Safety criteria for wet and dry spent fuel storage
Authors: M. Vitkova, I. Gorinov, D. Dacheva
Nuclear Regulatory Agency

Abstract
An overview of the safety criteria for both type of storage (wet and dry) is presented in this paper. The main criteria – thermal, shielding, radiological – are discussed in details. Some requirement to the materials and the operational regimes are also discussed. An attempt for comparison of the safety criteria and general problems for these both type of storage is made.

1. Introduction
The storage of spent (irradiated) nuclear fuel has been an important issue of nuclear fuel management since the first discharging of irradiated fuel from the X-10 research reactor in Oak Ridge-USA. In earlier years, the spent fuel storage at the reactor storage pools was considered to be limited to one or two years before being transported to the reprocessing plants. But insufficient capacities of these plants and higher cost of reprocessing are compelled many countries to defer their decision for spent fuel reprocessing. The strategies of spent fuel management and disposal may be different for various countries and may be oriented to the following options [1]:

- The reprocessing route: spent fuel is reprocessed, and the fissile material and depleted uranium are reused to produce new fuel, which is irradiated either in fast breeder or thermal reactors. The separated high level waste (HLW) containing most fission products and a small proportion of long lived alpha emitters as actinides are conditioned for geological disposal;
- The spent fuel disposal route: spent fuel is prepared after a sufficient decay period and after a convenient conditioning and packaging process, for so-called direct disposal;
- The spent fuel deferred period route: spent fuel is stored interim in wet or dry storage facilities for prolonged period of time till clearing of the alternative for further treatment or disposal of the spent fuel.

The delay in decisions related to spent fuel management has caused increasing requirements for the storage of the spent fuel for longer periods. The new challenges are to extend the life of existing and new wet and dry storage facilities and guarantee their safe performance for periods significantly extending 40 – 50 years [2]. The extension of the life of the spent fuel storage facilities requires re-examining of the safety requirements, which have been determined in the past.

The subject of spent fuel management is not yet an area where international standards have been developed. With the growing amount of spent fuel stored in countries, the ensured safety of medium and long term storage is becoming more and more important.

Recognizing the increasing need for guidance in this field, especially for developing countries, the IAEA has issued a set of safety publications on the subject. The aim of the publications is to provide advice to countries on the main issues of safe long-term storage of spent nuclear fuel. This programme complements and contributes to the IAEA’s overall Nuclear Safety Standards (NUSS). The following books in the Safety Series have been published:
Safety Guide: Design of Spent Fuel Storage Facilities [3];
Safety Guide: Operation of Spent Fuel Storage Facilities [4];
Safety Practice: Safety Assessment for Spent Fuel Storage Facilities [5].

Additionally, the IAEA has issued many technical documents (TECDOC) with main results from the operation experience and practice, research and developments in the field of storage technology and storage conditions, corrosion behaviour of fuel cladding and storage systems. Some of them are used as a source for development of this paper, which main purpose is to give to the public a systematic view of the main requirements addressed to long storage of the spent fuel.

2. Safety objectives

Spent fuel storage means emplacement of fuel units in a retrievable manner into a spent fuel storage facility affording adequate environmental, thermal, chemical and physical protection, including provisions for surveillance. The purpose of the safe interim storage is to maintain the integrity of the barriers and the irretrievability of the fuel without further degradation for a well-defined period.

The basic safety objectives during the storage of spent nuclear fuel, defined in the IAEA Safety documents [3, 4, 5], are as follows:

1) Maintenance of subcriticality;

2) Removal of residual heat;

3) Providing for radiation protection;

4) Maintain containment over the lifetime of the storage facility.

*Maintenance of subcriticality* means that the spent fuel handling, transfer and storage systems are designed to ensure nuclear criticality safety, including margins of safety for the nuclear criticality parameters, and are able to demonstrate nuclear safety for all operational conditions. Subcriticality of the spent fuel during its storage is ensured by the design features of the storage racks, baskets or canisters. The design features of the handling system ensure subcriticality of the spent fuel during normal handling.

*Removal of residual heat* means that the design of the storage system provides sufficient capabilities for adequate heat removal from spent fuel. Decay heat removal systems may be passive (natural convection and thermal radiation) for dry storage or may include active cooling systems (forced convection) for wet or dry storage. The design is intended to function within design basis thermal limits under normal, off-normal and accident conditions.

*Providing for radiation protection* means that the spent fuel handling, transfer and storage systems are designed to ensure radiation protection of the personnel, general public and environment. Biological shielding of the spent fuel during its storage is ensured by the design features of the storage pools and dry storage systems. The design features of the handling and transfer systems ensure biological shielding of the spent fuel during normal handling and transportation of the spent fuel.

*Maintain containment* means that the spent fuel system is designed to preserve the primary barrier of the spent fuel and provide additional secondary barrier against the potential release of particulate radioactive materials to the environment. The primary barrier normally is the fuel cladding for which protection against damage and degradation is provided by storage confinement, storage environment, fuel handling equipment and decay heat removal system.
Enhanced administration and operational procedures have to be developed and kept to fulfil these safety objectives. If appropriately managed and regulated, interim storage of spent nuclear fuel is very safe. By its nature, spent fuel storage is a process with very little going on, and very little that could go wrong that could result in radiation being released.

3. Containment Barriers

In general, the safe storage of spent fuel is achieved by maintaining a minimum of two independent barriers between the fuel and the environment. The fuel cladding is considered the primary barrier for undamaged fuel. In addition, the complete confinement system for the stored fuel is conservatively designed to withstand damaging events, including earthquake or other extreme natural phenomena. This confinement system is an effective secondary barrier to the release of radioactive materials under all credible conditions. The combination of primary and secondary barrier comprises a confinement system that provides the necessary radiological protection.

a) Specific to Wet Storage

The containment barriers that are specific for the pool type storage facilities are the hydraulic and effluent containment barriers.

The hydraulic containment barrier is the pool water, pool structure, structural supports, and components which preclude releases of the radioactivity to the surface or subsurface environment.

The effluent containment barrier is the ventilation system that precludes releases of the radioactive gases and aerosols to the environment. The effluent air from areas of the wet storage facility with the potential for significant release of airborne radioactivity is treated by the ventilation system to prevent release of the radioactivity to the environment.

Some spent fuel storage pools are provided with a secondary hydraulic containment system, which usually use for protection against radioactive release that might result from leaks or rupture of elements of the primary hydraulic containment, including equipment and pool drainage system.

b) Specific to dry storage

The storage confinement system for the dry storage facilities includes the shielding structure and associated internals, within which the spent fuel is stored and that provide both physical and radiological protection.

Vault type spent fuel storage facilities (SFSF)

For dry storage facilities with forced convection as dry vaults, the second containment barrier is the lids and seals of casks and canisters. The third containment barrier is the ventilation system. Such ventilation system includes all air moving and cleanup equipment and associated controls required to:

- protect the general public and personnel from potential release of airborne radioactive particulates from all storage, handling and processing areas;
- remove the decay heat from fuel during handling and storage;
- maintain air quality suitable for operational personnel;
- provide forced cooling of storage concepts where required.
A treating and cleaning of the air is required when defective un-canned fuel is stored in the dry spent fuel storage system.

Casks type SFSF

The containment barriers that are specific for the dry dual-purpose storage casks are mechanical seals that provide confinement boundary sealing surface. Typically, this means that field closures of the confinement boundary should either have double seal welds or double metallic O-ring seals. Some casks are provided with bolted closure. For such containment considers that a seal monitoring system has been needed in order to demonstrate that seals can function and maintain a helium atmosphere in the casks for the licensed period. A seal monitoring system combined with periodic surveillance enables to determine when to take corrective action to maintain safe storage conditions.

4. Identification of safety related parameters

All safety related activities and systems should be identified and ranked according to its impact on nuclear safety and radiation protection. The following are typical examples of parameters, which may have a limiting, bounding or guiding influence on safety and, therefore, should be addressed in the safety assessment:

- Design life of the storage facility;
- Selection of component materials;
- Fuel cladding temperature;
- Material temperatures (water or cask body temperatures);
- Radiation fields;
- Pool water chemistry and radioactivity;
- Gaseous and liquid releases inside the facility;
- Gaseous and liquid releases outside the facility.

All choices of this kind should be justified with appropriate data, safety analyses and reasoned argument. The safety analysis process is based on storage facility design information that is complete and accurate. This information covers all structures, systems and components of the facility, off-site interfaces and site specific characteristics.

5. Identification of initiating events and fault sequences

Systematic examination of potential features, events and processes can helps to identify the factors that might influence the long term safety of a spent fuel storage facility. Developing of a suitable list of scenarios is a main basis for safety assessment of the design. Such list of postulated initiating events (PIE) should include: all internal and external events, which can lead to violation of normal operation; external events of natural origin and events, which are initiated by human activities and human errors.

A schedule of faults has to be prepared, and for each fault (or group of faults having common characteristics) the procedures and/or engineered safety systems, which will be used, should be listed. The fault studies will assess the transient development of the faults in the fuel, coolant and structures, and any other critical parameters (e.g. pressure within closed containments) to show whether these remain acceptable, taking account of possible actions such as corrective action or repairs if the time-scale is sufficiently long.
6. **Safety criteria for wet storage**

The safety criteria are addressed to the behaviour of structural materials and components used in the spent fuel storage systems and to the degradation mechanisms that could compromise the protective barriers and could lead to the higher radiological risk for the personnel, the member of the public and the environment.

6.1. **Temperatures**

*Fuel cladding temperature*

The main limiting parameter for the fuel cladding integrity during spent fuel storage is the fuel cladding temperature. The acceptable cladding temperature limit ensures that no additional degradation (e.g. creep or embrittlement) of the irradiated Zr cladding, beyond that accumulated during reactor operation, is expected during wet storage of spent fuel. Certain limits for short-term accidents, fuel transfer and transport should also be defined with an adequate margin of safety. Temperature limits will be more restrictive with increased fuel cooling time (or increased burnup) mainly due to creep cavitations.

*Pool water temperature*

The acceptable limits for pool water temperatures for normal, off-normal and accident-level conditions ensures that the fuel cladding temperature will be kept under the safety limit. The possible range of boiling temperatures for the pool coolant solution are stated, with consideration of ranges of the solution, elevation above mean sea level, barometric pressure, and air pressure differential maintained between the pool facility and the outside. For the maximum normal heat load with normal cooling systems in operation, and assuming a single active failure coincident with a loss of all off-site power, the temperature of the pool water should be kept at or below 60°C. The temperature limits normally are kept about 45°C [6]. For away from reactor (AFR) storage facilities water temperature is lower and does not exceed 40°C in normal conditions [6]. Other considerations that make it preferable to operate pools at the lowest practicable temperature include reducing the release rate of radionuclides from defective fuels, minimizing bacterial or microbial growth, and lowering the humidity level in the storage area.

To keep the pool temperature limits, the spent fuel cooling system should have sufficient capability to transfer heat loads from safety-related systems to a heat sink under both normal operating and accident conditions. The spent fuel pool and cooling systems are designed so that in the event of failure of inlets, outlets, piping, or drains, the pool level will not be inadvertently drained below a point approximately 3 meters above the top of the spent fuel.

*Temperature restrictions on structure, systems and components*

Temperature restrictions on other SSCs important to safety usually identify with the aim to assure adequate structure behaviour during all operational states. The acceptable temperature limits for other materials that may provide integral containment (e.g. pool concrete structure) of the radioactive material, shielding, subcriticality assurance, or heat removal are dependent on the material and its importance. The acceptable temperature limits for structures and components are defined in the relevant industrial standards as Building Code Requirements for Reinforced Concrete ANSI/ACI 318-1983 and Specification for Structural Concrete for Buildings, ANSI/ACI 30-1984. Considerations for determining temperature limits for the material can include:

- temperature at which the structural strength of the material is affected and the time at that temperature required to cause the effect;
• temperature at which chemical reactions may take place (at a significant rate) that affect shielding, subcriticality assurance, or structural integrity;
• allowance to provide an acceptable margin of safety for uncertainties in the temperatures that may occur and in the thresholds for the effects;
• temperatures that may be reached in normal, off-normal, and accident-level conditions and events;
• potential combinations of temperature and environment (such as may produce significant reaction with borated water).

The acceptable temperature for the stored spent fuel itself may provide temperature limits for the thermal performance of the structural materials.

6.2. Structures and materials

Structure and layout

The storage pools and building containment are designed to withstand operational states and accident conditions without significant leakage of water. A proper system for detection, collection and removal of water leakage is included in the original design. The penetrations for pipes from the cooling and make-up systems are located above the elevation, specified as a minimum operational level, to avoid draining of the pools as a result of siphon effect and to assure sufficient water level for radiation protection. The water make-up system is designed to provide water at rate exceeding the maximum rate of pool draining as a result of losses during operation. For modular type spent fuel storage facilities, where storage pools are connecter by sluiceways, the sluice gates are designed to withstand anticipated water pressure.

Storage pools component and materials

The choice of pool components and materials is dependent on the type of fuel being stored, storage costs and methods for facilitation of the final pool decommissioning. All at reactor (AR) storage pools are stainless steel lined. Epoxy coated liners are used in CANDU AR storage pools and epoxy/paint is used in Magnox pools. In case of AFR storage installations all pools are stainless steel lined with the exception of UK AFR pools, where most are only lined at the water line, the rest is painted [6].

In case of concrete pools coated with epoxy, the cumulative dose rate on the epoxy has to be limited to prevent the epoxy degradation. To resolve the issue of the epoxy degradation, alternative paint systems have been developed and deployed in the UK [6].

The storage pools at research reactors are usually lined with aluminum sheets, mainly to ensure higher chemical compatibility between aluminum fuel cladding and pool liner as well as higher corrosion resistance in deionised water.

Storage racks and baskets

The materials of racks and basket construction for power reactors are primarily either borated stainless steel, or stainless steel usually in combination with a neutron absorbing material, for example Boral, Boraflex or Cadminox. One exception is the Magnox skip, painted mild steel, which is used to reduce the potential for electro-coupling between the fuel cladding and stainless steel [6]. The racks for storage of research reactor spent fuel are made from aluminum again to reduce galvanic potential between fuel cladding and storage racks.

6.3. Radiological protection
Radiation protection

An inherent feature of the spent fuel storage pools is providing a reliable radiation shielding by the pool water. This requires maintaining the water level at an elevation which provides the required degree of shielding. To limit the radiation fields originated from suspended radioactive materials the storage pools are provided with a water purification (make-up) system.

Appropriate ventilation, including filtration and monitoring systems is also required to be included into design as a protective barrier against airborne effluents to the environment. Such system allows to limit the concentration of airborne radioactive materials and thus to keep the exposures of personnel and public to acceptable levels.

Hollow handling tools intended for use under water are designed so that they fill with water upon submergence to maintain water shielding and drain upon removal.

To meet the regulatory requirements, a comprehensive programme for radiation protection and radiological monitoring with clear defining of organizational structure, main responsibilities, tasks and measurement activities, is required to be developed and implemented during operation of the spent fuel storage facilities.

Occupational doses

The basic safety functions of the spent fuel storage pools allows to adhere the main principles for radiation protection and to keeps the radiation doses at the levels, which are determined in the international standards for protection against ionizing radiation [7].

Operation of the spent fuel pools has not been a significant source of radiation dose to personnel in normal operational conditions. As an example, for CLAB occupational doses between 1986 and 1996 vary from 0.05 to 0.14 manSv/a depending on the amount of maintenance work performed. Assessing an average of 250 t/a spent fuel handled and loaded at CLAB and 25t/GWa, the occupational doses are approximately from 0.005 to 0.014 manSv/GWa [7].

7. Safety criteria for dry storage concept

Taking into consideration the 20-50 years or even longer period required of storage, it is obvious that the naturally cooled dry storage facilities could be an attractive alternative to water pools.

A review of spent fuel storage facilities implemented during the last 10 years shows that the storage in a dry environment is becoming more common. There are several generic types of these technologies available from vendors on the international market. There are also a large number of facility designs based on these generic technologies that are now available. These technologies differ largely in terms of materials of construction, size, modularity, spent fuel configuration, layout of the storage containers (horizontal, vertical etc) and methods for fuel handling. Multi-purpose technologies (i.e. a single technology for storage, transportation and disposal) have also been studied in some countries [8]. Further differences could be in terms of their placement above or under the earth’s surface. An increasing number of storage facilities are coming into operation in each of these types. Although there is no clear favorite technology world-wide, dry storage of spent fuel in casks is being particularly recognized as a flexible option with the advantages of transportability in case of future need, and the option of leasing of casks from vendors.

The spent fuel cladding is the primary structural component that is used to ensure that the spent fuel is contained in a known geometric configuration in storage. The loss of fuel integrity during dry storage means damage of the fuel cladding to an extent which would affect the retrieval and
subsequent handling of fuel or pose radiological problems. Fuel integrity criteria have been evolved on the basis of various phenomena affecting the integrity of fuel such as: cladding creep under internal gas pressure; stress corrosion cracking or delayed hydride cracking of clad; corrosion of clad due to oxidation; defect propagation of clad due to oxidation of UO₂, in case of defective fuel.

To guarantee the fuel integrity during dry storage, the design has been defined design criteria for spent fuel dry storage. The following aspects of the cask and facility design for normal operations and under accident conditions have been considered in a license application: structural robustness (including thermal and material considerations), adequacy of shielding components, maintenance of subcriticality, and adequacy of the confinement boundary.

### 7.1. Temperatures

**Fuel cladding temperature**

The relatively high temperatures, differential pressures, and corresponding hoop stress on the cladding during dry storage will result in permanent creep deformation of the cladding over time. That is why it is important to keep the spent fuel cladding temperatures below expected damage-threshold temperature in normal operation conditions with an adequate margin of safety. A certain limit for short-term accidents and for fuel transfer and transportation has to be defined to avoid appearance of additional thermal stresses in fuel cladding.

The typical maximum temperatures for fuel cladding (Zr based) in dry storage are in the range of 350 to 410°C [6]. As the temperature and decay heat both gradually decrease, the creep is only active for a limited time period, i.e. the first several years of dry storage. The licensed temperatures for LWR fuel also vary from 330 to 410°C. For CANDU fuel the licensed temperatures are up to 160°C [6].

For the storage of high burnup fuel it is necessary to demonstrate that the higher temperatures due to higher burnup will not involve additional clad degradation risk, which could lead to gross cladding rupture.

**Temperature restrictions on cask structure**

The temperature restriction concerning metal and concrete cask structure determines with aim to avoid change in material strength properties and appearance of dangerous thermal and tensile stresses in the cask body, which could lead to formation of cracks. The time dependent degradation processes such as creep, fatigue, crack growth and corrosion are also affected by the high temperatures. The lower temperature is also important because of possible brittle fracture of many metals (including some steels) at reduced temperature and because of possible loss of elasticity of seal materials. Some elastomers (e.g. fluorocarbons) lose their elasticity at temperatures of −20°C or less.

Other reason to keep the casks surface temperature below limiting value is to ensure that the fuel cladding temperatures will not exceed the licensed limits. That is way it is important to keep the cask surface temperatures within their maximum and minimum temperature criteria for all operating conditions.

A comparison of main characteristics of concrete (CONSTOR) and metal (CASTOR) casks, both loaded with RBMK-1500 fuel, is shown that the calculated temperatures for concrete cask are slightly higher that the temperatures for metal cask. For stand alone concrete cask with solar isolation the estimated temperature for metal cask are +72°C in summer and −13°C in winter and for concrete cask are +78°C in summer and −15°C in winter [9].
Some calculations and tests of two types concrete casks (one reinforced concrete cask-RCC and one concrete filled steel cask-CFSC) performed in Japan Central Research Institute of Electric Power Industry show that the maximum concrete surface temperature of RCC is +74°C, while the maximum steel surface temperature of CFSC is +72°C [10]. Some licensing conditions prescribe that the maximum temperature of the concrete wall should not exceed 110°C and maximum temperature drop through the wall thickness should be less than 60°C to avoid the concrete cracking [10].

Although a large reduction in tensile strength of steel occurs at temperature above 500°C, a licensed limit for maximum cask surface temperature for TN-40 steel cask is accepted to be 121°C.

### 7.2. Structures and materials

The casks, silos and vaults are designed to provide structural stability of the storage system against severe accidents. The foundation of the cask or silo storage area has a sufficient capability to withstand the load of the full containers and handling equipment without excessive ground instability which could lead to fuel damage. To avoid structural deformation leading to handling problems, the mechanical structure of the basket or canister is designed to withstand the thermal and mechanical stresses, corrosion and hydrogen attacks and environmental interactions as well as mechanical loads during transportation and accidents conditions.

Casks or silos are provided with a closure system which is secured to the body of the cask or the silo and allows safe retrieval of the spent fuel. Vaults also are provided with closure system for securing of storage canisters or tubes.

### 7.3. Radiological protection

*Radiation protection*

The design of casks, silos and vaults is provided for a reliable radiation shielding so that when they are loaded with fuel, the external radiation fields do not exceed the dose limits. The procedures for loading and unloading of the spent fuel into casks, silos or vaults are performed by using of equipment and methods, which allow reducing of radiological hazard and expected exposures.

Containment barriers (double lids and sealing) for prevention the release of radionuclides are incorporated into the design and form the integral part of the cask, silo or vault. Those areas of vaults affording significant potential for generating or accumulating unacceptable concentration of airborne radionuclides are provided with ventilation and filtration systems. A possibility for monitoring of the spent fuel containment and containment failure detection is incorporated into the design to verify by observation or measurement that the containment systems are performed satisfactory.

*Occupational doses*

The personnel worked at the dry storage facilities, receives very low individual annual doses. On the basis of recent studies [11] an occupational dose of 0.011 manSv/GWa has been assessed for dry cask storage of industrial scale on the basis of annual handling 34 CASTOR-V-19 storage casks holding about 10 tHM each.

### 8. Life of storage facility components

*Dry storage: Consideration should be given to the expected lifetime of selected components of the cask or vaults in order to ensure their proper function over the required period of time. A*
regulatory framework should be developed to provide their re-licensing and/or re-certification. Among the significant components expected to require attention are: sealing system, transportation interfaces (e.g., trunnions), neutron moderator, and monitoring equipment. Welding should also be considered in cases where welded components are integral to performance. For casks constructed with concrete as a significant component and for vault storages, aging of concrete needs to be carefully considered.

**Wet storage:** The durability of spent nuclear fuel facility components in wet storage depends mainly on corrosion status of the structural components. In the case of wet storage all materials corrode in the storage environment, the variance is in the rate of corrosion of the different materials. When the storage duration increases up to 50–100 years, the general corrosion rate for some materials used in storage systems can become a life-limiting factor. Also, the additives, which have been used to minimize other corrosion mechanisms or for system operability purposes, may have detrimental effects on the long-term use of some storage components. The corrosion rate can be reduced sufficiently if the water chemistry has been kept between safety margins, which are defined in the design of the storage facility. Special attention should be paid to the status of the neutron absorbers, storage racks and pool liners. Careful monitoring shall be addressed to the ageing of the storage racks and reinforced concrete structure of the pools.

9. **Burnup credit**

The implementation of burnup credit in spent fuel management systems means reducing the analysis conservatism while maintaining and adequate criticality safety margin. The motivation for using burnup credit in criticality safety applications is based on economic considerations and additional benefits contributing to public health and safety, resource conservatism and environmental quality. The burnup credit results in less transport, smaller number of storage facilities, uses of less gadolinium in dissolvers.

Burnup credit implementation introduced new parameters and effects that should be addresses in the criticality analysis (axial and radial burnup shapes, fuel irradiation history). Analysis of these parameters introduces new variations as well as the uncertainties that should be considered in the safety assessment of the system. Also, the need arises to validate the isotopic composition that results from depletion calculations, as well as to extend the current validation range of criticality codes to cover spent fuel [12].

From analytic point of view, the main difference between a burnup credit analysis and a traditional analysis lies in its complexity. The need for a depletion calculation heavily increases the number of parameters that need to be considered in the analysis. Most of them are operation conditions of the fuel, which sometimes are not so easy to know in detail. The analyst’s judgment to determine the parameter range that covers all the operation conditions (bounding approach) becomes then crucial, and should be exercised with care to avoid underestimation of the reactivity [13].

**Dry storage:** Until recently, criticality safety analysis performed to demonstrate subcriticality under storage conditions assumed that the spent fuel were in their most reactive state, i.e., the spent fuel were assumed unburned or fresh. The advantage of this fresh fuel assumption is simplicity and the disadvantage is an overestimation of the cask content reactivity that results in additional shipments, worker and public exposure and also expensive costs.

The use of burnup credit in criticality analysis is a mean to:

- Increase the cask capacity,
- Accommodate the use of higher initial enrichment fuel with higher burnup, and
• Reduce some costs (fixed poison, number of shipments, radiological protection).

On the other hand the use of burnup credit depends on:

• The verification and validation of computer codes used for criticality evaluation of stored fuel assemblies according to the highest available standards of reliability and quality. Such standards of reliability and quality assurance are normally a basic component of national nuclear regulatory programs. The particular concerns that are associated with the codes that would be used for such evaluations include concerns about biases and uncertainties of calculated $k_{eff}$.

• The availability of calculated and measurement-based burn-up values for all spent fuel assemblies loaded into these casks to assure the subcriticality of the cask content during the entire storage period. In this regard, existing guidance in some countries (USA, Germany) consistently requires measurement of each fuel assembly prior to loading casks, confirming the reactor records and calculated $k_{eff}$ values.

Burnup credit needs to be considered in terms of the cost and benefit of the approach. Special attention needs to be paid to proposals to grant burnup credit to MOX fuels because the nuclide composition is more complex. Individual States may develop standards for the application of burnup credit, based upon the national spent fuel program, particularly as it applies to final disposal options available.

*Wet storage:* In several countries the actinide plus fission product Burnup Credit level is approved and implemented for wet storage of PWR UOX fuel at reactor. Use of the actinide plus fission product level means that credit is taken for the net fissile content of the fuel (taking into account both burnup and buildup of the different fissile nuclides), the absorption effect of the actinides and the neutron absorption in the major fission products [12].

In some countries the actinide-only Burnup Credit level is applied to wet storage of PWR UOX fuel and for RBMK fuel. In this case credit is taken only for the net fissile content of the fuel and the absorption effect of the actinides.

For the wet storage of BWR fuel (UOX as well as MOX) the integral burnable absorber Burnup Credit level is usually used. Credit is taken for the initial presence of integral burnable absorbers (e.g. gadolinium) in the fuel design, and the maximum reactivity of the fuel under the storage conditions of interest is used, which is often not the initial reactivity.

Several countries have wet storage facilities that are away from reactor. In most cases, these pools are not borated. In PWR pools, criticality control may rely on a combination of Burnup Credit and soluble boron. Therefore, Burnup Credit approval may be different for PWR fuel in a un-borated away from reactor wet storage system than that used at the plant.

The fact that there is no critical or subcritical experiment using commercial spent fuel in a configuration of interest (e.g. cask configuration) is certainly one of the main reasons why the application of the actinide plus fission product burnup credit level is restricted to PWR wet storage ponds.

**Conclusions**

The spent fuel represents a potential danger to man and environment and has to be isolated from biosphere for a very long time. This requires some regulatory principles, requirements and measures for radiological protection of the personnel, the public and the environment to be formulated and adequately implemented so as the risk from the spent fuel storage can be
minimized. The new challenges are to extend the life of existing and new wet and dry storage facilities and guarantee their safe performance for periods significantly extending 40 – 50 years. An extension of the life of the spent fuel storage facilities requires re-examining of the safety requirements, which have been determined in the past. The main safety criteria and some requirements to the materials and to the operational conditions are discussed in this paper. An attempt for comparison of the safety criteria and general problems for the both type of storage (wet and dry) has been made.

References


