy metal GCR fuel.

11

TABLE III. SIZES OF SPENT FUEL STORAGE POOLS

Type of pools	Number of pools	Range	Average
PWR	39	$92-3000$ m^3	1126 m^3
BWR	38	$142-3072$ m^3	1092 m^3
HWR	4	$827-5000$ m^3	2277 m^3
AFR	7	$210-9800$ m$^{3\,b}$	3015 m^3
RR[a]	14	$60-\ 987$ m^3	261 m^3

[a] Research reactor.
[b] Windscale Bay $1-4$.
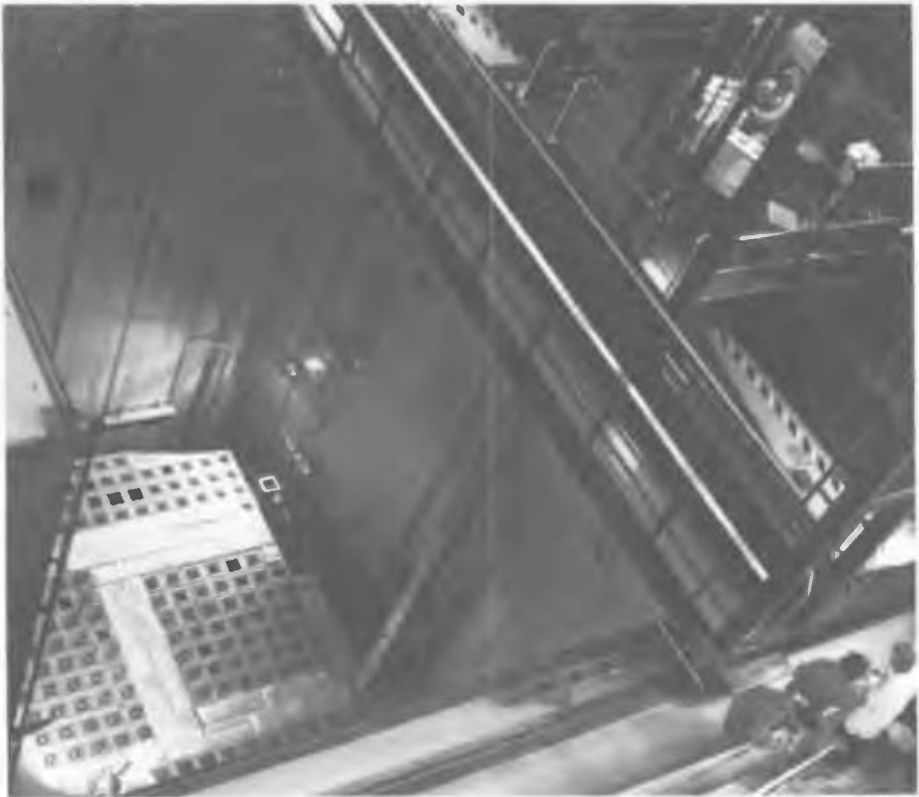
FIG.4. Light water reactor pool (PWR) at Biblis, Federal Republic of Germany. (New stainless steel racks installed.)

FIG.5. PHWR pool at Pickering reactor, Toronto, Canada.
(Fuel stored in stainless steel trays.)

3.3. DESCRIPTION OF SPENT FUEL STORAGE POOLS

The spent fuel pools reviewed were constructed according to established
engineering methods. The general design of wet storage facilities includes
features such as spent fuel transport cask handling, loading and decontamination
systems, a radioactive waste treatment and handling system, personnel support
systems, and buildings to house the required equipment. There is a wide range
of sizes (see Table III). Storage pools range from 10–20 m long and 7–15 m
wide. The storage area varies with the amount of fuel to be stored, which in
turn depends on the type and size of reactor. The specific design depends upon
the function of the pool: short-term AR pool; research reactor support; or
interim-storage AFR pool with capacity for multiple types of fuel. A simplified
cross-section of a typical pool with related water treatment systems is shown in
Fig.2.

Figures 4–7 show views of various spent fuel pools. The related pool
support equipment and systems that deal with safety are designed with appro-
priate component redundancy. The majority of pools have skimmers to remove

13

*FIG.6. AFR pool at General Electric Co., Morris, IL, USA
(Fuel stored in stainless steel baskets.)*

material floating on the pool surface. Dissolved impurities are removed from pool waters by ion-exchange systems. Both ion-exchange columns and filters remove particulate impurities suspended in the water. Vacuum cleaners and brushes remove particulate materials from pool walls and floors. These methods are effective in controlling radioactive species in spent fuel pools.
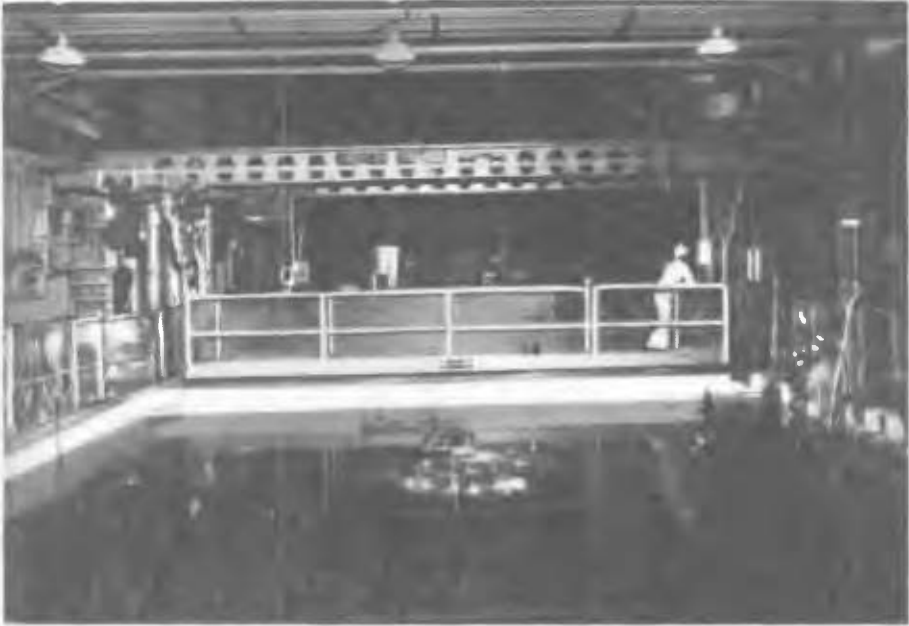
FIG.7. RBOF facility at Savannah River Plant, SC, USA.
(Receiving basin for spent fuel from university research reactors for storage by U.S. Department of Energy; fuel stored in aluminium cans in aluminium racks.)

4. CURRENT PRACTICE IN
SPENT FUEL POOL DESIGN AND OPERATION

Spent fuel storage practices vary according to the type of fuel to be stored and the type of facility the pool serves. The following sections discuss storage practices, reasons for draining spent fuel pools and measures to increase spent fuel storage capacities.

4.1. CURRENT PRACTICE AT LIGHT-WATER REACTOR
FUEL STORAGE POOLS

Most LWR fuel storage pool designs are similar: rectangular in horizontal cross-section and 12 13 m deep. Fuel assemblies are placed in storage racks or

FIG.8a. Top view of SS rack being removed from a PWR
spent fuel pool (rack dimensions: 295 cm X 195 cm).
Early design; does not utilize neutron absorbers.
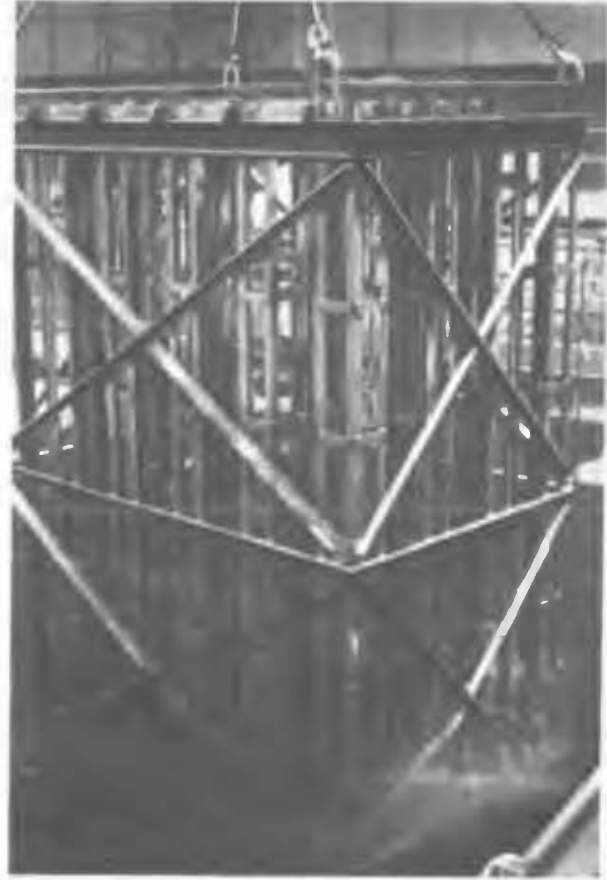
FIG.8b. Side view of SS rack shown in Fig.8a (rack height:
419 cm). Early design; does not utilize neutron absorbers.
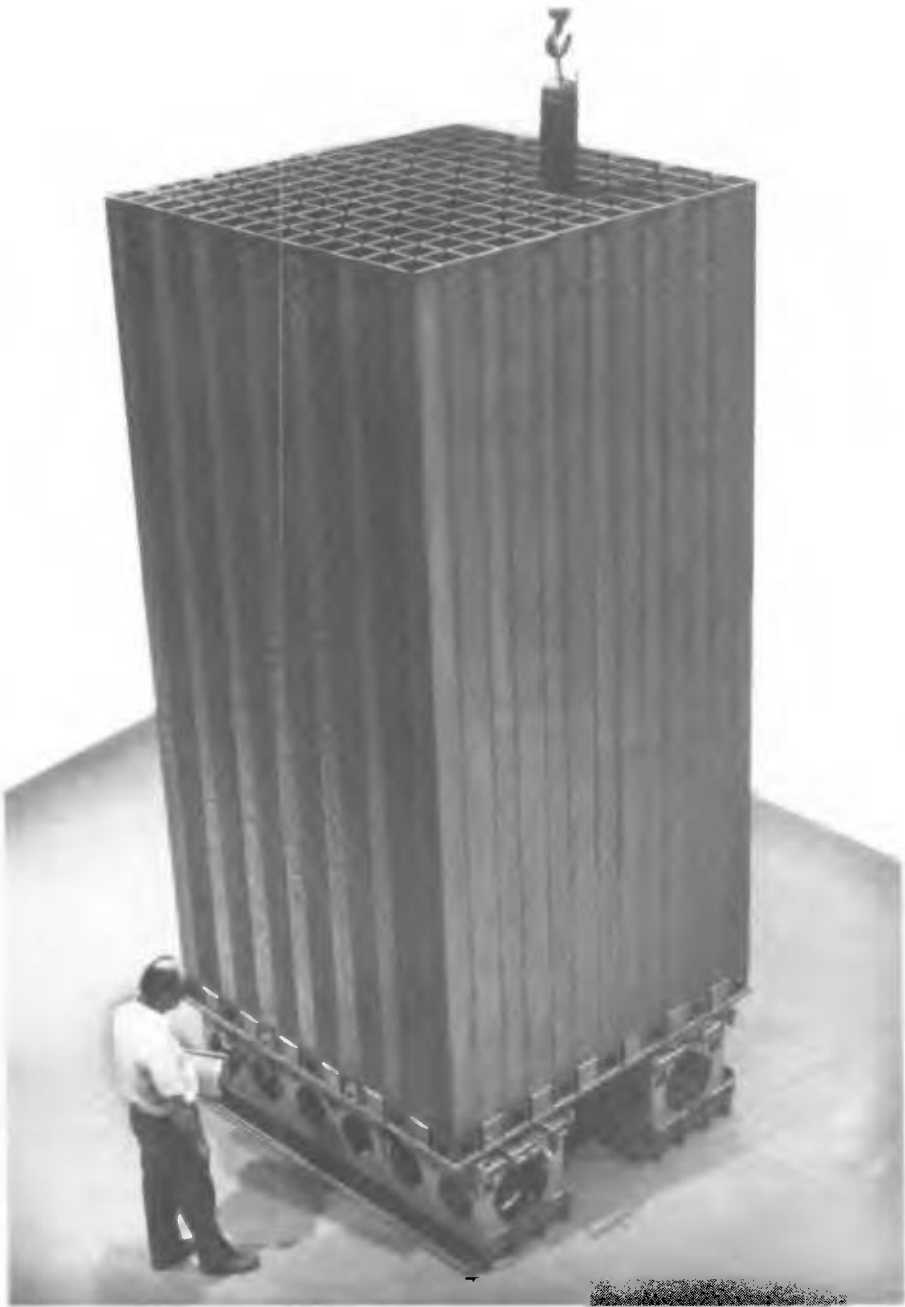
FIG.8c. As-fabricated BWR storage rack constructed of SS-clad boron-impregnated aluminium to permit closer packing of spent fuel assemblies (rack dimensions: 2.1 m X 2.1 m X 4.4 m).

baskets located at the bottom of the pool (see Figs 2, 4, 6, 8). The racks hold the assemblies vertically and maintain the prescribed spacing between assemblies to prevent criticality. The assemblies are normally inserted or removed vertically from above the racks, using safety-designed mechanical handling systems. The approximately 4.5 m long LWR fuel assemblies remain submerged during all fuel handling operations. The minimum shielding requirement is about 3 m of water for a high burn-up ($\sim$ 30 000 MW·d/t U) LWR fuel assembly at the time of discharge from the reactor. LWR rack depths generally are about 4.5 m; therefore, 12–13 m of water is ample for fuel insertion into stationary racks. Radiation levels at the pool surface from all stored fuel are very low because a total of $\sim$ 8 m of water shielding is generally available (equivalent to $\sim$ 3.4 m of concrete).

BWR pools are filled with demineralized water, and PWR pools are normally filled with a dilute ($\sim$ 0.2M) boric acid solution. In PWRs, the borated water in the primary system that is used for reactivity control mixes with pool water during refuelling operations when the pool is connected to the primary system. PWR pool water is slightly acidic (pH of 4.5 − 6) while BWR pool water is nearly neutral to slightly acidic (pH 5.8 − 7) because of equilibrium with atmospheric CO_2. Even though the design temperatures are 67°C for abnormal operation, the questionnaires indicate that pools normally operate at 40°C or less.

Figures 8a and 8b show a first-generation PWR storage rack being removed from a pool. It was replaced with racks having neutron absorbers that permit more fuel to be stored in a given space. Figure 8c shows a BWR rack that is constructed with SS-clad boron-impregnated aluminium to permit closer spacing of fuel assemblies.

The pool walls and floor are constructed of reinforced concrete of sufficient thickness to meet radiation shielding and structural requirements. Most power reactor and AFR pools are lined with welded SS plates (4–6 mm thick). Provisions are made for water leak detection.

BWR fuel storage pools have normally been located inside the reactor containment and are elevated approximately 15–30 m above ground level (Fig.9a). More recent BWRs have ground-level storage pools because the elevated position has higher seismic load design requirements and therefore higher costs.

PWR systems basically use a ground-level fuel storage pool located outside the containment building in an auxiliary building (see Fig.9b) as well as elevated storage pools inside the reactor containment for some limited storage. The refuelling operations require opening the reactor vessel and raising the water level to that in the pool. Fuel is removed from the reactor core and placed on a strong metal frame, which reverts to a horizontal position for movement through the fuel transfer tunnel into the transfer canal. In this canal the fuel is raised to a vertical position, picked up by the spent fuel pool handling machine, moved to the storage pool, and placed in stationary storage racks. During these
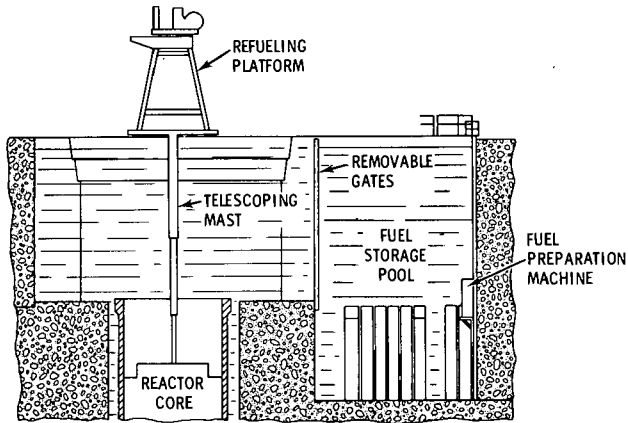
FIG.9a. *Cross-section showing relationship of BWR core and spent fuel pool (also applied in WWER type PWR reactor).*

Note: *Some newer BWRs have fuel pools at ground level.*
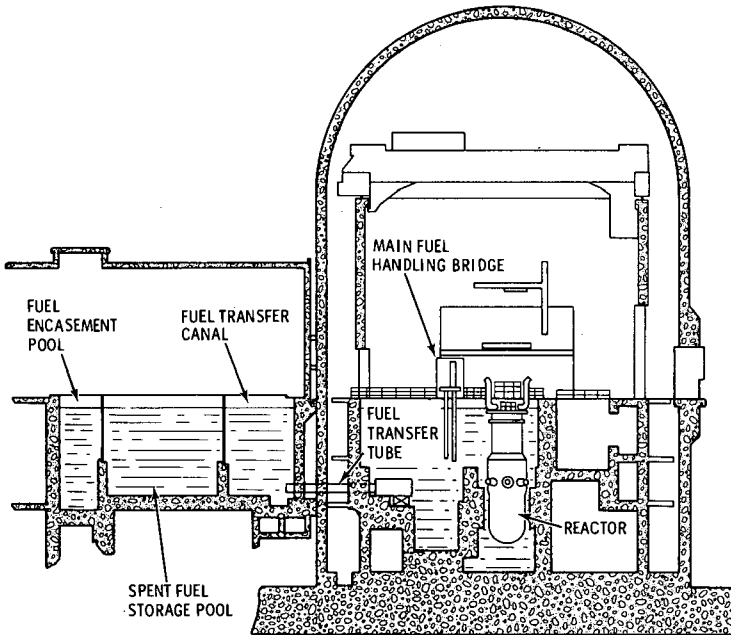
FIG.9b. *Cross-section showing relationship of PWR core and spent fuel pool.*

19
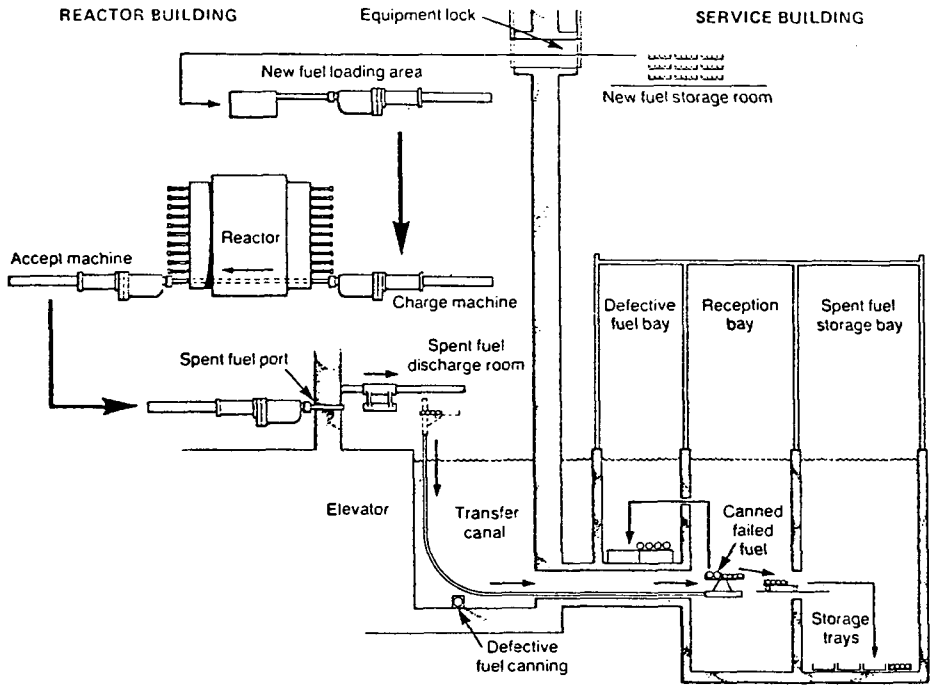
FIG.9c. Floor plan showing relationship of PHWR core and spent fuel pool.

operations the fuel is frequently moved to an inspection area for visual observations by either underwater periscope or television equipment.

The range of pool dimensions is given in Section 3.3.

4.2. CURRENT PRACTICE AT HEAVY-WATER REACTOR FUEL STORAGE POOLS

The requirements for storage of the Canadian (CANDU) HWR spent fuel are similar to those for LWR fuel, with the following exceptions:

— No criticality considerations, since natural uranium fuel is used
— Lower heat removal requirement and less water for shielding because of lower burn-ups
— Short assembly length (0.5 m) compared with LWR fuel assemblies (4 m), which allows the assemblies to be stored horizontally in SS trays (see Fig.5); the trays are stacked to maximize space utilization.
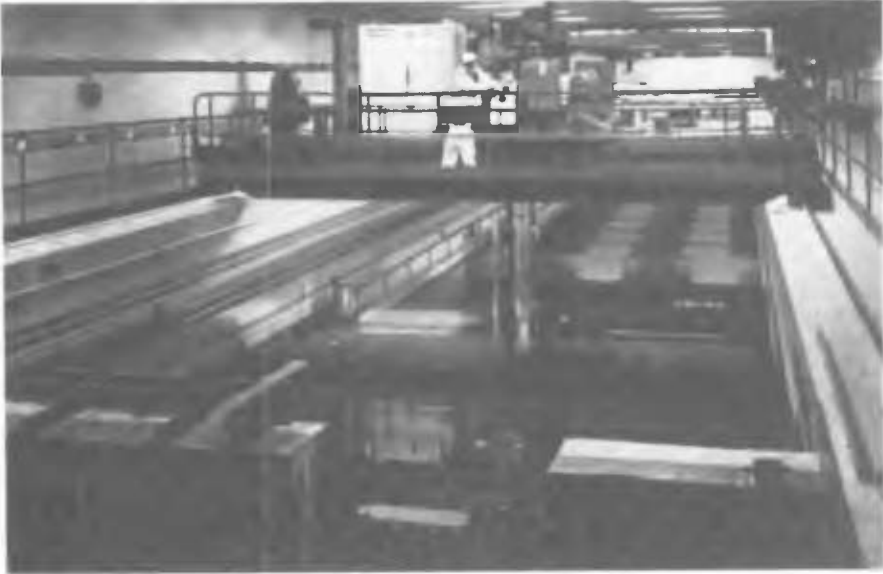
FIG.10.   Gas-cooled reactor pool.
(Fuel stored in painted carbon steel trays.)

The Atucha-1 reactor in Argentina and the Steam Generating Heavy Water Reactor (SGHWR) in the United Kingdom have longer fuel assemblies that are stored vertically.

CANDU fuel assemblies are normally discharged while the reactor is operating. During fuel transfer operations, the heavy water (D_2O) remains essentially isolated from the light water storage pool by the use of a fuel transfer machine or fuel elevator; therefore, the fuel assembly may be dry for a brief period during the transfer from heavy to light water. Figure 9c shows schematically the relationship of the reactor core to the spent fuel pool for a PHWR.

4.3. CURRENT PRACTICE AT GAS-COOLED REACTOR FUEL STORAGE POOLS

Gas-cooled Magnox fuel is stored horizontally in painted mild-steel skips (boxes) in water pools (see Fig.10). It is important to control the water chemistry in these pools to suppress Magnox corrosion (discussed in Section 5.4). The Magnox fuel normally remains at the reactor pool for only a few months before shipment to a reprocessing site; however, AR storage of Magnox fuel for up to ~ 1600 days has been accomplished in reactor pools where a carefully

21

FIG.11a. WAK pool, Karlsruhe, Federal Republic of Germany, showing stationary stainless steel and aluminium fuel storage racks.

FIG.11b. G.E. Morris operation pool, Morris, IL, USA. Fully loaded BWR spent fuel storage basket (stainless steel) being transported to a pool storage location; water depth: 8.7 m.

formulated water chemistry is maintained [2]. One reactor, Wylfa, has developed a dry storage facility for Magnox spent fuel [3].

SS-clad advanced gas-cooled reactor (AGR) spent fuel is stored vertically in metal boxes in neutral pH water. Normal AR storage times are one year before shipment to a reprocessing facility.

4.4. CURRENT PRACTICE AT RESEARCH REACTOR
FUEL STORAGE POOLS

As indicated earlier, the world's first spent fuel pool is located at the Oak Ridge X-10 research reactor (Fig.1) which began operation in 1943 and is still in use. The walls and floor of this canal are unpainted concrete; however, some more recent research reactor canals have metal liners.

Many research reactors have relatively small pools or canals for temporary storage of spent fuel until it is sent for reprocessing. However, some reactors (such as NRU and NRX) have stored spent fuel continuously for nearly two decades. The pools have facilities for water purity control; some have installed heat exchangers, others have no need for them.

4.5. CURRENT PRACTICE AT AWAY-FROM-REACTOR
FUEL STORAGE POOLS

Away-from-reactor (AFR) storage pools receive fuel from reactor pools in either wet (H_2O) or dry (He, N_2 or air) casks. Some AFR pools store fuel in stationary racks (Fig.11a) while others store fuel in movable baskets (Fig.11b). At least two AFR pools, the Savannah River RBOF pool (Fig.7) and the Windscale B-27 pool, store defective and non-defective fuel in semi-closed canisters.

Storage pools at spent fuel reprocessing plants for water reactor fuel were generally designed on the assumption that spent fuel that was received would soon be reprocessed. Sufficient space was provided for fuel storage equivalent to some 3 to 4 months of reprocessing plant throughput. Some reprocessing plants are increasing their pool storage capacities so as to act as an operational buffer. Designs for AFR fuel storage at reprocessing sites are based on relatively conservative assumptions regarding water purity control, heat removal and fuel handling activities.

FIG.12a. IF-300 rail cask capable of holding 7 PWR or 18 BWR assemblies.

FIG.12b. Truck cask loaded on a special trailer.

FIG.13. WAK pool receiving shipping cask.

4.6. SPENT FUEL SHIPMENT AND HANDLING

Spent fuel is shipped from one pool to another in shielded metal casks of high integrity. Rail casks (Fig.12a) are designed to carry several assemblies; truck casks (Fig.12b) are designed to carry one or two assemblies. Large cranes at the spent fuel pools move the casks (Fig.13) in and out of a small receiving pool that is connected to the storage pool. Smaller fuel handling machines move the assemblies, one at a time (Fig.14), from the shipping casks to storage baskets or racks. The casks and handling equipment are designed according to stringent safety standards. Fuel handling operations provide an opportunity to inspect the fuel assemblies visually.

FIG.14. BWR fuel assembly transfer from shipping cask to storage basket.

TABLE IV.   DRAINING OF SPENT FUEL POOLS[a]

Reason for draining	Number of pools covered by survey
New rack installation	11
Pool cleaning	5
Repair of pool liners (leaks)	2
Repair of unlined pool (painting, cracks)	3
Installation of SS liner	3

[a] Some facilities were involved in more than one procedure.

4.7. EXPERIENCE WITH DRAINING SPENT FUEL POOLS

Nineteen operators reported that their pools had been drained one or more times (see Table IV). Most of the pools were drained to install new racks or for general maintenance.

At the JEN-1 (Spain) research reactor, the concrete pool was drained each year (which is apparently more often than for other pools with painted walls) from 1959 to 1969 for repainting because the paint had deteriorated. In 1969, the pool was drained to install a SS liner. At the Yankee Rowe PWR pool, installation of a SS liner began in 1979 after 18 years of operation with painted concrete (see Section 9.4 for further details). At the NRX research reactor in Canada, a SS liner was installed in 1959 in the storage pool, which represents one of the earliest metal-lined pools. The Swedish Ringhals-2 PWR fuel cavity was decontaminated chemically while it was drained (see Section 9.2).

4.8. MEASURES TO INCREASE SPENT FUEL STORAGE CAPACITIES

Since decisions regarding the future of spent fuel have been delayed, the storage space provided for early reactors has been inadequate. A number of methods to increase storage capacities in existing pools are being used and others are being studied (see Table V). The following main alternative solutions to provide additional storage space have been considered:

TABLE V. ADVANCED RE-RACKING CONCEPTS (PWR FUEL) [4]

Status	Re-racking concepts	Storage density (t heavy metal/m^2)
At present in use	Non-poisoned racks	4.2
	Poisoned racks	5.6
Advanced concept	Cored plate storage	7.1
	Shot-filled canister storage	8.4
	Stacked racks	8.4
	Compacted fuel assembly storage	10
	Pin storage (= rod consolidation)	12

(a) Expansion of existing pool storage capacities:
  (i) Storage densification (compaction): more storage capability is added to existing storage pools by providing racks that allow closer spacing of assemblies
  (ii) Double tiering: addition of a second level of storage racks above the existing racks; the two levels may have different densification factors
(b) Expansion of pool volumes: the storage capacity is increased by increasing the dimensions of existing pools
(c) Additional wet storage facilities: additional storage facilities are provided at the reactor site or at an independent location.

Implementation of these alternative storage technologies has progressed, with the following results.

4.8.1. Expansion of existing pool storage capacities

A large number of reactor pools have been modified to provide significant and rapid increases in storage capacity by storage densification. The following techniques have been used:

— Use of a design value for K_{eff} of 0.95 instead of 0.90 and use of more sophisticated techniques for criticality calculations; in some cases (for PWRs), this alone doubles the potential storage capacity
— Use of SS, boron in SS, or boron in aluminium as neutron absorbers to permit greater storage density
— Filling unused pool area with fuel storage racks
— Replacing non-fuel racks with racks suitable for fuel storage
— Double-tiering of spent fuel storage racks has been accomplished in some locations: Atucha I (HWR) in Argentina stores the 6 m long fuel assemblies in double stacks [5]; the La Crosse (BWR) pool in the USA is preparing to use double-tiered racks; the Yankee Rowe (PWR) reactor has made provisions for double-tiering during recent pool modifications [6].

4.8.2. Expansion of pool volumes

Some AR pools are expanding their pool volumes; other AR pools are anticipating future expansion.

At several AFR sites, the designs include provisions for expansion. A significant increase in storage capacity is anticipated by this technique which is undergoing licensing review (for example, at Windscale in the United Kingdom).

4.8.3. Additional wet storage facilities

Some facilities are under construction or are in preliminary planning stages; for example, the CLAB pool that is under construction in Sweden [7].

4.8.4. Significance and status of dry storage

Dry storage of spent fuel is being evaluated for two potential applications: (1) as an interim option to wet storage, and (2) as a method of final spent fuel disposal. Dry storage demonstration programmes are under way at several sites. Other sites have used dry storage as a routine storage method for selected types of spent fuel.

It is important to recognize that dry storage of water reactor fuel would be preceded by a period of wet storage until residual heat dissipation is sufficient to provide acceptable fuel temperature in dry storage.

Currently, dry storage of water reactor fuel is not a licensed option. Nevertheless, the status of dry storage technology is reviewed briefly in Appendix F to indicate that significant progress has been made toward development of a basis for licensing.

5. SPENT FUEL POOL CHEMISTRIES

The water purity in storage pools is controlled to suppress conditions that might lead to a corrosive environment for the spent fuel and related pool components. Because of the extensive scope of the questionnaire responses, the body of the report only summarizes these findings; detailed responses can be found in Appendix D.

Sources of potential chemical contaminants at spent fuel pools include airborne materials (dust, etc.), make-up water, and leaching from materials in the pool. Generally, the contaminant levels are quite low. For example, the TAN pool (see Section 9.5) remained on standby for 12 years without purification and accumulated only about 1.8 ppm Cl^- during that time.

5.1. CONTROL MEASURES OF WATER PURITY IN SPENT FUEL POOLS

Spent fuel pool operators use combinations of the following measures to control water purity:

- Ion-exchange systems to control ionic impurities
- Filters to control particulate impurities (ion-exchange columns provide considerable filtering action)

- Skimmers to remove species from the pool surface
- Vacuum cleaners to remove particles from the pool racks and floor
- Scrubbers to remove materials adsorbed on pool walls, particularly at the water/air interface.

5.2. POOL CHEMISTRY IN DEIONIZED WATER POOLS (AFR, BWR, HWR, RR)

Deionized water pools generally operate without chemical additives.[3] Since the pool water is in contact with the atmosphere, it is saturated with oxygen. This corresponds to about 8 ppm O_2 at 25°C and decreases as the temperature increases. At 93°C — the highest designed deionized pool temperature identified in the survey — the oxygen concentration would be 1.2 ppm; and at 52°C — the highest reported operating temperature — the oxygen concentration would be 4.9 ppm. Carbon dioxide absorbed from the atmosphere reacts with water to form carbonic acid, which tends to make the pH mildly acidic (pH 5.5). Water purity is maintained by ion exchange and filtration in most pools.

5.3. POOL CHEMISTRY IN BORATED WATER POOLS (PWR)

The pool chemistry in PWR pools differs markedly from that in deionized water pools. Most PWRs operate with boric acid ($\sim$ 2000 ppm B) and lithium hydroxide (0.2 – 2.2 ppm Li) additions to the reactor primary system. The boron provides reactivity control, the lithium provides pH control.

During refuelling, the pool and primary system waters mix. To avoid concern about meeting boron specifications in the primary system during shut-down, most PWR pools use the same boron concentrations in the spent fuel pool water. Some lithium is carried into the spent fuel pool with the primary coolant, but intentional lithium additions to the spent fuel pool water are rarely made. Lithium results collected from the questionnaire were very limited; many facilities did not report data regarding lithium concentration in the water. The range of lithium values reported was from 3 ppb to 2.2 ppm; the normal range was from 0.1 to 0.5 ppm. Owing to the boric acid concentrations, the PWR pool pH values are mildly acidic at pool temperatures.

In PWR spent fuel pools, special ion-exchange resins must be used that are designed to remove chlorides even when loaded with boric acid.

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[3] A few pool operators add small amounts of nitric acid or caustic to maintain the pH within prescribed values.

There are a few exceptions to the general status of PWR water chemistry outlined above:

- Even though the Shippingport reactor is listed as a PWR, it does not use boric acid for reactivity control; consequently, the spent fuel pool has always operated with deionized water
- The Yankee Rowe pool began operation with deionized water, but allowed the boric acid content to rise as the primary system (borated) water mixed with the pool water. Since 1962, the boron level in the pool has risen to a maximum of 800 ppm; it was reduced to ∼ 50 ppm during recent pool modifications.

5.4. OTHER POOL CHEMISTRIES

Some pools deviate from the two general pool chemistries indicated above:

(a) Spent fuel pools at the plutonium production reactors at Savannah River and Hanford in the USA typically have used treated river water as the pool coolant.

(b) The Fuel Receiving and Storage Facility (FRSF) at the Idaho National Engineering Laboratory (INEL) has operated since 1952. A major outbreak of algae growth led to the use of calcium hypochlorite. As a result, chloride levels in the pool water rose to about 700 ppm [8]. Sodium nitrite was added as a corrosion inhibitor to concentrations of about 400 ppm. More recently, a reverse-osmosis method has reduced the chloride levels to about 300 ppm. An ultra-violet light system was also installed to assist in the control of biological growth; a side-stream from the pool passes through the ultra-violet light system. Aluminium racks (6061 alloy) corroded in the high chloride environment. In contrast, aluminium-clad fuel has not appeared to degrade in the pool, probably because of protection by the reactor-formed oxide film. Both Zircaloy-clad and SS-clad fuels have been satisfactorily stored in the FRSF pool.

(c) The Magnox (magnesium alloy) cladding on gas reactor fuel is susceptible to aqueous corrosion under normal deionized water conditions. Magnox corrosion is suppressed by: (a) maintaining the pool water at pH 11.5 or above; (b) controlling the chloride and sulphate concentrations to less than 1 mg/l; and (c) suppressing sludge in the storage pool [2].

(d) Some SS cladding of AGR fuel sensitizes during reactor exposure and therefore can be susceptible to intergranular corrosion under pool storage conditions [9]. In AR pools, about 1000 ppm boron is added as boric acid for reactivity control; there is some evidence that it acts as a corrosion inhibitor. The AR pool is adjusted to pH 7 by adding 100 g/m^3 NaOH.

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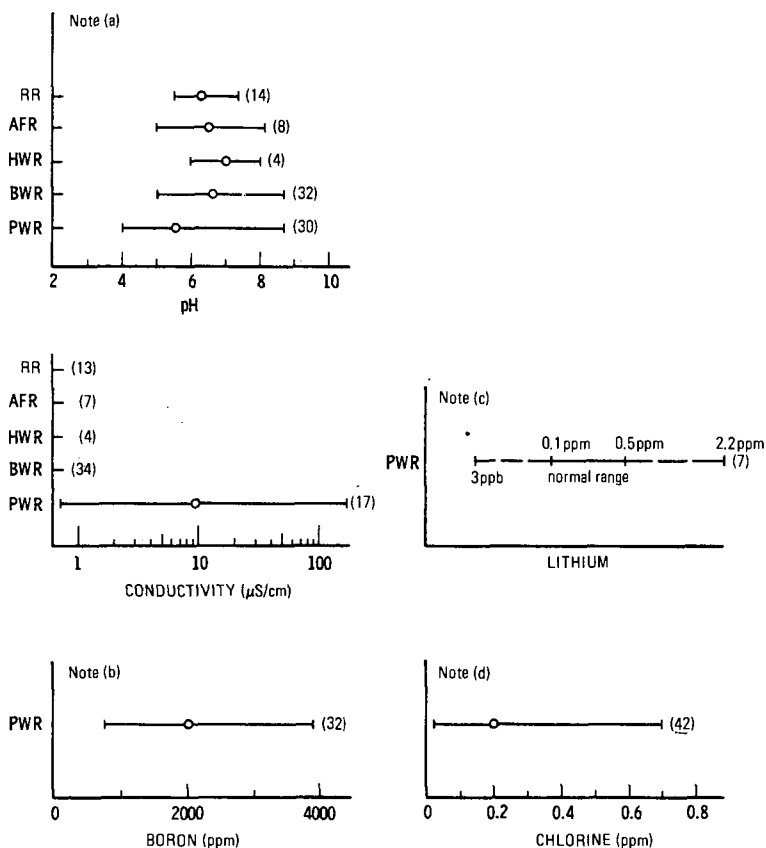
FIG.15. Summary of spent fuel pool chemistry data.
Notes: *Some data reported in the survey appear to be design parameters rather than from actual experience. The average (− ○ −) is only of the reported actual data. The range reflects the upper and lower limits of the reported ranges. (a) Upper and lower ranges are probably specifications rather than experience data. (b) Boron is added only in PWRs. (c) The normal maximum for lithium in reactor coolant is 2.2 ppm. (d) All reactors.*
Figures in parentheses indicate the number of pools for which data are summarized (see Appendix D).

5.5. SUMMARY OF POOL CHEMISTRY DATA

Figure 15 reflects survey results regarding pH, conductivity, and boron, lithium and chlorine concentrations. It was sometimes difficult to determine whether the questionnaire responses reported design base data or data from actual experience. Attempts were made to differentiate between the two types of data. At many spent fuel pools the sampling frequency is once a week.

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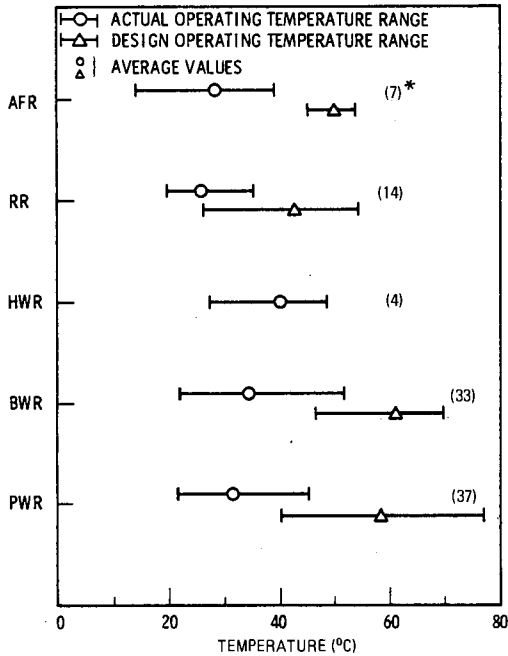
FIG.16. *Summary of spent fuel temperatures including operating data and design ranges.*
* Figures in parentheses indicate number of pools for which data are summarized
(see Appendix D).

Boron is added to spent fuel pools as boric acid with a boron concentration of about 2000 ppm, corresponding to a boric acid concentration of 13 000 ppm or about 0.2 molar.

Limited information was given on the following species:

	Averages of survey data	Ranges of survey data
Cr	0.02 ppm	0.02 − < 0.1 ppm
Cu	0.06 ppm	0.001 − < 0.1 ppm
F	0.1 ppm	0.01 − 0.6 ppm
Fe	< 0.1 − 5.0 ppm	< 0.1 − 20 ppm
Mg	< 0.1 ppm	< 0.1 ppm
Na	0.1 − 0.6 ppm	0 − 0.6 ppm
Ni	0.02 ppm	0.02 − < 0.1 ppm
Turbidity	0.4 JTUs	0.05 − 0.7 JTUs

Figure 16 summarizes spent fuel pool temperatures reported in the questionnaire. Average operating temperatures were used, even though a range

was sometimes given. The upper end of the range is normally due to the short-term rise in temperature associated with refuelling and represents a small fraction of the pool operating time.

The survey indicates that, in general, PWR and BWR pool temperatures are approximately the same, with BWR pools running slightly higher. Pool temperatures of HWRs also appear to be higher on the average than those of PWRs. Research reactor average pool temperatures and design temperatures are lower than power reactor pool temperatures.

The only reported incidents of biological growth occurred in either research reactor or AFR facilities. Although in general they were reported as minor and were mostly corrected by brushing or vacuuming, two cases should be noted. In one facility (Whiteshell, Canada), algae growth occurred when the operating temperature exceeded 32°C; it was suppressed by lowering the temperature to 10°C and shutting off the lights. In another facility (JEN, Spain), algae formed in the pool following a summer shut-down; the problem was corrected by adding H_2O_2 and operating the filtration system.

A severe case of algae growth at the FRSF pool of the Idaho National Engineering Laboratory (USA) was dealt with by chlorination and later by installation of an ultra-violet light system [8], as explained in Section 5.4.

6. RADIOCHEMISTRY

Radioactivity in spent fuel pool waters arises from radioactive species generated while the fuel resided in the reactor. The radioactive species are of three types:
— Activation products
— Fission products
— Transuranics.
Section 6.5 describes how the radioactive species arrive in the spent fuel pools. Section 6.6 summarizes the range of concentrations of radioactive species in spent fuel pool waters.

6.1. ACTIVATION PRODUCTS

Both soluble (ionic) and particulate species circulate in the reactor coolant at low concentrations (generally a few ppb or less). The species adsorb on the fuel rod surfaces, where neutron-induced reactions convert some atoms to radioactive species (indicated by *), for example:

$$^{58}Fe + n \rightarrow {}^{59}Fe*$$
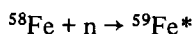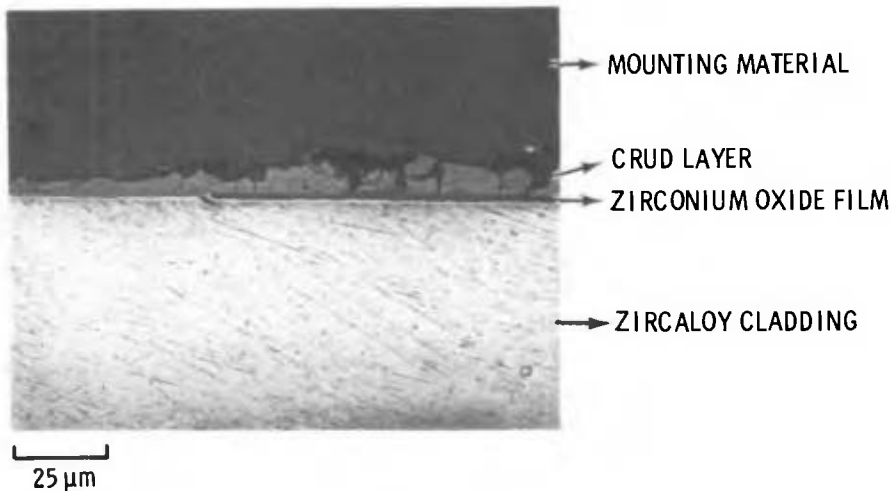
FIG.17. Metallographic cross-section of irradiated fuel rod from Shippingport reactor (USA) showing relationship of crud deposit, oxide layer and Zircaloy fuel cladding.

The circulating species come mainly from corrosion products on reactor coolant system surfaces, principally iron-base and nickel-base alloys. Small but important amounts of radioactive species also arise from cobalt-base alloys and in some reactors from impurities that enter the reactor circuit (e.g. Cu and Zn). Some corrosion-product oxides remain on the fuel-rod surfaces as a deposit overlaying the tenacious ZrO_2 layer (Fig.17).

Activation products with short half-lives decay to insignificant levels before the fuel is discharged from the reactor. Table VI indicates the most important activation-product isotopes that are carried into the spent fuel pools.

6.2. FISSION PRODUCTS

The second type of radioactivity in spent fuel pools arises from fission products. The main source of fission products is fuel clad defects that develop during reactor exposure. Pinholes in the cladding will release principally gaseous fission products (e.g. krypton and xenon isotopes) to the reactor coolant. Larger clad defects will release both gaseous and soluble fission products such as caesium, strontium and cerium isotopes.

Most of the gaseous isotopes are removed in the reactor coolant gas collection system. The soluble fission products circulate in the reactor coolant and some adsorb on the fuel assembly surfaces, particularly on the crud layers. Table VII shows the principal fission products transported to spent fuel pools by mixing with reactor coolant or desorption from spent fuel assembly surfaces.

35

TABLE VI. PRINCIPAL ACTIVATION PRODUCTS RELEASED FROM FUEL ASSEMBLIES DURING POOL·STORAGE

Nuclide	Half-life	Production reaction
^{184}W[a]	24 hours	^{187}W (n-γ)
^{65}Ni[a]	2.5 days	^{64}Ni (n-γ)
^{51}Cr	28 days	^{50}Cr (n-γ)
^{59}Fe	45 days	^{58}Fe (n-γ)
^{58}Co	72 days	^{58}Ni (n-p)
^{65}Zn	243 days	^{64}Zn (n-γ)
^{54}Mn	310 days	^{54}Fe (n-p)
^{60}Co	5.3 years	^{59}Co (n-γ)

[a] Only significant in AR pools.

TABLE VII. PRINCIPAL FISSION PRODUCTS RELEASED TO SPENT FUEL POOL WATERS

Isotope	Half-life
^{131}I[a]	8.05 days
^{126}Sb[a]	12.4 days
^{124}Sb[a]	60.2 days
^{95}Zr-^{95}Nb[a]	65–35 days
^{144}Ce	285 days
^{106}Ru-^{106}Rh[a]	1.0 year to 2.2 hours
^{134}Cs[b]	2.1 years
^{125}Sb	2.7 years
^{3}H	12.3 years
^{90}Sr	28.8 years
^{137}Cs	30 years

[a] Only significant in AR pools.
[b] Formed by neutron activation of ^{133}Cs.

36

6.3. TRANSURANICS

A fraction of the uranium atoms in the fuel absorbs neutrons and trans-mutes to atoms with atomic numbers above uranium in the Periodic Table. Common transuranics are neptunium (^{93}Np), plutonium (^{94}Pu) and americium (^{95}Am). Alpha-particle emission is a principal factor in the decay of the transuranics. Activity from transuranics will be measurable only at spent fuel pools where fuel with failed cladding is discharged or handled.

6.4. NATURE OF DEPOSITS ON FUEL RODS

Oxide deposits develop on fuel rod surfaces and include tenacious layers that grow directly on the fuel rod surface and superficial layers that deposit from the circulating coolant. Figure 17 shows a thin ZrO_2 layer on the fuel rod surface and other superficial oxide deposits (commonly called crud layers). The deposits form from circulating corrosion products that either dissolve or spall from reactor coolant system surfaces, principally iron-base or nickel-base alloys. Small but important concentrations of cobalt also contribute to the deposit inventories. Since the deposits reside in the neutron flux, a fraction of the atoms become radioactive. The deposits are principally mixed oxides of iron, chromium and nickel, with smaller amounts of cobalt, manganese and others.

PWR and PHWR deposits are dark and generally quite tenacious. The BWR deposits are duplex: a tenacious inner layer and a loose reddish-brown outer layer of Fe_2O_3 (haematite). Sometimes, during handling of BWR fuel in the pools, a fraction of the reddish-brown deposit is released as particles; however, the oxide deposits and the oxides that grow on the fuel-rod surfaces have extremely low solubilities at spent fuel pool temperatures. Thus, concentrations of soluble radioactive oxide species are low in spent fuel pools, generally much lower than soluble fission products such as the caesium isotopes (see Appendix D).

The magnitude of particulate releases depends to some extent on the shipping mode. Dry shipments promote elevated temperatures and may cause some crud spallation, depending on the temperatures reached and the amount and type of crud. Wet shipments maintain relatively low fuel-rod temperatures but may release loose crud particles during shipment, owing to the 'washing machine' action [10].

Control of the released radioactivity in spent fuel pools has been manageable by methods discussed in Section 5.1.

Zima [11] has discussed crud layers on spent fuel rods and their implications for spent fuel pool storage technology.

6.5. TRANSPORT OF RADIOACTIVE SPECIES INTO SPENT FUEL POOLS

Most of the radioactive inventory in LWR pools and research reactor canals is transported from the reactor by two mechanisms:

(a) Mixing of reactor coolant and spent fuel pool waters during fuel discharges
(b) Desorption (solubles) or spallation (particulates) of radioactive species from fuel assembly surfaces.

BWRs and PWRs are generally shut down for several days before fuel discharge, which allows short-lived radioactive species to decay and minimizes the radioactive inventory transferred to spent fuel pools. Other measures are also taken to reduce the radioactive inventory on the fuel and in the reactor water. For example, hydrogen peroxide is added to the reactor water in some PWRs during cool-down to dissolve radioactive species, principally cobalt isotopes. The species are removed from the reactor water by ion exchange before the spent fuel is transferred.

Fuel assemblies that have rods with reactor-induced defects are stored in spent fuel pools (see Section 8.6). Many of the defects are pinholes with no exposed uranium oxide. A small fraction of fuel rods have larger defects that expose some fuel pellet areas to the pool water. Leaching of radioactivity from the exposed fuel areas could be considered a third mechanism for transfer of radioactivity to the pool water. However, this appears to be a minor source because the total area of exposed fuel is small and the leach rates from fuel pellets are relatively low (Section 8.6).

Fuel discharges in PHWRs normally occur while the reactor is on line. The spent fuel is removed to chambers in the refuelling machine while still being submerged in primary coolant (D_2O). The refuelling machine then interfaces with a transfer port or fuel elevator that takes the fuel from the refuelling machine to the light water storage pool. For a period of about 1 minute during this operation the fuel is in a dry state. During the operation there is no opportunity for transfer of radioactivity by mixing of the D_2O reactor coolant and the H_2O in the storage pool. The only radioactivity transfer occurs via the crud layers on the spent fuel rod surfaces.

GCRs have no direct connection between reactor coolant and storage pool water. The release of radioactivity to the pool comes via the radioactivity inventory of the surface layer on the fuel assemblies and also via the corrosion of the cladding during pool storage.

AFR pools generally receive fuel after months or years of storage in AR pools; therefore, short-lived isotopes are no longer significant. If the shipment is wet, a relatively small radioactive inventory from the AR pool will be carried in the cask water. The principal transfer of radioactivity to the AFR pool occurs via radioactive species in the crud layers or adsorbed on them.

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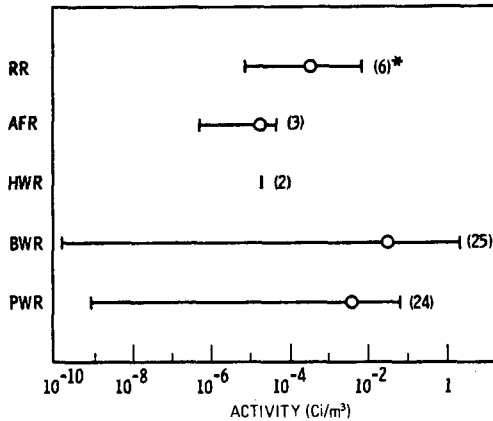
FIG.18. Summary of total beta/gamma activities in spent fuel pools.
* Figures in parentheses indicate number of pools for which data are summarized
(see Appendix D).

6.6. SUMMARY OF RADIOCHEMISTRY DATA FROM THE SURVEY

Appendix D summarizes the radiochemistry data reported in the survey for
individual pools. Figure 18 indicates the ranges of beta/gamma activities for
various types of spent fuel pools. BWR and PWR pools have the widest ranges
and the highest average values. The low end of the ranges probably corresponds
to periods soon after reactor start-up, and the upper end corresponds to
refuelling periods in reactors where cladding defects have developed during the
reactor exposure. The ranges for research reactors also depend on whether
cladding defects have occurred in the reactor. AFR pools have lower ranges and
lower average beta/gamma radiation levels because time and fuel transport have
reduced the radioactive inventories. The HWR CANDU pools have relatively
low radioactive inventories because reactor and spent fuel pool waters do not
mix during refuelling.

Figure 19 indicates the percentages of the total beta/gamma activities that
are accounted for by caesium isotopes. The ranges vary greatly, depending on
the number of in-reactor fission product releases and the nature of the water
purification systems. Caesium ranges at up to 95% of the pool activity with
high-rated fuel and low pool water purification rates. In these cases, the cobalt
activation products, ^{58}Co and ^{60}Co, are frequently dominant for modern low-
rated fuel and high water purification rates. For example, for many years in
the G.E. Morris pool (USA) the ratio of radiocaesium to radiocobalt was
20 to 30. When the purification system was changed to include a powdered
Zeolite, the caesium concentration was reduced by a factor of 20–30, but the
cobalt was unaffected; currently the ratio is about unity.

39
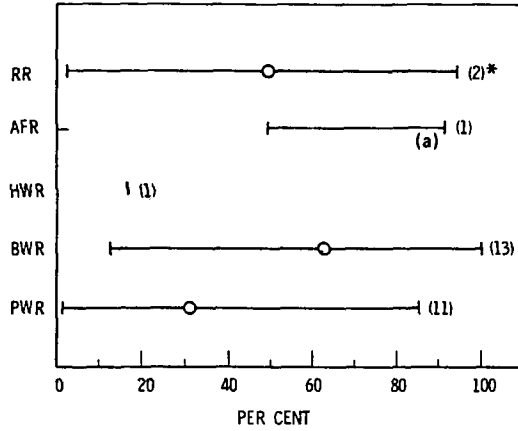
FIG.19. *Caesium isotopes as a percentage of total beta/gamma activities in spent fuel pool waters. (a) G.E. Morris pool (see Section 6.6).*
* *Figures in parentheses indicate number of pools for which data are summarized (see Appendix D).*

TABLE VIII. ALPHA ACTIVITY LEVELS IN THE WATER OF SPENT FUEL POOLS COVERED BY THE SURVEY[a]

Reactor type	Alpha activity (Ci/m^3)
PWR	3×10^{-7} [b]
BWR	2×10^{-7}, 1×10^{-5}, 1×10^{-5}, 1×10^{-5}
HWR	Not reported[c]
AFR	1×10^{-6}, 5×10^{-5}
RR	1×10^{-7}, $< 5 \times 10^{-7}$, 4×10^{-4}

[a] Very limited data were provided.
[b] Up to 2×10^{-6} Ci/m^3 during refuelling was reported by one reactor.
[c] Alpha contamination in CANDU pools is minimized because the reactor coolant does not mix with the spent fuel pool water.

Table VIII indicates the few alpha activity values reported for storage pools. Alpha activities generally are an order of magnitude or more below the corresponding beta/gamma activities.

6.7. STEADY-STATE AIRBORNE ACTIVITIES AT SPENT FUEL POOLS

Airborne contamination levels when fuel is not being handled in the pools were reported in U.S. questionnaires from the U.S. Department of Energy. Some pools reported total activities; some used filters to separate particulate and gaseous species.

Airborne activities at reactor pools generally are $0.1 - 1\%$ of maximum permissible concentrations, typically in the range of from 10^{-10} to $10^{-11}\,\mu Ci/cm^3$. The principal airborne species are ^{131}I, ^{133}I, ^{137}Cs, ^{134}Cs, ^3H, ^{58}Co and ^{60}Co.

7. SPENT FUEL POOL COMPONENTS

Spent fuel pool components have undergone a marked evolution in design to accommodate changes in fuel configurations. The major transition began in about 1960. Figure 2 is a schematic view of major spent fuel pool component configurations; Figs 4−14 show actual views of various components.

The questionnaire requested information regarding spent fuel pool component materials and behaviour. This information from the survey and data from the literature are summarized in the following sections.

7.1. RANGE OF SPENT FUEL POOL MATERIALS

Table IX indicates the range of materials of spent fuel pool components. Since the table is a general summary, it cannot list every alloy/material in every spent fuel pool. Most major metallic components are of SS; aluminium alloys have found substantial use as rack materials.

Figures 20, 21 and 22 summarize the length of time that components have resided in spent fuel pools, for SS, aluminium alloys and miscellaneous materials, respectively, based on data from the survey. The materials are summarized separately for the two major water chemistries; the data are displayed by reactor and by component.

Figure 20 indicates that, as of 1980, the maximum residence time of SS is 24 years in a deionized water pool and 19 years in a boric acid pool. Early

TABLE IX. SUMMARY OF MATERIALS IN FUEL POOLS

Component	Subcomponent	Material[a]
Wall	—	Reinforced concrete
Pool liner	—	Stainless steel, epoxy, fibre-glass, painted carbon steel
Heat exchanger	—	Stainless steel, titanium[b]
Filter	Vessel	Stainless steel
	Filter elements	Stainless steel, diatomic earth, fibre
Deionization unit	Tank	Stainless steel
Fuel storage racks and canisters	—	Stainless steel, aluminium[c,d]
Cask handling crane	Cable and grapple	Stainless steel
Canister crane	Cable and grapple	Stainless steel
Fuel storage trays	—	Stainless steel, painted carbon steel
Piping	—	Stainless steel

[a] Types identified in survey; other types may be used in some pools.
[b] Carbon steel tubes were originally installed in heat exchangers at one pool; severe rusting caused visibility problems in the pool water, resulting in retubing with stainless steel (see comment in Section 7.3.3). Copper alloy tubes are used at one R&D facility pool.
[c] Newer rack and canister walls contain boron-impregnated aluminium for reactivity control, clad with stainless steel or aluminium.
[d] Type 17-4 PH stainless steels are used as restraints for storage racks at a number of pools.

spent fuel pools with metallic components have operated longer, for example the Oak Ridge X-10 pool (see Fig. 1).

Figure 21 indicates that the maximum residence time of aluminium alloy components is 21 years in deionized water and 17 years in boric acid (1000 ppm B, maximum).

Figure 22 indicates several other materials that have functioned in specific spent fuel pools, including tile material, painted carbon steel, Monel, epoxy paints and titanium.

In most cases the components are continuing to function in the pools. However, the situation regarding racks is complex because in many locations older racks have been replaced by racks that permit more fuel to be stored in the existing pool.
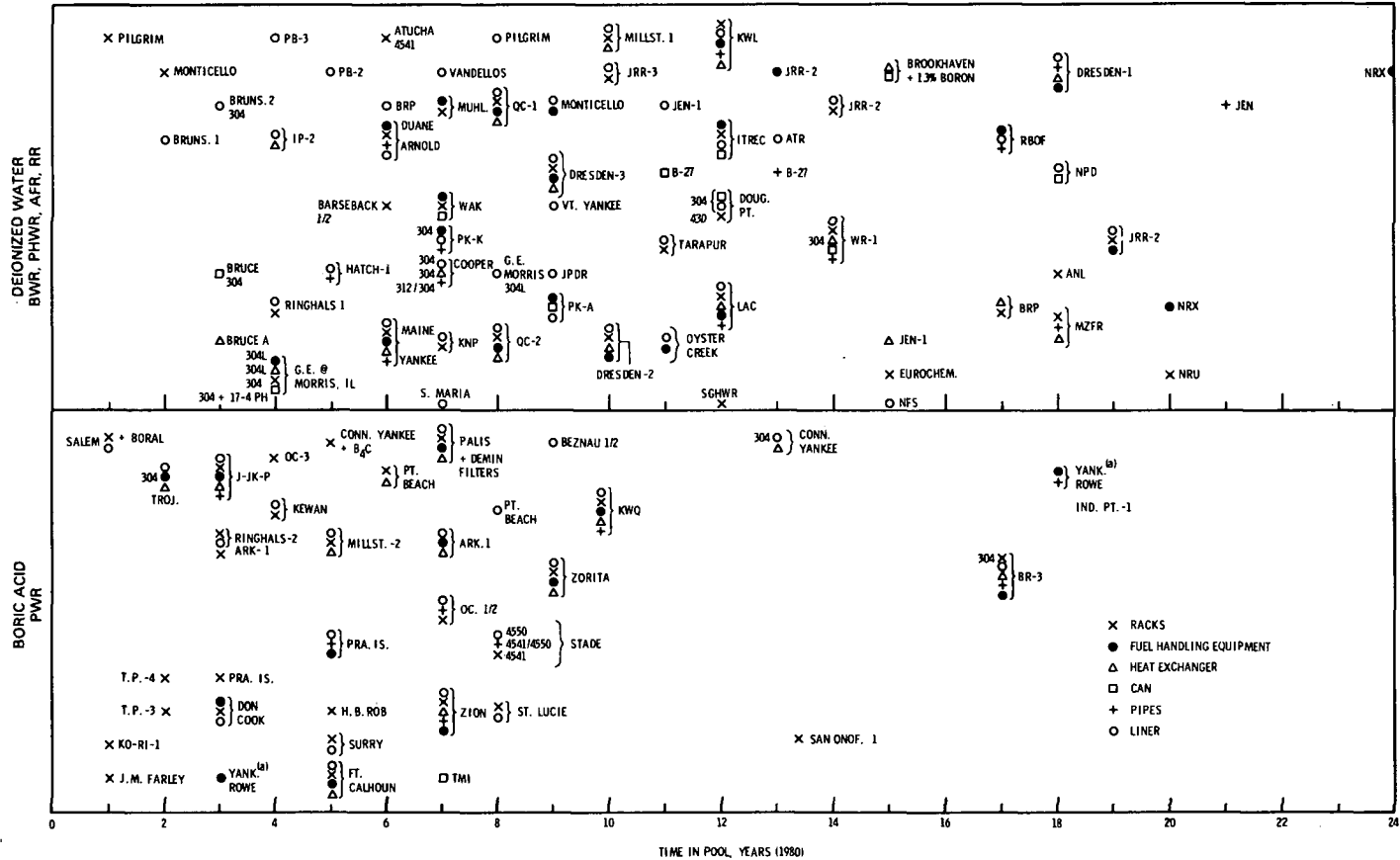
FIG.20. Summary of residence times in spent fuel pools for stainless steel components, based on the survey.

(a) Total time 18 years; boric acid was added slowly to pool at beginning of 1961; reached ~ 1000 ppm B in 1979; decreased to 50 ppm B when pool was lined with SS in 1980.

TIME IN POOL, YEARS (1980)

DEIONIZED WATER
BWR, PHWR, AFR, RR

BORIC ACID
PWR

Legend:
X RACKS
● FUEL HANDLING EQUIPMENT
△ HEAT EXCHANGER
□ CAN
+ PIPES
○ LINER

44

X J-TOK-B

BWN(c) FERRY X   X BWN(c) FERRY X BWN(c) FERRY 304 + BORAL   X HATCH-1   □ KRB 6061   ○ EC   X □ } BRP   X DIORIT

X BARSEBACK   X VERMONT(d) YANKEE   X EUREX

X COOPER 6161T6   X PEACH BOTTOM-3(c)   □ B-27   □ ATR   ○ X } RBOF   X JEN

X PEACH(c) BOTTOM-2   X STUDSVIK   X DRESDEN-3   □ X } NFS

X BRUNS-1(d)   X JRR-3 X WAK   △ JJR-2

X PILGRIM-1(c)   X TARAPUR

X BRUNS 2(d)   X JPDR   X HALDEN   X DRESDEN-1

X QC-1   ○ NRU/X

X RACKS   X DRESDEN-2   X BROOKHAVEN NAT'L LAB
○ FUEL HANDLING EQUIPMENT
△ HEAT EXCHANGER
□ CANS   X OYSTER CREEK

DEIONIZED WATER BWR, PHWR, AFR, RR

BORIC ACID PWR

X MAINE YANKEE   X TMI-1

X YANKEE(a) ROWE

OTHER

(a) TOTAL TIME 18 a; BORIC ACID ADDED SLOWLY TO POOL BEGINNING 1961; REACHED ~1000 ppm B IN 1979; DECREASED TO 50 ppm WHEN POOL LINED WITH STAINLESS STEEL (1980).
(b) RACKS REMOVED, 1978; NEW DENSE Al RACKS INSTALLED, 1980.

X FRSF (HIGH Cl⁻)

(c) HI DENSITY Al RACK INSTALLED, 1979.
(d) HI DENSITY Al RACK INSTALLED, 1978.

0   2   4   6   8   10   12   14   16   18   20   22

TIME IN POOL, YEARS (1980)

FIG.21.   Summary of residence times in spent fuel pools for aluminium components, based on the survey.
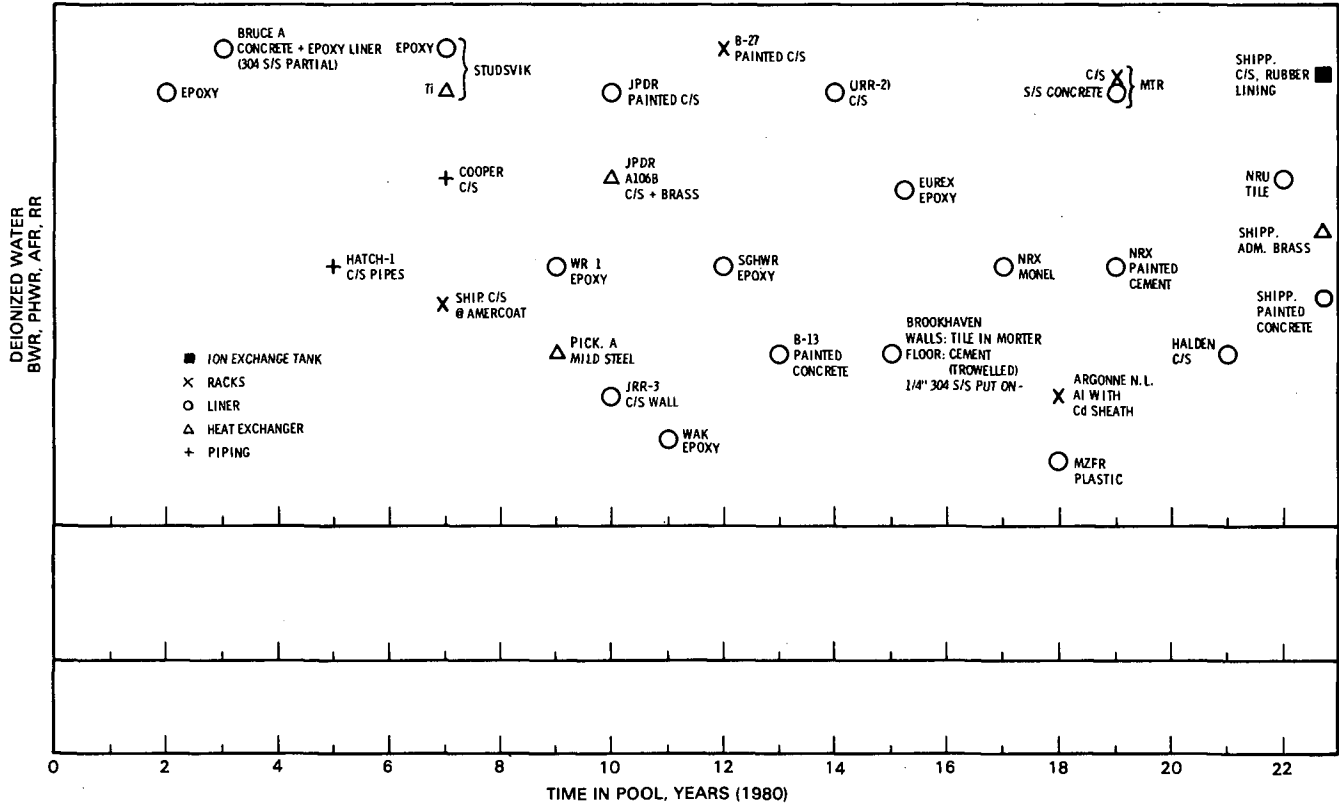
FIG.22. Summary of residence times in spent fuel pools for miscellaneous materials, based on the survey.

7.2. BEHAVIOUR OF SPENT FUEL POOL COMPONENTS

Spent fuel pool components have performed with relatively few problems. However, as in all other technologies, some equipment problems have developed. Examples include fuel assemblies that were dropped into pools during handling; pump seals and hose connections that broke, releasing some mildly radioactive water; swelling of storage rack walls due to accumulation of hydrogen produced by corrosion or by radiation-induced decomposition of organic materials; and some pool liners that developed small leaks. None of these events resulted in significant environmental impacts. However, pool designers and operators should analyse such events for areas where changes in materials or procedures may assist in reducing the number of adverse occurrences.

Comments regarding component behaviour are summarized in the following sections.

7.2.1. Spent fuel pool liners

Several types of materials for spent fuel pool liners have been used, but SS has been the predominant liner material in pools built since 1960. The liner thickness varies from 3 to 5 mm. The metal liners are placed at reinforced concrete walls and floors. The thicknesses of concrete walls vary from 0.3 to 2 m; floor thicknesses vary from 1 to 2 m.

Stainless steel liners have been installed in spent fuel pools for over two decades. A SS liner was installed in the NRX pool (deionized water) in 1956. The first SS-lined PWR (boric acid) pool appears to be that for BR-3 (1962) for which, however, the spent fuel pool water was not borated over the full span of reactor operation. Both pools continue to store fuel. The first fully borated pool ($\sim$ 2000 ppm B) with a SS liner appears to be that for Connecticut Yankee, which has operated since 1968.

Many pools have leak collection systems integral with the liner, along all seam welds, both vertical and horizontal. If leakage occurs, it is channelled to a detection and collection system. Leakage is piped to a collection sump and eventually treated in the radwaste system. Where liner leakage has occurred, it generally has been minor, amounting to a few litres per day, which is a fraction of the pool evaporation rates. For example, the pool operator of the G.E. Morris reactor (USA) estimated an evaporation rate of about 5600 l/day, with a heat load of about 200 kW from the spent fuel. During this time, the pool temperature was $\sim$ 46°C; the pool area is about 255 m^2. An event at the Morris pool involved a cask that tilted against the wall of the receiving pool, creating a hole in the SS liner. The hole was about 3.7 cm long and allowed several hundred litres of pool water to leak out between the liner and the concrete walls and floor before repair was implemented [12].

Other examples of fuel pool liner problems include the following cases:

— The SS liner for the San Onofre Unit 2 (PWR) spent fuel pool was stored for an extended period in the damp marine atmosphere at the reactor site [13]. Intergranular stress corrosion cracking was observed in the heat-affected zone of a weld before the liner was installed.
— At the Turkey Point PWR station, a relatively thin liner was installed in one spent fuel pool. The liner buckled and cracked at welds when subjected to stresses associated with filling the pool with water. The leakage was channelled to the collection system and was pumped back into the pool until the freshly off-loaded fuel was transferred to an adjacent pool so that the pool could be re-lined.
— At the Salem PWR, a small leak developed in the pool liner several months after the pool was initially filled with water [13]. A plate was welded over the leaking area by divers working under water.

Other pool liners have developed small leaks when the pool was first filled, but the leak rates have been sufficiently low so that no repair action has been necessary.

Pool liner repairs have been completed, by draining the pool, by the use of divers while the fuel was stored in the pool [13], or by the use of a caisson which allowed a welder to work under dry conditions in the pool [12]. In one case, a SS liner was installed in a pool in two stages: the liner was installed at one side of the pool while the fuel was stored at the other side (see Section 9.4).

A painted carbon steel liner has functioned satisfactorily at the Halden reactor pool since 1958.

In summary, SS liners have generally performed well in spent fuel pools. While some liner leaks have occurred in a number of spent fuel pools, leakage rates are small. Leakage is contained in leak collection systems or by the concrete structure. In several cases, pool liner leaks have been repaired. In general, the leakage has little impact on pool operation and repairs are not considered necessary.

7.2.2. Fuel storage racks

Figure 23 compares the relative use of alternative rack materials in deionized water pools as reported in the survey; Fig.24 is a corresponding comparison for boric acid pools.

Stainless steel racks are installed in both boric acid and deionized water pools. Numerous first-generation racks (see Figs 8a and 8b) have been replaced by high-density racks (see Fig.8c). Both visual and metallographic examination of the rack shown in Figs 8a and 8b indicated no evidence of significant corrosion, including welds, after $6\frac{2}{3}$ years in a boric acid (PWR) pool [14]. Stainless steel
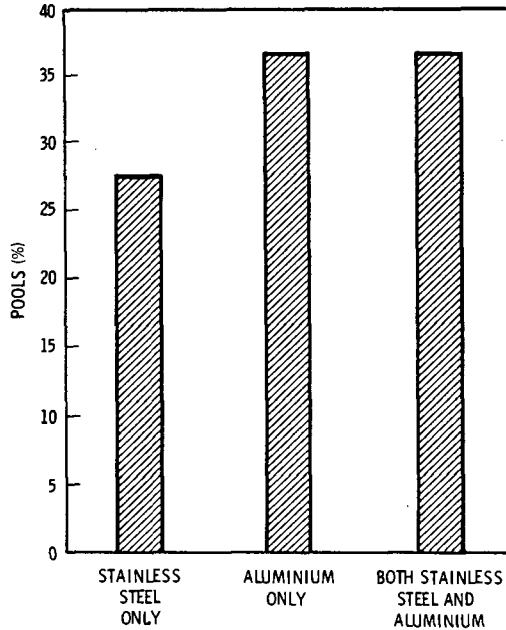
FIG.23. Relative use of alternative spent fuel storage rack materials in deionized water pools, based on the survey.

racks have performed for up to 18 years in boric acid pools and for up to 24 years in deionized water pools, according to the survey. Metal pipes and a metal fuel chute have remained in the X-10 pool since 1943 without replacement (culinary water was used in the pool until about 1960; deionized water has been used since 1960).

The survey did not indicate any instances where SS racks deteriorated in either boric acid or deionized water pools. This observation is supported by published information [14].

Aluminium racks have functioned in a PWR pool for 17 years with only minor pitting; however, the maximum boric acid concentration was 0.1M, as compared with the normal concentration of 0.2M. Aluminium racks have remained in deionized water for up to 24 years.

As suggested by Fig.21, aluminium racks are much more frequently installed in deionized water pools than in borated water pools. However, the performance of aluminium in borated water has been satisfactory. In general, the racks are installed in pools having stainless steel floors. In some cases, the aluminium rack feet are insulated from the stainless steel floor.

Observations on racks removed after extended residence in deionized water pools suggest that direct galvanic contacts promote some mild pitting of the

48
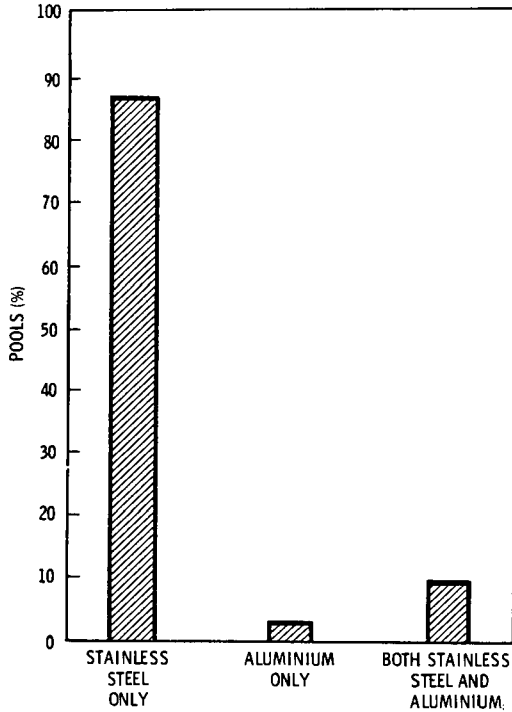
FIG.24. *Relative use of alternative spent fuel storage rack materials in borated water pools, based on the survey.*

aluminium, but no serious corrosion [13]. Prudence suggests that insulation of the rack feet is more likely to be necessary in borated water pools because there the water conductivities are higher than in deionized water pools.

Aluminium racks corroded at inferior welds in the G.E. Morris deionized water pool after a few years. The corroded welds were all associated with a modification of the feet on the baskets, and corrosion was due to the wrong choice of welding rod. All of the original welds showed no evidence of significant corrosion after several years in the pool. Eventually, the aluminium baskets were replaced by SS baskets, but the pool operator believes that aluminium would also function well in the deionized water pool. Aluminium (6061-T-6) racks pitted in the FRSF pool (Idaho National Engineering Laboratory, USA) with up to 700 ppm chloride but maintained adequate structural integrity when they were removed after ten years. Some hydrogen evolution was noted on racks placed in the WAK deionized water pool without passivation. After passivation (1969), no more evidence of corrosion was noted [15].

With the exceptions noted above, aluminium alloy racks appear to have functioned well for the periods shown in Fig.21.

Storage racks at some pools are fitted with seismic restraints fabricated from SS 17-4 PH. There has been a tendency to specify the H-900 condition to provide a relatively high strength. Reference [13] cites cases where the H-900 condition has failed during some types of service. Currently, utilities are specifying H-1025 or H-1100 conditions for SS 17-4 PH components for spent fuel pools, to avoid the more corrosion-prone condition.

It is also recommended that, when the H-1100 treatment of SS 17-4 PH is used, oxide scales formed during the heat treatment be removed by chemical cleaning. There is evidence that the scale promotes rusting of the metal surface [13].

7.2.3. Neutron absorber materials

When it became necessary at numerous pools to increase the storage capacities, this generally was accomplished by installing fuel storage racks which permitted closer packing of the spent fuel. Since boron is an excellent neutron absorber, it has been used to control fuel criticality in the denser fuel configurations. Borated stainless steels have been utilized. Other materials are B_4C-aluminium compacts (commonly called Boral) or B_4C with organic binders. The compacts generally are clad with thin, integral layers of aluminium, and then further clad, either with stainless steel or aluminium side-plates.

At a few nuclear power stations, the storage-rack side-plates swelled, owing to accumulation of hydrogen inside the plates [13]. The sources of the hydrogen have been two-fold:

— Initial corrosion of aluminium caused by leakage of pool water inside the rack walls at weld defects; eventually the aluminium—water reaction would lead to passivation of the aluminium [13].
— Radiolytic decomposition of organic materials in the B_4C compacts, due to radiation from spent fuel placed in the racks; again, the radiolysis produces hydrogen which causes the rack walls to swell.

The immediate problem of the swelled racks was solved by drilling holes at the top of the rack panels to vent the hydrogen. Intentional venting is also being implemented as the longer-term solution to the problem of hydrogen accumulation. The vent holes at the top of the panels enable a limited ingress of pool water to the neutron absorber plates. The reasons why this is not likely to present significant problems are discussed in Ref.[13]. It is also pointed out that in most pools with dense racks representative control specimens are inserted into the pool, at locations which are irradiated by the spent fuel, to anticipate problems in rack behaviour. An actual case where rack swelling was dealt with in a reactor pool is described in Ref.[16].

50

7.2.4. Piping and heat exchangers

Most spent fuel pool piping and heat exchangers are made of SS. Exceptional cases include some early use of carbon steel and at least one case of a titanium heat exchanger. An example of one exception to the generally good behaviour of SS piping involves an intergranular stress corrosion cracking (SCC) phenomenon that has developed at heat-affected zones of SS piping in several PWR pools [17, 18]. The corrosion has occurred in redundant heat exchanger circuits and in piping legs that remain stagnant for extended periods.

A carbon steel heat exchanger that was not used for an extended period developed loose corrosion products, which impeded pool clarity when the exchanger was returned to service (see Section 7.3.3 for further explanation). The exchanger was replaced by one fabricated of SS. In another case, freezing of an air-cooled heat exchanger caused a few litres of mildly radioactive ($\sim 10^{-3}$ Ci/m^3) pool coolant to leak to the ground beneath the exchanger. Removal of one or two barrels of soil was the only environmental impact [19].

Large numbers of SS piping and heat exchanger components have functioned well in spent fuel pool systems with boric acid and deionized water. However, the appearance of intergranular SCC in stagnant pipe legs of PWR pools has initiated surveillance and elimination of pipe defects [20].

7.2.5. Fuel handling systems

Fuel handling may be divided into two types of operation: fuel movements in and out of the pool, and fuel movements within the pool.

Fuel is received at AFR pools in heavy shielded casks that are transferred by an overhead crane to a pool bay. The design for remote handling operations in the pool bay is well established. Stainless steel is chosen for most fuel handling equipment to minimize corrosion problems and hence reduce maintenance times and the need for decontamination of equipment.

After the fuel has been received, it is transferred to storage positions. This involves relatively simple mechanical handling operations. As in the fuel receiving operations, SS is the prime choice to minimize the necessity for maintenance. Section 9.3 describes a case where a spent fuel handling machine was disassembled and inspected after 12 years in a boric acid pool and showed no evidence of significant degradation.

Some spent fuel pool handling mechanisms have malfunctioned [21, 22], but the resulting events have had minimal impacts on the spent fuel. Appendix G summarizes data on fuel dropping events, based on survey responses.

7.2.6. Purification systems

Clean-up systems for fuel storage pool water are available to remove both soluble and insoluble species. The systems are relatively simple extensions of existing technologies, using ion-exchange units for removal of soluble species and filtration for removal of suspended solids. Boric acid systems use a resin in the ion-exchange units different from that used in deionized water systems, but both systems have had satisfactory experience.

The various filter media listed in Table IX have given satisfactory performance. The majority of pools appear to use disposable fibre filters. Vessels and piping for ion-exchange and filter systems are fabricated of SS.

7.3. BEHAVIOUR OF SPENT FUEL POOL MATERIALS

In relatively pure, low-temperature pool environments, spent fuel pool materials have generally had an excellent performance record. Figures 20—22 indicate fuel components which are still in service after two decades. But there are also some cautions regarding materials selection and use; these points are noted below.

7.3.1. Aluminium alloys

Aluminium alloys have a good record of performance in many deionized water pools and a few borated water pools. The few cases where problems with aluminium developed involved unusual situations:

— Aluminium racks corroded in a pool with ~ 700 ppm Cl⁻; the high chloride content developed owing to algae control measures; even so, the racks had a useful life of about 10 years.
— Improper selection of welding rods caused corrosion of welded aluminium storage baskets; properly made welds on the same baskets did not corrode significantly.

7.3.2. Stainless steel

Several types of SS components, i.e. storage racks, pool liners, heat exchangers, piping and fuel handling equipment, generally have functioned well, both in deionized and borated water pools. The few problems that have developed suggest a need for the following measures:

— Attention to shipping and storage conditions for pool components in order to minimize contaminants which may degrade them

52

— Specification of H-1025 or H-1100 heat treatments for SS 17-4 PH materials
— Attention to materials selection, stress levels and weld procedures for SS components
— Possible use of low-carbon or stabilized grades of stainless steels for pool components. (Many regular SS 304 components are performing without problems in pool environments. Studies are under way to better define the stress corrosion resistance of SS variants [18].)

7.3.3. Carbon steel

Unpainted carbon steel tends to rust in low-temperature water containing oxygen. One PWR pool operator indicated that rapid corrosion of unpainted carbon steel had occurred in a borated water pool [23]. The case of a rusting carbon steel heat exchanger at an AFR pool is mentioned in Table IX. The pool operator offers the explanation that at the time when the heat exchangers were first placed in operation, the pH of the pool water was rather low, namely about 4.5. This occurred because sodium nitrate was used as an anti-freezing agent in shipping casks, so fuel off-loadings caused contamination of the pool. Also, at that time the powdered resin anion and cation exchangers were operated at a ratio which buffered the water at that pH. The pool operator suggests that operation of the heat exchangers and considerably higher pHs may have resulted in satisfactory performance.

Painted carbon steel has functioned for twenty years as a pool liner at the Halden reactor, and for lesser periods as fuel storage skips at GCRs.

7.3.4. Other materials

Several other types of materials are used at some pools (see Fig. 22). Epoxy paints serve as coatings for pool walls. They function satisfactorily over long periods in low radiation fields, but are prone to degradation, particularly at radiation doses exceeding 10^9 rad.

Other materials, e.g. titanium and Monel, appear to have functioned well, but experience is limited.

8. SPENT FUEL HISTORY AND BEHAVIOUR

Almost all nuclear reactors discharge irradiated fuel to water pools; and most of the survey responses involve pools that store commercial water reactor fuel. However, some information from research reactors (aluminium-clad fuel) and gas reactors (Magnox and SS-clad fuel) is also included here.

TABLE X. FUEL CHARACTERISTICS

Characteristics	LWR		HWR	
	PWR 1000 MW(e)	BWR 1000 MW(e)	CANDU 540 MW(e)	Atucha 370 MW(e)
Physical				
Total length (mm)	3200–4827	4470	495	6180
Pin length (mm)	3848–4407	4065	492–495	5650
Cross-section side (mm)	197–230	138–152.5		
Cross-section diameter (mm)			81.4–102.5	108
Total weight per assembly (kg)	480–840	250–307	16.6–24.7	210
Heavy metal weight per assembly [a] (kg)	122–548	172–194	13.4–19.8	152.5
Number of fuel rods per assembly	126–331	47–64	19–37	36
Pellet diameter (mm)	8–9.6	10.4–12.7	12.2–14.3	10.6
Pellet length (mm)	11–18	10–13	15–20	12
Cladding	Zry-4	Zry-2	Zry-4	Zry-4
Nuclear				
Fuel type	UO_2	UO_2	UO_2	UO_2
Specific power (MW/t)	33–37	22–28	19	30
Initial enrichment ^{235}U/Pu fiss. (%)	3.0–4.4	2.5–3.5	Natural	Natural
Final enrichment				
total Pu (g/kg) (initial HM)	9–11	8–10	3.43–3.81	
fiss. Pu (g/kg) (initial HM)	6–7	5–7	2.43–2.61	
^{235}U (%)	0.8–1.26	0.8–1.0	0.205–0.282	

Characteristics	LWR		HWR	
	PWR 1000 MW(e)	BWR 1000 MW(e)	CANDU 540 MW(e)	Atucha 370 MW(e)
Nuclear (cont.)				
Total activity (Ci/kg)				
After 150 days	4.6×10^3 [b]	3.8×10^3 [c]		
After 1 year	2.3×10^3 [b]	1.9×10^3 [c]	7.9×10^2 [d]	7.3×10^2
After 10 years	3.2×10^2 [b]	2.9×10^2 [c]	8.4×10^1 [d]	7.7×10^1
Decay heat (W/kg)				
After 150 days	24.3 [b]	18.7 [c]		
After 1 year	10.4 [b]	8.2 [c]	3.15 [d]	2.9
After 10 years	2.3 [a]	2.2 [c]	0.22 [d]	0.2

[a] Range of existing reactors.
[b] Burn-up 32.2 GW·d/t.
[c] Burn-up 30 GW·d/t.
[d] Burn-up 7.5 GW·d/t.

ROD CLUSTER
CONTROL ASSEMBLY

CONTROL ROD

TOP
NOZZLE

FUEL ROD

GRID ASSEMBLY

406 cm

380 cm

BOTTOM
NOZZLE

(a)

END PLUG

WELD

SPRING

PELLETS

16 cm

FUEL-CLAD GAP

ZIRCALOY CLAD

380 cm   366 cm

WELD

(b)

56
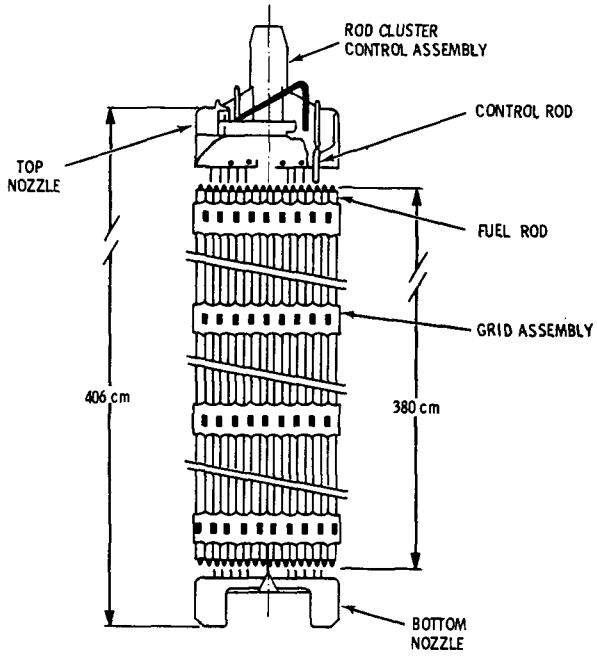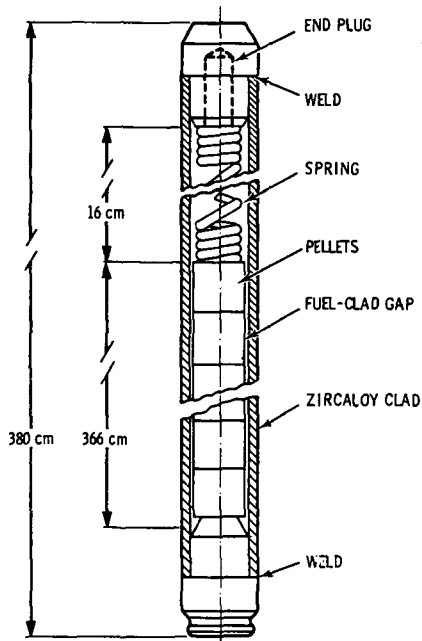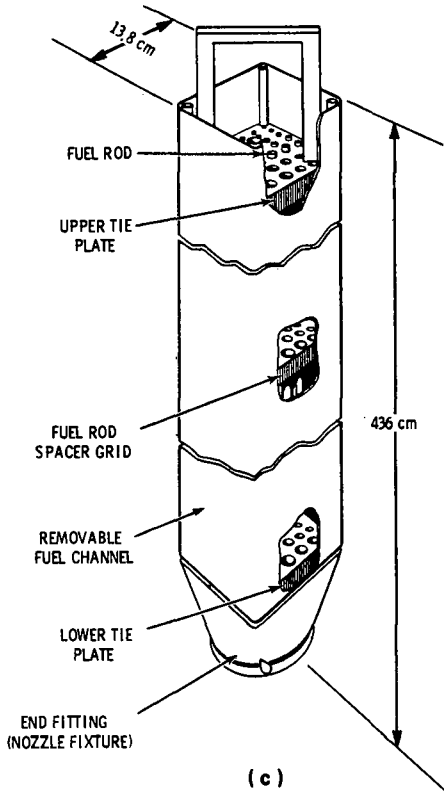
FIG.25. Typical light water reactor fuel.
(a) PWR fuel assembly; (b) LWR fuel rod; (c) BWR fuel assembly.

A large fraction of the water reac, ʃr spent fuel is destined to remain in water storage for several years and possibly for several decades. A major aspect of the survey is to better define the storage characteristics of this fuel.

8.1. FUEL DESCRIPTION

Water reactor fuel is generally constituted of fuel assemblies comprising a number of fuel rods. Table X summarizes design, operational and post-operational characteristics of water reactor fuel. The rods (see Fig.25a) usually consist of uranium oxide pellets encapsulated in a tube (cladding) of zirconium alloy or SS. Table XI provides a summary of major fuel types, burn-ups and AR pool residence times. Table XII indicates the magnitude of water reactor fuel discharges.

Typically, fresh LWR fuel is 3–4% enriched in ^{235}U. Mixed-oxide LWR fuel contains up to 0.8% ^{235}U (natural or recycled) and 3% fissionable Pu. HWR fuel has natural uranium with 0.7% ^{235}U. For various fuel designs the pellet diameters vary from 0.75 to 1.2 cm and the pellet lengths are about 1.5 cm. Fuel rods are arranged into assemblies in a geometrical array by structural elements (spacer grids, tie plates and fitting devices).

LWR and HWR-CANDU fuels differ in the following aspects:

— The CANDU assembly is much shorter (1/9 of the LWR assembly length)
— The CANDU assembly cross-sections are round; the LWR fuel has a square cross-section
— The CANDU fuel uses natural uranium; the LWR fuel generally is enriched in ^{235}U
— The ratio of cladding thickness to OD is typically 3% for CANDU and 6% for LWR fuel
— Fuel burn-ups at discharge are typically 6.5 – 8 GW·d/t U for CANDU fuel and 26–40 GW·d/t U for LWR fuel
— Fuel densities are about 94% of theoretical density for LWR fuel and 98% for CANDU fuel.

Radioactive decay, with ejection of alpha and/or beta particles or gamma rays from the nucleus, is the source of heat generation in spent fuel assemblies. For example, heat generation in spent fuel exposed to burn-ups of 25 000 MW·d/t U at a specific power of 35 MW/t decays from a thermal power of 100 kW/t at 10 days to less than 1 kW/t as the fuel nears 100 days of cooling.

Several aspects of spent fuel are considered in spent fuel pool design, including heat generation, criticality and radioactive inventories (both internal and external to the cladding).

8.1.1. Fuel cladding

Zirconium alloys are the principal cladding materials for water reactor fuel, including Zircaloy-2, Zircaloy-4, Zr–1Nb and Zr–2.5Nb. Stainless steel alloy cladding (304, 304L, 348 and 316) is still used in four operating PWRs and one operating BWR. A 1979 assessment [24] indicated that about 2200 SS-clad LWR spent fuel assemblies were in water storage world-wide (USA and Europe). About two-thirds of the SS-clad fuel was in U.S. pools, representing about 1500 assemblies, which was about 7% of the total U.S. LWR spent fuel inventory in 1979.

8.1.2. Fuel rods

Fuel rods are generally similar for the various types of LWR power plants (see Fig.25a). Differences between LWR and HWR-CANDU fuel rod designs are summarized above.

TABLE XI.   COMPARISON OF NUCLEAR REACTOR FUELS

| Reactor | Fuel | Cladding | Average discharge burn-up (GW·d/t) | Typical minimum residence time | |
				In reactor (years)	In spent fuel pool at reactor site[a] (years)
PWR	Oxide	Zry-4[b]	26−33	3	2
		SS[c]	28−35	3	2
BWR	Oxide	Zry-2[b]	28−30	4	1.5
		SS[d]	28−30	4	1.5
HWR	Oxide	Zry-4[e]	6.5−8	1	1−4
GCR	Metal	Magnox	5−5.5	2−7	0.3
	Oxide	SS	10−25[f]	4	1
	Carbide or oxide	Graphite	100	6	n.a.
FBR	Oxide	SS	60−80	1−2.5	g
RR	Alloy or dispersion	Aluminium	100	2	Variable

[a] Approximate minimum time that fuel remains in the reactor pool before shipment for reprocessing or storage elsewhere.
[b] Some Zr-Nb (USSR reactors).
[c] Only Chooz, Connecticut Yankee, Indian Point 1, San Onofre and Trino.
[d] Only LACBWR.
[e] Some Zry-2 or Zr-Nb.
[f] Projected.
[g] First in sodium during 30 days (min.), then in air during 70 days (min.), then in water; shipment to AFR pool after 170 days.

TABLE XII.   WATER REACTOR FUEL DISCHARGES

| Annual discharge | LWR | | CANDU 540 MW(e) |
	PWR 1000 MW(e)	BWR 1000 MW(e)	
Assemblies	41−64	170−210	4863
Uranium (t)	26.3−32.9	35.8−38	90.9
Plutonium (kg)	258−316	260−313	345

INTER-ELEMENT SPACERS

END VIEW

URANIUM DIOXIDE PELLETS

ZIRCALOY FUEL SHEATH

ZIRCALOY BEARING PAD

ZIRCALOY END
SUPPORT PLATE
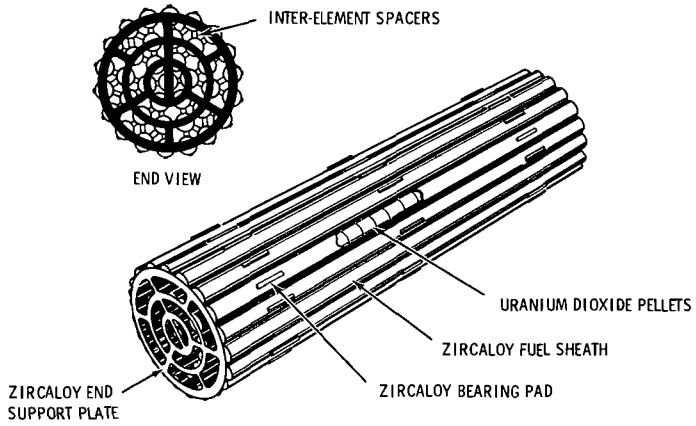
FIG.26.   HWR fuel bundle (CANDU) with 37 rods.

76.1 ± 0.5 mm

HANDLE

80.5 ± 0.1 mm

873 ± 0.5 mm

COMB

INNER FUEL PLATES

OUTER FUEL PLATES

SIDE-PLATE

END-FITTING
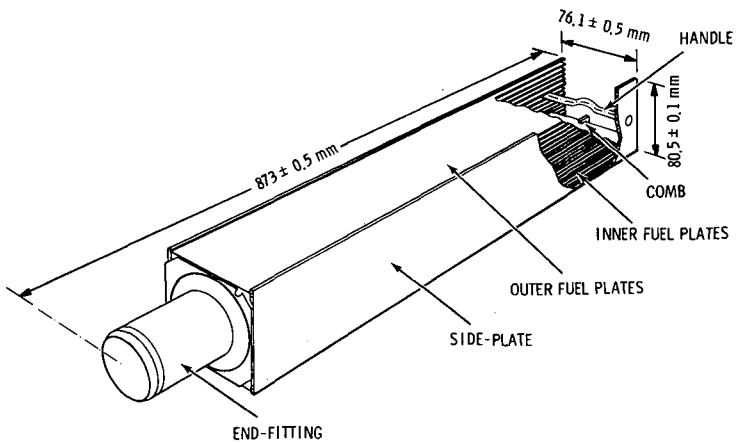
FIG.27.   Research reactor fuel assembly (MTR design).

8.1.3. Fuel assemblies

The fuel assemblies differ according to reactor type. There may also be small differences in assembly design for the same reactor among different fuel vendors. However, the differences do not have significant impacts on storage characteristics. Figures 25–27 give respective views of:

— a PWR assembly (17 × 17 design)
— a BWR assembly (8 × 8 design)
— a HWR assembly (Bruce design)
— a research reactor element (MTR design).

Some commercial fuel assembly designs differ from the typical views shown. Again, the variations will not significantly change storage characteristics.

8.2. EFFECTS OF REACTOR OPERATION

Several aspects of reactor operation influence fuel storage characteristics, including the type and number of cladding defects and the type and extent of crud layers on the cladding surfaces. The following sections briefly discuss these aspects.

8.2.1. Pressurized-water reactors

In PWRs, the fuel currently (1980) operates at burn-ups in the range indicated in Table XII. PWRs operate with high-pressure coolant, with boric acid additions for reactivity control; the pH is adjusted by additives (Li or K hydroxide); hydrogen is added to suppress oxygen. The crud deposits on the fuel rods are usually quite adherent; their thickness varies over a large range, not only from plant to plant but also from one reactor cycle to the next. The crud consists principally of oxides of iron, chromium and nickel. In view of the extended residence times and discharge burn-ups foreseen in the present decade, various research and surveillance programmes are under way [25, 26] and the IAEA is preparing a survey of the state-of-the-art concerning coolant/cladding interactions. Burn-ups for demon-stration fuel have reached 49–70 GW·d/t U, providing a basis for a decision regarding extension to higher discharge burn-ups [27].

The general behaviour of the PWR fuel has been satisfactory and has improved over the years, with a progressive elimination of the earlier causes of failure (clad collapse, hydriding, fretting, etc.). Experience indicates that a failure level of 0.01 – 0.02% of the fuel rods is typical [28]. This level is mainly due to pellet/cladding interaction and unsystematic causes, principally attributable to the probabilistic nature of quality control at the fabrication stage. Because of

the large number of fuel rods in a typical PWR assembly, the proportion of defective assemblies to be stored may be 3–5% of the discharged assemblies. Most of the failures are of the pinhole type, except in SS-clad fuel where a few longitudinal splits have occurred in the cladding. Experience indicates that this level of failure is not affecting the safety of the water storage facilities (see Section 8.6).

8.2.2. Boiling-water reactors

In BWRs, the fuel reaches slightly lower burn-ups than in PWRs. The reactor coolant operates at a lower temperature and pressure, with a higher oxygen activity ($0.1-0.5$ ppm O_2). The zirconium oxide layer builds up thicker than on PWR rods and varies with the steam fraction of the coolant (from undercooled at the inlet to bulk boiling in the upper part of the assembly). The crud deposits generally consist of a tenacious inner layer and a loose outer layer and exhibit features related to the steam fraction of the coolant along the fuel assembly. Both the outer and inner layers are principally Fe_2O_3.

Reactivity is controlled by partial insertion of control rods from the bottom (coolant inlet); control-rod movements during fuel life modify the rod surface conditions (oxidation and crud deposition) and subject the fuel to variable power duties. After progressive elimination of earlier causes of failure (fretting, hydriding, etc.), it is now considered that a failure level of $0.02-0.07\%$ for BWR fuel rods can be maintained [28]. This failure rate is mainly due to pellet/cladding interaction and fabrication-related defects. Because of the smaller number of fuel rods in a BWR assembly, the corresponding proportion of defective assemblies to be stored may be $1-4\%$ of the discharged assemblies, i.e. equivalent to the defective percentage in PWRs. Only a small fraction of the fuel failures is severe enough to expose fuel pellets to visual detection. The storage of defective fuel has relatively little impact on fuel storage because of the small area of exposed fuel, the low rates of fuel pellet leachability and releases of the mobile radio-active inventory before release of the reactor coolant [29].

8.2.3. Heavy-water reactors

The fuel in HWRs operates at much lower burn-ups than the fuel in current LWRs. Some early LWR fuel was discharged at burn-ups that overlap the burn-ups for HWR fuel. The coolant conditions are like those for PWRs (except for a lower pressure and the absence of boric acid) in PHWRs and like those for BWRs in BHWRs.

For a CANDU fuel rod, the burn-up is 3–4 times lower and the length is 6–9 times smaller than for a LWR fuel rod; consequently, the failure level should typically be $0.0005-0.0007\%$ of the discharged fuel rods, i.e. $0.01-0.02\%$ of the discharged fuel assemblies; this is indeed the observed magnitude [30].

62

The fraction of assemblies that have reactor-induced defects is smaller for CANDU fuel than for LWR fuel. However, the total number of such assemblies is larger for CANDU fuel because CANDU assemblies are smaller and consequently more numerous.

CANDU reactors discharge fuel on-line; therefore, the failed fuel is discharged while thermally hot, and it is immediately canned. Most LWR fuel is discharged after cooling for several days, and only a fraction of the LWR fuel with failed rods is canned upon discharge. Experience suggests that the failed fuel has a minimal impact on spent fuel storage in water [29].

8.2.4. Increase of discharge burn-up

The situation as discussed in the three previous paragraphs is likely to be valid for the next years. But a progressive evolution towards higher burn-ups is foreseen by the end of the 1980s. The driving forces are:

- the increasing costs of fissile material (uranium ore and enrichment services) and the back-end of the fuel cycle (reprocessing and radioactive waste disposal)
- delays in plans for reprocessing
- the advantages of increasing reactor cycle lengths to improve power plant availability and to decrease personnel exposure.

There is a large incentive, under these circumstances, for LWRs to increase the average discharge burn-up. Demonstration programmes are going on at both national and international levels to assess the behaviour of the fuel and safety-related features likely to be influenced by an increase of discharge burn-ups. As a result of these programmes, a progressive increase of commercial fuel burn-ups is very likely in the years to come. This would decrease the amount of fuel to be stored per unit of power generated.

This trend to extend burn-ups to higher values is developing at a measured pace so that both reactor [25, 26] and storage [24] behaviour will be characterized in extended burn-up programmes before a major fraction of the fuel is committed to high burn-up.

8.2.5. Other fuels

Table XI includes fuel data from gas-cooled and fast breeder reactors for comparison with water reactor fuel. The Magnox-type GCR fuel differs markedly from water reactor fuel. It is generally accepted that it should not be stored in water for extended periods unless appropriate conditioning measures are taken. Magnox is a magnesium alloy that corrodes in deionized water at $25-30°C$. As indicated earlier, the corrosion can be suppressed by proper water chemistry, including a pH of 11.5 [2]. Dry storage of Magnox fuel is briefly described in

Appendix F. Because of its uniqueness, this experience has been reviewed only briefly in the present survey.

Fuel of civil advanced gas-cooled reactors (AGR) has some features in common with water reactor fuel, including the use of SS cladding. Differences include a thinner cladding, operating at a higher upper temperature (730°C) in a carbon dioxide atmosphere and to a lower discharge burn-up. By comparison, LWR SS-clad fuel operates to an upper clad temperature of ~ 340°C. The AGR fuel assembly has a circular shape. To some extent, information regarding water storage of LWR and AGR fuel can be mutually beneficial. However, some AGR SS cladding sensitizes during reactor exposure and may become susceptible to corrosion at pool storage temperatures. Corrosion can be controlled by water chemistry control.

The high-temperature reactor (HTR) fuel consists of coated particles embedded in a graphite body (block or pebbles). Both fuel morphology and operating conditions differ markedly from those for water reactor fuel. Some HTR fuel storage information may be useful when contemplating dry storage as an option for water reactor fuel; the Fort St. Vrain storage conditions are described in Appendix F.

A SS-clad FBR fuel rod differs substantially from a SS-clad LWR rod; the diameter is smaller and the cladding is thicker; it operates at higher temperatures in a sodium coolant (390–500°C) to a higher burn-up. The FBR fuel assembly has some unique characteristics: the close packing of the fuel rods and the thick SS shroud. Since the sodium contamination and the other particulars of spent FBR fuel are irrelevant to water reactor fuel, FBR fuel experience is not included in the survey.

Most research reactor fuels consist of fuel plates with aluminium cladding (Fig.27). The fuel assemblies are generally not stored for extended periods. It was, however, deemed valuable to incorporate their storage experience in the present survey, since many commercial storage pools include aluminium parts or components. In addition, research reactors represent the longest pool operational experience.

8.2.6. Comparison of reactor and pool storage conditions

Table XIII compares exposure conditions for spent fuel under reactor and pool storage conditions. The principal point of the comparison is that the fuel remains intact in the reactor under much higher temperatures, pressures and radiation levels than those existing in spent fuel pools. Normally, the reactor fuel resides in the reactor for 1–3 years, depending on reactor type. However, some fuel has remained in the reactor beyond normal exposure times. Six Shippingport fuel bundles have remained in the reactor for 17 years; 12.3 years were at reactor operating conditions [31]. CANDU fuel assemblies have operated successfully in the NPD (Canadian) reactor since 1962 [32].

64

TABLE XIII. COMPARISON OF IRRADIATION AND STORAGE CONDITIONS FOR WATER REACTOR FUELS[a]

Item	In reactor			In pool
	PWR	BWR	HWR	
Fuel centre temperature (°C)	1200—1700	1400—1800	1300—1700	100
ID clad temperature (°C)	340—370	320—360	300—350	30—60[b]
Water temperature (°C)	300—330	260—330	260—300	20—50
Pressure inside fuel rod (atm)	38—150	5—49	23—100	(c)
Pressure outside fuel rod (atm)	140—160	70	70—110	2
Fission gases released to rod filler gas (%)	1—13	1—11	2—18	(d)
Assembly burn-up (GW·d/t U)	35	27	7	same
OD heat fluxes (W/cm^2)	100	70	100	0.03[e]
Neutron flux, > 1 MeV (max.) (n/cm^2·s)	$(5-6) \times 10^{13}$	$(4-6) \times 10^{13}$	$(4-6) \times 10^{13}$	10^5
Gamma field (max.) (R/h)	$\sim 10^9$	$\sim 10^9$	$\sim 10^9$	$10^{5\,e}$

[a] Peak values during normal operation.
[b] Depends on water temperature and decreases with age of spent fuel.
[c] One-half of the in-reactor pressure.
[d] Additional fission gas release during storage is negligible.
[e] Decreases with age of spent fuel.

8.3. SPENT FUEL TRANSPORT

Spent fuel is transported in a variety of casks, depending upon the fuel type and mode of transportation; examples of truck and rail casks are shown in Fig.12. Spent fuel transport is a well-established technology that has been documented by the INFCE Working Group 6 [1]. There is extensive experience with safe transport of spent fuel. The questionnaire responses show that approximately 60% of the facilities utilize dry transport; 6% can utilize both wet and dry shipments. Water is used as a heat transfer medium in wet transport, apart from one case where D$_2$O may be used. Pool operators normally utilize only one mode of transport for receipt, but some operators can accept both wet and dry shipping casks.

Experience regarding damage of fuel during transport is discussed in Ref.[22].

TABLE XIV. MAXIMUM RESIDENCE TIMES AND FUEL BURN-UPS FOR SPENT FUEL
STORED IN WATER

Country and storage facility	Fuel cladding	Residence time in the reactor BOL-EOL[a] (years)	Burn-up (GW·d/t) Assembly average	Peak pellet	Wet storage after EOL (years) AR H₃BO₃	Deionized	AFR Deionized	Total residence time in water[b] (years in 1980)
PWR	H₃BO₃							
Belgium, BR3 ·	Zry-4	6	44	56	1.5	—	—	7.5
Belgium, BR3	Zry-4	5	41	49	4.5	—	—	9.5
Belgium, BR3	Zry-4	4.5	34	51	6	—	—	10.5
Belgium, BR3	Zry-4	7.5	50	70	—	—	—	7.5
Belgium, BR3, and Windscale	SS	2	32	42	—	1	10	13
Belgium, BR3	SS	3	36	46	1	—	5	9
Switzerland, Beznau	Zry-4	3	22	27	1	—	6	10
Germany (Fed. Rep.), KWO and WAK	Zry-4	4	29	32	2	—	7	13
Spain, Zorita	Zry-4	5	36	55	2	—	—	8.5[c]
United Kingdom, Windscale	Zry-4	2	18	23	3.5	—	5.5	11
USA, Prairie Island	Zry-4	4	40	45	1	—	—	5
USA, H.B. Robinson, Brunswick 1	Zry-4	2	17	20	4	3	—	9
USA, Point Beach 2, G.E. Morris	Zry-4	3	40	45	0.5	—	2.5	6
USA, Zion	Zry-4	3	40	44	0.5	—	—	3.5
USA, San Onofre, G.E. Morris	SS	3	18	20	2	—	6.5	11.5
USA, Conn. Yankee	SS	2	19	23	9	—	—	11
USA, Yankee Rowe	SS	4.5	29	32	7.5	—	—	12
USA, Point Beach 2, NFS	Zry-4	2	19	21	2	—	5	9

Country and storage facility	Fuel cladding	Residence time in the reactor			Wet storage after EOL (years)			Total residence time in water[b] (years in 1980)
		BOL-EOL[a] (years)	Burn-up (GW·d/t)		AR		AFR	
			Assembly average	Peak pellet	H_3BO_3	Deionized	Deionized	
PWR (cont.)		NH$_4$OH						
USA, Shippingport, ECF	Zry-2	17	41	45	—	6	--	23
USA, Shippingport, ECF	Zry-2	2	5	6	—	1	20	23
BWR		Deionized						
United Kingdom, Windscale	Zry-2	4	27	35	—	1.5	4	8.5
Italy, Garigliano	Zry-2	10	22	26	—	—	—	10
Netherlands, Dodewaard	Zry-2	6.5	33	44	—	—	—	6.5
Norway, Halden	Zry-2	6	9	10	—	10	—	16
USA, Big Rock Pt., NFS	Zry-2	1	8	10	—	1–5	1–4	14
USA, Cooper	Zry-2	5	26	31	—	0.5	—	5.5
USA, Dresden 1, NFS	Zry-2	5	32	38	--	3	7	15
USA, Dresden 2	Zry-2	4	28	33	—	0.5	—	4.5
USA, Elk River, ITREC(I)	SS	4.8	13	15	—	1	10	16
HWR		Deionized						
Canada, Chalk River	Zry-4	2.5	18	19	—	3	—	5.5
Canada, Chalk River	Zry-4	2	9	10	—	12.	—	14
Canada, NPD	Zry-2	0.2	negl.	negl.	--	—	18	18
Others								
Japan, JRR-3	Al	1	0.6	0.9	—	10	—	11
Netherlands, HFR	Al	1	550	700	—	2	—	3

[a] BOL: beginning of life, start of power operation; EOL: end of life, end of power operation.

[b] Reactor and pool residence time.

[c] Including 1.5 years of wet storage before BOL.

8.4. HISTORY OF WATER REACTOR FUEL STORAGE IN WATER

The historical aspects of several types of spent fuel storage pools are summarized in Section 1. The historical and technical characteristics of spent water reactor fuel, including the longest pool residence times and the highest burn-ups, are discussed below. Also included are characteristics of fuel that has been or is being examined in several national spent fuel surveillance programmes.

The questionnaire responses addressed water reactor fuel stored in AFR pools, BWRs, HWRs and PWRs. The responses involved both SS-clad and Zircaloy-clad fuel and fuel with a wide range of burn-ups and pool residence times. Appendix E provides details of fuel residence times at individual pools and indicates cases where fuel was stored in more than one pool.

8.4.1. Pool residence times and burn-up characteristics

Table XIV lists fuel with the longest pool residence times and highest burn-ups for Zircaloy- and SS-clad fuel and for fuel from BWRs, PWRs and HWRs; some information on GCR and research reactor fuel is also included.

The longest pool residence for any water reactor fuel involves Zircaloy-clad Shippingport (USA) fuel that was discharged in 1959 (see Ref.[33] for results of a 1980 examination). The oldest Shippingport fuel reached a burn-up of only 4800 MW·d/t U; however, several companion assemblies placed in the reactor at the same time (1957) were discharged and examined periodically through 1974 after reaching burn-ups of up to ~41 000 MW·d/t U. Results for the maximum exposure (17 years total, of which 12.3 years were under reactor operating conditions) of the fuel cladding are reported in Ref.[31].

The oldest Zircaloy-clad fuel stored in borated water (PWR) is at the H.B. Robinson (USA) pool (stored since May 1973). While relatively little water reactor fuel with burn-ups of more than 50 GW·d/t U is being stored, numerous commercial assemblies with burn-ups at or near 40 GW·d/t U are in water storage. Several high-burn-up demonstration programmes are under way which investigate the technical and economic incentives to more fully utilize the available energy in the fuel. There is an intention to include high-burn-up demonstration fuel in spent fuel surveillance programmes [24].

BWR fuel is available that has been successively stored in an AR and an AFR facility since 1966 at a burn-up of 8–10 GW·d/t U, and since 1969 at a burn-up higher than currently adopted (32–38 GW·d/t U). Garigliano fuel has remained in the reactor core for over 10 years, and a large fraction of this time has been under shut-down conditions. The good behaviour of this fuel provides evidence of the absence of serious effects of water chemistry on storage life.

HWR fuel representative of today's burn-ups has been stored since 1965. Zircaloy-clad fuel charged into the NPD reactor in 1962 is still operating satisfactorily

in 1980 [27]. Other CANDU fuel was recharged successfully in the reactor after water storage for up to 10 years [21]. Sufficient experience is therefore available for HWR fuel for over 16 years of storage, and the surveillance programmes under way in Canada will achieve more experience for an even longer time of storage [34].

8.5. BASES TO ASSESS SPENT FUEL BEHAVIOUR IN STORAGE

The bases to assess the behaviour of spent fuel during storage include:

— Spent fuel pool operator observations: Is there evidence that water reactor spent fuel is degrading?
— Examinations of spent fuel, specifically to determine if degradation is occurring during storage.

8.5.1. Relevance of pool operator observations

Metals corroding in water release hydrogen by the reaction:

$$xM + yH_2O \rightarrow M_xO_y + yH_{2(gas)}$$
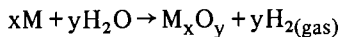
where M is a metal atom and x and y are small integers. Cases are cited where gas bubble release was observable in a spent fuel pool. For example, unpassivated aluminium racks were placed in the WAK fuel pool [15]. Release of hydrogen bubbles signalled that corrosion of the unpassivated aluminium surface was occurring. The racks were removed, passivated, and returned to the pool. No further evidence of corrosion on the racks was observed. This and similar observations suggest that substantial general corrosion of fuel rods or assembly components would be accompanied by release of observable hydrogen bubbles.

Complete penetration of the cladding by corrosion would result in observable release of gas inside the fuel rod, release of fission products to the pool water, and possible changes in fuel rod appearance.

Pool operators have opportunities to observe gas releases during frequent (daily at most pools) inspection of the pool surface. They also frequently (weekly at most pools) monitor pool water radioactivity concentrations and, therefore, are in a position to assess unexplained increases in fission products. During fuel handling operations there are opportunities to observe unusual appearances of spent fuel that could signal severe degradation.

Thus, pool operator observations are a significant source of information regarding spent fuel and pool component behaviour. The operators are in a position to observe both early degradation (hydrogen bubbles) and severe degradation (gas release, radiation release, or visual appearance).

FIG.28. Visual underwater inspection of upper end of BWR fuel assembly (stainless steel tie plate and Zircaloy-clad fuel rods).

8.5.2. Summary of pool operator observations

Question 2.1 of the questionnaire is: "Has any degradation of your spent fuel been observed during pool storage? If so, explain." Operators of 115 water reactor spent fuel pools responded to the survey (see Appendix D). All pool operators indicated that they had not seen evidence that spent commercial water reactor fuel was degrading, based on visual observations and radiation monitoring of pool water and air.

One operator [21] (NFS) reported to have seen radiation releases from Zircaloy-clad metallic uranium fuel during pool storage. The releases occurred owing to corrosion of metallic uranium exposed to the pool water at defects in the Zircaloy cladding. Hydrogen releases were also evident as the metallic fuel corroded. The defects arose either in the reactor or during discharge of the fuel from the reactor. In contrast, degradation of oxide fuel occurs very slowly at cladding defects of water reactor fuel [29].

FIG.29. Non-destructive underwater examination of BWR fuel assembly.

At the Windscale Inquiry in the United Kingdom in 1977, observers of spent fuel pools reported that irradiated Magnox GCR fuel corroded in deionized water at pool storage temperatures, with associated visible hydrogen release [9, 35]. However, the Magnox corrosion can be controlled if the pool is operated at $pH \geqslant 11.5$, coupled with control of sulphate, chloride and sludge [2].

Pool operators also found by metallographic examination that SS-clad GCR fuel may undergo intergranular corrosion under water pool storage conditions [9] owing to sensitization of some SS cladding at GCR temperatures. Procedures such as chemistry control are available to mitigate the cladding corrosion in water storage.

At pool temperatures, water reactor fuel with SS cladding is not susceptible to intergranular corrosion due to reactor-induced sensitization, because the cladding temperatures in the reactor are below the range where SS sensitizes significantly over the time span that the fuel resides in the reactor (3–4 years). This has been confirmed by examination of irradiated SS-clad fuel [9, 33]. If incipient cracks are present at the outer cladding surface as a result of the irradiation, they may propagate at pool conditions owing to a combination of stresses and crevice corrosion.

The fact that no pool operator has seen evidence that commercial water reactor fuel is degrading in water storage is significant, particularly in conjunction with evidence from spent fuel examinations.

71

FIG.30.   Hot-cell facility for detailed examination of spent fuel.

MOUNT

OXIDE FILM
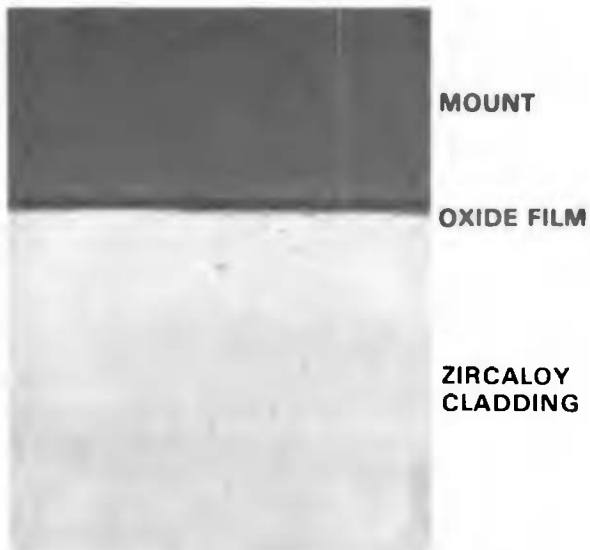
ZIRCALOY
CLADDING

FIG.31.   Metallurgical hot-cell examination showing thin oxide (0.6 μm) film on Zircaloy-clad fuel stored in water for 21 years. The oxide was formed during in-reactor exposure and did not thicken significantly during pool storage.

8.5.3. Spent fuel surveillance and examination

Several levels of surveillance are applied to define the condition of spent fuel. Figures 4, 6, 11b and 14 show views of spent fuel assemblies during storage or handling, indicating that there are opportunities for visual inspection of fuel assemblies. Spent fuel pool waters are monitored frequently for radioactive species.

Figure 28 shows an assembly viewed through an underwater periscope. Individual fuel rods can be viewed or photographed in colour, at magnifications of up to about 10 diameters, by sophisticated periscopes and underwater television equipment.

Figure 29 shows an assembly in a spent fuel pool undergoing non-destructive testing. Individual rods are removed and examined under water by profilometry, eddy current, ultrasonic and gamma scanning to define cladding integrity without removing the fuel assembly from the pool.

Figure 30 indicates a hot cell where full-sized fuel assemblies are viewed and disassembled. Individual fuel rods are removed for numerous non-destructive and destructive examinations. Most of the analytical techniques that can be applied to non-radioactive materials can also be performed on radioactive specimens, including metallography, scanning electron microscopy, density measurement, chemical analysis, and several other operations.

Figure 31 shows how even very thin oxide films on irradiated metal can be characterized by in-cell metallographic techniques.

Programmes are under way in several countries to investigate the condition of spent fuel after significant pool residence times [9, 15, 24, 32–38]. The scope of the spent fuel surveillance programmes is outlined in Table XV.

8.5.4. Destructive examination

Some spent fuel rods have been examined by detailed metallurgical methods in hot cells to determine their behaviour during extended water storage (Table XV). Metallographic techniques permit measurement of oxide thicknesses (Fig.31) to a fraction of a micrometre, resolution of microcracks in the fuel and cladding, and observations regarding concentrations of species such as hydrides and inclusions in the cladding. Analytical methods such as chemical and microprobe analyses can identify concentrations and distributions of impurities. Zircaloy-clad Shippingport fuel, stored since 1959, has been examined, indicating that pool-induced degradation was not occurring [33]. Other fuel from the same reactor reached a burn-up of 41 GW·d/t U and was examined after 23 years residence under a combination of reactor and pool conditions; it was found fully satisfactory. Zircaloy-clad fuel with burn-ups of up to 39 000 MW·d/t U is being periodically monitored by non-destructive techniques while stored in a borated pool [37]. Zircaloy-clad CANDU fuel, stored in water for 16 years, also showed no evidence

TABLE XV. SUMMARY OF SPENT FUEL EXAMINATIONS TO DEFINE STATUS OF POOL-STORED FUEL

Fuel type/reactor	Fuel: where inspected/ by whom	Fuel characteristics		When examined	How examined	Remarks
		Burn-up (MW·d/t U)	First water storage			
Zircaloy/UO$_2$/KWO[a]/PWR	KWO Pool/KWU	up to 39 000	1974	1975/ 77/80	NDT Eddy current Profilometry Visual Photography	No evidence that reactor-induced defects are changing; no evidence that intact cladding is degrading
Zircaloy/UO$_2$[b]/PWR	Windscale/UKAEA/BNFL	33 000	1972	1977	NDT/Hot cell	No evidence of pool-induced degradation
Zircaloy/UO$_2$[b]/BWR	Windscale/UKAEA/BNFL	20 000	1971	1977	NDT/Hot cell	No evidence of pool-induced degradation
Zircaloy/UO$_2$/SGHWR	Windscale/UKAEA/BNFL	1 900	1968	1977	Hot cell	No significant degradation at reactor-induced defects
SS/UO$_2$[b]/PWR	Windscale/UKAEA/BNFL	28 700	1973	1977/78	NDT/Hot cell	No evidence of pool-induced degradation
Zircaloy/UO$_2$[b]/PHWR	Windscale/UKAEA/BNFL	6 500	1966	1977	NDT/Hot cell	No evidence of pool-induced degradation
Zircaloy/UO$_2$/NRU NRX/Douglas Pt./NPD[c]	Chalk River/AECL	up to ~ 8 000	1962	1978	NDT/Hot cell	No evidence of pool-induced degradation

Fuel type/reactor	Fuel: where inspected/ by whom	Fuel characteristics		When examined	How examined	Remarks
		Burn-up (MW·d/t U)	First water storage			
Zircaloy/UO$_2$/ Shippingport[d]/PWR	Battelle/PNL/BCL	4 800/ 18 000	20 years/ 16 years	1980	NDT/Hot cell	No evidence of pool-induced degradation
SS/UO$_2$/PWR Conn. Yankee[d]	Battelle/PNL/BCL	32 000	6 years	1980	NDT/Hot cell	No evidence of pool-induced degradation

[a] 28 rods are periodically examined: 10 with reactor-induced defects, 18 intact.
[b] Proprietary.
[c] Approximately 140 rods are selected for the Canadian surveillance programme, to be examined periodically through the year 2000.
[d] Fuel examined under U.S. DOE programme; to be placed in water storage for extended surveillance.

of degradation at metallurgical examination [34]. Examination of SS-clad
PWR rods also has indicated that degradation is not occurring after borated water
storage for 5 years [9, 33].

8.5.5. Summary of spent fuel surveillance

In summary, spent fuel surveillance activities comprise the following:

(a) Visual inspection
(b) Radiation monitoring of spent fuel pool water and air
(c) Non-destructive examinations: eddy current scans to detect cladding
    defects and oxide thickness; ultrasonic scans to detect moisture intrusions;
    profilometry to assess possible changes in fuel rod dimensions; and under-
    water visual/photographic inspections by television cameras or periscopes
(d) Destructive examinations: sampling of gases inside the fuel rod to determine
    fission gas release and to look for evidence of moisture intrusions; metallo-
    graphic examinations to determine oxide thicknesses, hydride distributions
    and other evidence of cladding and assembly hardware condition; hot vacuum
    extraction to determine total hydrogen contents; and mechanical property
    tests to determine strength and ductility.

Fuel examinations have been conducted in four countries (Table XV) to
specifically define whether spent fuel is degrading in water storage. None of the
water reactor fuel examinations has indicated any evidence that the fuel cladding
is degrading during water storage (Table XV). Where contact of fuel pellets with
pool water is reported, it resulted from cladding failures during irradiation or
from mechanical handling damage.

8.6. STORAGE OF DEFECTIVE FUEL

Operators are able to detect the presence of in-reactor leaking fuel assemblies
by monitoring the radioactivity in the primary water or in the off-gas systems
during operation. Following the discharge of the fuel to the storage pool, gross
defects may be visible in peripheral rods, but most defects are either small or
hidden. To detect the specific assembly that contains leaking rods, a procedure
called "sipping' is applied [39].

Section 8.2 indicates that only a small percentage of water reactor fuel rods
develop defects during reactor operation. However, in the past, the fuel failure
levels were an order of magnitude higher than at present [28]. A significant amount
of experience on the storage of defective fuel is therefore available.

Table XVI summarizes the information received from those answers that
provided enough details to quantify the number of defective assemblies stored at

TABLE XVI. DEFECTIVE FUEL REPORTED IN THE SURVEY

Plant	Clad	Responses[a]	Assemblies per plant[b]	Rods per assembly[c]
PWR	SS	4	13	nd
PWR	Zry-4	17	17	1.5
BWR	SS	1	100	1.9
BWR	Zry-2	26	60	3.6
HWR	Zry-2, Zry-4	13	25	1.1
GCR	Magnox	1	23	nd
RR	Al, Zry-2	2	7	nd
AFR pools	Miscellaneous	3	20	nd

[a] Number of plants that responded to this question.
[b] Average number of defective assemblies stored per plant type.
[c] Average number of failed rods observed per failed assembly examined in the pool.
 nd = not determined.

the site and to calculate the average number of failed rods in the defective assemblies. Details are provided in Appendix G.

The nature of the defects varies from pinholes to small holes or cracks, and in a few cases fuel pellets are exposed. No growth of cladding defects has been observed during fuel storage [9, 29, 37]. In addition, the readily mobile radioactive inventories, both gaseous and soluble, were released in the reactor. Several case histories of storage of uncanned defective fuel [29] suggest that radiation releases from the defects are minor under spent fuel pool conditions. The gas inventories escaped before the fuel was discharged from the reactor. The leach-rates from the relatively few exposed fuel pellets are low at spent fuel pool temperatures [29].

At some spent fuel pools, assemblies with failed rods are stored in closed canisters. However, most pools store defective assemblies on the same basis as intact assemblies. Appendix G summarizes data from the survey regarding storage practice for defective fuel.

The results of the survey indicate that about 30% of spent fuel pools store defective assemblies in canisters. Defective CANDU fuel is routinely canned because it is generally discharged while the reactor is operating and therefore is thermally hot upon discharge.

77

9. SPECIAL OPERATIONS

9.1. DECONTAMINATION EXPERIENCE

Valuable information on decontamination of water storage pools has been obtained during operations at the EUROCHEMIC fuel receiving pools [40–42]. The following decontamination procedures were applied:

(a) High-pressure water jets (250–400 bar)
(b) Intermediate-pressure water jets (80 bar), allowing the addition of decontamination chemicals and heating of the solution
(c) Mechanical decontamination by brushing with various decontamination agents.

In general, the high-pressure water jetting technique has given full satisfaction, with respect to both efficiency and waste produced (jetting rate $15-25$ m^3/h, specific water consumption $55-60$ l/m^2 surface). Furthermore, the waste solution is practically salt-free and therefore can be easily concentrated into negligible amounts of liquid waste concentrates.

Efficient decontamination was achieved by spraying a 0.1N citric acid solution (60–100 bar) on contaminated surfaces. However, when both procedures failed or residual spots of resisting contamination were left, mechanical techniques were applied successfully.

9.2. CHEMICAL DECONTAMINATION OF A SWEDISH PWR CAVITY AT RINGHALS-2

During a reactor outage in April 1978, repair work was planned for the fuel transfer mechanism in the reactor cavity. However, the radiation levels were too high owing to crud accumulation in the cavity. A decontamination using chemicals and high-pressure water flushing was carried out in the lowest part of the cavity. Since the active crud particles consisted of nearly pure magnetite, a one-step chemical treatment was used. The crud particles were deposited as a very thin layer on all of the vertical surfaces. The lower areas where the repairs were planned had a number of hot spots with dose rates of from 2 to 70 R/h. This area was filled to a depth of about 60 cm (5 m^3 of solution). Rubber tubes were connected in series with a vessel having electric heaters and a pump.

During the treatment, it was impossible to maintain the intended temperature (70°C); the temperature decreased to 40°C. The circulation lasted for about 6 hours; the activity in the water had then reached a constant level. When flushing with high-pressure water was started, large amounts of crud were trapped in the draining valves, making these troublesome to operate. Tygon hoses were

attached to the valves to remove crud particles by flushing. The decontamination was as a whole successful; the decontamination factors were from 10 to 40 and all the hot spots were removed, even though the chemical did not completely dissolve crud particles. The cavity had numerous crevices and corners where crud could accumulate, prompting the need for decontamination.

9.3. DISASSEMBLY AND INSPECTION OF A FUEL HANDLING MACHINE EXPOSED TO BORIC ACID POOL CHEMISTRY

A fuel handling machine that had performed for 11–12 years in a boric acid pool at the Obrigheim reactor (PWR) in Germany (Fed. Rep.) was disassembled and inspected; no evidence of degradation was found. The same components were used, including welded segments, when the machine was reassembled. The alloy was 1.4550 (Nb-stabilized) SS. The machine began operation in 1967 and was examined in 1978; it has functioned well since reassembly.

9.4. INSTALLATION OF A SS LINER IN A POOL WHERE SPENT FUEL IS STORED [6]

The Yankee Rowe (PWR) spent fuel pool has operated since September 1961. The original pool walls were painted concrete. Some chalking of the epoxy coating occurred where it was subject to radiation from the spent fuel. The wall was recoated in 1971.

In 1978, operations began to install a full SS liner in the pool [6]. A major incentive was to prepare the pool for eventual double tiering. Several operations preceded the liner installation, including building modifications, addition of a new fuel storage vault, relocation of the cooling system, and installation of a redundant pump.

The pool lining operation began in the winter of 1978 with the installation of a coffer dam to permit independent draining of the north and south ends of the pool. The U-shaped SS coffer dam bracket is a permanent fixture that is welded to the pool liner. The bracket was installed under water using divers. Bracket installation required about three months during the winter of 1978. Underwater welding was required, using a wet-rod technique. The weld seams have double SS barriers. Voids in the concrete behind the liner were grouted to preclude spaces where leakage could accumulate. All welds were inspected by liquid dye penetrant.

The coffer dam bracket was completed early in 1979. The carbon steel dam is coated with radiation-resistant paint. It slides into and out of the bracket; inflatable Neoprene provides sealing. After the dam was installed, the south end

of the pool was dewatered and decontaminated by hydrolasing (high-pressure water jet) and by scrubbing with a detergent. The pool surface radiation levels were reduced from 30 to 10 mR/h.

For the lining operation, brackets were installed in the floor and walls for racks. Second-level rack frames were shop-fabricated before installation at the pool. The liner is of SS 304 alloy, 0.7 cm thick, and the racks are constructed of aluminium-clad boral.

Lining the south end was completed in May 1980, including some refitting of the coffer dam bracket. Lining the north end began in November 1980 and was completed in March 1981. During the south-end lining operation, spent PWR assemblies were stored in the north end. Lead panels were used to shield personnel working near the dam after the south end was dewatered.

A similar solution was adopted at the CNA plant at Chooz, France, for modifying the pool equipment and performing liner repair.

9.5. EFFECT OF LEAVING A SPENT FUEL POOL WITHOUT CLEAN-UP

A spent fuel pool at the Test Area North (TAN) of the Idaho National Engineering Laboratory (INEL), USA, was left for 12 years without operating the clean-up system, because no fuel was stored in the pool. The pool had been used for storage of fast reactor fuel exposed to molten sodium-potassium (NaK). The pool is housed inside a cinder-block building and is thus largely isolated from the surrounding desert environment. However, some particulates enter the building through cracks in the mortice during windy periods.

In 1980, a sample of the pool water was analysed. Some sodium and potassium almost certainly reflect earlier storage of fuel with NaK surface contamination. The most significant feature is the chloride analysis (1.8 ppm), which indicated that the pool environment had not become highly contaminated even after over a decade of inattention.

9.6. USE OF DIVERS TO INSTALL FUEL STORAGE RACKS

To preclude shut-down of the Ginna reactor, a decision was made in 1975 to install high-density racks. The expanded pool capacity will provide for reactor operation until 1987, including space for a full core discharge reserve.

At the time the re-racking decision was made, 92 spent fuel assemblies were located in the pool so that the pool could not be drained for rack removal and replacement. Therefore, professional divers using underwater tools were employed. The divers installed the racks without being exposed to hazardous

radiation levels. A detailed description of the procedure and the health physics measures taken is available from the literature [23].

Similar procedures have been used elsewhere many times, including the reactors Prairie Island, Salem and Connecticut Yankee.

10. MEASURES TO CONTROL RADIATION DOSES AND WASTE VOLUMES

The survey requested information regarding measures used at spent fuel pools to minimize radiation doses to the pool staff and measures to minimize low- and intermediate-level waste.

10.1. CONTROL OF RADIATION DOSES

A number of suggestions provided by responders to the questionnaire regarding measures to control radiation doses are listed below. (Not all statements are necessarily useful or applicable to each spent fuel pool.)

- Strict adherence to standard health physics procedures
- Weekly radiation surveys and smear survey of the building; continuous health physics surveillance during fuel receipt or shipping (including use of radiation work permits for fuel movements)
- Continuous air sampling
- Use of protective clothing
- Taking care to avoid the need to retrieve loose articles from the pool, including taping the pockets of workers and tying down loose articles that need to remain on the pool deck
- Proper briefing and training of personnel regarding fuel handling and emergency procedures (one pool operator mentions a 16 hour training programme)
- Maintaining the spent fuel pool building as a locked radiation area with access controlled by the shift foreman
- Minimization of stay times; posting of hot spots; use of temporary lead shielding, as required (for example, during pool-side and underwater maintenance)
- Monitoring of workers with thermal luminescent dose meters and pocket dose meters
- Use of visual and audible radiation alarms to alert personnel to excessive dose rates (such doses occur very infrequently around spent fuel pools)
- Use of an air ventilation sweep just above the water level to minimize airborne activity

— One pool found that the use of pool filters was not necessary; ion-exchange resins provided ample filtering action; elimination of filter changes reduced radiation exposure of workers; resin transfers can be accomplished remotely with minimal radiation doses to workers
— Maintaining the pool water level as prescribed in the operating procedures to provide ample shielding
— Maintaining the fuel pool purification system at maximum capacity when moving fuel
— Use of underwater vacuum cleaners to remove particulates from racks and pool floor (the NRU pool uses an air-lift pump system; a steam ejector apparatus is used at the NRX pool)
— Utilization of an electrochemical decontamination unit to reduce radiation doses due to surface contamination of metal equipment
— Use of air-activated and manual grapples to move radioactive material under water
— Labelling of buckets and containers attached to the pool railing with caution cards indicating exposure rates
— Decontamination of fuel handling machine mast
— Use of mock-up training for inexperienced fuel handlers, including dry runs with an empty fuel cask
— Change of demineralizer resins and filters on a schedule to maintain ample purification
— Use of safety interlocks on fuel handling equipment to prevent inadvertently raising fuel too close to the water surface
— Keeping work areas clean and uncluttered; storing tools that could become contaminated in a separate room when not in use
— For PWRs, use of hydrogen peroxide injection of the reactor coolant to minimize radioactivity inventories by reducing corrosion products deposited on the fuel; the procedure is combined with purification of the reactor water before moving fuel to the pool
— Control of reactor ramp rates and other procedures to minimize in-reactor fuel failures
— Storage of radioactive materials in shielded containers
— Cleaning of materials to be removed from the spent fuel pool (such as racks and fuel handling equipment) by hydrolasing (a procedure that utilizes a jet of high-pressure water)
— Shielding and/or cleaning of internally contaminated piping
— Replacing hoses and valves when exposure levels reach the prescribed values and cleaning is not practical
— Design of tools and equipment so as to minimize working times in exposure control areas, e.g. quick-disconnects and air-operated torque wrenches
— Unpacking or uncrating of equipment before movement to the radiation area.

Several pool operators indicated that spent fuel pool operations are a minor source of radiation dose. The following statement from a PWR pool operator illustrates the dose levels associated with pool operation:

" Operation of the spent fuel pool has not been a significant source of radiation dose to workers. The maximum dose rate through the 5 ft thick walls is calculated to be about 1 mR/h with a fresh core unload immediately adjacent to the wall. Maximum dose rates without a core unload are calculated to be less than 0.3 mR/h. The direct radiation dose rate from the fuel at the surface of the water is approximately 2×10^{-8} mR/h. The dose rate at the surface of the pool from the concentration of radionuclides within the pool water is about 3—4 mR/h. Radionuclides are removed from the water by the spent fuel pool demineralizer. Operation of the spent fuel pool has a negligible impact on occupational dose to workers and is consistent with all the ALARA policies implemented at the Point Beach Nuclear Plant."

10.2. MEASURES TO MINIMIZE VOLUMES OF LOW- AND INTERMEDIATE-LEVEL WASTE AT SPENT FUEL POOLS

The principal sources of routine radioactive waste from spent fuel pool operations are ion-exchange resins and pool-water filters. These constitute a relatively small waste volume because of infrequent need for resin and filter changes. This is illustrated by the comments below from two pool operators.

(a) The volume of waste resulting from operation of the spent fuel pool is negligible. It consists of a skimmer filter (~ 0.023 m^3), which is replaced about two times a year; a purification system filter (~ 0.07 m^3), which is replaced about once a year; and the demineralizer resin (~ 0.06 m^3), which is replaced about once a year. This volume of waste is insignificant compared with the overall annual waste volume.

(b) The spent fuel storage facility at Surry by design and usage provides the station with minimal amounts of low- or intermediate-level liquid waste.

The systems are designed and maintained to minimize leakage. The pool has a SS liner that is leak-tight. The pumps are provided with a shaft seal so leakage is zero. All leakage that would occur in the building is directed to the building sump and pumped to the liquid waste system.

Normal operation utilizes a spent fuel pool purification system that has an ion exchanger and filter to remove activity and impurities from the water. The ion-exchange bed contains 1.3 m^3 of H$^+$OH$^-$resin and requires change-out about once per year. The change-out is performed when the bed differential pressure reaches a prescribed value or the ionic decontamination factor is low, indicating resin exchange depletion. The resin is shipped for burial in a type-A cask. The

water used to move this resin contributes to liquid waste. Each transfer requires 1000 gal of water, which is treated as intermediate liquid waste.

The filter is used to retain resin fines and to remove particulate matter from the spent fuel pool water. The filter medium consists of 16 disposable cartridges, stacked in tiers. The filter is changed out about once per year when the differential pressure exceeds the operational limits. The filter is shipped to the burial site in a type-B cask.

When the spent fuel storage racks were changed out for high-density racks, the old racks were shipped and buried; they accounted for approximately 60 m^3 of waste.

Compactors are used to minimize low-level waste volumes at some pools. One operator indicated that a compactor of 8000 lb/in^2 was replaced by a compactor of 60000 − 80000 lb/in^2, resulting in further volume reductions. At some pools, waste solidification systems are used to minimize low- and intermediate-level waste volumes.

One pool operator reported the following measures: removal of all packaging before taking materials or equipment into controlled areas; use of thinner plastic sheeting; use of paper coveralls; limiting the amount of wood around the spent fuel pool.

An underwater probe is used to segregate waste according to contact radiation levels. Low-level waste is placed in steel drums, immobilized with concrete, and shipped to a burial site. Intermediate-level waste is loaded into liners inside casks; the liners are capped and shipped to burial.

Contaminated and non-contaminated solid wastes from the spent fuel pool are segregated.

One pool operator indicated change-out of filters at a predetermined differential pressure selected to assure that the filter does not fail. Another operator found that the ion-exchange resin provided sufficient filtering action. Elimination of the filters reduced the amount of intermediate-level waste.

One pool operator indicated use of on-site dry cleaning for anti-contamination clothing. All liquid waste in the plant is recycled, except for chemical wastes, which are mixed with solid wastes and solidified.

Minimizing crud transport from the reactor vessel to the spent fuel pool minimizes pool radioactivity inventories. This is done by ion exchange and filtration of the reactor water before fuel discharge.

Limiting the number of sinks and floor drains decreases the volume of liquid waste.

Administrative controls are useful to minimize waste volumes.

Waste generated in cleaning operations is minimized by pre-planning and controls on procedures.

11. SPENT FUEL POOL PRACTICES AND INNOVATIONS

Practices and innovations at spent fuel pools that might be useful for pool operators were reported during the survey and are listed below.

- In the view of one pool operator, a shallow pool with baskets has advantages over a deep pool with racks. The baskets are loaded in a smaller and deeper receiving pool and are then moved to the storage location. Stationary racks require extra pool depth to permit fuel assemblies to be inserted.
- An extension hook on the crane block during cask handling operations in the pool keeps the block out of the water, reducing maintenance and spread of contamination.
- Use of an underwater oxygen cutting torch was indicated at one pool.
- A dam was installed at one pool to facilitate installation of a SS liner while irradiated fuel was stored in the pool (see Section 9.4).
- A chemical decontamination was conducted on a section of a fuel handling cavity (see Section 9.2).
- Double tiering of fuel racks is being considered or has been installed at some pools to utilize the existing spent fuel pool volume more effectively.
- Installation of an underwater fuel inspection elevator and periscope has been useful.
- Installation of new spent fuel pool racks should be done while the pool is dry, if possible.
- Divers have been used for liner repair and pool modifications.
- A load cell on the fuel handling machine to monitor lift weights is valuable; it eliminates the need for scales and can be fitted with an automatic stop when the weight reaches a pre-set value.
- A versatile set of underwater viewing equipment is valuable for problem solving, audits, fuel inspections, etc. The equipment includes television camera and monitor, lights, taping equipment, and fixtures.
- A retrieval tool kit to remove unwanted items from the pool is useful, including grapple, magnet, tubing, remote-operating vise-grips, and special hooks.
- Water shields (aluminium boxes) and water windows are used to shield the pool sides when required.
- Water or lead shields under the fuel handling machine cab minimize doses to the operator.
- An automatic radiation monitor with local readout inside the cab is useful for the fuel handling machine operator.
- A fuel handling grapple with computerized grid logic permits safer and faster fuel movements.
- Improved hydraulic manipulators are useful to handle radioactive material under water.

- Filters with 1-μm openings remove 99% of dose-causing radioisotopes.
- At a pool where trans-shipments are possible, fuel racks were designed so that both BWR and PWR fuel can be stored.
- Deck gratings over the transfer canal are useful.
- Spent fuel pools should be designed to be expandable, as necessary.
- The pool design should include adequate handling and layout areas.
- A portable floating skimmer is used at some spent fuel pools; other pools use fixed skimmers.
- Replacement of a pre-coat filter by a plate-type filter reduced the volume of radioactive waste.

12. INTERIM DRY STORAGE OF SPENT FUEL

Currently (1980), wet storage is the only interim LWR or HWR spent fuel storage option. However, a substantial data base exists for dry storage of irradiated fuel. Appendix F gives examples of irradiated fuel in dry storage.

The successful developmental experience with dry storage to date suggests that there are no technological limitations which would prevent eventual licensing. Whether or not dry storage becomes a major factor in routine interim storage of spent fuel, it provides a back-up technology for wet storage.

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Appendix A

WORLD SURVEY OF WATER REACTOR
SPENT FUEL STORAGE EXPERIENCE

Questionnaire and list of responding countries

The following information was sent to 22 IAEA Member States in June 1979. The purpose of the survey is explained first, then follows the questionnaire that the Member States responded to. Responses were to be returned to the IAEA by December 1979. Some responses which arrived after that date have also been factored into the summaries of survey results.

INTRODUCTION

Spent nuclear fuel elements require a period of 'cooling' after withdrawal from a nuclear reactor. This is done in water storage pools located at the reactor facility. The minimum storage time before subsequent operations with the spent fuel is recognized to be 6 – 12 months. After the initial storage period for cooling, the subsequent storage time in water pools could vary from a few years to several decades, depending on the fuel cycle options chosen and the availability of the relevant fuel cycle services (fuel reprocessing or long-term storage facilities).

Experience gained from observation and investigation of non-defective spent fuel elements stored in water pools makes it possible to conclude that storage of bare or canned LWR and HWR spent fuel elements in water pools does not pose significant problems for a period of up to two decades because of the negligible effect of corrosion under the controlled low-temperature conditions.

To date, fuel examinations have not indicated that degradation of LWR and HWR fuel cladding is occurring. However, periods of extended storage may be necessary and, therefore, further confirmation studies must be made on the fuel integrity, including selective monitoring, as spent fuel residence times in storage increase, particularly on LWR fuel with higher operational burn-ups. In order to collect and organize additional information on experience by Member States, notably on nuclear safety issues, the questionnaire has been prepared.

Explanation of the Questionnaire

The questionnaire is structured to cover the following areas:
— Spent fuel history
— Spent fuel behaviour
— Pool history and water chemistry
— Spent fuel pool equipment behaviour
— Measures to control radiation doses and waste volume.

The questionnaire addresses itself only to the most representative spent fuel assemblies as indicated under 1.1 and 1.2 (i.e. the well-characterized fuel with a storage period of at least 5 years). It does not concern information on the bulk of spent fuel stored routinely in reactor operation, unless the general experience gained is of direct value for assessing the behaviour of spent fuel during extended storage. Information on problems encountered during storage is as important as that on successful operation.

89

QUESTIONNAIRE

1. **Spent fuel history**

   1.1. Longest spent fuel storage [Zircaloy-2, Zircaloy-4, and other zirconium alloys, stainless steel -- for each clad type: include bundle average and local peak burn-up (MW·d/t U), irradiation and power history, time stored at reactor, time at other pool(s) and whether still stored].

   1.2. Highest burn-up fuel stored (include same information as above).

   1.3. Types of container and/or racks for *undamaged* and for *defective* fuel; is canned fuel stored wet or dry?

   1.4. For defective fuel, provide if possible: approximate number of bundles and/or defective rods stored for each clad type; size and type of defects; behaviour of exposed fuel pellets. Is degradation at the defect apparent? If so, how were observations made?

   1.5. Is fuel shipped wet or dry?

   1.6. Have spent fuel bundles been dropped in handling? How many? What damage and consequences?

2. **Spent fuel behaviour**

   2.1. Has any degradation of your spent fuel been observed during pool storage? If so, explain.

   2.2. Has fuel been damaged in shipment? Give details.

   2.3. Method(s) used to define condition of your spent fuel (visual, radiation monitoring, non-destructive, and destructive); theoretical assessments.

   2.4. Experimental data available on spent fuel (mentioned in 1.1 and 1.2).

3. **Pool history and water chemistry**

   3.1. Date of first pool storage.

   3.2. Pool drained? When/Why?

   3.3. Other (re-racking, new liner, etc.).

   3.4. Pool dimensions (in metres) and water volume (m^3).

   3.5. Pool chemistry; pH, conductivity (μS/cm), boron (ppm B), Li (ppm Li), other (show normal value and range of values and maximum limit if possible).

   3.6. Pool temperature, °C; normal, range and limit.

   3.7. Radiochemistry (Ci/m^3 or Ci/ml): total pool water activity and activities of principal isotopes (normal, range and limits if possible); total alpha activity.

   3.8. Procedures for chemistry and radiochemistry control (e.g. ion exchange, filters, etc.).

   3.9. Have biological growths occurred? Explain and indicate measures to control.

4. **Spent fuel pool equipment behaviour**

   4.1. Indicate material and longest pool residence for materials in pool (liner, racks, handling equipment, heat exchanger, etc.).

   4.2. Summarize problems with pool equipment (liner leaks, racks, heat exchanger, etc.) and measures used to correct problems.

90

5. **Measures to control radiation doses and waste volume**

    5.1. Indicate measures you have found useful to minimize radiation doses to workers.
    5.2. Give information on volumes of low- and intermediate-level waste produced and measures to minimize them.

6. **Indicate any design and operational innovations that may be useful to other pool operators, including spent fuel surveillance procedures.**

Country   Storage pool   Organization operating
storage pool

Name(s) of person(s) providing information   Title

Organization

Address

Telephone

Telex

LIST OF RESPONDING COUNTRIES

COUNTRY	ABBREVIATION[b]
Argentina	AR
Belgium (including Eurochemic)	BE
Brazil[a]	BR
Czechoslovakia[a]	CS
Canada	CA
Finland[a]	FI
France	FR
Germany, Federal Republic of	DE
India	IN
Italy	IT
Japan	JP
Korea, Republic of	KR
Netherlands (incl. JRC-Petten)	NL
Norway[c]	NO
Pakistan	PK
Spain	ES
Sweden	SE
Switzerland	CH
United Kingdom of Great Britain and Northern Ireland	GB
United States of America	US

[a] Responded, but no data provided.
[b] Country codes established from IAEA publication: Power Reactors in Member States.
[c] The OECD reactor, Halden, responded informally; the survey was not formally sent to Norway since there is no current nuclear power programme.

Appendix B

CONSULTANT GROUP ON WORLD EXPERIENCE WITH STORAGE OF SPENT FUEL IN WATER POOLS

The following group of specialists in the field of spent fuel behaviour compiled and evaluated the responses to the joint IAEA/NEA questionnaire that was sent to 22 Member States.

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93

Appendix C

NUCLEAR FACILITIES RESPONDING TO
IAEA/NEA QUESTIONNAIRE

Table C-1 lists the responses to the joint IAEA/NEA questionnaire that was sent to 22 Member States. The country, name of the storage facility, number of pools, reactor type, and year of commercial operation are provided.

TABLE C-1. NUCLEAR FACILITIES RESPONDING TO QUESTIONNAIRE

Unit No.	Country[a]	Station name	No. of pools	Facility type	Year of commercial operation
1	BE	BR-3	1	PWR	1962
2	CA	NPD	1	PHWR[b]	1962
3	CA	Douglas Point	1	PHWR	1968
4–7	CA	Bruce 1–4	2	PHWR	1977–1979
8–11	CA	Pickering 1–4	2	PHWR	1971–1973
12–13	CH	Beznau 1–2	2	PWR	1969–1971
14	CH	Mühleberg	1	BWR	1972
15	CH	Gösgen	1	PWR	1979
16	DE	Obrigheim (KWO)	1	PWR	1969
17	DE	Brunsbüttel (KKB)	1	BWR	1977
18	DE	Lingen (KWL)	1	BWR	1968
19	DE	Gundremmingen (KRB)	1	BWR	1967
20	DE	Stade (KKS)	1	PWR	1972
21	DE	Kahl (VAK)	1	BWR	1962
22	ES	José Cabrera	1	PWR	1969
23	ES	Santa María de Garoña	1	BWR	1971
24	ES	Vandellos	1	GCR	1972
25	FR	Ardennes (Chooz)	1	PWR	1967
26–27	IN	Tarapur 1-2	2	BWR	1969
28	IN	Rajasthan	1	PHWR	1973
29	JP	Fukushima-1	1	BWR	1971

[a] See Appendix A for country codes.
[b] Converted from PHWR to BHWR in 1968 and back to PHWR in 1971.

TABLE C-1. (cont.)

Unit No.	Country	Station name	No. of pools	Facility type	Year of commercial operation
30	JP	Genkai-1	1	PWR	1975
31	JP	JPDR	1	BWR	1963
32	KR	KO-RI-1	1	PWR	1978
33	NL	Dodewaard	1	BWR	1969
34	PK	Kanupp	1	PHWR	1972
35–36	SE	Oskarshamn 1-2	3	BWR	1972–1974
37–38	SE	Barsebaeck 1-2	4	BWR	1975–1977
39–40	SE	Ringhals 1-2	4	BWR/PWR	1975–1976
41	GB	Winfrith SGHWR	1	SGHWR	1968
42–43	US	Arkansas 1-2	2	PWR	1974–1975
44–45	US	Browns Ferry 1-2	1	BWR	1974–1975
46–48	US	Indian Point 1-3	3	PWR	1962–1973
49–51	US	Oconee 1-3	2	PWR	1973–1974
52–53	US	Point Beach 1-2	1	PWR	1970–1972
54	US	La Crosse	1	BWR	1969
55	US	Beaver Valley	1	PWR	1976
56	US	Duane Arnold	1	BWR	1975
57	US	Vermont Yankee	1	BWR	1972
58	US	Yankee Rowe	1	PWR	1961
59	US	Fort Calhoun	1	PWR	1973
60	US	J.M. Farley	1	PWR	1977
61	US	Davis-Besse	1	PWR	1977
62	US	H.B. Robinson-2	1	PWR	1971
63–64	US	Brunswick 1-2	2	BWR	1975–1977
65–66	US	Donald C. Cook 1-2	2	PWR	1975–1978
67	US	Trojan	1	PWR	1976
68	US	Fort St. Vrain	1	HTGR	1979
69–70	US	Surry 1-2	1	PWR	1972–1973
71	US	Prairie Island	1	PWR	1973
72	US	Monticello	1	BWR	1971
73	US	Salem	1	PWR	1977

TABLE C-1. (cont.)

Unit No.	Country	Station name	No. of pools	Facility type	Year of commercial operation
74−75	US	Peach Bottom 2-3	2	BWR	1974
76−77	US	Hatch 1-2	1	BWR	1975−1978
78	US	Maine Yankee	1	PWR	1972
79−80	US	Zion 1-2	1	PWR	1973−1974
81−83	US	Dresden 1-3	3	BWR	1960−1970 −1971
84−85	US	Quad Cities 1-2	1	BWR	1972
86	US	Palisades	1	PWR	1971
87	US	Big Rock Point	1	BWR	1963
88−89	US	Millstone 1-2	2	BWR/PWR	1971−1975
90	US	Haddam Neck (Connecticut Yankee)	1	PWR	1968
91	US	Kewaunee	1	PWR	1974
92	US	Cooper	1	BWR	1974
93	US	Pilgrim	1	BWR	1972
94	US	San Onofre 1	1	PWR	1968
95	US	St. Lucie 1	1	PWR	1976
96−97	US	Turkey Point 3-4	2	PWR	1972−1973
98	US	Shippingport[c]	1	PWR	1957
99	AR	Atucha-1	1	PHWR	1974
100	NE	Borssele	1	BWR	1973
101	IT	Trino Vercellese	1	PWR	1965
102	US	Elk River	1	BWR	
103	IT	Latina	1	GCR	1964
201	CA	NRX	1	RR[e]	1948
202	CA	NRU	1	RR	1958
203	CA	WR-1[d]	1	RR	1965
204	ES	JEN-1	1	RR	1959
205	JP	JRR-2	1	RR	1961

[c] Not typical of commercial PWR; has Zry-2 cladding; no boric acid in primary system or spent fuel pool.

[d] Organic-cooled experimental reactor.

[e] Research reactor.

96

TABLE C-1. (cont.)

Unit No.	Country[a]	Station name	No. of pools	Facility type	Year of commercial operation
206	JP	JRR-3	1	RR	1965
207	NL	HFR	1	RR	1961
208	NO	Halden	1	RR	1959
209	SE	ÅGESTA	1	PWR	1972
210	US	HFBR	1	RR	1966
211	US	ETR	1	RR	1957
212	US	ATR	1	RR	1967
213	US	MTR	1	RR	1951
214	US	CP-5	1	RR	1961
215–216	SE	Studsvik	2	RR	1973–1974
217	US	X-10	1	RR	1943
218	IT	Ispra-1	1	RR	
301	BE	Eurochemic	1	AFR	1965
302	DE	WAK	1	AFR	1969
303	FR	La Hague	1	AFR	1975
304	IT	Eurex	1	AFR	1965
305	IT	Itrec	1[f]	AFR	1968
306	GB	Windscale (B-27)	1	AFR	1967
307	US	G.E. Morris	1	AFR	1972
308	US	FRSF	1	AFR	1951
309	US	RBOF	1	AFR	1963
310	US	NFS	1	AFR	1965

[f] Information received from only one pool that stores water reactor oxide fuel.

Appendix D

SUMMARY OF SPENT FUEL POOL CHEMISTRY,
RADIOCHEMISTRY AND OPERATIONAL DATA

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
1	BR-3 BE PWR	8/1963	1965 new racks 1972 cleaning of pool bottom 1975 cleaning of pool bottom	Partial drainage for equipment installation and maintenance	6.0 × 6.0 × 6.7 (215 m³)	~6	1–10, down to 0.1 (purification by filter and demineralizer)	None	None
8–11	Pickering 1–4 CA PHWR	10/1971	No	Original 100% epoxy lining intact	5000 m³	5.5–6.5	2–5		
12–13	Beznau 1–2 CH PWR	1971	1978 re-racking		2 pools 10 × 10 × 6 (500 m³ each)	4.5		4000	
14	Mühleberg CH BWR	9/1973	No	Re-racking	12 × 6 × 12 (850 m³)	5–7	0.6–1.2		
15	Gösgen CH PWR	6/1980	Yes, to enable the storage cells to be changed	None	9.7 × 7.9 × 12.6 (925 m³)	6		2000–2500	200–900
16	Obrigheim (KWO) DE PWR	1970	No	No	8 × 6.2 × 11	5	8	1800	0.1
17	Brunsbüttel (KKB) DE BWR	10/1978		No	10.8 × 9.5 × 12.6	5.6–8.6	1–5	None	None
18	Lingen (KWL) DE BWR	1970	No	No	9 × 7 × 10 (600 m³)	6.2 (5.8–7) Max. 7	2 (0.8–5) Max. 5		
19	Gundremmingen DE BWR	1967	No	No	8.8 × 8.3 × 11.7 (880 m³)	7 (6–8)	<1.0 (<1.0–10)		

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m³)						Total activity (Ci/m³)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
1	Cl⁻ and SiO₂ <100 ppb insoluble part. (crud: Fe and Si)	~25 (lim. 52)			During refuelling: 2×10^{-4}		During refuelling: 2.5×10^{-3}	During refuelling: 1×10^{-5}	During refuelling: $\beta, \gamma = 3 \times 10^{-3}$ $\alpha \leqslant (0.5 - 22) \times 10^{-5}$ $\beta, \gamma = (1 - 2) \times 10^{-3}$ with ⩾90% Co-60 After refuelling: $\alpha \leqslant (0.5 - 5) \times 10^{-5}$	Filters, ion exchange	None
8–11		20–30	1.4×10^{-3}	3.0×10^{-4}	7.4×10^{-5}	2.5×10^{-5}	4.1×10^{-4} Co-58: $<2.9 \times 10^{-7}$	$<2.6 \times 10^{-7}$		Filters, ion exchange	None
12–13	Saturated O₂ Cl⁻: <0.2 ppm	20–40							$10^{-3} - 10^{-2}$ Mainly Co-58, Cs-137 and Cs-134	Ion exchange	None
14		25–30			3×10^{-4}	2×10^{-4}	1×10^{-4}		$\beta, \gamma: <10^{-3}$	Filters, ion exchange	None
15		50 (15–60)								Ion exchange	
16		30 (lim. 60)			Cs-134 + Cs-137: 8×10^{-4}		Co-58 + Co-60: 2×10^{-3}			Filters, ion exchange	None
17	Cl⁻: ≤0.5 ppm	20 (lim. 40)							1×10^{-4} to 1×10^{-3}		None
18	Fe: <5 ppm (5–20 ppm) max. 30 ppm Cl⁻: <10 ppm (10–20 ppm) max. 20 ppm	Water temp. during reactor operation: 30; range: 25–30. 1 year after reactor shut-down also cooling system shut-down; temperature stabilized at 48°C and decreased in 2 years to 40°C.							During pool operation, inspection and transit: 10^{-5} to 10^{-3} (mainly due to Cs-137, Cs-134 (ratio 2:1) and Co-60 (10%)). During non-operation of purification system: γ-activity: 8×10^{-3} (80% due to Cs-137, 19% to Cs-134 and 1% to Co-60)	Ion-exchange	None
19		22 (16–30) (lim. 45)	2×10^{-5} to 8×10^{-3}	1×10^{-5} to 3×10^{-2}	1×10^{-5} to 2×10^{-2}	1×10^{-3} to 2×10^{-2}	1×10^{-3} to 2×10^{-2} Co-58: 6×10^{-5} to 5×10^{-3}	3×10^{-6} to 3×10^{-3}	5×10^{-3} to 7×10^{-2}	Filters, ion exchange	None

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
20	Stade (KKS) DE PWR	7/1973	No	No	Reactor pool: 12.7 × 7.7 × 9.3 (859 m³) Fuel assembly storage pool: 9.7 × 9.0 × 13.5 (1138 m³)	5.0 (4.6–5.4)	8 (6–10)	2200 (<2500)	0.5 (0.25–1)
21	Kahl (VAK) DE BWR	1969	No	No	15 × 7 × 12.5 (1000 m³)	5.8	0.1		
22	Jose Cabrera ES PWR	4/1971	No	No	7 × 6.5 × 12 (290 m³)	4.8 (4.5–6.7)	13 (7–50)	2150 (1900–2300) (max. (2000–4000))	0.22 (0.22–0.38)
23	Santa Maria de Garoña ES BWR	6/1972	No	No	12 × 7 × 11.5	6.3–6.9 (at three different levels)	1.9–4.3 (at three different levels)		
24	Vandellos ES GCR	4/1973	No	No	Final storage pool 17.5 × 7.3 × 8.5 (768 m³)	11.8 (treatment with Na₂CO₃ and NaOH)			
25	CNA (Chooz) FR PWR	1967	2/1978	Re-racking and modification of coolant circuit	13 × 5.9 (1000 m³)	5.8 (5.7–5.9)		1500 (1500–2000)	None
26–27	Tarapur 1–2 IN BWR	2/1971	No	No	620 m³	5.6–8.6	2.0	None	None
28	Rajasthan IN PHWR	Insp. bay 8/1972 storage pool 8/1974	Inspection bay: three times; storage pool: no	Re-racking	Inspection bay 7.3 × 3.4 × 4.6 (112 m³) storage pool 20.8 × 7.6 × 7.2 (1132 m³)	6.5–7	10–25	None	None
29	Fukushima-1 JP BWR	10/1971	No	Re-racking	6 units 1: 12 × 7 × 11 2–5: 12 × 10 × 12 6: 16 × 12 × 12	6.5 (6–6.8) (lim. 5.3–8.6)	1.0 (0.8–1.0) <2.0	None	None

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54	Total activity (Ci/m³)	Chemistry control	Biological growth
			Radioactive species (Ci/m³)								
20	SiO_2: 1.5 ppm	20–30 (lim. 50)			2×10^{-3} (2×10^{-4} to 4×10^{-3})	1×10^{-3} (3×10^{-4} to 2×10^{-2}) 5×10^{-3} (1×10^{-4} to 2×10^{-2})	5×10^{-3} (1×10^{-4} to 2×10^{-2})		1.5×10^{-2} (1.5×10^{-3} to 1×10^{-1}) Sb-124: 5×10^{-4} (5×10^{-5} to 2×10^{-2}) α: 4×10^{-2}	Filters, ion exchange	None
21		27 (lim. 45)								Filters, ion exchange	
22	Na: 0.06 ppm (0–0.6 ppm) Cl⁻: 0.1 ppm (0.03–0.8 ppm) max: 0.15 ppm F⁻: 0.12 ppm (0.02–0.6 ppm) max: 0.15 ppm SiO_2: 0.65 ppm (0.6–5 ppm) Crud = 0.1–0.9 ppm	24 (20–50) (lim. 65)	3×10^{-4} (5.6×10^{-5} to 4.8×10^{-4})	6×10^{-4} (1.4×10^{-5} to 4.8×10^{-3}) I-132: 5×10^{-4} (3.4×10^{-6} to 6.6×10^{-4})	3.6×10^{-3} (1.5×10^{-3} to 5.8×10^{-3}) Cs-136: 3×10^{-4} (1.2×10^{-4} to 4.3×10^{-4})	3×10^{-3} (1.6×10^{-3} to 5.0×10^{-3})	6.5×10^{-3} (1.0×10^{-3} to 1.8×10^{-2}) Co-58: 5×10^{-2} (1.9×10^{-2} to 6.9×10^{-2})		6×10^{-2} (2.5×10^{-4} to 9.7×10^{-2}) H-3: 1.1×10^{-1}	Filters, ion exchange	*None*
23	Cl⁻: <10 ppb SiO_2: 56–89 ppb Insolubles: 247–936 ppb Fe: 193 ppb Cu: 83 ppb Ni: 20 ppb	28 (20–32)			4.9×10^{-3}	2×10^{-3}	1.9×10^{-3} Co-58: 3.1×10^{-5}	2.3×10^{-4}	γ: 1×10^{-3} to 3×10^{-3}	Filters, ion exchange	None
24		16 (winter) 26 (summer) (lim. 30)							5×10^{-3} (90% Cs-137 and Cs-134) α: 10^{-6} to 10^{-5}	pH checked every two days, filters, ion exchange	
25		46 (lim. 93)							$\beta = 10^{-4}$ $\gamma = (2-5) \times 10^{-4}$	Filters, ion exchange	None
26–27		42 (lim. 100)							2×10^{-3} (1.0×10^{-3} to 1.0×10^{-2}) (Cs-134 + Cs-137: >80% bal. Co-60)	Filters, ion exchange	None
28		35 (lim. 55)								Filters, ion exchange	None
29		32–37 (lim. 65)							5×10^{-4} (1×10^{-4} to 1×10^{-3}) (lim. 1×10^{-3})	Ion exchange	None

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
30	Genkai-1 JP PWR	11/1976	No	Re-racking 1976 (increase from 4/3 to 8/3 core)	9.6 × 7.5 × 12.5 (882 m³)	4.8 (4–8)		2103 (>2000)	
31	JPDR JP BWR	9/1970	No	No	6.1 × 2.3 × 6.2 (103 m³) (inside reactor containment)	5.5–6.5 (lim. 5.5–7.5)	0.5–2 (lim. 5.0)		
32	KO-RI-1 KR PWR	11/1979	No	No	14.8 × 7.9 × 12.4 (1130 m³)	4.4 (4.0–4.7)	≤40	2100 (>2100)	0.04 (<0.15)
33	Dodewaard NL BWR	1971	No	No	8 × 5 × 8 (320 m³)	5.5–7	1.4 (1–2)	None	None
34	Kanupp PK PHWR	6/1973	No	No	18.2 × 7.6 × 6.0	6–8	0.1		
35	Oskarshamn-1 SE BWR	1972		New racks in 1978	10.5 × 9.8 (1155 m³)	5.6	0.9 ± 0.1		
36	Oskarshamn-2 SE BWR	1976	1978: One of two pools for re-racking	New racks in 1978	2 pools 1: 10.8 × 7.1 (805 m³) 2: 10.8 × 3.5 (500 m³)	5.6	0.9 ± 0.1		
37	Barsebaeck-1 SE BWR	1977	Pools drained on several occasions for cleaning and re-racking		2 pools 8 × 7 × 14 (800 m³) 11 × 4 × 14 (600 m³)		1.0 (0.9–1.2)	None	None
38	Barsebaeck-2 SE BWR	1977	Pools drained on several occasions for cleaning and re-racking		2 pools 8 × 7 × 14 (800 m³) 11 × 4 × 14 (600 m³)		1.0 (0.9–1.2)	None	None

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m^3)						Total activity (Ci/m^3)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
30		24–30 (lim. 60)			7×10^{-6}	5×10^{-6}	2×10^{-4} Co-58: 4×10^{-5}		10^{-4} No α	Filters, ion exchange	None
31	Cl = 0.02–0.06 ppm (lim. 0.5 ppm)	15–30 (lim. 50)			$<5 \times 10^{-2}$		$10^1 - 10^0$		1.9×10^{-5}	Filters, ion exchange	
32		20.2 (lim. 65.5)			2.7×10^{-6}	3.7×10^{-6}	1.0×10^{-5} Co-58: 9.4×10^{-5}	3.4×10^{-6}	$(5-6) \times 10^{-5}$ Cr-51: 5.2×10^{-6} Nb-95: 1.0×10^{-5} Zr-95: 2.2×10^{-6}	Filters, ion exchange	None
33		25–30			2.0×10^{-3} $((0.13-6) \times 10^{-3})$	0.6×10^{-3} $((0.1-3.6) \times 10^{-3})$	5.0×10^{-3} $((0.7-11) \times 10^{-3})$	2.0×10^{-3} $((0.25-3.2) \times 10^{-3})$	1.3×10^{-2} $((1.0-1.8) \times 10^{-2})$	Hydrocyclone, ion exchange	None (pH control)
34	Cl$^-$: 0.2 ppm	38–43							HTO: 1.5×10^{-3} $\beta, \gamma = 5 \times 10^{-7}$ No α	Filters, ion exchange	
35	SiO$_2$: 50–300 ppb Cu: 0.01–3 ppb	20–30 (lim. 40 for operations, lim. 60 for construction)			5×10^{-5} $(<5 \times 10^{-5})$	2×10^{-5} $(<5 \times 10^{-5})$	4×10^{-6} $(<3 \times 10^{-5})$		α: $-(<2 \times 10^{-7})$ β: 6×10^{-5} $(<3 \times 10^{-4})$ H-3: $<1 \times 10^{-4}$ Zn-65: 9×10^{-6} $(<1 \times 10^{-4})$	Filters, ion exchange	None
36	SiO$_2$: 50–300 ppb Cu: 0.01–3 ppb	20–30 (lim. 40 for operations, lim. 60 for construction)			8×10^{-6} $(<5 \times 10^{-6})$	— $(<2 \times 10^{-5})$	9×10^{-6} $(<3 \times 10^{-4})$		β: 1×10^{-5} $(<2 \times 10^{-4})$ Zn-65: 6×10^{-5} $(<5 \times 10^{-4})$	Filters, ion exchange	None
37	SiO$_2$: 200 ppb	25–30 (max. calc. temp. for full core load: 55)					$(5-30) \times 10^{-6}$ Co-58: $(0.2-10) \times 10^{-6}$	$(0.2-5) \times 10^{-6}$	$(5-100) \times 10^{-6}$ Zn-65: $(0.2-5) \times 10^{-6}$ Sb-124: $(0.5-20) \times 10^{-6}$ Sb-125: $(1-5) \times 10^{-6}$ Ag-110m: $(0.2-2) \times 10^{-6}$	Filters, ion exchange	None
38	SiO$_2$: 200 ppb	25–30 (max. calc. temp. for full core load: 55)					$(5-30) \times 10^{-6}$ Co-58: $(0.2-10) \times 10^{-6}$	$(0.2-5) \times 10^{-6}$	$(5-100) \times 10^{-6}$ Zn-65: $(0.2-5) \times 10^{-6}$ Sb-126: $(0.5-20) \times 10^{-6}$ Sb-125: $(1-5) \times 10^{-6}$ Ag-110m: $(0.2-2) \times 10^{-6}$	Filters, ion exchange	None

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
39	Ringhals-1 SE BWR	1976	6/1977 for re-racking 4/1978 and 12/1978 modification	No	10.5 × 6.4 × 14 (940 m³) 2 pools of same dimensions	5.5–8.6	1.0 (<5)		
40	Ringhals-2 SE PWR	1977	No	No	8.0 × 6.5 × 12 (615 m³) 2 pools of same dimensions	4.8 (4.6–4.9)	7.3 (7.0–7.7)	1990 (1990–2050)	3 ppb (<1–5 ppb)
41	Winfrith GB SGHWR	5/1968	No	Some modification of racks	23.8 × 4.9 × 10.6 (1240 m³)	5.7 ± 0.2 (5–6)	<5 (1.5–4)		1
42	Arkansas-1 US PWR	4/1976	1976 installation of racks	1977 re-racking	13.4 × 7.0 × 12.8 (1088 m³)	5.4 (4.7–7.7)	20 (6.7–104)	1800 (1863–2490)	
44–45	Browns Ferry 1–2 US BWR	1: 10/1977 2: 3/1978	No	No	2 pools, each 12.2 × 10.8 × 11.5 (1453 m³)	6.0–7.5	<10		
46	Indian Point-1 US BWR	10/1965			2 pools 11 × 5.5 × 12 12 × 5.5 × 12			2000	
47	Indian Point-2 US PWR	4/1976	No	4/1976 re-racking	~10 × 10 × 12 (1090 m³)	5.3–5.5		>2000	

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m³)						Total activity (Ci/m³)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
39	Na: <0.01 ppm Cl⁻: <0.01 ppm (lim. <0.5 ppm) SiO_2: 0.015 ppm (lim. <2.0 ppm) Ca: 0.002 ppm Fe: 0.002 ppm Cu: 0.001 ppm Zn: 0.001 ppm	23–25 (lim. 55)		3.5×10^{-7} to 2.3×10^{-3}	1.9×10^{-6} to 1.0×10^{-4}	4.1×10^{-7} to 3.0×10^{-4}	8.4×10^{-7} to 1.9×10^{-4} Co-58: 1.6×10^{-7} to 4.3×10^{-5}		Zn-65: 1.0×10^{-7} to 2.2×10^{-3} Sb-124: 1.2×10^{-7} to 7.6×10^{-5}	Filters	None
40	Na: 10 ppb (<1–20 ppb) Cl⁻: <100 ppb (<100–150 ppb) lim. 150 ppb F: <20 ppb (<150 ppb)	20 (lim. 51.5)		3.2×10^{-6} to 2.6×10^{-5}	2.1×10^{-6} to 2.3×10^{-5}	9.5×10^{-8} to 2.4×10^{-5}	7.6×10^{-6} to 8.4×10^{-4} Co-58: 4.1×10^{-6} to 2.0×10^{-3}	·	Zn-65: 3.0×10^{-6} to 1.1×10^{-5} Sb-124: 1.6×10^{-7} to 2.7×10^{-4}	Filters, ion exchange	None
41	Cl⁻: <250 ppb (50–400 ppb) SiO_2: <4000 ppb (1000–4000 ppb)	40 (28–52) (lim. 52)		$<1 \times 10^{-4}$ $((1-10) \times 10^{-4})$	1×10^{-4} $(2 \times 10^{-5}$ to $4 \times 10^{-4})$	5×10^{-6} $(2 \times 10^{-6}$ to $5 \times 10^{-5})$	1×10^{-5} $((1-2) \times 10^{-5})$ Co-58: 1×10^{-6} $((1-2) \times 10^{-6})$	1×10^{-6} $((1-6) \times 10^{-6})$	Fe-59: 1×10^{-6} $((1-3) \times 10^{-6})$ Zn-65: 3×10^{-6} $((1-12) \times 10^{-6})$ Cr-51: 3×10^{-6} $((1-10) \times 10^{-6})$	Filters, ion exchange	
42	TDS: 0.05 ppm (0.01–0.5 ppm) Cl⁻: 0.1 ppm (0.01–7.25 ppm) F⁻: 0.01 ppm (0.01–0.1 ppm)	37 (23–45) (lim. 93) (design: lim. 121)								Filters, ion exchange	None
44–45	Cu, Ni, Fe, Mg } <0.1 ppm Cl⁻: <0.5 ppm	52 (lim. 65.5)							$10^{-4}-10^{-3}$ Mainly Cs-137 and Cs-134, Sr-89 and Sr-90	Filters, ion exchange	None
46		21–27 (lim. 60)			6.7×10^{-2}	8.7×10^{-3}	5.3×10^{-3}	5.4×10^{-4}		Filters, ion exchange	Yes, removed with filters
47	Cl⁻: <0.05 ppm F⁻: <0.05 ppm	<60			8×10^{-4}	6×10^{-4}	1×10^{-3} Co-58: 3×10^{-2}	1×10^{-4}		Ion exchange	

108

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
49–51	Oconee 1–3 US PWR	1/2: 10/1974 3: 10/1976	1/2: no 3: for re-racking	1/2: re-racking 1979 3: re-racking 1976	1/2: 25.7 × 7 × 11.6 (2087 m³) 3: 17.7 × 7 × 11.6 (1437 m³)	5 (4.5–6)		2712 (2300–2800)	
52–53	Point Beach 1–2 US PWR	9/1972	No	1975, 1979, 1980: re-racking	20.7 × 5.6 (1240 m³)	4.8 (4.7–4.9)	7.7	2135 (2060–2240) (ljm. 1800)	
54	La Crosse US BWR	12/1968	11/1969 leak repair 10/1970 leak repair 8/1971 leak repair	12/1976 new racks	3.4 × 3.4 × 12.6 (142 m³)	6.2 (5–6.7)	0.5 (0.3–2.1)	None	None
55	Beaver Valley. US PWR	No spent fuel stored yet	1975 tested and then drained	Spring 1979: unit-1 pool re-racked	2 pools, each 1728 m³			2000	
56	Duane Arnold US BWR	6/1975	No	1979 re-racking	12.2 × 6.1 × 11.9 (884 m³)	6.2 (5.1–7.2)	0.9 (0.7–1.5)		
57	Vermont Yankee US BWR	9/1971	No	3/1978 re-racking	12 × 7.9 × 11.9 (1120 m³)	6.2 (5.9–6.2) (lim. 5.8–8.0)	0.7 (<1)		
58	Yankee Rowe US PWR	5/1962	1967 refinish of concrete walls 1969 idem 1971 repair of fuel handling mechanism 1970 routine	1977 re-racking 1979 SS liner installation	10.3 × 5 × 10.9 (558 m³)	6.4 (5.5–7) (lim. 4.5–10.5)	24 (3–50)	800 (0–800)	

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m³)						Total activity (Ci/m³)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
49–51	Cl⁻: 0.1 ppm (0.05–0.42 ppm) F⁻: <0.05 ppm (<0.05–0.01 ppm) Turbidity: 0.15 JTU (0.06–0.6) TDS: <10 ppb (<10–10 ppb)	20 (15–52) (lim. 65.6)							γ: 3.3 × 10⁻³ (7.6 × 10⁻⁴ to 9.2 × 10⁻²) H-3: 0.1 (0.03–1.8)	Filters, ion exchange	None
52–53	Cl⁻: <0.05 ppm (<0.05–0.06 ppm) (lim. 0.15) F⁻: <0.02 (0.02–0.025) (lim. 0.15)	24–27 (lim. 49)	2.8 × 10⁻¹³	2.6 × 10⁻¹¹	2.5 ×10⁻¹¹		1.7 × 10⁻⁹ Co-58: 1.1 × 10⁻⁹	1.7 × 10⁻¹¹	β,γ: 1.2 × 10⁻³ (5.0 × 10⁻⁴ to 3.2 × 10⁻³) H-3: 2.1 × 10⁻¹ γ: 3.0 × 10⁻³ (2.0 × 10⁻³ to 4.8 × 10⁻³)	Filters, ion exchange	None
54		21 (8–31) (lim. 65.5)			3 × 10⁻⁵	1 × 10⁻⁴	4 × 10⁻⁵		3.2 × 10⁻³ (1.1 × 10⁻⁴ to 1.5 × 10⁻²) α: 2.1 × 10⁻⁷ (<0.4 × 10⁻⁷ to 5.6 × 10⁻⁶)	Filters, ion exchange	None
55		52 (21–60) (lim. 63)									None
56	SiO₂: 74 ppb (4–174) Turbidity: 0.4 JTU (0.1–1.5)	30 (20–65) (lim. 65)								Filters, ion exchange (includes operating instructions for pool and cleaning system)	None
57	Cl⁻: 50 ppb (lim. 500 ppb) SiO₂: 200 ppb (lim. 1000 ppb)	38 (lim. 52)			2.3 × 10⁻⁴	1.5 × 10⁻⁴	5.7 × 10⁻⁴	4.9 × 10⁻⁵	1.2 × 10⁻³ Total water activity: 1.06 Ci Zn-65: 2.0 × 10⁻⁴ α: 1.6 × 10⁻⁸	Filters, ion exchange	None
58	Cl⁻: <0.15 ppm (0–2) (lim. 0.15)	27–32		1 × 10⁻⁶ (1 × 10⁻⁶ to 2 × 10⁻⁴)	4 × 10⁻⁴ (2 × 10⁻⁵ to 3 × 10⁻³) Cs-139: 4 × 10⁻⁴ (2 × 10⁻⁵ to 3 × 10⁻³)		Co-58, 60: 6 × 10⁻⁶ (6 × 10⁻⁶ to 1 × 10⁻⁴)		α: 5 × 10⁻⁸ H-3: 3 × 10⁻³	Filters, ion exchange	None

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
59	Fort Calhoun US PWR	3/1975	No	1979 new racks	10.8 × 6.8 × 14.1 (814 m³)	4.5	0.2	2103	None
60	J.M. Farley US PWR	2/1979	No	No	13.5 × 8.2 × 12.2 (1361 m³)			2000–2200	
61	Davis-Besse US PWR				16.2 × 6.1 × 12.0	4.5–4.6		>1800	
62	H.B. Robinson-2 US PWR	3/1973	No	1975 new racks added	10.2 × 9.5 × 11.7 (1128 m³)			2238 (2050–3000)	
63	Brunswick-1 US BWR	10/1977	1977 for re-racking	1978 new racks	14 × 8.5 × 11.8 (1218 m³)	6.8 (5.2–8.0)	0.9 (0.7–6.3)		
64	Brunswick-2 US BWR	9/1977	1978 for re-racking	1978 new racks	14 × 8.5 × 11.8 (1218 m³)	6.7 (5.3–8.1)	0.8 (0.5–8.6)		
65–66	D.C. Cook 1–2 US PWR	1/1977	No	No	17.8 × 12 × 13.4 (3000 m³)	4.0–4.7		2000	
67	Trojan US PWR	3/1978	No	1979 re-racking	12 × 8.8 × 12.2 (1470 m³)	4.5 (4.0–4.7)	7.0 (1.0–40)	2150 (>2000)	
69–70	Surry 1–2 US PWR	10/1974	No	4/1978 re-racking	22 × 7.5 × 11.7 (2102 m³)			2000	
71	Prairie Island-1 US PWR	3/1976	No		(1) 5.8 × 5.6 × 12.7 (404 m³) (2) 13.2 × 5.8 × 12.7 (964 m³)			2000–4000	

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54	Total activity (Ci/m³)	Chemistry control	Biological growth
					Radioactive species (Ci/m³)						
59		38–48 (lim. 60)			5.7×10^{-4}	3.7×10^{-3}	1.0×10^{-4} Co-58: 4.1×10^{-4}		9.9×10^{-3}	Filters, ion exchange	None
60	Cl⁻ F⁻ } <0.15 ppm Ca Mg } <1.0 ppm	43 (lim. 54)							1.1×10^{-2} mainly Co-60 and Co-58 (>70% of total)	Filters, ion exchange	None
61	Chlorides: <0.15 ppm Fluorides: <0.15 ppm TDS: <1 ppm	38								Filters, ion exchange, surface skimmers	
62	Cl⁻: 0.03 ppm (lim. 0.15 ppm)	22–48 (lim. 60)					1.7×10^{-3} Co-58: 3.9×10^{-3}		α: 0 H-3: 7.5×10^{-3} Total: 6.9×10^{-5}	Filters, ion exchange	None
63	Cl⁻: <50 ppb	34 (32–38) (lim. 51)							β: 5.8×10^{-3} (1.1×10^{-5} to 2.8×10^{-2})	Filters, ion exchange	None
64	Cl⁻: <50 ppm	34 (32–38) (lim. 51)							β: 1.3×10^{-3} (6.3×10^{-6} to 1.6×10^{-3})	Filters, ion exchange	None
65–66	Cl⁻ F⁻ } <0.15 ppm	32 (21–49) (lim. 66)							0.001	Filters, ion exchange	None
67		27 (lim. 60)			1.5×10^{-6}		2.5×10^{-4} Co-58: 4.2×10^{-5} Co-57: 3.9×10^{-6}	2.3×10^{-6}	γ: 3×10^{-4} β: 7.7×10^{-5} H-3: 7×10^{-3}	Filters, ion exchange	None
69–70	Cl⁻ F⁻ } <0.15 ppm	35 (21–46) (lim. 77)	0 ($(0-6.5) \times 10^{-5}$)	$10^{-4} - 10^{-5}$ ($(0-1.3) \times 10^{-4}$)	0 ($(0-1.2) \times 10^{-4}$)		$10^{-4} - 10^{-3}$ (4.8×10^{-4} to 1.1×10^{-3}) Co-58: $10^{-4} - 10^{-3}$ (6.6×10^{-4} to 1.5×10^{-3})		$10^{-5} - 10^{-3}$ (5.0×10^{-5} to 1.1×10^{-3})	Filters, ion exchange	None
71	Cl⁻: <0.15 ppm F⁻: <0.15 ppm Ca: <0.1 ppm Mg: <0.1 ppm	43–46 (lim. 49)			1.9×10^{-4}	3.3×10^{-4}	2.2×10^{-3} Co-58: 2.3×10^{-3} Co-57: 4.7×10^{-5}		1.7×10^{-3} Sb-124: 2.2×10^{-4} Na-24: 4.0×10^{-5}	Filters, ion exchange	None

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
72	Monticello US BWR	3/1973	No		12 × 7.8 × 12 (1147 m³)	7.0 (6.4–7.9) (lim. 6.0–8.0)	0.8 0.69–0.88 (lim. 1)		
73	Salem US PWR	4/1979	No	No	11.3 × 8.7 × 13.1 (1170 m³)	4.8–6.5		2000	
74	Peach Bottom-2 US BWR	11/1975	No	1979 re-racking	12.2 × 10.8 × 11.5 (1515 m³)	5.6	0.9		
75	Peach Bottom-3 US BWR	1/1976	No	1979 re-racking	12.2 × 10.8 × 11.5 (1515 m³)	5.5	1.0		
76	Hatch-1 US BWR	11/1975	No	1980 re-racking	14.1 × 7.6 × 11.7 (1100 m³)	7–8	0.5–1		
78	Maine Yankee US PWR	7/1974	No	Re-racking	12.6 × 11.3 × 11.1 (1585 m³)	5 (4.5–6)	7 (5–10)	1800 (1720–1850) (lim. 1720)	
79–80	Zion 1–2 US PWR	6/1973	No	Re-racking	18.3 × 10.1 × 12.2 (2132 m³)	4.0–8.0		2000–4000	0.2–2.2
81	Dresden-1 US BWR	11/1962	1966 cleaning of walls and floor	No	11.6 × 9.8 × 12.2 (1343 m³)	6–7.5	<1		
82	Dresden-2 US BWR	4/1970	No	New racks added	12.4 × 10.1 × 12.1 (1502 m³)	6–7.5	<1		
83	Dresden-3 US BWR	7/1971	No	New racks added	12.5 × 10.1 × 12.2 (1502 m³)	6–7.5	<1		
84–85	Quad Cities 1-2 US BWR	1: 4/1972 2: 5/1972	No	No	2 pools 12.5 × 10.1 × 12.2 (1502 m³)	6–7.5	<1		

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m³)						Total activity (Ci/m³)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
72	Cl⁻: <20 ppb (<500 ppb) SiO₂: 100 ppb (<100−160 ppb) (lim. 1000 ppb) TDS: <10 ppb (<10−25 ppb) (lim. 1000 ppb)	32 (lim 52)			7.5×10^{-4}	1.9×10^{-4}	4.9×10^{-4}	4×10^{-5}	Zn-65: 8.4×10^{-5}	Filters, ion exchange	None
73		32−43								Filters, ion exchange	None
74	Turbidity 0.7 JTU Cl⁻: <20 ppb SiO₂: 110 ppb	24 (20−27) (lim. 65)							γ: 1.1×10^{-4} H-3: 1.3×10^{-3}	Filters, ion exchange	None
75	Turbidity 0.13 JTU Cl⁻: <20 ppb SiO₂: 160 ppb	24 (20−27) (lim. 65)							γ: 3.26×10^{-4} H-3: 1.27×10^{-3}	Filters, ion exchange	None
76		42 (38−47) (lim. 66)			3.9×10^{-5}	5.1×10^{-1}	2.5×10^{-1} Co-58: 1.1	5.2×10^{-6}	1.9 Zn-65: 5.6×10^{-2} α: 9×10^{-3}	Filters, ion exchange	None
78		22 (20−25) (lim. 68)			5.1×10^{-3}	1.6×10^{-3}	Co-58: 5.1×10^{-3}		$(1.5-2.5) \times 10^{-2}$	Filters, ion exchange	None
79−80		35							β, γ: 1×10^{-3} Mainly Co-58, Co-60, Cs-137, Cs-134	Filters, ion exchange	None
81	Cl⁻: <0.5 ppm SiO₂: <1 ppm Turbidity: <1 JTU	35							α: $<1 \times 10^{-5}$ β: $<1 \times 10^{-2}$	Ion exchange	None
82	Cl⁻: <0.5 ppm SiO₂: <1 ppm Turbidity: <1 JTU	35							β, γ: $<1 \times 10^{-5}$ α: $<1 \times 10^{-5}$ Mainly Co-58, Co-60, Cs-134, Cs-137	Ion exchange	None
83	Cl⁻: <0.5 ppm SiO₂: <1 ppm Turbidity: <1 JTU	35							β, γ: $<1 \times 10^{-2}$ α: $<1 \times 10^{-5}$ Mainly Co-58, Co-60, Cs-134, Cs-137	Ion exchange	None
84−85	Cl⁻: <0.5 ppm SiO₂: <1 ppm Turbidity: <1 JTU	35							β, γ: $<1 \times 10^{-2}$ α: $<1 \times 10^{-5}$	Ion exchange	None

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
86	Palisades US PWR	1974	No	No	11.5 × 4.2 × 11.6 (550 m³) 6.2 × 1.3 × 11.6 (92 m³)	4.5–7.0	5–15	1820–2500	
87	Big Rock Point US BWR	1963	1974 for liner installation	No	7.6 × 6.1 × 8.8 (370 m³)	6.5 (6–7)	5 (2–13)		
88	Millstone-1 US BWR	9/1972	No	1976 re-racking 1978 re-racking	12.3 × 9.3 × 11.9 (1314 m³)	5.5–8.5	0.6–0.8 (<3)	None	None
89	Millstone-2 US PWR	11/1977	No	1977 re-racking	12.8 × 7.6 × 12.5 (1145 m³)	4.8–5.8	4–7	>1720 <2046	
90	Haddam Neck (Conn. Yankee) US PWR	2/1970	No	1975 re-racking 1978 re-racking	11.3 × 11 × 10.2 (1200 m³)	4.2–4.8	0.6–0.7	2300–2500	
91	Kewaunee US PWR	2/1976	No	4/1979 re-racking	5.8 × 5.2 × 12.3 (371 m³) 9.9 × 5.8 × 12.3 (706 m³)			2100–2200	
92	Cooper US BWR	10/1975	No	1978 new racks	8.5 × 12.2 × 11.8 (1231 m³)	6.4 (5.5–7.6) (lim. 5.5–8.5)	1.0 0.8–2.5 (lim. 5)		
93	Pilgrim US BWR	1/1972	Yes, before operation for leak check	1980 re-racking	12 × 9 × 12 (1300 m³)	6	8.5		
94	San Onofre-1 US PWR	10/1970	No	No	15.9 × 6.4 × 11.8 (1200 m³)			3100–3200 (lim. 2925)	
99	Atucha-1 AR PHWR	9/1974	No	Increased from 1762 to 3240 units by rack re-design	2 pools: 8 × 5.3 × 15.8 1 pool: 12 × 4.2 × 15.8 (total vol.: 2150 m³)	6.4–7.3	2.7–5.1	None	<0.01
201	NRX CA RR	5/1948	(1) 1959 to modify water system, put stainless steel on walls (2) Partial drainages for cleaning and maintenance	6/1979: Inspection bay and storage bay drained for installation of door between the two 1961: Monel lining	Originally: 505 m², 2065 m³ After 1959 changes: 137 m², 478 m³	6.2 (6.0–7.4)	4.0	<0.01	<0.01

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54	Total activity (Ci/m³)	Chemistry control	Biological growth
86	Na: 0–5 ppm	30 (27–38) (lim. 66)							5×10^{-5} (1×10^{-6} to 1×10^{-3})	Filters, ion exchange	None
87	Turbidity = 0 (0–1)	20 (16–26) (lim. 27)		Total iodine: 1×10^{-6}	6.1×10^{-3}	1.5×10^{-3}	1×10^{-6} Co-58: 1.3×10^{-5}	4.2×10^{-4}	10^{-5} (10^{-6} to 10^{-3}) Zn-65: 1.1×10^{-4}; Sb-124: 1.2×10^{-3}; Ba-141: 4.6×10^{-4}	Filters	None
88		38–52 (lim. 60)							2×10^{-4} to 2×10^{-2}		None
89		34 (lim. 65.5)							2×10^{-3} to 8×10^{-3}		None
90		41 (lim. 60)							10^{-3} to 10^{-1}		None
91		26–44							1×10^{-1} to 1×10^{-3} Mainly Co and Cs α: $\leqslant 1 \times 10^{-7}$	Filters, ion exchange	None
92	Cl⁻: <30 ppb (<500 ppb) SiO₂: 108 ppb (50–225 ppb) (<1000 ppb) Turbidity: 0.05–0.58 FTU (<0.2 FTU)	32 ± 12 (lim. 66)		4.2×10^{-6}	1.6×10^{-4} Cs-136: 3.3×10^{-4}	1.8×10^{-4}	9.5×10^{-5} Co-58: 2.0×10^{-5}	2.6×10^{-5}	$<1 \times 10^{-9}$ α: $\leqslant 1.1 \times 10^{-7}$ Zn-65: 8.9×10^{-6}	Filters, ion exchange	None
93	Cl⁻: <100 ppb SiO₂: 0–900 ppb TDS: 10–75 ppb	22 (21–28) (lim. 35)			1×10^{-4}	3×10^{-5}	1.5×10^{-5}		2×10^{-4}		None
94	Cl⁻: <0.15	~27 (lim. ~49)							5×10^{-4}	Surface skimmer, filters	None
99	SiO₂: 0.1–0.4 ppm	45		5×10^{-6}	5×10^{-5}	1×10^{-5}	6×10^{-5}	3.5×10^{-4}		Filters, ion exchange	None
201		28 (27.8–28.9)			4.6×10^{-4}	1.5×10^{-4}	7×10^{-6}		6.2×10^{-4} Total pool water activity: 0.3 Ci α: 4×10^{-4} Ci	Filters, ion exchange	Algae growth reduced by installation of ion-exchange system

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
202	NRU CA RR	4/1958	No	1964: re-racking for enriched rods	150 m² 987 m³	6	4.4		
203	WR-1 CA RR	7/1966	1969: repair of leak and installation of racks 1970: modification for shipping cask 1971: paint replaced by epoxy paint	Partial re-racking	275 m³	7.0	4–6		
204	JEN-1 ES RR	11/1959	Every year until 1969 repainting	1969: Stainless steel liner installation	5.7 × 3.7 × 9 (175 m³)	6	0.5		
205	JRR-2 JP RR	1961	1977 for repainting	No	4 × 2.5 × 6.6	5.5 - 6.5	1.6	None	None
206	JRR-3 JP RR	1961	1965 for rearrangement	No	11 × 5.5 × 7.4	5.5–6.5	1.6	None	None
207	HFR NL RR	1961	No	No	5 × 2.5 × 8	6–7	<1		
208	Halden NO RR	1959	1963/65 to install racks	1965 new racks installed		6.5	2–3		
209	Ågesta SE PWR	12/1973	No	No	2 circular pools 3.8 dia. × 8.2 (85 m³)	7–7.5	50		

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m³)						Total activity (Ci/m³)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
202		17							1.3 Total pool water activity: 1300 Ci H-3: 1.3 α: 9 × 10⁻⁴ Ci	Filters, ion exchange	Algae growth *reduced by* installation of ion-exchange system
203		20 (19–22) (lim. 18–26)							Since fuel rods are placed in cans with organic coolant, no radioactivity	Filters, ion exchange	Only when temp. was raised to 32°C, algae growth occurred, eliminated by cooling to 10°C and shutting off lights
204		24 (12–34)								Filtration, ion exchange	Biological growth during summer shut-down; eliminated by H_2O addition; operation eliminated growth
205		25–30 (lim. 30)					1.1×10^{-5}			Ion exchange	Some (cleaning by draining and re-painting)
206		10–25 (lim. 30)					1.1×10^{-4}			Ion exchange	Some cleaned by vacuum
207		30 ± 10							β, γ: $(0.8–5) \times 10^{-3}$ α: $<0.5 \times 10^{-6}$	Filters, ion exchange	Minor algae growth; no corrective measures
208	Cl⁻: <determination limit	20 (17–21)			$\sim 10^{-4}$	$\sim 10^{-5}$				Filters, ion exchange	None
209		26–28							Pool A, total: α: 10^{-7} β: 1.5×10^{-5} H-3: 3×10^{-7} (mostly Co-60) Pool B, total: α: 10^{-7} β: 5×10^{-5} H-3: 3×10^{-7}	Ion exchange	None

| Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
210	HFBR US RR	4/1966	No	No	13.1 × 2.4 × 6.1 side-pool: 3.1 × 2.4 × 6.1 (257.5 m^3)	6–7	~0.5		
211	ETR US RR					~6			
212	ATR US RR	1967							
213	MTR US RR	1951				5.5–6	<10		
214	CP-5 US RR	1961	No	No	6.1 × 2.4 × 7.3 (109 m^3)	~7.0	~0.3		
301	Eurochemic BE AFR	1/1965	Yes, before commissioning, to repair cracks	New liner from 'Antiporporan', reinforced with glass fibre plus 0.2 mm of lead	24 × 9 × 8.5 (1600 m^3)	6.5	100–150	None	None
303	La Hague FR AFR	1975							
304	Eurex IT AFR	3/1965	No	Holding arms for TREFOIL-shaped baskets were dismantled to leave room for the TRINO containers	16.6 × 7.4 × 7.6 (700 m^3)	5.5–7.5	10	None	None
305	Itrec IT AFR	12/1968	No		Parallelepiped 10 × 3 × 7	6.2–9	3.5×10^{-5} – 1.1×10^{-1}		0.9–2.5

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m³)						Total activity (Ci/m³)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
210		38 (30–40)					3×10^{-6} (3×10^{-7} to 3×10^{-5})		β: 5×10^{-5} α: $<1.5 \times 10^{-7}$ H-3: 3×10^{-2} Cr-51: 5×10^{-5} (5×10^{-6} to 5×10^{-4}) Zn-65: 2×10^{-6} (2×10^{-7} to 2×10^{-5})	Ion exchange	Yes, but only minor
211		Ambient								Plan to install ion exchange	UV sterilization
212	200 ppm TDS	~16								Surface skimmer, filters, ion exchange	No, UV sterilization system
213	CO_2 and HNO_3 added to deionized water	~21								Ion exchange	
214		~20 (10–37) (lim. 7–45)								Filters, ion exchange	Yes, but removal control
301		No cooling provided; max. value recorded: 35							β: 10^{-4}–10^{-3} α: 10^{-6}–10^{-5} peak β: 10^{-3}–10^{-2}	Filters, ion exchange	Some when water treatment system not in operation
303									10^{-4}	Ion exchange	
304	Ce: <0.5 ppm	17 ± 2							10^{-4} (10^{-5}–10^{-3}) α: 10^{-8} (10^{-8}–10^{-7})	Filters, ion exchange	Slow phenomena of biol. growth at the bottom of the pool
305	Cl: 0.5–5 ppm Mg: 9.8×10^{-4} to 1.0×10^{-2} ppm Ca: 9.2×10^{-3} to 1.6×10^{-1} ppm	Winter: 20 Summer: 25								Filters, ion exchange	None

Unit No.	Stations country, Facility type	Date of first storage	Pool drained, when/why	Other operations	Pool dimensions (m)	pH	Conductivity (μS/cm)	Boron (ppm)	Li (ppm)
306	Windscale GB AFR	1967	No	All water reactor fuel containerized	Storage bays 1–4: 76 × 18 × 7.3 (9800 m³)	5–8		1	
307	Morris US AFR	1/1972	No	1975 re-racking	2500 m³	5.8 (5.6–5.9)	1.1 (1.0–1.6)	0.9 (0.8–1.0)	None
308	FRSF US AFR	1951 or 1952			5700 m³	4–6			

Unit No.	Additional analytical data	Pool temp. range, limit (°C)	Radioactive species (Ci/m³)						Total activity (Ci/m³)	Chemistry control	Biological growth
			Xe-133	I-131	Cs-137	Cs-134	Co-60	Mn-54			
306	Cl^-: <1 ppm SO_4: <1 ppm	10–25 (lim. 40)			$(0.5-1) \times 10^{-3}$		$(0.75-1) \times 10^{-4}$		α: <6 × 10⁻⁴ β: (0.5–1.5) × 10⁻³	Deionized water discharged to sea	Some at water surface and wall interface; scrubbing with brush
307	Cl^-: <0.1 ppm $NaNO_3$: <0.8 ppm	28 (25–47)			1.5×10^{-4} $((0.8-9.0) \times 10^{-4})$	2.5×10^{-5} $((0.14-1.4) \times 10^{-4})$	1.5×10^{-4} $((0.1-2.0) \times 10^{-3})$		β: 2.3 × 10⁻⁴ ((0.2–3.0) × 10⁻³) α: <3 × 10⁻⁷	Filters, ion exchange	Before 1973, when nitrate values were much higher than at present
308	TDS: ~⅓ of max. will further reduce: 300 → 50	24							<0.3	Ion exchange	Yes; previously *calcium-hypo-chlorite*, now UV and filter

SUMMARY OF LONGEST RESIDENCE TIME OF SPENT FUEL
IN SPECIFIC STORAGE POOLS
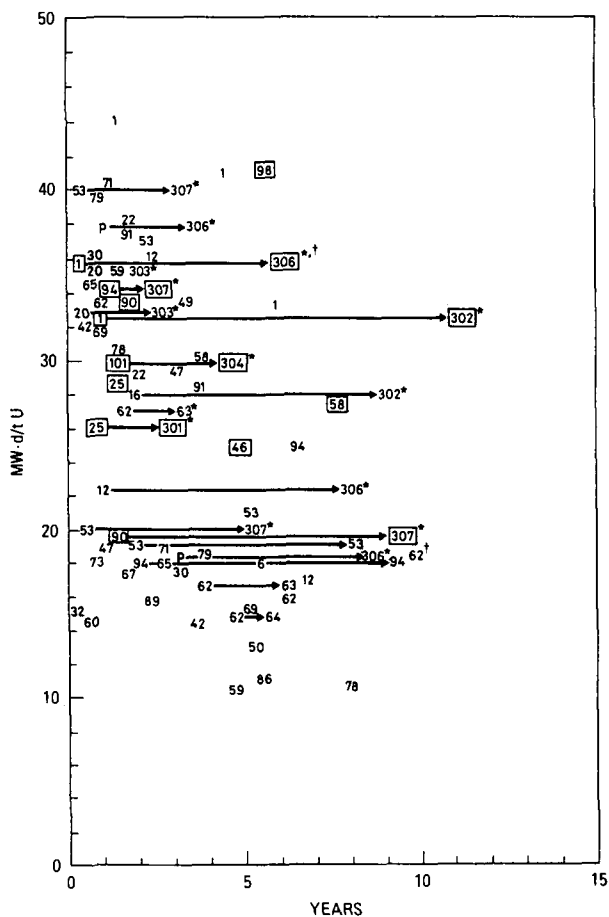
1	BE	BR-3
12	CH	Beznau-1
16	DE	Obrigheim (KWO)
20	DE	Stade (KKS)
22	ES	José Cabrera
25	FR	Ardennes (Chooz)
30	JP	Genkai-1
32	KR	KO-RI-1
42	US	Arkansas-1
46	US	Indian Point 1 (SS)
47	US	Indian Point 2
49	US	Oconee-1
50	US	Oconee-2
53	US	Point Beach 2
58	US	Yankee Rowe
59	US	Fort Calhoun
60	US	J.M. Farley
62	US	H.B. Robinson-2
63	US	Brunswick-1
64	US	Brunswick-2
65	US	D.C. Cook
67	US	Trojan
69	US	Surry-1
71	US	Prairie Island
73	US	Salem
78	US	Maine Yankee
79	US	Zion-1
86	US	Palisades
89	US	Millstone-2
90	US	Haddam Neck (SS) (Connecticut Yankee)
91	US	Kewaunee
94	US	San Onofre 1 (SS)
98	US	Shippingport (Zry-2)
101	IT	Trino Vercellese
301	BE	Eurochemic
302	DE	WAK
303	FR	La Hague
304	IT	Eurex
306	GB	Windscale
307	US	G.E. Morris
p		proprietary

*FIG. E-1. Average assembly burn-up of spent PWR fuel versus pool residence time. The numbers indicate at-reactor (AR) pools, except for those marked by * which are for away-from-reactor (AFR) pools; † indicates AFR storage in canisters. A square around the number indicates unconventional fuel cladding.*
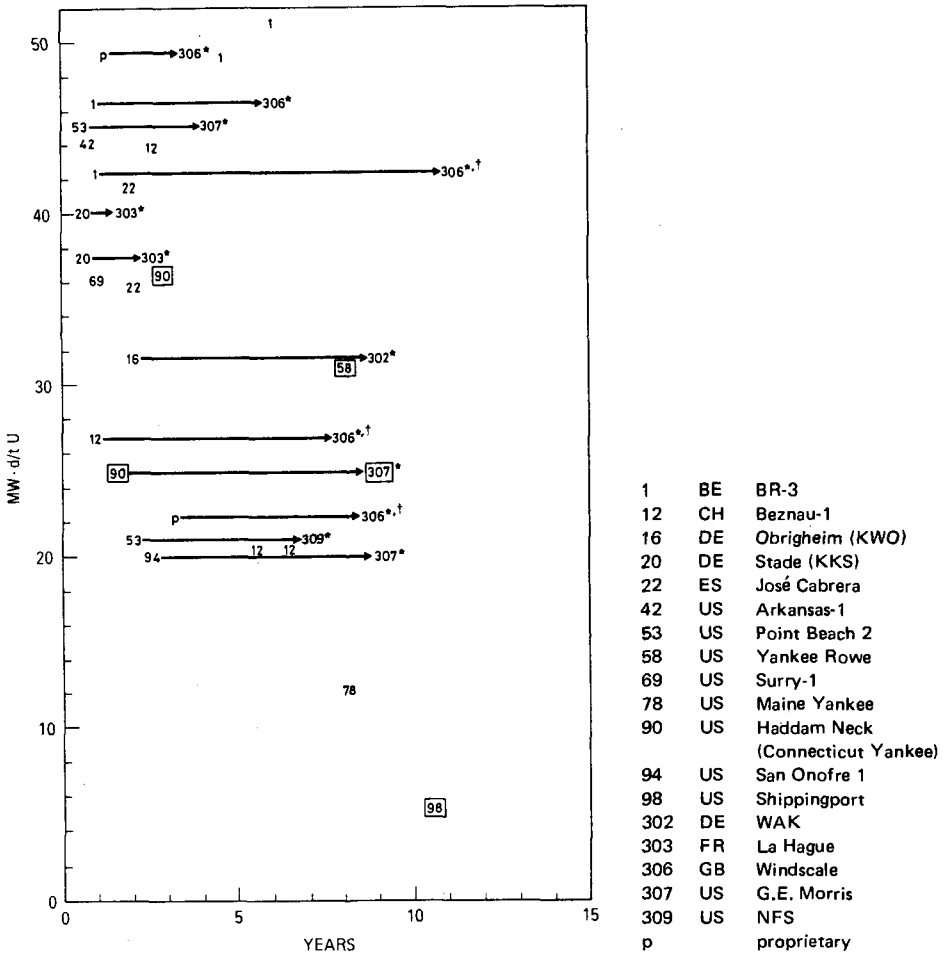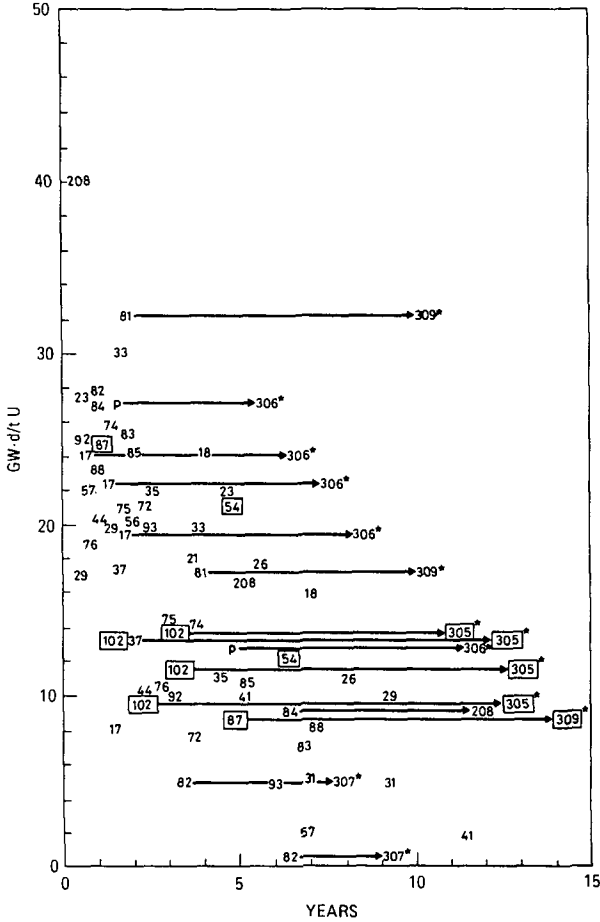
122

FIG.E-2. *Peak pellet burn-up of spent PWR fuel versus pool residence time. The numbers indicate AR pools, except for those marked by * which are for AFR pools;* † *indicates AFR storage in canisters. A square around the number indicates unconventional fuel cladding.*

17	DE	Brunsbüttel (KKB)
18	DE	Lingen (KWL)
21	DE	Kahl (VAK)
23	ES	Santa Maria de Garoña
26	IN	Tarapur-1
29	JP	Fukushima-1
31	JP	JPDR
33	NL	Dodewaard
35	SE	Oskarshamn-1
37	SE	Barsebaeck-1
41	GB	Winfrith SGHWR
44	US	Browns Ferry 1
54	US	La Crosse
56	US	Duane Arnold
57	US	Vermont Yankee
64	US	Brunswick-2
72	US	Monticello
74	US	Peach Bottom 2
75	US	Peach Bottom 3
76	US	Hatch-1
81	US	Dresden-1
82	US	Dresden-2
83	US	Dresden-3
84	US	Quad Cities 1
85	US	Quad Cities 2
87	US	Big Rock Point (Zry-2 + SS + ZrNb)
88	US	Millstone-1
92	US	Cooper
93	US	Pilgrim
102	US	Elk River (SS)
208	NO	Halden
305	IT	Itrec
306	GB	Windscale
307	US	G.E. Morris
309	US	NFS
p		proprietary

FIG.E-3. Average assembly burn-up of spent BWR fuel versus pool residence time. The numbers indicate AR pools, except for those marked by * which are for AFR pools; † indicates AFR storage in canisters. A square around the number indicates unconventional fuel cladding.

124

GW·d/t U

50

-208

40
33

81 →309*
p →306*
82

30
33
23

37

20
37
81 →309*
p →306*

41

10
87 208 →309*

41

0
0   5   10   15
YEARS

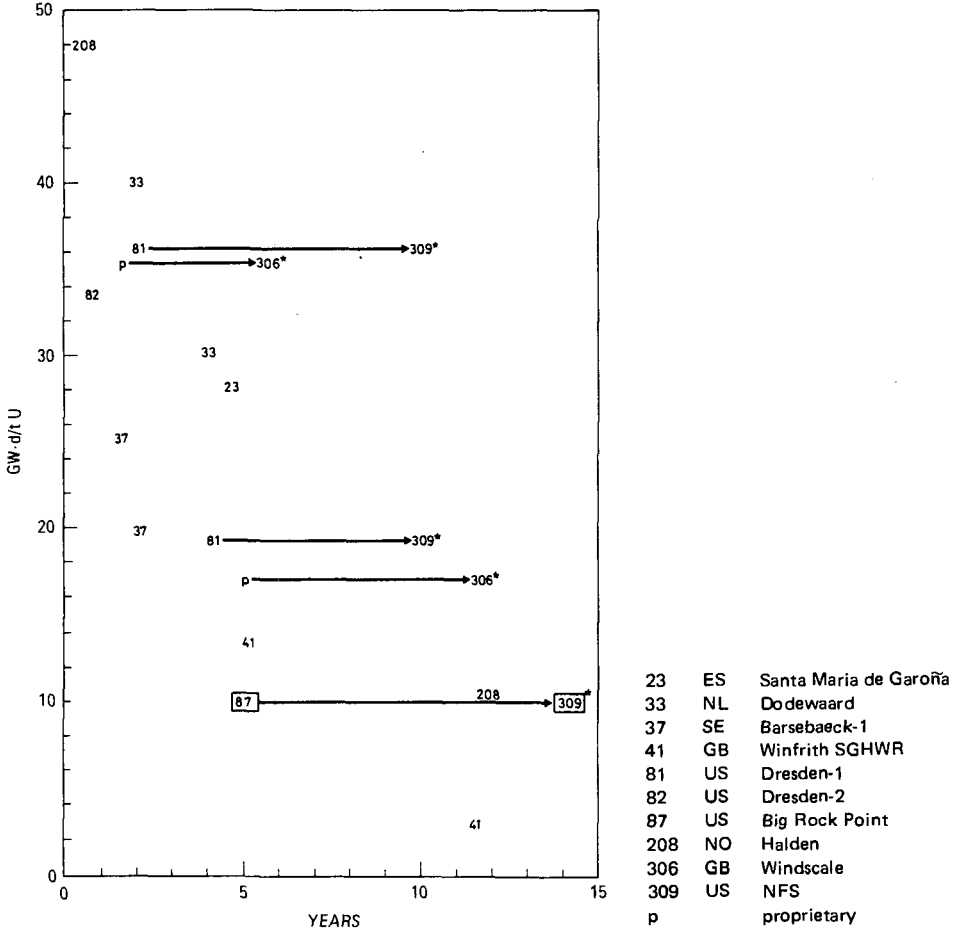| 23 | ES | Santa Maria de Garoña |
33	NL	Dodewaard
37	SE	Barsebaeck-1
41	GB	Winfrith SGHWR
81	US	Dresden-1
82	US	Dresden-2
87	US	Big Rock Point
208	NO	Halden
306	GB	Windscale
309	US	NFS
p		proprietary

FIG.E-4. Peak pellet burn-up of spent BWR fuel versus pool residence time. The numbers indicate AR pools, except for those marked by * which are for AFR pools.
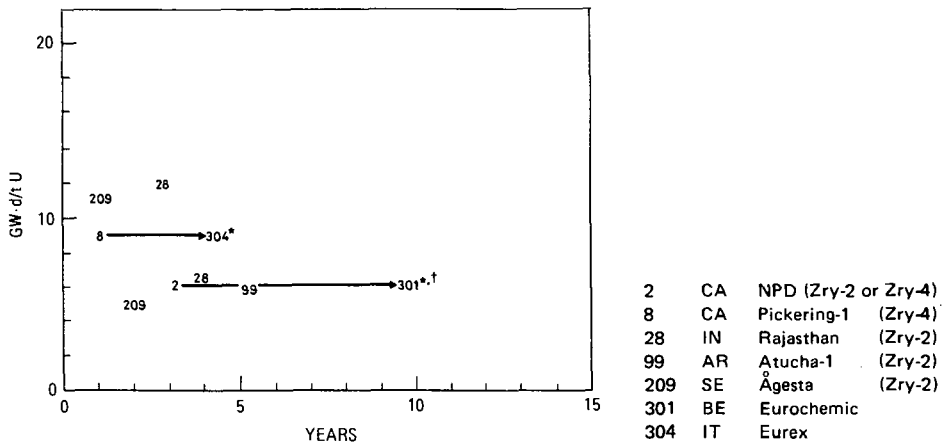
125

FIG.E-5.   Average assembly burn-up of spent HWR fuel versus pool residence time.   The numbers indicate AR pools, except for that marked by * which is for an AFR pool; † indicates AFR storage in canisters.
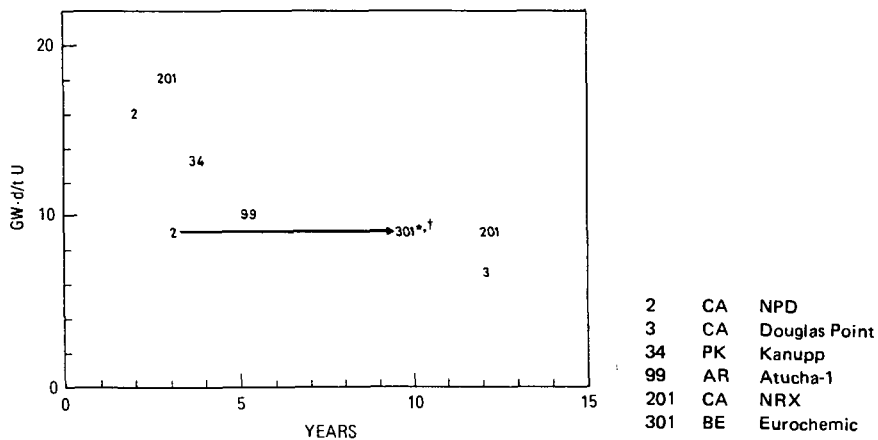

FIG.E-6.   Peak pellet burn-up of spent HWR fuel versus pool residence time.   The numbers indicate AR pools; † indicates AFR storage in canisters.
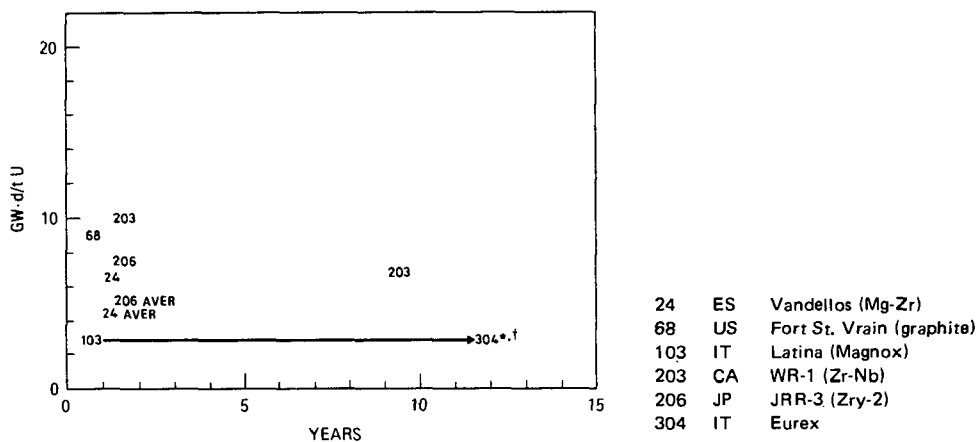
126

FIG.E-7. Peak pellet and average assembly (indicated by AVER) burn-up of miscellaneous spent fuel versus pool residence time. The numbers indicate AR pools; † indicates AFR storage in canisters.
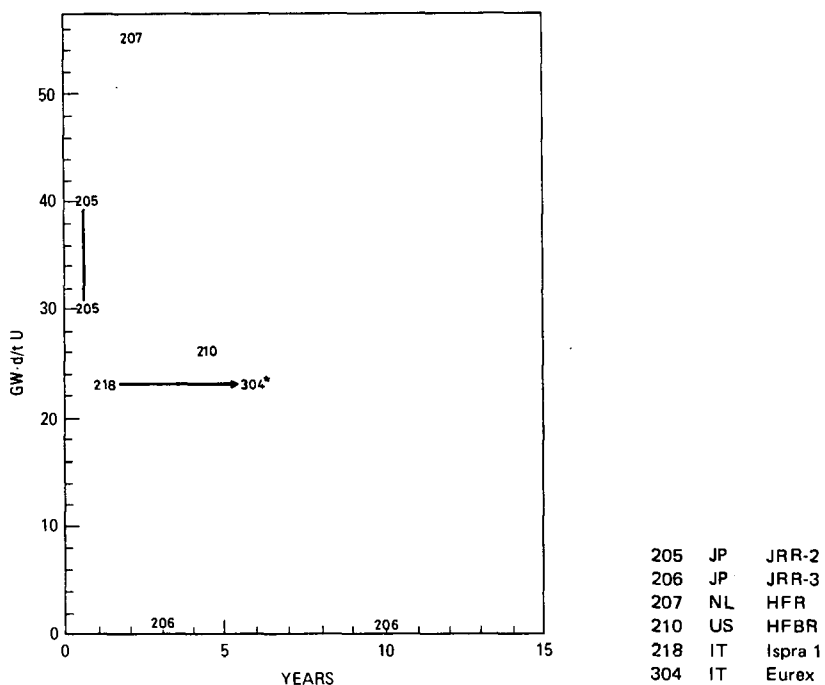

FIG.E-8. Average assembly burn-up of spent research reactor (RR) fuel versus pool residence time. The numbers indicate AR pools, except for that marked by * which is for an AFR pool.

127

Appendix F

DRY STORAGE OF IRRADIATED FUEL

The cases cited below represent examples rather than an exhaustive summary of reactor fuel stored under dry conditions.

HTGR FUEL

The Fort St. Vrain reactor (USA) is a high-temperature gas-cooled reactor (HTGR). The fuel is uranium and thorium with a non-metallic (pyrocarbon-silicon carbide) coating. The facility for storage of irradiated fuel consists of nine cylindrical mild steel wells. The facility is cooled by water tubes welded to the external surfaces of the wells. A helium cover gas (slightly less than 1 atm) is maintained over the fuel. Provisions are made to store broken fuel, if any develops, in hexagonal cans. Irradiated fuel was first stored in the facility in 1979. The average burn-up on the fuel was 9480 MW·d/t U.

MAGNOX FUEL

Magnox fuel is stored under dry conditions at the Wylfa power station, United Kingdom. The Magnox elements are about 1 m long. There are two dry stores at Wylfa. The first has sealed tubes, each holding 12 elements in CO_2 at 3 lbf/in^2 (g). The tubes are cooled by natural convection of atmospheric air. The second store has metal boxes (skips), each containing 192 open-topped cans, each holding one element. The store atmosphere is air. Fans draw air out of the top of the store and the air passes through water-cooled heat exchangers and is recycled. Elements discharged from the reactor are kept in the first store for 150 days and then may be transferred to the second store or retained in the first one.

WATER REACTOR FUEL

Demonstration programmes are under way in Canada [F1], the United States of America [F2] and the Federal Republic of Germany, involving dry storage of irradiated water reactor fuel. Several interim dry storage concepts are being evaluated, including metal casks, concrete silos, dry wells and concrete canyons.

Note: Reference [F3] provides a comprehensive summary of dry storage technology for irradiated fuel of several types.

REFERENCES TO APPENDIX F

[F1] OHTA, M.M., "Status of dry storage of irradiated fuel in Canada", Spent Fuel Storage Alternatives (Proc. IAEA Adv. Group/Specialists Meeting, Las Vegas, 1980), National Technical Information Service, Springfield, VA (1980) 383.
[F2] BLOMGREN, C.R., "Summary of spent fuel dry storage testing at the E-MAD facility", ibid., p.257.
[F3] ANDERSEN, P.A., MEYER, H.S., Dry Storage of Spent Nuclear Fuel, A Preliminary Study of Existing Technology and Experience, Rep. NUREG/CR-1223, Nuclear Regulatory Commission, Washington, DC (Apr. 1980).

Appendix G

DATA ON DEFECTIVE FUEL
AND FUEL INCIDENTS

G-1. REMARKS ON DEFECTIVE FUEL

Currently, fuel failure rates are low for water-cooled power reactors. Several fuel failure mechanisms have developed in the past, but have since been corrected. These mechanisms have generated fuel with defective cladding, some of which was reprocessed and some of which has remained in storage. The nature of the defect is very much dependent on the cladding. SS-clad fuel develops long axial cracks, exposing the fuel to the water; experience has shown that the fuel remains inert and that no measurable radioactivity is released, except during handling of the assemblies. Zircaloy-clad fuel usually has pinhole defects, sometimes small cracks or perforations and unfrequently a rupture of the rod; no further extensions of the defects were noticeable during subsequent storage of the spent fuel.

In BWR plants with Zircaloy-clad fuel, the defects range from pinholes to cracks involving pellet/clad interaction. Some assemblies can be repaired; this technology is sometimes applied to group all or most failed rods into a few assemblies, in order to facilitate surveillance of spent fuel storage. Even at facilities where large numbers of assemblies with defective fuel are stored

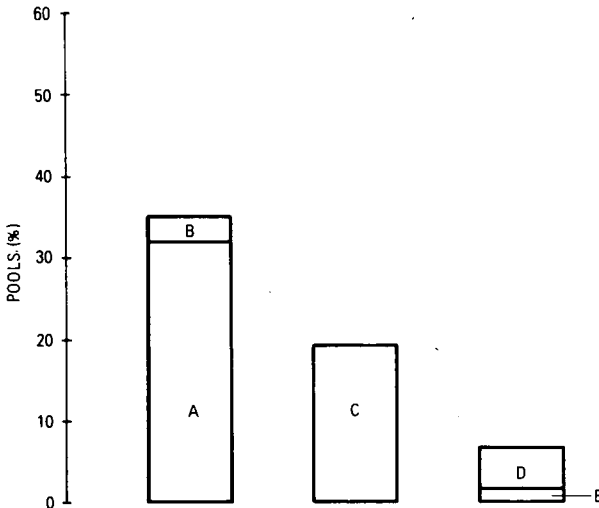

FIG. G-1. Summary of practices regarding encapsulation of spent fuel with or without defective cladding (based on survey responses). A — encapsulation of defective fuel assemblies;
B — encapsulation of defective fuel rods; C — storage of defective fuel in baskets;
D — encapsulation of undamaged fuel at receiving pools of reprocessing plants;
E — encapsulation of undamaged fuel at the reactor.
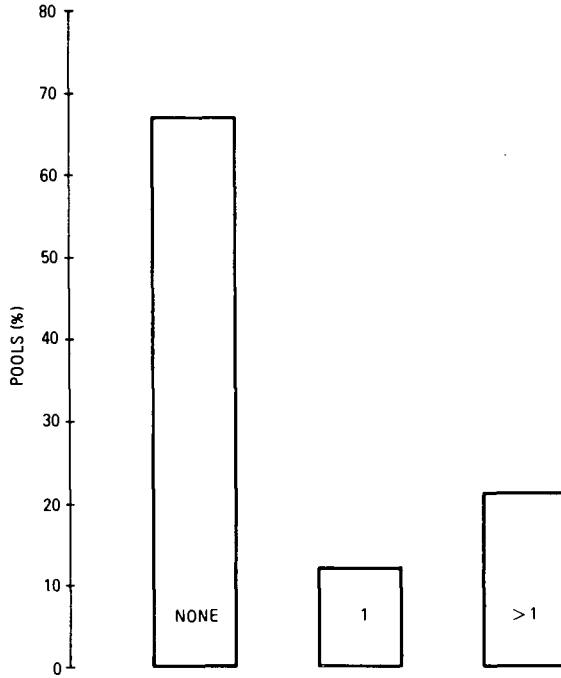
FIG.G-2. Summary of fuel assembly dropping events during fuel handling operations (based on survey responses).

directly in the pool, the transfer of radiocaesium from the fuel to the water remains well within limits controllable by the pool chemistry and the radiochemistry purification system. CANDU fuel is discharged while the reactor is operating, so the freshly discharged fuel is thermally hot; therefore, defective assemblies are canned routinely.

G-2. ENCAPSULATION OF DEFECTIVE FUEL

There is a diversity of philosophy among spent fuel pool operators regarding encapsulation of fuel with reactor-induced defects. Figure G-1 summarizes the various storage practices for defective fuel, on the basis of survey responses. It is indicated that about 30% of pool operators encapsulate assemblies with defective rods; 5% encapsulate defective rods removed from assemblies; 20% store defective fuel in enclosed baskets. The majority (60%) of the facilities store defective fuel in the same way as intact fuel. Note also that about 5% of the responding pool operators encapsulate non-defective fuel for storage.

Storage of defective fuel is discussed in Section 8.6.

G-3. INCIDENCE OF DROPPING EVENTS DURING FUEL HANDLING OPERATIONS IN SPENT FUEL POOLS

Occasionally, during spent fuel handling operations, a fuel assembly is dropped, owing to either operator error or equipment malfunction. Figure G-2 summarizes pool operator experience regarding the incidence of fuel dropping events. Approximately 65% of the responding pool operators indicated that they have not had a dropping event, about 12% had one event and about 23% indicated more than one event.

A total of about 30 water reactor fuel assemblies were dropped without serious consequences such as contamination or fission product release. Damage to structural parts of the assembly resulted, in a few cases, in disruption of the assembly into individual rods, which remained intact. One incident resulted in severe mechanical damage to an assembly rod, which was bent by approximately 45°. A case is reported where a detectable radiation release occurred when one dropped assembly was subsequently moved (Ref. [21] to main text).

Appendix H

SOME ASPECTS OF SPENT FUEL STORAGE
IN WATER POOLS IN THE USSR

H-1. INTRODUCTION

Nuclear power development in the USSR is now based upon water-cooled reactors of the
WWER and RBMK type. Both types of reactors use slightly enriched uranium as fuel (3.3% and
1.8%, respectively); the fuel elements have zirconium alloy cladding. The average burn-up is
28 000 MW·d/t U for WWER fuel and 18 500 MW·d/t U for RBMK fuel. After discharge from
the reactor, spent fuel is stored in a water pool at the reactor (AR). AR storage for spent fuel
cooling is normally for up to three years; after that, the fuel should be transported to
reprocessing plants.

Some parameters of the fuel used in USSR power reactors are shown in Tables H-1 and
H-2. Reloading operations are being done by special reloading machines. For WWER reactors,
reloading is being done once a year, replacing one third of the core. During reloading, the
reactor is shut down and all operations are being done under water. In order to suppress
criticality, boric acid is added, with concentrations of up to 12 g/l (for WWER-440) and
16 g/l (for WWER-1000). To avoid corrosion problems, the water chemistry is adjusted by
adding ammonia and hydrazine. The fuel bundles are stored in baskets. For the channel-type
reactor, reloading can be done without reactor shut-down.

Since large commercial nuclear power plants have been operational for almost 20 years,
good experience in spent fuel storage in reactor pools has been achieved. Based upon this
experience, a large central spent fuel storage facility has been designed (see Section H-2).
A number of R and D work is being done in this area to provide information for operation
and design. Aspects such as fuel cladding behaviour at extended storage time, corrosion
behaviour of pool equipment and lining, and improvements in water conditioning and
decontamination are being studied.

H-2. DEVELOPMENT OF A CENTRAL SPENT FUEL STORAGE FACILITY

It was considered that, after three years of storage in AR pools, spent fuel is transported
to a reprocessing plant. Large-scale commercial reprocessing of water reactor fuel is needed
when commercial breeder reactors are put into operation. Because of delays in the develop-
ment of commercial breeders, the decision was made for water reactors to extend spent fuel
storage and to construct additional storage facilities for a period of 10 years. The first of such
a storage facility is being developed for the nuclear power plant Kozloduj in Bulgaria. Experience
gained in the USSR for water pool operation was used in the design of this facility. The facility
is designed for storage of 600 t of spent fuel, deriving from the operation of four WWER-440
plants during a period of 10 years (5000 fuel assemblies). The facility is a separate building,
consisting of three main sections (see Figs H-1, H-2):

1. Entrance, discharge and exit of transport containers
2. Storage pools
3. Technological and auxiliary systems.

132

TABLE H-1. FUEL CHARACTERISTICS OF USSR POWER REACTORS

Reactor type	Electrical power (MW)	Fuel charge, UO_2 (t)	Average burn-up level (MW·d/t U)	Number of fuel assemblies	Fuel assembly dimensions, $S \times L$[a] (mm)
WWER-210	210	44	13	349	144 × 3200
WWER-365	365	44	28	349	144 × 3200
WWER-440	440	44	28	349	144 × 3200
WWER-1000	1000	72	41	151	238 × 4665
RBMK-1000	1000	210	18.5	1693	79[b] × 10 065

[a] S − 'end-fitting' dimension; L − assembly length.
[b] Bundle diameter.

TABLE H-2. RESIDUAL HEAT RELEASE OF SPENT FUEL ASSEMBLIES AND THEIR SPECIFIC GAMMA ACTIVITY AS A FUNCTION OF STORAGE TIME

Reactor type	Residual heat release of assembly after storage (kW per assembly)				Specific γ-activity (10^3 gram-equiv. per assembly)			
	Storage time (years)				Storage time (years)			
	0.5	1	2	3	0.5	1	2	3
WWER-210	1.2	0.7	0.3	0.2	37.0	10.0	4.4	3.5
WWER-365	2.1	1.1	0.5	0.3	64.0	18.0	7.5	6.0
WWER-440	2.2	1.2	0.6	0.3	67.0	19.0	7.9	6.3
WWER-1000	11.1	6.0	2.8	1.7	340.0	96.0	40.0	32.0
RBMK-1000	1.0	0.6	0.3	0.2	28.0	8.6	3.5	2.9
AEPP[a]	1.1	0.6	0.3	0.2	34.0	9.7	4.0	3.2

[a] Reinsberg, German Democratic Republic.

133

Fuel reception area

Washing area for fuel assemblies

Storage area

Deactivation well for transport containers
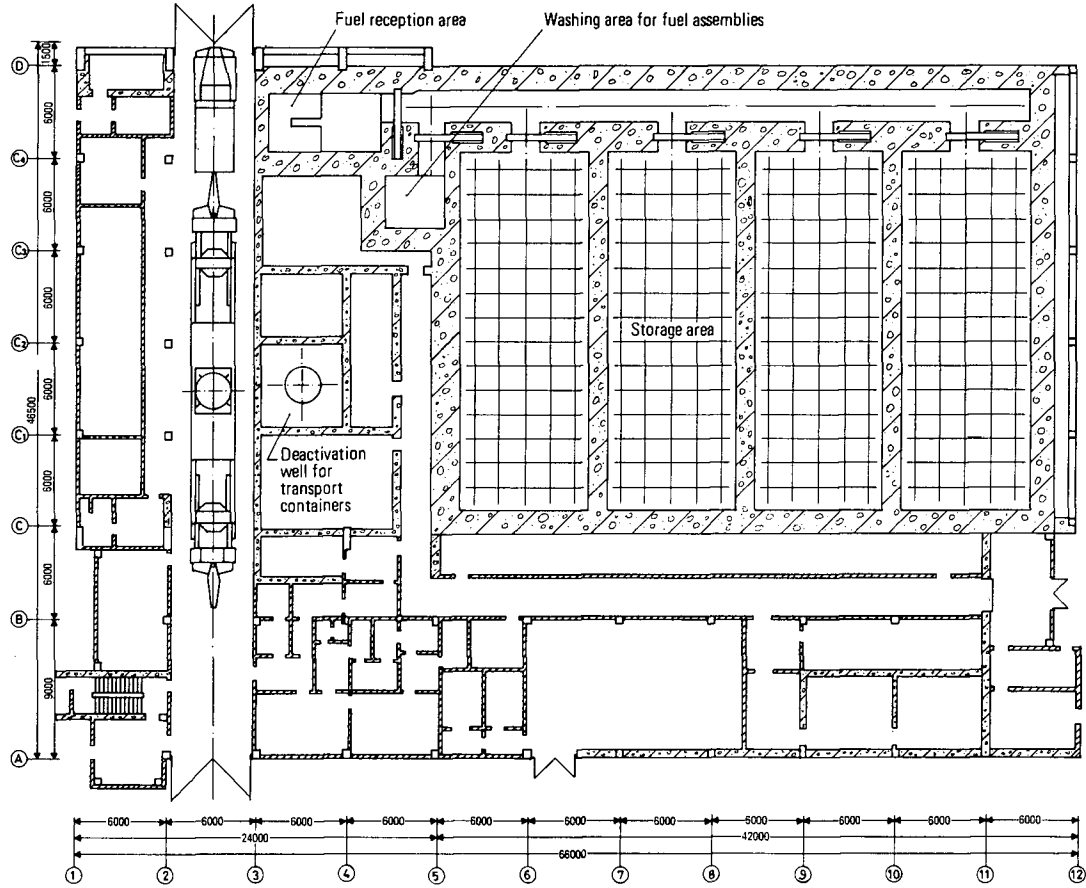
FIG.H-1. *Ground-level plan of spent fuel storage.*

Travelling crane

Travelling crane (lifting capacity 15 t)

+22.00

+15.20

+7.00

+7.00

+6.10

+3.00

0.00

−0.50

−4.00

6000 6000 6000 6000 6000 6000 6000 6000 6000 6000 6000

24000

42000

66000

① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ ⑫

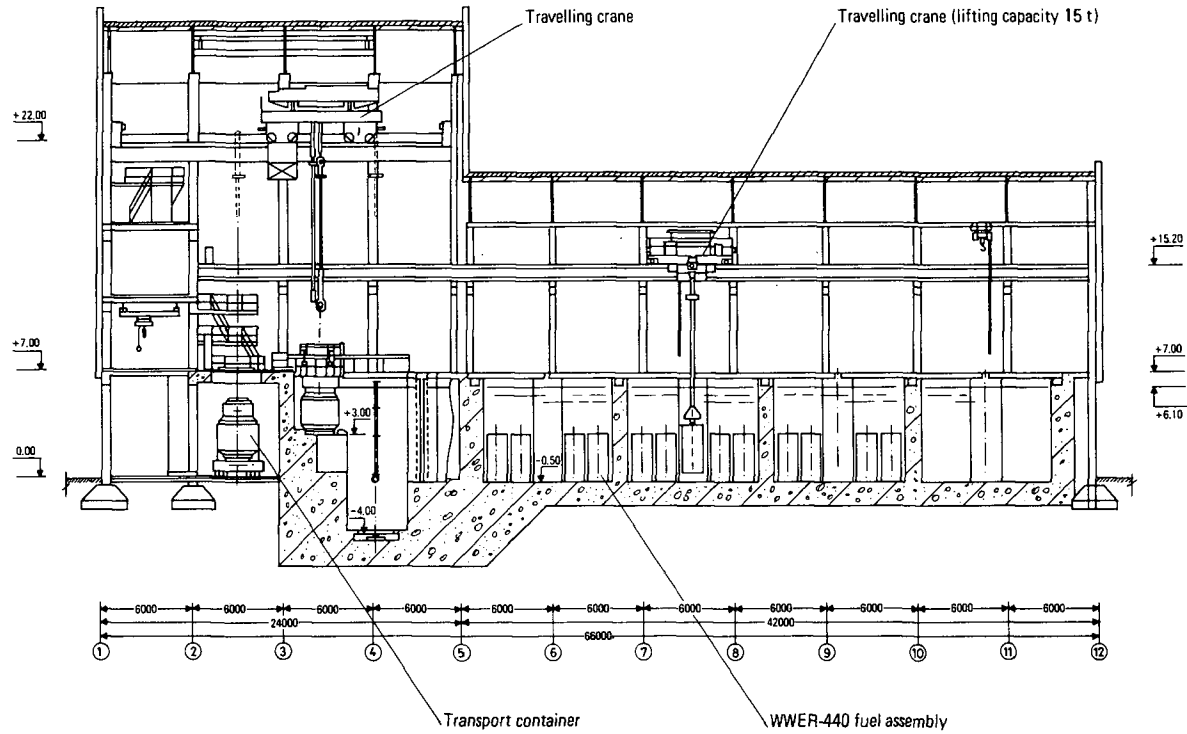Transport container

WWER-440 fuel assembly

FIG.H-2.   Longitudinal section of spent fuel storage.

The storage area consists of four separate pools, interconnected by a transport corridor which is also connected with discharge and washing areas of container wells. The floor and walls of the pools are lined with two layers made of carbon and stainless steel, to prevent leakage of water. Auxiliary systems include water cooling and purification, ventilation, decontamination of containers, rooms and equipment, instrumentation and others.

The TK-6 container is used for transportation of spent fuel from the reactor building in which a transport basket is loaded with 30 spent fuel assemblies. The container is transported by a vehicle to the discharge areas. In a water-filled discharge section the basket with the fuel is removed and transported to a certain place in a pool. After decontamination, the container with a new basket is returned to the reactor building. The same procedure is used for transportation of fuel from this facility. Four containers could be loaded with fuel simultaneously. The storage of fuel in baskets is considered to be more reliable and efficient than putting fuel assemblies separately on shelves and requires less time for loading and unloading operations.

The storage pool is filled with water which serves as coolant and shielding. Three metres of water above the 'active' part of the fuel is considered to be enough for these purposes. To prevent corrosion damage of fuel and other equipment, demineralized water is used and a purification system controls the water quality. Based on experience, the following requirements for water quality have been set:

pH: 6.0−7.5
Conductivity: <3 μS/kg
Concentration of crud: <0.5 ppm
Concentration of halogens ($Cl^- + F^-$): $\leqslant 500$ ppb

These conditions provide good water transparency and corrosion resistance of fuel cladding and other structures in the pool. The purification system consists of pre-filters to remove crud and of demineralizers; both remove radioactive products (suspended and dissolved). Filters coated with Perlite as auxiliary filter material or cationic filters could be used as pre-filters. Demineralizers could be filled with mixed-bed or separate cationic and anionic resins.

The capacity of the purification system is 40 m^3/h. Strongly basic cationic and strongly acidic anionic resins are used in demineralizers. All necessary safety measures are provided to prevent accidents and contamination of the environment. Criticality is excluded by appropriate distribution of the assemblies in baskets and containers ($K_{eff} = 0.9$).

Accidental dropping of a container and basket loaded with fuel was considered in the design, as well as leakage of water, cooling system failures and energy supply failures. The design water temperature is 50°C. No accidental rise of temperature can be expected. An effective ventilation system is provided with air purification by filtration. The ventilation air is discharged through a 35 m high stack.

All technical decisions taken in the project provide safe and reliable operation of the facility.

Appendix I

GLOSSARY

activation. Process of making a material radioactive by bombardment with neutrons, protons or other nuclear particles.

activity. For an amount of a radioactive nuclide in a particular energy state at a given time, the quotient of dN by dt is the expectation value of the number of spontaneous nuclear transitions from that energy state in the time interval dt. The special name for the SI unit of activity is becquerel (Bq); the curie (Ci) may be used temporarily. (See ICRU Report 33.)

advanced gas-cooled reactor (AGR). Power-generating nuclear reactor with steel-clad uranium dioxide fuel elements; cooled by carbon dioxide gas.

ALARA. "As low as reasonably achievable, economic and social factors being taken into account." A basic princple of radiation protection taken from the Recommendations of the ICRP, ICRP Publication No. 26 (p. 3).

at-reactor (AR). Refers to a spent fuel storage facility that is integral with a reactor.

away-from-reactor (AFR). Refers to a spent fuel storage facility not connected to a reactor.

becquerel (Bq). The SI unit of radioactivity, equivalent to 1 disintegration per second (approx. 2.7×10^{-11} Ci).

boiling-water reactor (BWR). A reactor that uses a boiling-water primary cooling system. Primary-cooling-system steam is used directly for electricity generation, i.e. there is no heat exchanger or secondary cooling system.

burn-up. A measure of reactor fuel consumption, expressed as either the percentage of fuel atoms that have undergone fission (common for test reactor fuel) or the amount of energy released per unit mass of nuclear fuel in the reactor (common for power reactor fuel). Typical units for the latter are megawatt-days per tonne of uranium (MW·d/t) or gigawatt-days per tonne (GW·d/t).

canal. Fuel handling and storage facility at a research reactor.

canister. A container (usually cylindrical) for solid radioactive waste. A canister affords physical containment; shielding is provided by a cask, but extra shielding may be required. (*See* cask.)

cask (*or* flask). A massive transport container providing shielding for radioactive materials and holding one or more canisters.

cladding (material). An external layer of material directly surrounding nuclear fuel or other material that provides protection from a chemically reactive environment and provides containment of radioactive materials produced during the irradiation of the composite. It may also provide structural support.

critical. A condition or state in which a self-sustaining nuclear chain reaction occurs, i.e. the effective neutron multiplication faction is equal to unity.

crud. Oxide deposits that form on the surface of the normal oxides on fuel assembly surfaces; the deposits come from low concentrations of dissolved and particulate species circulating in the reactor coolant; neutron activation causes the crud deposits to become radioactive.

curie (Ci). A unit of activity equal to 3.7×10^{10} becquerels.

decontamination. Removal or reduction of radioactive contamination.

deionized water (DIW). Water that has undergone anion/cation exchange to remove ionic impurities.

dry storage. Storage of fuel assemblies such that they are surrounded by a gaseous medium such as helium or air.

ECF. Expended core facility, INEL, Idaho, USA.

EOL. End of life, i.e. date of last reactor operation.

FGR. Fission gas release from the fuel pellets to the internal free volume of a fuel rod.

fission product. A nuclide produced either by fission or by the subsequent radioactive decay of a radioactive nuclide thus formed.

FRSF. Fuel receiving and storage facility, INEL, Idaho, USA.

fuel, nuclear reactor. Fissile and fertile material used as the source of energy when placed in a critical arrangement in a nuclear reactor.

fuel assembly. A grouping of fuel elements and supporting structures which is normally treated as a unit for handling and accountability purposes.

fuel basket. A holder for spent fuel in the water storage pool or a device for transferring spent fuel to such a pool (also called fuel thimble).

fuel element (*or* fuel pin). The smallest structurally discrete part of a nuclear reactor fuel assembly which has fuel as its principal constituent.

fuel rod. *See* fuel element.

full-core reserve. Space in the reactor pool to accommodate all of the nuclear fuel contained in the reactor.

gas-cooled reactor (GCR). A reactor in which a gas such as air, carbon dioxide or helium is used as a coolant.

heavy-water reactor (HWR). A reactor in which heavy water (D_2O) serves a moderator and sometimes as coolant.

high-temperature gas-cooled reactor (HTGR). Helium-cooled reactor; the fuel is clad with graphite and pyrocarbon.

hot cell. A heavily shielded enclosure in which highly radioactive materials can be safely handled using remote manipulators. The operators look through shielded windows or periscopes, or use remote viewing equipment.

ICRP. International Commission on Radiological Protection.

JTU. One of the units of turbidity.

K_{eff}. Effective neutron multiplication factor (*see* **critical**).

light-water reactor (LWR). A reactor that uses ordinary water (H_2O) as coolant and moderator: may be either a boiling-water reactor (BWR) or a pressurized-water reactor (PWR).

Magnox. Magnesium alloy cladding for GCR fuel.

pellet/clad interaction (PCI). The interaction between the nuclear fuel and the cladding. The attack on the cladding interior surface involves a combination of mechanical interaction with the fuel and chemical action by fission products, e.g. radioiodine. Certain types of interaction lead to stress-corrosion-cracking (SCC) failures in the cladding.

pressurized heavy-water reactor (PHWR). A pressurized-water reactor (*see below*) that uses heavy water (D_2O) in the primary cooling circuit.

pressurized-water reactor (PWR). A type of reactor that uses a pressurized-water primary cooling system. The water in the primary cooling system does not boil. Its heat is used to provide steam in the secondary cooling circuit via a heat exchanger. The water and steam in the secondary circuit are isolated from the reactor by the heat exchanger.

re-racking. Replacement of existing fuel racks by racks that permit more fuel assemblies to be stored without increasing the pool dimensions.

research reactor (RR). A reactor used principally for research and/or isotope production rather than for electricity generation.

sensitization. Chromium depletion of stainless steel and similar metals near grain boundaries due to diffusion and reaction with carbon in the grain boundaries; may render the metal prone to corrosion.

SFA. Spent fuel assembly.

shielding. A material interposed between a source of radiation and personnel or equipment, etc. for protection from radiation. Common shielding materials are concrete, water and lead.

shipping cask. A shielding container used for transporting and handling high-level and medium-level nuclear materials (also called shipping flask).

sipping. Procedure by which the amount and characteristics of gases escaping from a defective fuel assembly are determined.

spent fuel. Nuclear reactor fuel elements that have been irradiated in a reactor and have been utilized to an extent such that their further use is no longer efficient.

spent fuel pool. A specially designed and operated water pool for storing, cooling, maintaining and shielding spent fuel assemblies; also known as basin or pond.

storage canister (or storage bottle). *See* **canister.**

storage rack. Metal structure in the water storage pool that holds spent fuel assemblies or storage canisters to preclude criticality and seismic damage.

subcritical. A condition or state wherein fissionable material is present in insufficient quantity or in improper geometry to sustain a nuclear chain reaction (*see* **critical**).

trans-shipment. Shipping spent fuel from one fuel pool to another.

water pool storage. *See* **spent fuel pool.**

water reactor (WR). A reactor cooled by either light (H_2O) or heavy (D_2O) water.

wet storage. Storage of fuel assemblies in water.

WWER. USSR type of PWR.

Zry. Zircaloy; a zirconium alloy containing ~1.5 wt% tin and small concentrations of iron, chromium and nickel; Zircaloy-2 is a formulation with a higher nickel content (~0.05 wt%); Zircaloy-4 has a lower nickel content (~0.007 wt%).

The following conversion table is provided for the convenience of readers

FACTORS FOR CONVERTING SOME OF THE MORE COMMON UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI) EQUIVALENTS

NOTES:
(1) SI base units are the metre (m), kilogram (kg), second (s), ampere (A), kelvin (K), candela (cd) and mole (mol).
(2) ▶ indicates SI derived units and those accepted for use with SI;
   ▷ indicates additional units accepted for use with SI for a limited time.
   [For further information see the current edition of The International System of Units (SI), published in English by HMSO, London, and National Bureau of Standards, Washington, DC, and International Standards ISO-1000 and the several parts of ISO-31, published by ISO, Geneva.]
(3) The correct symbol for the unit in column 1 is given in column 2.
(4) ✻ indicates conversion factors given exactly; other factors are given rounded, mostly to 4 significant figures:
   ≡ indicates a definition of an SI derived unit; [ ] in columns 3+4 enclose factors given for the sake of completeness.

Column 1 Multiply data given in:	Column 2	Column 3 by:	Column 4 to obtain data in:	
Radiation units				
▶ becquerel	1 Bq	(has dimensions of s^{-1})		
disintegrations per second (= dis/s)	$1\ s^{-1}$	≡ 1.00 × 10^0	Bq	✻
▷ curie	1 Ci	= 3.70 × 10^{10}	Bq	✻
▷ roentgen	1 R	[≈ 2.58 × 10^{-4}	C/kg]	✻
▶ gray	1 Gy	[≡ 1.00 × 10^0	J/kg]	✻
▷ rad	1 rad	= 1.00 × 10^{-2}	Gy	✻
▶ sievert (radiation protection only)	1 Sv	[≙ 1.00 × 10^0	J/kg]	✻
▷ rem (radiation protection only)	1 rem	= 1.00 × 10^{-2}	Sv	✻
Mass				
▶ unified atomic mass unit ($\frac{1}{12}$ of the mass of ^{12}C)	1 u	[≈ 1.660 57 × 10^{-27}	kg, approx.]	
▶ tonne (= metric ton)	1 t	[= 1.00 × 10^3	kg]	✻
pound mass (avoirdupois)	1 lbm	= 4.536 × 10^{-1}	kg	
ounce mass (avoirdupois)	1 ozm	= 2.835 × 10^1	g	
ton (long) (= 2240 lbm)	1 ton	= 1.016 × 10^3	kg	
ton (short) (= 2000 lbm)	1 short ton	= 9.072 × 10^2	kg	
Length				
statute mile	1 mile	= 1.609 × 10^0	km	
▷ nautical mile (international)	1 n mile	= 1.852 × 10^0	km	✻
yard	1 yd	= 9.144 × 10^{-1}	m	✻
foot	1 ft	= 3.048 × 10^{-1}	m	✻
inch	1 in	= 2.54 × 10^1	mm	✻
mil (= 10^{-3} in)	1 mil	= 2.54 × 10^{-2}	mm	✻
Area				
▷ hectare	1 ha	[= 1.00 × 10^4	m^2]	✻
▷ barn (effective cross-section, nuclear physics)	1 b	[= 1.00 × 10^{-28}	m^2]	✻
square mile, (statute mile)^2	1 mile^2	= 2.590 × 10^0	km^2	
acre	1 acre	= 4.047 × 10^3	m^2	
square yard	1 yd^2	= 8.361 × 10^{-1}	m^2	
square foot	1 ft^2	= 9.290 × 10^{-2}	m^2	
square inch	1 in^2	= 6.452 × 10^2	mm^2	
Volume				
▶ litre	1 l or 1 L	[= 1.00 × 10^{-3}	m^3]	✻
cubic yard	1 yd^3	= 7.646 × 10^{-1}	m^3	
cubic foot	1 ft^3	= 2.832 × 10^{-2}	m^3	
cubic inch	1 in^3	= 1.639 × 10^4	mm^3	
gallon (imperial)	1 gal (UK)	= 4.546 × 10^{-3}	m^3	
gallon (US liquid)	1 gal (US)	= 3.785 × 10^{-3}	m^3	

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Column 1 Multiply data given in:	Column 2	Column 3 by:	Column 4 to obtain data in:

Velocity, acceleration

foot per second (= fps)	1 ft/s	$= 3.048 \times 10^{-1}$	m/s *
foot per minute	1 ft/min	$= 5.08 \times 10^{-3}$	m/s *
mile per hour (= mph)	1 mile/h	$= \begin{cases} 4.470 \times 10^{-1} \\ 1.609 \times 10^{0} \end{cases}$	m/s km/h
▷ knot (international)	1 knot	$= 1.852 \times 10^{0}$	km/h *
free fall, standard, g		$= 9.807 \times 10^{0}$	m/s^2
foot per second squared	1 ft/s^2	$= 3.048 \times 10^{-1}$	m/s^2 *

Density, volumetric rate

pound mass per cubic inch	1 lbm/in^3	$= 2.768 \times 10^{4}$	kg/m^3
pound mass per cubic foot	1 lbm/ft^3	$= 1.602 \times 10^{1}$	kg/m^3
cubic feet per second	1 ft^3/s	$= 2.832 \times 10^{-2}$	m^3/s
cubic feet per minute	1 ft^3/min	$= 4.719 \times 10^{-4}$	m^3/s

Force

▶ newton	1 N	$[\equiv 1.00 \times 10^{0}$	m·kg·s^{-2}]*
dyne	1 dyn	$= 1.00 \times 10^{-5}$	N *
kilogram force (= kilopond (kp))	1 kgf	$= 9.807 \times 10^{0}$	N
poundal	1 pdl	$= 1.383 \times 10^{-1}$	N
pound force (avoirdupois)	1 lbf	$= 4.448 \times 10^{0}$	N
ounce force (avoirdupois)	1 ozf	$= 2.780 \times 10^{-1}$	N

Pressure, stress

▶ pascal[a]	1 Pa	$[\equiv 1.00 \times 10^{0}$	N/m^2] *
atmosphere[b], standard	1 atm	$= 1.013\ 25 \times 10^{5}$	Pa *
▷ bar	1 bar	$= 1.00 \times 10^{5}$	Pa *
centimetres of mercury (0°C)	1 cmHg	$= 1.333 \times 10^{3}$	Pa
dyne per square centimetre	1 dyn/cm^2	$= 1.00 \times 10^{-1}$	Pa *
feet of water (4°C)	1 ftH$_2$O	$= 2.989 \times 10^{3}$	Pa
inches of mercury (0°C)	1 inHg	$= 3.386 \times 10^{3}$	Pa
inches of water (4°C)	1 inH$_2$O	$= 2.491 \times 10^{2}$	Pa
kilogram force per square centimetre	1 kgf/cm^2	$= 9.807 \times 10^{4}$	Pa
pound force per square foot	1 lbf/ft^2	$= 4.788 \times 10^{1}$	Pa
pound force per square inch (= psi)[c]	1 lbf/in^2	$= 6.895 \times 10^{3}$	Pa
torr (0°C) (= mmHg)	1 torr	$= 1.333 \times 10^{2}$	Pa

Energy, work, quantity of heat

▶ joule ($\equiv$ W·s)	1 J	$[\equiv 1.00 \times 10^{0}$	N·m] *
▶ electronvolt	1 eV	$[= 1.602\ 19 \times 10^{-19}$	J, approx.]
British thermal unit (International Table)	1 Btu	$= 1.055 \times 10^{3}$	J
calorie (thermochemical)	1 cal	$= 4.184 \times 10^{0}$	J *
calorie (International Table)	1 cal$_{IT}$	$= 4.187 \times 10^{0}$	J
erg	1 erg	$= 1.00 \times 10^{-7}$	J *
foot-pound force	1 ft·lbf	$= 1.356 \times 10^{0}$	J
kilowatt-hour	1 kW·h	$= 3.60 \times 10^{6}$	J *
kiloton explosive yield (PNE) ($\equiv 10^{12}$ g-cal)	1 kt yield	$\simeq 4.2 \times 10^{12}$	J

---

[a] Pa (g): pascals gauge   [b] atm (g) (= atü): atmospheres gauge   [c] lbf/in^2 (g) (= psig): gauge pressure
Pa abs: pascals absolute   atm abs (= ata): atmospheres absolute   lbf/in^2 abs (= psia): absolute pressure

Column 1 *Multiply data given in:*	Column 2	Column 3 *by:*	Column 4 *to obtain data in:*

Power, radiant flux

▶ watt   1 W $[\equiv 1.00 \times 10^0$ J/s]   *

British thermal unit (International Table) per second   1 Btu/s $= 1.055 \times 10^3$ W

calorie (International Table) per second   1 cal$_{IT}$/s $= 4.187 \times 10^0$ W

foot-pound force/second   1 ft·lbf/s $= 1.356 \times 10^0$ W

horsepower (electric)   1 hp $= 7.46 \times 10^2$ W   *

horsepower (metric) (= ps)   1 ps $= 7.355 \times 10^2$ W

horsepower (550 ft·lbf/s)   1 hp $= 7.457 \times 10^2$ W

Temperature

▶ kelvin K

▶ degrees Celsius, t $t = T - T_0$ *

where T is the thermodynamic temperature in kelvin
and T_0 is defined as 273.15 K

degree Fahrenheit $t_{°F} - 32$

degree Rankine $T_{°R}$ $\times \left(\dfrac{5}{9}\right)$ gives

temperature difference^d $\Delta T_{°R}\ (= \Delta t_{°F})$

giving: t *(in degrees Celsius)* * ; T *(in kelvin)* * ; $\Delta T\ (= \Delta t)$ *

Thermal conductivity^d

1 Btu·in/(ft²·s·°F)	*(International Table Btu)*	$= 5.192 \times 10^2$	$W \cdot m^{-1} \cdot K^{-1}$
1 Btu/(ft·s·°F)	*(International Table Btu)*	$= 6.231 \times 10^3$	$W \cdot m^{-1} \cdot K^{-1}$
1 cal$_{IT}$/(cm·s·°C)		$= 4.187 \times 10^2$	$W \cdot m^{-1} \cdot K^{-1}$

Miscellaneous quantities

litre per mole per centimetre   (1 M/cm =) 1 L·mol^{-1}·cm^{-1} $= 1.00 \times 10^{-1}$ m²/mol   *
(molar extinction coefficient or molar absorption coefficient)

G-value, traditionally quoted per 100 eV
   of energy absorbed 1×10^{-2} eV^{-1} $= 6.24 \times 10^{16}$ J^{-1}
(radiation yield of a chemical substance)

mass per unit area   1 g/cm² $[= 1.00 \times 10^1$ kg/m²]   *
(absorber thickness and mean mass range)

---

^{d} A temperature interval or a Celsius temperature difference can be expressed in degrees Celsius as well as in kelvins.

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