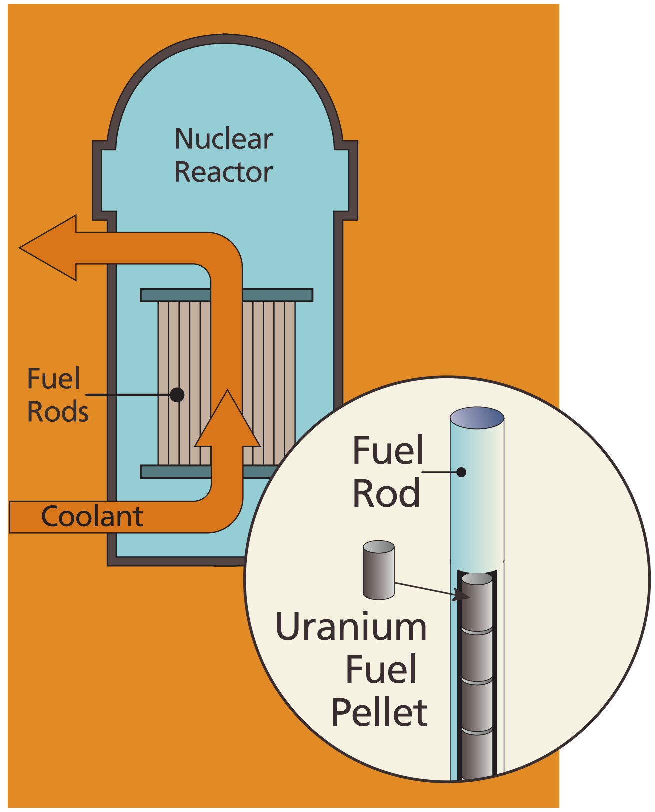
Appendix B
Safety of Spent Fuel Storage
NUREG BR-0528

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Safety of Spent Fuel Storage

What Is Spent Fuel?



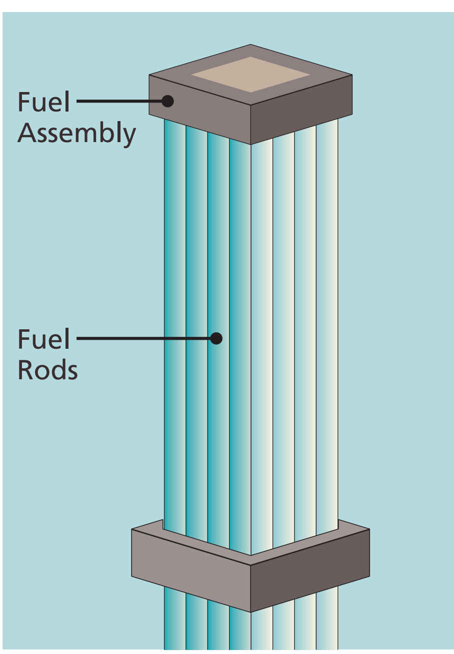
Nuclear reactors use uranium fuel rods bundled into fuel assemblies to generate the heat that turns generators. These generators produce electricity that powers people's homes.

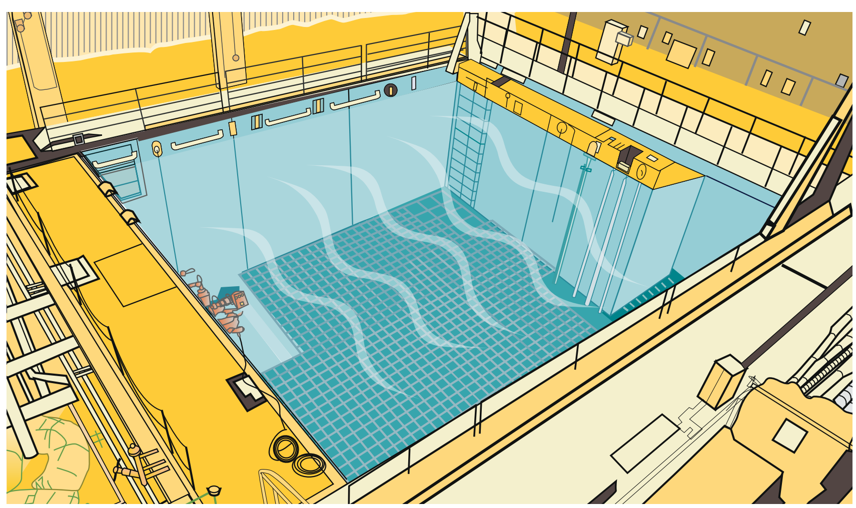
As it burns in the reactor, this fuel becomes very hot and very radioactive. After about 5 years, the fuel is no longer useful and is removed. Reactor operators have to manage the heat and radioactivity that remains in this spent fuel.

In the United States, every reactor site has at least one pool on site for spent fuel storage. Plant personnel move the spent fuel underwater from the reactor to the pool. Over time, spent fuel in the pool cools as the radioactivity decays away.

These pools were intended to provide temporary storage. The idea was that after a few years, the spent fuel would be shipped offsite to be reprocessed, or separated so usable portions could be recycled into new fuel. But reprocessing did not succeed in the United States, and the pools began to fill up.

In the early 1980s, reactor operators began to look for ways to increase the amount of spent fuel they could store onsite. They began to place fuel in dry casks that could be stored in specially built facilities on their sites. Most nuclear plants today use dry storage.





Spent fuel pool

Dry Cask Storage—The Basics

At least 23 feet of water covers the fuel assemblies in the spent fuel pool of Unit 2 at the Brunswick Nuclear Power Plant in Southport, NC.
(Courtesy: Matt Born/Wilmington Star-News)

A dry cask storage system is a cylinder that operators lower into the pool and fill with spent fuel. They raise the cylinder, drain, and dry it, before sealing and placing it outdoors on a concrete pad. There are many varieties of spent fuel storage casks. They all need to:

- Maintain confinement of the spent fuel
- Prevent nuclear fission (the chain reaction that allows a reactor to produce heat)
- Provide radiation shielding
- Maintain the ability to retrieve the spent fuel, if necessary
- Resist earthquakes, tornadoes, floods, temperature extremes, and other scenarios.

Casks come in different sizes. They are tall enough to hold spent fuel, which can be up to 14 feet long, and they can weigh up to 150 tons—as much as 50 midsize cars. Plants may need a special crane that can handle heavy loads to be able to lift a loaded cask full of water out of the pool for drying. After the casks are dried, robotic equipment is used to seal them closed to keep doses to workers as low as possible.

Two basic designs are in wide use today. Welded, canister-based systems feature an inner steel canister that contains the fuel surrounded by 3 feet or more of steel and concrete. The canisters may be oriented either vertically or horizontally. In bolted cask systems, there is no inner canister. Bolted casks have thick steel shells, sometimes with several inches of radiation shielding inside.

Plants use special transporters to move the loaded cask outdoors to where it will be stored. At that point, the radioactivity from the cask must be less than 25 millirem per year at the site boundary. That means the highest dose allowed to someone standing at the fence for a full year is about the dose someone would receive going around the world in an airplane. The actual dose at the site boundary is typically much lower.

Dry cask storage has proven to be a safe technology over the 30 years it has been used. Since the first casks were loaded in 1986, dry storage has released no radiation that affected the public or contaminated the environment. As of January 2017, more than 2,400 casks have been loaded and are safely storing 100,000 spent fuel assemblies. Tests on spent fuel and cask components after years in dry storage confirm that the systems continue to provide safe storage.

Loading spent fuel cask under water.
(Courtesy: Holtec International)

The U.S. Nuclear Regulatory Commission (NRC) analyzed the risks from loading and storing spent fuel in dry casks. Two separate studies found the potential health risks are very, very small. To ensure continued safe dry storage of spent fuel, the NRC is further studying how the fuel and storage systems perform over time. The NRC is also staying on top of related research planned by the Department of Energy and the nuclear industry.

Workers prepare to load an AREVA-TN NUHOMS canister into a concrete storage module at the Calvert Cliffs Nuclear Power Plant in Lusby, MD. (Courtesy: Exelon)

What We Regulate and Why

The NRC oversees the design, manufacturing, and use of dry casks. This oversight ensures licensees and designers are following safety and security requirements, meeting the terms of their licenses, and implementing quality assurance programs.

The NRC's regulations appear in Chapter 10 of the Code of Federal Regulations*, also known as 10 CFR.*

Cask designers must show that their systems meet the NRC's regulatory requirements. The NRC staff reviews cask applications in detail. The agency will only approve a system that meets NRC requirements and can perform safely. NRC inspectors visit cask designer offices, fabricators and spent fuel storage facilities to ensure they are meeting all our regulations. Cask design applications, the NRC's documentation of reviews, and NRC inspection reports are available to the public on the agency website at www.nrc.gov.

There are strict security requirements in place to protect the stored fuel. Security has multiple layers, including the ability to detect, assess, and respond to an intrusion. Our general security requirements for dry cask storage are in 10 CFR Part 73 (https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/). The specific requirements in NRC orders and the licensee's security plans are not available to the public, as they could give an adversary the ability to defeat the security measures and compromise the safety systems. There have been no known or suspected attempts to sabotage cask storage facilities.

The NRC's requirements for dry cask storage can be found in 10 CFR Part 72 (https://www.nrc.gov/reading-rm/doc-collections/cfr/part072/), which requires all structures, systems, and components important to safety to meet quality standards for design, fabrication, and testing. Part 72 and related NRC guidance on casks and storage facilities also detail specific engineering requirements.

The NRC has dozens of experts in different scientific and engineering disciplines whose job is to review cask applications (which can be hundreds of pages long) and the detailed technical designs they contain. The agency will only approve a storage cask design if these experts are satisfied that all the specific safety requirements in each discipline have been met.

Cask transporter moves loaded spent fuel storage cask to storage pad.

The following sections discuss technical evaluations the NRC conducts during technical
reviews of dry cask storage.

Materials

NUHOMS horizontal spent fuel storage system under construction at the Calvert Cliffs Nuclear Power Plant in Lusby, MD.

Materials—the stuff of which everything is made. In every case—the metal in a car door, the plastic used in airplane windows, or the steel used in elevator cables—the selection of appropriate materials is critical to safety.

Systems that transport and store spent nuclear fuel and other radioactive substances are made of a variety of materials. All of them are reviewed to confirm that those systems can protect the public and environment from the effects of radiation. The NRC does not dictate what materials are used. Rather, the NRC evaluates the choice of materials proposed by applicants. What makes a material "appropriate" to transport and store radioactive substances depends on a number of factors.

First, materials must be adequate for the job. In other words, the mechanical and physical properties of the materials have to meet certain requirements. For example, the steel chosen for a storage cask has to withstand possible impacts such as from tornadoes or earthquakes.

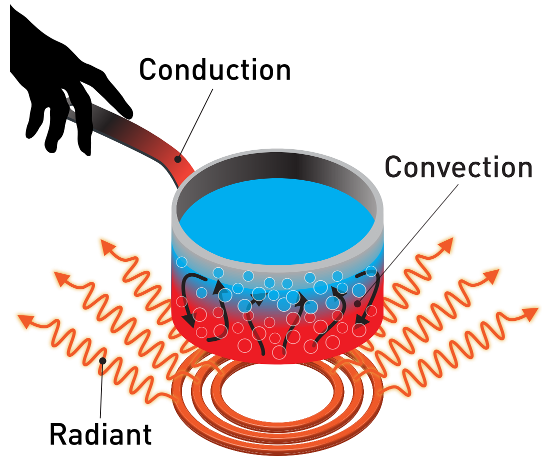
Next, when making a complex metal system, parts often are welded together—that is, partially melted—in a way that ensures that the joints themselves are adequate. The welder actually creates a new material at the joint with its own unique properties. That is why the NRC looks at how this is done, including the selection of weld filler metals, how heat is controlled to ensure good welds, and the use of examinations and testing to verify that no defects are present.

Finally, the NRC considers how materials degrade over time. Reviewers must take into account a material's chemical properties, how it was manufactured, and how it reacts with its environment. Just as iron rusts and elastic materials become brittle over time, all materials can degrade. This degradation and its impact must be well understood. Materials must be selected based on their present condition and their projected condition throughout their lifetimes.

Loaded vertical HI-STORM 100 casks are storing spent fuel at the Diablo Canyon Power Plant in Avila Beach, CA.

Best practices for appropriately selecting materials and the processes used to join them often can be found in consensus codes and standards. These guidelines are typically developed over many years of operational experience, and through industrywide and government technical discussions and agreement. The NRC also relies on both historical operating experience and the latest materials performance and testing data.

Managing Heat



Three different methods transfer heat.

Keeping the spent fuel from getting too hot is one way to ensure casks will be safe. The NRC requires the cask and fuel to remain within a certain temperature range. These requirements protect the cladding (the metal tube that holds the fuel pellets). As the fuel cools, heat is transferred from inside the cask to the outside. NRC experts examine how that heat will move through the cask and into the environment.

The method used to remove heat has to be reliable and provable. It must also be passive—that is, without the need for electrical power or mechanical device. Casks use conduction, convection, and radiation to transfer the heat to the outside.

Conduction transfers heat from a burner through a pot to the handle. The process of heat rising (and cold falling) is known as convection. The heat coming from a hot stove is known as radiant heat.

These methods work the same way in a storage cask. Where the structure containing the fuel touches the fuel assemblies, it conducts heat toward the outside of the cask. Most casks have vents that allow outside air to flow naturally into the cask and around the canister to cool it (convection). And most casks would feel warm to the touch from radiant heat, much like a home radiator.

The NRC also confirms that the pressure inside a cask is below the design limit so it will not impact the structure or operations. Technical experts review applications for cask designs carefully to verify that the fuel cladding and cask component temperatures and the internal pressure will remain below specified limits.

Each storage cask is designed to withstand the effects from a certain amount of heat. This amount is called the heat load. The NRC reviews whether the designer correctly considered how the heat load will affect cask component and fuel temperatures, and how this heat load was calculated. Cask designs must show that heat from spent fuel can be effectively transferred to the outside of the cask.

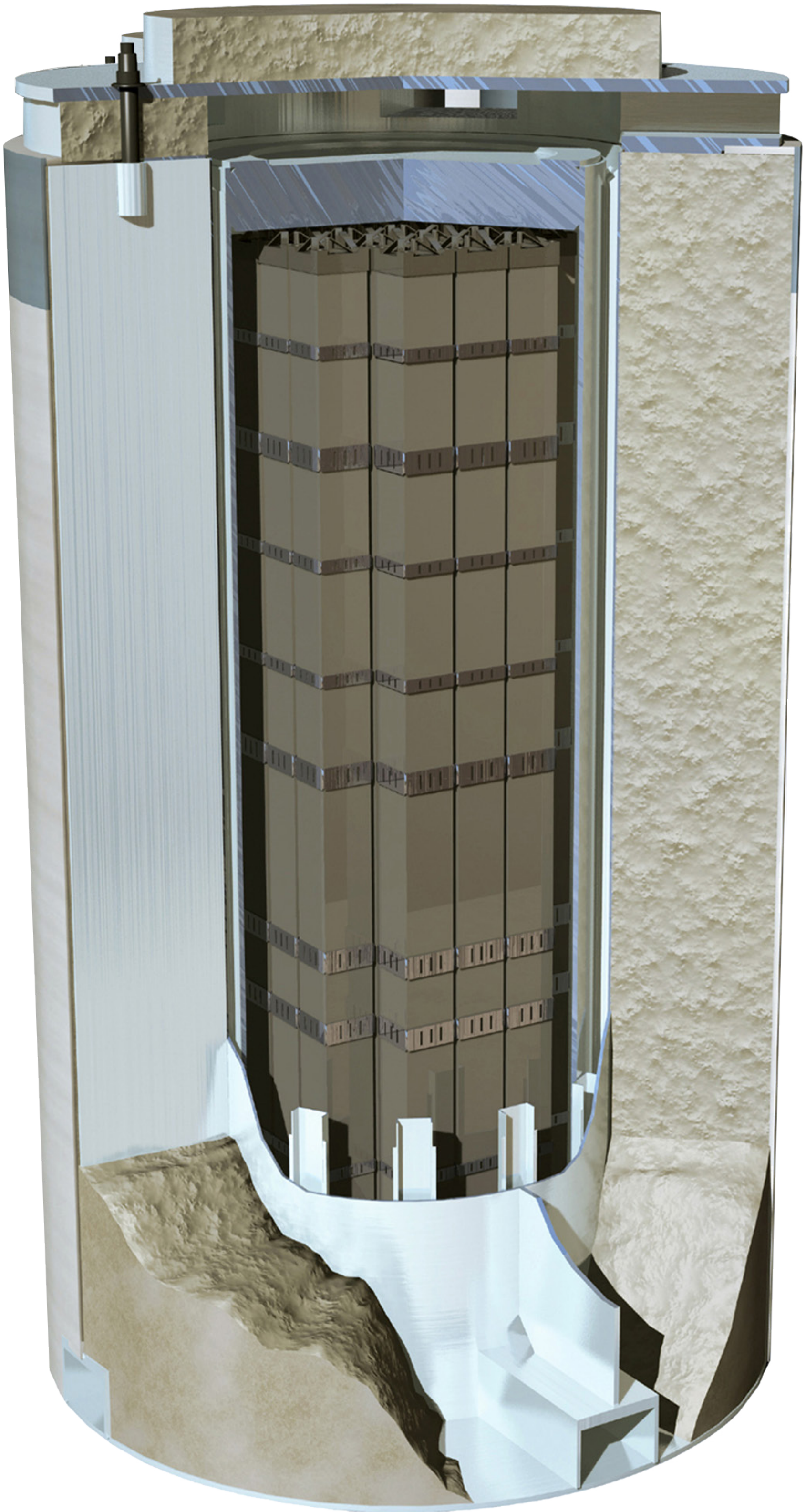
The NRC's review also verifies that the cask designer looked at all the environmental conditions that can be expected to affect cask components and fuel temperatures. These conditions may include windspeed and direction, temperature extremes, and a site's elevation. To make sure the right values are considered, the NRC verifies that they match the historical records for a site or region.

NRC reviewers consider all of the methods used to prove that the storage system can handle the specified heat loads. They verify computer codes, making sure they are the latest versions and have been endorsed by experts. They look at the values used in the codes, such as for material properties, and confirm calculations for temperature and pressure. The NRC might run its own analysis using a different computer code to see if those results match the application.

Making Sure Casks Will Hold Up

In its application, the cask designer must provide an evaluation that shows the system will be strong and stable enough to perform its safety functions even after experiencing a load, such as if the cask were dropped. NRC reviewers examine the structural design and analysis of the system under all credible loads for normal conditions—that is, planned operations and environmental conditions that can be expected to occur often during storage. They also look at accidents, natural events, and conditions that can be expected to occur from time to time, but not regularly.

The NRC review looks at whether the cask designer evaluated the proper loading conditions. It will also ensure the designer evaluated the system's response to those loads accurately and completely. Reviewers must verify whether the resulting stresses in the material meet the acceptance criteria in the appropriate code. The NRC's review also looks at several different realistic combinations of loads. These cases are analyzed to determine the stresses placed on the material used to construct the cask system. To be conservative, the NRC and the designers overestimate loads and underestimate material strength. Doing this enhances the NRC's assurance that the design is adequate.



Cutaway of spent fuel storage cask shows spent fuel assemblies surrounded by steel and thick concrete shielding.

Confinement

The cask design must prevent the release of radioactive material. This role is performed by the confinement boundary, which usually includes a metal canister with a lid that has at least two closures. Some casks have two separate lids that are each welded closed. Others are bolted and have two separate seals. Having both closures provides an extra layer of protection to ensure the radioactive materials remain confined.

Loaded spent fuel storage casks are in place on storage pad at the Haddam Neck Plant in Meriden, CT. (Courtesy: Connecticut Yankee)

The design must also keep the fuel assemblies in a protected, or "inert," environment. This is important to keep the fuel cladding from degrading. Once the water is removed from inside the cask, it is filled with a gas such as helium that will not react with fuel cladding.

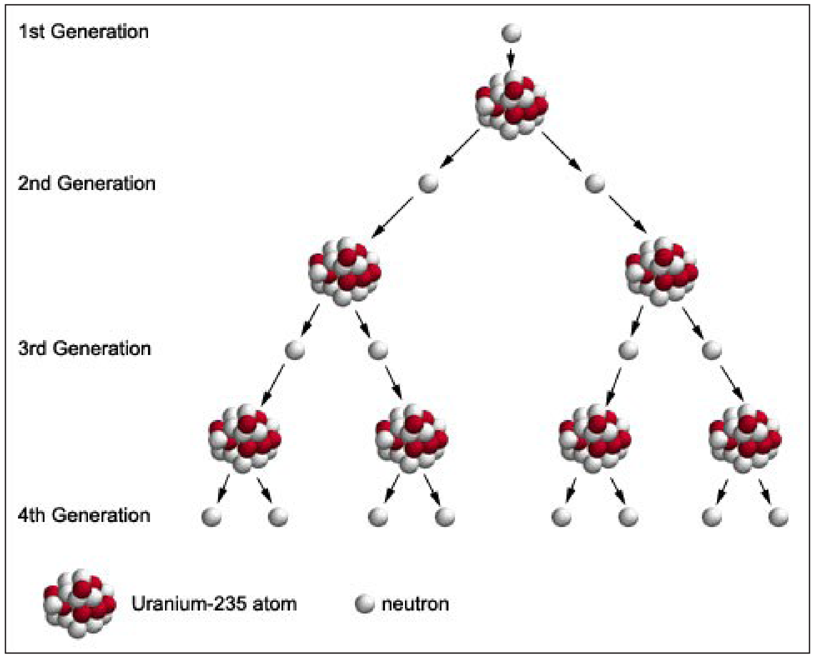
Cask users must monitor the confinement boundary. The monitoring requirements depend on whether a cask is bolted or welded. Bolted confinement boundaries with O-ring seals need to have alarms to alert the user if a seal starts to leak. In that case, the seal would need to be repaired or replaced to ensure the cask continues to have redundant confinement. Our experts review the proposed monitoring programs to make sure they are adequate. Welded closures do not need to be monitored in the same way. This is because the welds are examined closely after they are made to ensure they do not leak.

The NRC's review of a cask's confinement boundary looks at the "source term." This is the inventory of radioactive material inside the cask. While the redundant closures and other requirements ensure the material will remain safely confined, the NRC requires cask designers to look at the dose rates in case some material were to come out. They also need to analyze how those dose rates compare to the NRC's regulatory limits.

Loaded spent fuel storage cask on transporter is moved from the fuel handling building at the Surry Power Station in Surry, VA.

Finally, cask designers must provide an analysis of how the confinement boundary works. Casks must be designed and tested to meet criteria approved by the American National Standards Institute, or ANSI. The ANSI standard for leak tests on radioactive materials packages was put together by a committee of experts and went through a lengthy review and approval process before it was adopted.

Criticality Safety



Neutrons cause uranium-235 atoms to split in a nuclear chain reaction.

The nuclear chain reaction used to create heat in a reactor is known as fission. In this process, uranium atoms in the fuel break apart, or disintegrate, into smaller atoms. These atoms cause other atoms to split, and so on. Another word for this process is criticality.

The potential for criticality is an important thing to consider about reactor fuel throughout its life. Fuel is most likely to go critical when it is fresh. The longer the fuel is in the reactor, the less likely it is to go critical. This is why it is removed from the reactor after several years—it loses energy and will no longer easily support a self-sustaining chain reaction. Once fuel is removed from the reactor, the NRC requires licensees to ensure it will never again be critical. This state is referred to as "subcriticality."

Subcriticality is required whether the fuel is stored in a pool or a dry cask. It is required for both normal operating conditions and any accident that could occur at any time.

Many methods help to control criticality. The way spent fuel assemblies are positioned is an important one. How close they are to each other and the burnup of (or amount of energy extracted from) nearby assemblies all have an impact. This method of control is referred to as fuel geometry.

Certain chemicals, such as boron, can also slow down a chain reaction by absorbing neutrons released during fission, and keeping them from striking other uranium atoms.

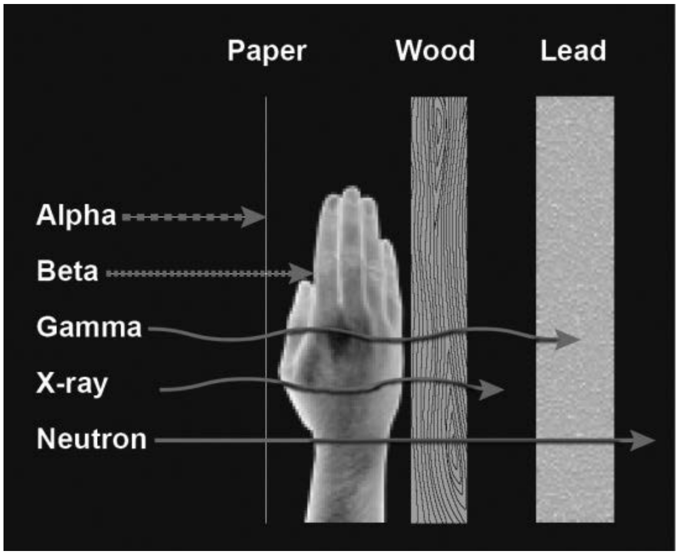
Casks have strong baskets to maintain fuel geometry. They also have solid neutron absorbers, typically made of aluminum and boron, between fuel assemblies. A cask application must include an analysis of all the elements that contribute to criticality safety during both normal and accident conditions.

NRC technical experts review this analysis to verify several things:

- The factors that could affect criticality have been identified.
- The models address each of these factors in a realistic way.
- Any assumptions used in the models are conservative—they result in more challenging conditions than would actually be expected.

Radiation Shielding

The fission process turns uranium into a number of other elements, many of which are radioactive. These elements continue to produce large amounts of radiation even when the fuel is no longer supporting a chain reaction. Shielding is necessary to block this radiation and protect workers and the public.



Different types of radiation have different properties.

The four major types of radiation differ in mass, energy, and how deeply they penetrate people and objects. Alpha radiation—particles consisting of two protons and two neutrons—are the heaviest type. Beta particles—free electrons—have a small mass and a negative charge. Neither alpha nor beta particles will move outside the fuel itself.

But spent fuel also emits neutron radiation (particles from the nucleus that have no charge) and gamma radiation (a type of electromagnetic ray that carries a lot of energy). Both neutron and gamma radiation are highly penetrating and require shielding.

Shielding for the two main types of dry storage casks is configured in slightly different ways. For welded, canister-based systems, the thick steel-reinforced concrete vault that surrounds an inner canister provides shielding for both neutron and gamma radiation. Shielding in bolted cask systems comes from their thick steel shells that may have several inches of lead gamma shielding inside. These systems have a neutron shield on the outside consisting of low-density plastic material, typically mixed with boron to absorb neutrons.

The NRC's reviews ensure that dry cask designs meet regulatory limits on radiation doses at the site boundary, under both normal and accident conditions, and that dose rates in general are kept as low as possible. Every applicant must provide a radiation shielding analysis. This analysis uses a computer model to simulate how radiation penetrates through the fuel and into thick shielding materials under normal operating and accident conditions. Reviewers ensure the analysis has identified all the important radiation-shielding parameters and models them conservatively, in a way that maximizes radiation sources and external dose rates.

At right, a dry storage cask recently loaded with spent fuel is lifted from a horizontal transporter to be placed on a specially designed storage pad. (Courtesy: Sandia National Laboratories)

Inspections

Inspectors examine dry storage casks containing spent nuclear fuel.

As part of its oversight function, the NRC inspects the companies that design and fabricate dry storage casks and the facilities that use them. Inspectors from NRC headquarters and the four regional offices conduct these inspections and issue their findings in publicly available reports.

Cask designers are responsible for ensuring that the fabricated cask components comply with the design as approved by the NRC. To do this, they are required to have a quality assurance program that meets the 18 criteria described in NRC dry storage regulations. The NRC reviews and approves these programs.

The designers must make sure their quality assurance programs are properly implemented during both design and fabrication. The NRC conducts periodic safety inspections to independently assess and verify that the designers are doing so. Some inspections look at design activities carried out at corporate offices. At fabrication facilities, both in the United States and overseas, NRC inspectors look at controls for fabrication, the process for verifying that the fabricated components comply with the approved design, and how the designer ensures that the fabricator meets its quality assurance program.

Each licensee is responsible for ensuring that its storage facility meets NRC regulations during construction and operation. NRC inspectors verify that the licensees are properly implementing the regulations. These inspections cover the design and construction of the concrete pad or modules that support the storage casks, preoperational testing (also referred to as dry runs), cask loading, and routine monitoring of operating dry storage facilities.

Transportable spent fuel storage casks sit on a storage pad.
(Courtesy: Holtec International)

Managing Aging

Cutting-edge robotic technology is making it easier to inspect inside spent fuel dry cask storage systems. As these casks remain in use for longer time frames, the ability to inspect canister surfaces and welds will become an important aspect of the NRC's confidence in their safety.

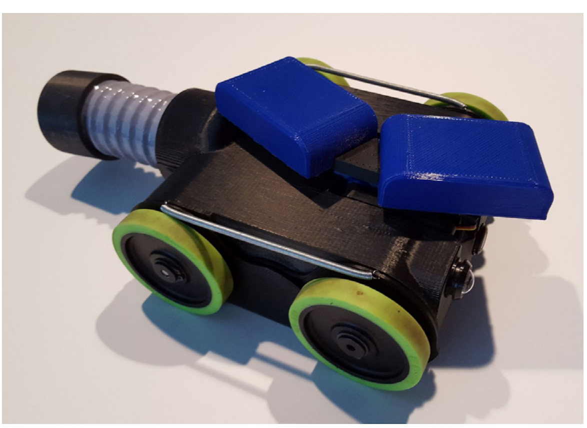
The techniques for inspecting canister surfaces and welds have been used for decades. These techniques are collectively known as nondestructive examination (NDE) and include a variety of methods, such as visual, ultrasonic, eddy current, and guided wave examinations.

Cutaway mockup of NAC International MAGNASTOR cask system at Palo Verde Nuclear Generating Station in Wintersburg, AZ. (Courtesy: EPRI/APS)

Robots are being developed to apply these NDE techniques inside casks. These robots need to fit into small spaces and withstand the heat and radiation inside the cask. The state-of-the-art robot technology is evolving quickly.

The Electric Power Research Institute and cask manufacturers have successfully demonstrated robotic inspection techniques to NRC staff several times at different reactor sites. These demonstrations are helping to refine the robots' designs.

In one demonstration, a robot inside a spent fuel storage cask maneuvered a camera with a fiber optic probe, which meets the industry code for visual examinations. The robot was able to access the entire height of the canister, allowing the camera to capture images of the fabrication and closure welds. The welds showed no signs of degradation. The canister was intact and in good condition.



Prototype robotic delivery system. (Courtesy: EPRI/RTT)

The robot was also able to obtain samples from surfaces of the cask and canister. These samples were analyzed for atmospheric deposits that could cause corrosion.

If degradation is identified, cask users would select their preferred mitigation and repair option. They would have to meet the NRC's safety requirements before implementing it.

Cask inspections are important to ensure continued safe storage of spent nuclear fuel, and robots will continue to be a helpful tool in this important activity.

For more information on spent fuel and dry cask storage, visit the NRC's website:

https://www.nrc.gov/waste/spent-fuel-storage.html

Cover Photos:

Top: Massive storage casks loaded with spent nuclear fuel sit on a concrete pad inside a secure storage facility.

Middle: A transportable spent fuel storage system is moved to a storage pad at the Peach Bottom Atomic Power Station in Delta, PA. (Courtesy: AREVA)

Bottom: A horizontal spent fuel storage system sits behind a secure fence at the Calvert Cliffs Nuclear Power Plant in Lusby, MD.

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