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Aging Effects on Structural Concrete and Long-term Storage of Spent Nuclear Fuel in DCSS at ISFSIs in the USA

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ABSTRACT

As the wet spent fuel pools at the operating commercial nuclear reactor facilities in the US reach their storage capacity the licensees transfer the Spent Nuclear Fuel (SNF) to Dry Cask Storage System (DCSS) and move these casks to Independent Spent Fuel Storage Installations (ISFSIs). Existing ISFSIs in the United States of America were licensed for an initial period of 20 years. The U.S. Nuclear Regulatory Commission (NRC) has revised 10 CFR Part 72, so that the initial licenses and renewal may now be issued for periods not to exceed 40 years. Thus in effect upon first renewal, the approved design bases for the facility must be maintained for periods up to 60 years. Short of any permanent repository and/or interim consolidated storage facilities, these ISFSIs may be storing SNF on the order of 100 years and beyond. Licensees must include an aging management program (AMP) as defined in the 10 CFR Part 72 regulations for renewals of existing ISFSIs.

The DCSS consists of various structural materials including structural concrete. Therefore to ensure the safety of these DCSS, it is important that the structural concrete perform its intended safety functions for a considerable length of time, after the initial construction. This paper will briefly discuss aging effects on safety related concrete structures used for long-term storage of SNF in DCSS. The degradation of structural concrete over an extended period of time, a few major mechanisms and its effects on the structural concrete, deterioration of concrete, detection, inspection, measurement, prevention and mitigation, are some of the issues addressed in this paper.

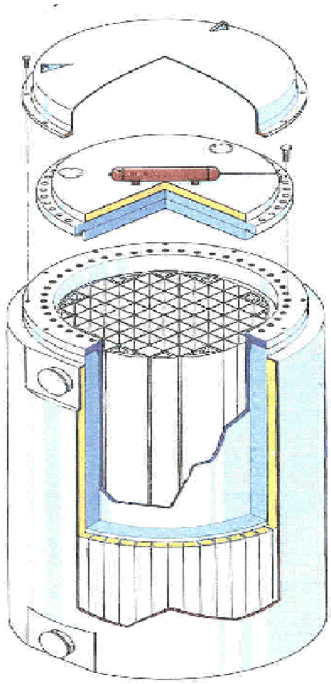
INTRODUCTION

ISFSI designs in the United States utilize DCSSs that provide confinement, radiological shielding, retrievability, maintain sub-criticality, and provide inherently passive cooling of its spent nuclear fuel during normal, off-normal, and accident conditions. The NRC staff developed 10 CFR Part 72 (2015) to regulate spent fuel storage outside reactor storage basins, the High Level Waste (HLW), and Greater Than Class C (GTCC) waste. The regulation covers both wet and dry storage systems for general licensees, and site-specific licensees of ISFSIs that can be located either at reactor sites or away from them. Therefore, an ISFSI license is a materials license and not a facility license (NUREG-1571). In 1986, the Surry Nuclear Power Plant became the first utility in the U.S. to obtain a license to store spent nuclear fuel in a site-specific ISFSI under the requirements of 10 CFR Part 72. Since then, many DCSS design types have been approved for use in licensed ISFSIs: metal storage casks, concrete storage casks, metal canisters housed in concrete modules, concrete storage vaults, casks designed for high floods, wind and seismic forces, underground storage, etc.

There are two basic types of DCSS used. As shown in Figure 1, and Figure 2, they are oriented either vertical or horizontal. They may be stored either above ground, or below ground. Most of them are unanchored simply resting on the reinforced concrete supporting pad. A typical ISFSI consists of several DCSSs arranged on a reinforced-concrete pad in a secured area within the physical boundary of a nuclear power plant. In a few cases ISFSIs are away from reactors or stand-alone at a few decommissioned sites.

Because currently there is no other federal disposal option, U.S. utilities have developed ISFSIs as a means for expanding their spent fuel storage capacity on an interim basis.

Steel Cask with Bolted Closure



Concrete Cask with Welded Closure

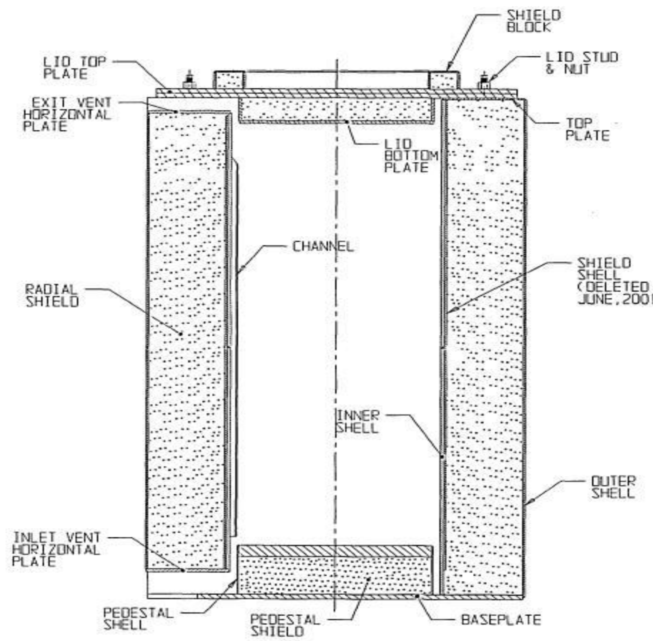


Figure-1 Vertical DCSS

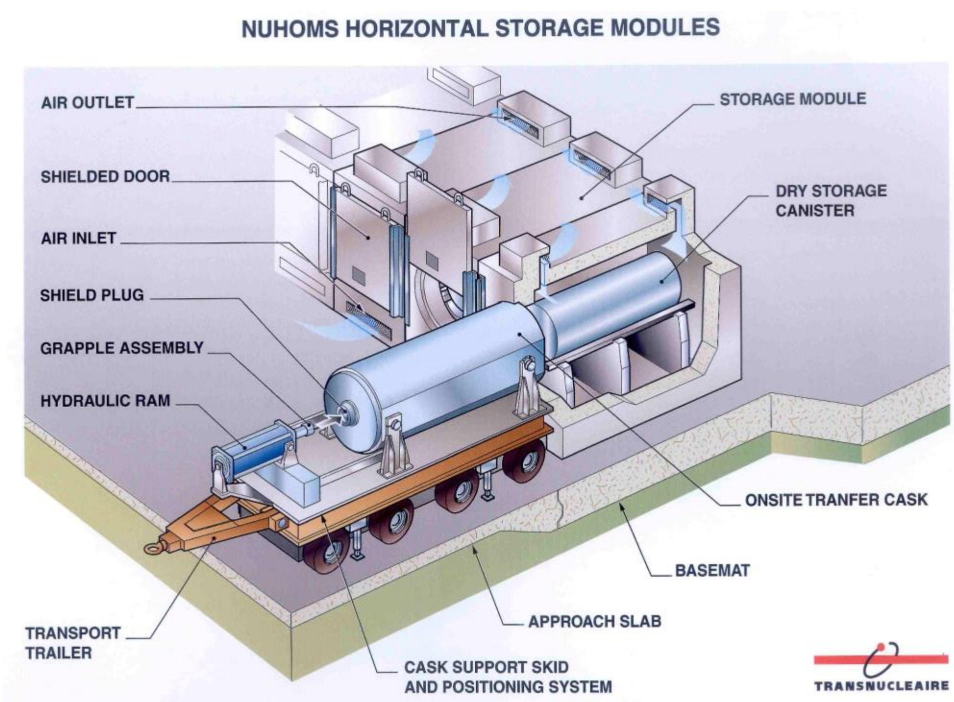


Figure-2 Horizontal DCSS

Structural concrete deteriorates over time with age and with use, and potential external events, such as winds, tornados earthquakes, etc. In the United States, the DCSS and the related structures of ISFSIs are governed by the regulations as provided in Code of Federal Regulation 10 CFR Part 72. The use of concrete in DCSS and their safety functions and associated technical challenges are as summarized in the tablet below: The concrete (unreinforced or reinforced) is used to support the external and internal loads that are postulated for the design life, and also to provide adequate protection (shielding) from potential source of radiation expected over the functional design life of a particular storage system.

- **DCSS is designed and built to comply with 10 CFR Part 72 regulations**

- **Safety Functions**
  - Structural/Material integrity
    - ✓ Robustness against severe man-made events
    - ✓ Withstand external natural phenomena hazard (NPH) events
  - Radiological Shielding and Criticality Control
  - Heat Transfer

- **Technical Challenge is to maintain intended design safety functions for:**
  - Initial license (20 Yrs.)
  - Renewal license (First Renewal up to 40 Yrs.)
  - Extended Storage - Long-term (a period of up to 300 years)

A list of major mechanisms and its effects on concrete aging are shown in Table-1. For detailed discussions of these aging mechanisms and its effects on concrete, refer to [Torres, R. D., et, al., 2015].

Table - 1 Mechanism and Effects of Concrete Aging

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Mechanism	Effects
Freeze-thaw	Cracking, loss of material (spalling, scaling)
Chemical attack [Cl, SO_4]	Cracking, loss of material (spalling, scaling)
Aggregate reactions/expansion	Cracking and loss of strength
Corrosion of embedded steel	Cracking, loss of material (spalling, scaling) and loss of bond
Leaching of $Ca(OH)_2 \rightarrow Ca(CO)_3$	Increase in porosity/permeability, loss of strength
Settlement (short & long-term)	Cracking, distortion
Gamma irradiation	Cracking, reduction in strength (change in mechanical properties)
High temperature dehydration	Cracking, reduction in strength (change in mechanical properties)

CONCRETE DEGRADATION

A long service life is considered synonymous with durability. Since durability under one set of conditions does not necessarily mean durability under another, we will include a general reference to the environment when defining durability. American Concrete Institute (ACI) Committee 201 (2008) defines durability of Portland cement concrete as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration; that is, durable concrete will retain its original form, quality, and serviceability when exposed to its envisioned environment.

No structural material is indefinitely durable; as a result of environmental interactions, the microstructure, and consequently the properties of materials change with time. A material is assumed to reach the end of service life when its properties under given conditions of use have deteriorated to an extent that the continuing use of the material is ruled either unsafe or uneconomical. Concrete structures are generally designed for a service life of 50 years, but experience shows that in urban and coastal environments many structures begin to deteriorate in 20 to 30 years or even less time (Ref. Mehta P. K. July 1998).

The likelihood and amount of cracking in concrete depend on the following items: (1) contraction (from drying and/or cooling); (2) restraint (may be external or internal; full or partial); (3) elasticity, or stiffness (stress per unit length of restraint); (4) stress (tensile; elastic); (5) creep; (6) net tensile stress; (7) tensile strength. As shown in Figure-3, the magnitude of the shrinkage strain is just one of the factors governing the cracking of concrete. As such the concrete reliability also relies on potential deformations caused by applied stress, strain, thermal, and moisture-related effects, and whether or not their interaction would lead to cracking.

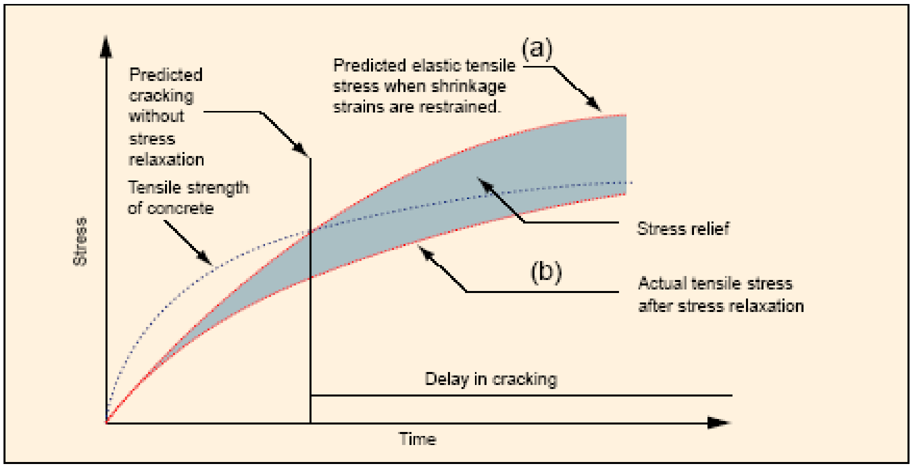

Figure-3 Cracking of Concrete [Mehta P. K., 1998]

A few of the other major factors that impact durability include the materials:

• Modulus of elasticity. The lower the modulus of elasticity, the lower will be the amount of the induced elastic tensile stress for a given magnitude of shrinkage.

• Tensile strength. The higher the tensile strength, the lower is the risk that the tensile stress will exceed the strength and crack the material.

The combination of factors that are desirable to reduce the advent of cracking in concrete can be described by a single term called extensibility. Concrete is said to have a high degree of extensibility when subjected to large deformations without cracking. For minimizing the risk of cracking, the concrete should undergo not only less shrinkage, but also have a high degree of extensibility (i.e., low elastic modulus, high creep, and high tensile strength). In general, high strength concretes are more prone to cracking because of greater shrinkage and lower creep properties; on the other hand, low strength concretes exhibit lower shrinkage and higher creep and tends to crack less.

It is a well-known fact that Portland cement concrete mixtures are highly crack-prone and therefore become permeable during service. The embedded steel reinforcement in permeable concrete corrodes when conditions for corrosion are present, causing progressive deterioration of the structure. The end result is that the extensibility or crack-resistance of modern concrete is poor because of the high tensile stress induced by too much thermal contraction and drying shrinkage, and too little creep relaxation. With optimum mix of cement; aggregate; water; and admixtures, the durability of concrete structures can be increased to last for up to 500 years (Dhir R.; Hewlett P., 2003). The high-volume fly ash concrete system provides a future model for making concrete mixtures that will relatively shrink less and crack less than the one with low-volume or no fly ash, and would be far more durable and resource-efficient than conventional Portland cement concrete. The unreinforced Roman concrete (mixed with fly ash) continues to be in good condition even after almost 2000 years. With modern know-how one can certainly do equal, if not better.

DCSS AND ISFSI - CONCRETE

The spent nuclear fuel assemblies are loaded into a canister (or cask) under water in the spent-fuel pool. The canister (or cask) containing the spent fuel assemblies is then drained, vacuum dried, and back-filled with helium through a drain port after the lid is closed, either by welding or by bolted closure. The welded canister (after being placed inside a transfer cask) and the bolted cask are moved to an outdoor concrete pad of an ISFSI for safe storage per10 CFR 72.42. Approximately 2,000+ dry casks have begun storage under the initial license terms; some of them have been in storage for over 20 years and are already in the license renewal term for up to 40 years [ANL-13/15, Sept. 2014].

DCSSs and ISFSIs design must ensure that the design bases and the safety functions are maintained throughout the storage period. As prevention of concrete degradation is more desirable and better than mitigation and/or repair/rebuild, what is needed is a comprehensive Aging Management Program (AMP) or Time Limited Aging Analysis (TLAA). AMP or TLAA is only required at the time of the storage license renewals. At the NRC these steps are being taken as evidenced in the NRC Guidance document NUREG -1927, Revision 1 (2015). A DCSS applicant may propose an AMP based on alternate guidelines. Exclusion of aging effects/mechanisms in the applicable codes/standards should be justified with a site-specific technical basis (e.g., engineering analysis, operational experience data, and environmental conditions). Justification should demonstrate that the excluded aging mechanisms will not adversely affect the ability of the in-scope concrete structure to perform its intended important to safety (ITS) function during the license period of extended operation [Torres, R. D., et, al., 2015]

Structural concrete consists of three basic ingredients; Portland cement, aggregates (both fine/sand and coarse/stone) and water. The ingredients are mixed to form a mixture able to flow that can be placed in forms that mold the concrete into the desired shape. After the concrete ingredients are mixed, the Portland cement begins to hydrate. This process involves the chemical bonding of the cement with the water molecules, which will eventually form a hardened matrix. Hardened concrete has very good compressive strength, but very poor tensile strength. It is well known from the concrete industry open literature that concrete tensile strength is about 10% of its compressive strength.

There are a few other issues with hardened concrete that may potentially prove damaging to the vertical DCSS, such as an increase in the maximum deceleration during a non-mechanistic tip-over condition, which has to be met subsequent to concrete hardening over extended period of time (Tripathi, B. P. 2007); (Tripathi, B. P. 2011). Reinforcing steel on the other hand has both very good tensile strength and thermal properties that are compatible with concrete. The complementary properties of concrete and steel are combined to provide reinforced concrete structures that are capable of supporting considerable loads for decades. Deterioration in concrete can result in the potential loss of strength and may lead to unsafe conditions. Therefore it is important to have an understanding of the vulnerabilities of concrete structures in order to help minimize long-term repair and maintenance costs. A photograph of the effects of concrete deterioration due to sulfur is shown in Figure-4 below.

Figure-4 Concrete Deterioration due to Sulfur

The reason that reinforcing steel in concrete is protected against corrosion is because the alkalinity of the concrete allows the steel to form a protective layer that prevents the anodic dissolution of the iron. If carbonation of the concrete causes a drop in the normal pH level of the matrix below a threshold level, or if the chloride content of the concrete at the reinforcing location exceeds a critical value, then the protective layer around the steel will dissolve and deterioration in the form of corrosion of the steel will start. In both cases, however, the presence of moisture is necessary to perpetuate the deterioration process. While carbon dioxide needs air-filled pores for penetration, chloride spreads by diffusion through totally or partly water-filled pores. The wetting and drying of a concrete surface with chloride containing water will cause a high concentration of chloride at the surface. Due to the diffusion process, the chloride concentration will normally decrease between the surface and the interior of the concrete. In structures containing cracks, both carbonation and chlorides tend to penetrate faster towards the embedded reinforcing. Narrow cracks can limit the amount of penetration, but wider cracks often have a high chloride concentration at the root of the crack in the region of the reinforcing. [D. Matthew Stuart, 2013]

The sulphate attack is a chemical breakdown mechanism where sulphate ions attack components of the cement paste. The compounds responsible for sulphate attack are water-soluble sulfate containing salts, such as alkali-earth (calcium, magnesium) and alkali (sodium, potassium) sulphates that are capable of chemically reacting with components of concrete. Rotting seaweed has been known to produce sulfur. Sulfur can be easily converted to sulfuric acid (See Figure - 4). The presence of sulfuric acid on concrete leads to concrete disintegration. The growth of seaweed may also create a problem if the seaweed is exposed at low tide. When the seaweed is exposed at low tide, the seawater that is retained by the seaweed becomes more concentrated by evaporation. There is a potential of this damage to the ISFSI

support pad at a few locations in the vicinity of sea shores. As the concentration of seawater increases, its effect on concrete increases.

As structural concrete is highly alkaline, it provides an environment that limits the corrosion of embedded steel and helps to assure the durability of the reinforced concrete member. For this reason reinforcing bars are embedded well below the concrete surface. The required cover typically ranges from 1½ to 3 inches, depending on the type of environmental exposure. Although, ACI 318-11 and ACI 349-13 has minimum concrete cover requirements, maintaining proper cover during construction, if not adequately monitored, has a potential of being compromised. Consequently insufficient cover is a common occurrence. The closer the steel is to the concrete surface, the more likely it will corrode. Long-term deterioration can occur at the embedded reinforcing steel as well as at the exposed concrete surface.

A few of the other significant mechanisms of deterioration in concrete, and ways to detect them are listed below:

- Deterioration can occur by surface wear by Abrasion: dry attrition (wear on concrete pad), Erosion: wear produced by abrasive action of fluids containing solid particles in suspension (inside the storage module), and Cavitation: loss of mass by formation of vapor bubbles and their subsequent collapse (e.g. inside the horizontal storage module).

- Deterioration by frost action "Freeze-Thaw" (See Figure-5) can occur when water freezes; there is an expansion of 9%. However, some of the water may migrate through the boundary, decreasing the hydraulic pressure. Hydraulic pressure depends on: rate at which ice is formed, permeability of the material and the distance to an "escape boundary".

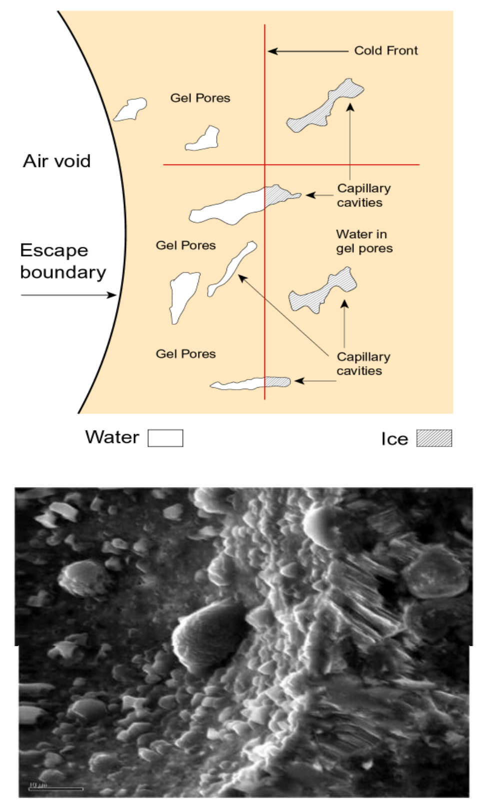

Figure-5- Freeze-Thaw and Escape Boundary [Mehta and Monteiro, 2013]

- Phenomena such as: delayed etringite formation, corrosion of rebar, radiation damage and alkali-silica reaction (ASR) reactions.

- Salt scaling and crystallization, aggressive ion (e.g. H^+ or Mg^{++}) attack. Chloride ion ingress for broader coverage of the steel corrosion problem in concrete. These mechanisms may have low likelihood of occurrence in DCSS for spent nuclear fuel, but they are as important.

- The effects of creep, carbonation, and radiation damage, can be assessed by visual inspection. Other degradation mechanisms, such as sulphate attack and fatigue, are only marginally detected by visual observation.

Visual inspection (digital images); electrochemical potential; laboratory analysis of material samples, coarse NDE methods to estimate extent of cracking, etc. are appropriate for exposed concrete. New, emerging techniques, such as laser-induced breakdown spectroscopy (LIBS) may also find use for exposed concrete.

OTHER STORAGE SYSTEMS

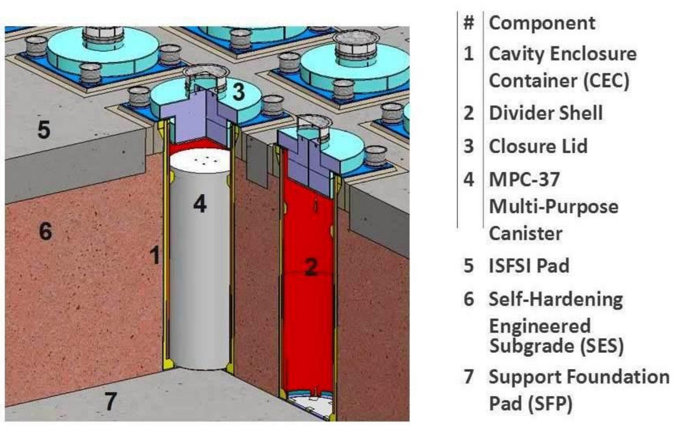

Figure -6 HOLTEC UMAX Systems - Version MSE

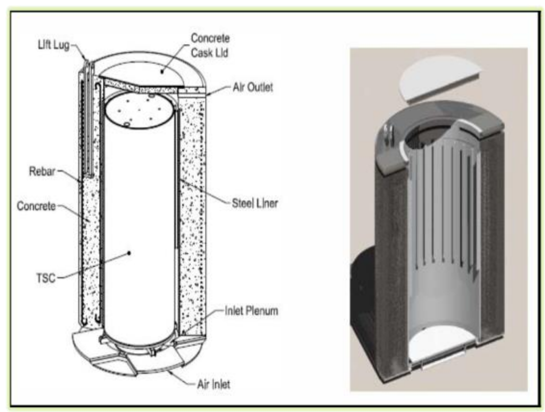

Figure - 7 MAGNASTOR Systems

As illustrated in Figure 6, and 7 above, there are a wide variety of systems currently being used in the U. S for dry storage of spent nuclear fuel; using a combination of steel and/or concrete. Aging management programs are being developed by the NRC to ensure that potential degradation mechanisms are identified, and the design safety functions are maintained for long-term storage.

A few concrete industry publications for standard specifications and structural conditions assessment of existing concrete, such as: ACI 201.1R-08, ACI 224.1R-07, ACI 318-11, ACI 349-06, ACI 349.3R-02, SEI/ASCE 11-99, ASTM C260, ASTM C295, etc. are listed in the references herein, and their context is as detailed in reference [Torres, R. D., et.al). Prevention, mitigation, inspection and monitoring, AMP and TLAA, remediation and repair, are just a few of the topics that are further investigated currently by the NRC staff, in order to ensure the long-term functional capabilities of the ISFSI related ITS reinforced concrete structures. These issues are further addressed, in detail, in NRC NUREG - 1927, Revision 1(2015).

CONCLUSION

This paper briefly discussed aging effects on structural Concrete for safety related structures, used for storage of SNF in DCSS, at the ISFSIs in the USA. Various mechanisms of concrete degradation and its effects on performance of concrete were addressed. In this regard, in evaluating component and system aging, the staff analyzes for period that extends from initial licensing of 20 years and renewal of up to 40 years of dry storage, and this is reflected in the staff's approach for time-limited aging analysis.

Within the extended storage of SNF regulatory program, the aging of systems and components may have to be viewed as occurring on a continuum that extends from initial licensing and renewal, through longer periods of extended storage.

The functionality of the degraded structural system is dependent on the structural configuration, environment, and operating conditions. Addressing these attributes in the aging management program provides a reasonable assurance that the SNF storage system's safety functions will continue to perform as intended. The regulators and industry are reviewing the potential degradation mechanisms. The aging management program addresses these reviews to comply with the design bases and the required safety functions of the DCSS, and thereby protecting public health and safety.

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