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Extended Discussion

Storage and Transportation of Used Fuel: Does Storage/Transport System Hardening Enhance Safety and Security

Overview

“Hardening” of used fuel storage/transport systems is typically interpreted to be any approach intended to increase resistance of the system to failure (release of radioactive material) from, or reduce the likelihood of success of, an external threat involving beyond-design-basis (BDB) events, including attack or sabotage. There are several conceptual approaches to hardening a used fuel dry storage system on a reactor site: the storage technology may already be integrally hardened as part of the system design to sufficiently resist, not only accident conditions, but also BDB events; each storage system may be supplemented with additional hardening features that enhance the integral hardening; hardening features may be added over and above the individual system; or any combination of the preceding approaches may be used to maximize the perceived protection of the used fuel and elevate public and regulatory confidence in the protection of the used fuel. Hardening can, therefore, cover a large array of considerations having significant impacts on such things as system thermal limitations, ready access to the storage systems for inspection and maintenance, ability to efficiently perform off-site transport, facility staffing, fuel that may be stored, accident or BDB event recovery, project schedules and budgets, and the like. Hardened On-Site Storage (HOSS) is one approach, originally proposed by Dr. Gordon Thompson in 2003, and involves discrete “over-structures” built above and around each storage system, apparently to address a concern over a weapons attack. His concept figures show what is essentially an old, “munitions bunker” design that may be observed at a number of current weapons storage facilities. This discussion applies to Dr. Thompson’s HOSS concept, but includes observations relevant to more general hardening and security considerations for spent fuel dry storage.

Dry storage and transport systems will not fail under design basis (DB) events, since system designs comply with regulations and have been approved by the NRC for DB events before the systems are deployed. Storage and transport system designs consistently exceed regulatory requirements. Further, dry storage systems, in concert with national and station security systems, are designed to resist a defined paramilitary-type threat, known as the Design Basis Threat (DBT). Threats at power plants (including those with dry storage facilities) greater than a DBT may be considered to arise from “enemies of the state” and the full force of the U.S. government, including the military, law enforcement and intelligence agencies, are established to intercede for mitigating such threats. With this as background, additional details follow, but it must be considered that hardening for one type of BDB event may, in fact, impair dry storage system resistance to or recovery from other types of BDB events. The law of unintended consequences is fully operative here. Therefore, appropriate safety and security may be better achieved, not by further hardening, but by the current approach of effective, tiered deterrence/resistance: effective security systems, national and local; effective security forces; and continued use of conservative, robust and resistant technology

Some who advocate for the HOSS concept or other hardened dry storage approaches may not be aware of the hardening features already part of dry storage systems and of the large safety margins on DB events that can also mitigate the effects of BDB events. NAC dry storage systems use vertical concrete casks (VCC), or storage overpacks, with thick steel shells, thick concrete walls with density enhancing aggregates, and layers of reinforcing bar in the concrete that provide shielding and structural threat protection for the inner canister holding the used fuel. These external shells of the VCC are not fully challenged structurally for DB events because their primary function is to provide gamma shielding. As a result, nuclear packagings have large, real mechanical margins against failure from all threats of a structural nature, especially when compared to other hazardous material packagings. Such multiple material layer densities are also more resistant to external penetration by missiles and projectiles and can be provided in various thicknesses to meet customers’ desires. Figure 1 shows an example of NAC dry storage system technology with a VCC that encloses and protects the used fuel canister (transportable storage canister, or TSC). The following sections briefly discuss the advantages of these integral hardening features included in the design of the NAC dry storage technologies.

Militant Acts of Destructiveness (MADness): Integral Hardening and Canister Armoring

For MADness events involving high velocity impacts of heavy masses (aircraft) or of non-military missiles (jet engine turbine rotors), with associated dispersion of flammable materials (jet fuel), NAC dry storage designs offer substantial protections. This is because of the “hardened canister” design approach incorporated in the NAC systems. The best way to protect thin shell canisters from general impact and penetration events, and to protect recovery workers from excessive risk during recovery operations following such a MADness event, is to harden the structures that immediately surround the canister with thick metal armor protection, as with military structures.

There is a unique property of nuclear packagings among all hazardous material packagings, and that is the need for shielding of the package contents. Gamma shielding comprises heavy, dense materials and these materials provide excellent structural support for other materials designed for containment and confinement of the package contents under DB conditions. As a consequence, nuclear packagings have large, real mechanical margins against failure from all threats of a structural nature. This is one reason why nuclear packagings have better safety margins than other hazardous material packagings. Additionally, dry storage systems are designed to very conservative codes and standards. For instance, the materials used in critical safety structures can have a substantial level of increased energy absorption capability above that permitted by our codes, standards, and licensing requirements before material failure (exceeding ultimate strain) would occur. That is, the elastic stress/strain relationship for many materials that the codes, standards, and regulations allow packaging materials to experience under DB conditions only covers a small range of the material's true stress/strain relationship, so that the material's ultimate strain will occur only after additional energy is imparted to the material beyond that allowed for the DB condition, providing extensive safety margin against real (vs. regulatory) failure.

Concrete is relatively heavy, strong in compression but weak in tension, and offers only energy absorption and thermal insulation under MADness events. By itself, then, it is not very effective in resisting high velocity impacts or penetration. A key principle in retarding high energy penetration devices within structures, however, is to assure that the medium being penetrated presents density variations to the penetrator, a feature that results in the breakup, "pancaking," and slowing of that penetrator. NAC systems use concrete, but the rebar cages in the concrete outer shell also serve to enhance the energy absorbing effectiveness of the concrete by providing the desired density variation. Further, the addition of aggregates to the concrete enhances the retarding effect within the concrete shell. The principal hardening for canister protection does come from the thick metal inner shell that serves as the final layer of armor to protect the canister. Additionally, and very importantly for protection of recovery personnel at each plant, the armoring also fully surrounds the canister as an integral structure to assure that recovery of the system is facilitated with little threat to recovery personnel. That shell can also serve as a lifting attachment surface and shielding device for recovery, facilitating the up-righting and positioning of potentially overturned casks.

NAC Analysis of Large Aircraft Impact

NAC has demonstrated the resistance of its dry storage systems to very substantial BDB events, such as large aircraft impact. Three different BDB impact loadings from a large aircraft have been considered in addition to the cask being exposed to a post-impact fire. In the first impact analysis, full scale testing results by Sandia National Laboratory [*Full-scale Aircraft Impact Test for Evaluation of Impact Force, Part 2: Analysis of the Results*, Transactions of the 10th International Conference on Structural Mechanics in Reactor Technology, Volume J, Extreme Loads Analysis, August 14-18, 1989, Anaheim, CA, USA, p293] were employed to develop a conservative impact force time-history of a Boeing 747 airplane traveling at 500 mph, which was then used to determine the slap-down velocity of the VCC caused by the impact of the 747 aircraft. The analysis approach was considered to be conservative for the following reasons:

- The rebar cages in the VCC were ignored
- The canister was assumed to be empty, with no basket offering reinforcement or support for the canister shell
- The cask was assumed to rotate about a fulcrum at the bottom, maximizing slap-down velocity and damage; no sliding was permitted, which would decrease slap-down velocity/damage
- The aircraft velocity was more than 30% higher than the velocity assumed by other industry groups, such as the Electric Power Research Institute (EPRI), in their assessments of credible velocities for aircraft impacts with dry storage structures
- The turbine rotor was assumed to be a rigid body, which it is not by design
- The use of the Boeing 747 jet engine turbine rotor vs. the Boeing 767 turbine rotor used by others in the industry is smaller in diameter, and, with the higher impact velocity assumed, its impact energy per unit area is substantially above that for a 767 rotor, improving its penetration potential.

Following the aircraft impact, the slap-down velocity of the VCC with the pad was determined. Then, using an even more conservative slap-down velocity 15% higher, the maximum strains in critical canister locations were determined, showing that canister materials and welds do not fail ,and, not only single lid confinement, but double lid confinement of the used fuel is maintained. Margins above ultimate strain were very good.

Another impact analysis representing a Boeing 747 jet engine turbine rotor at 500 mph in a most critical location to damage the canister was shown to result in acceptable strains within the canister shell and closure with good margins, thereby retaining confinement of the used fuel. Finally, an assessment of the analyses of a post-impact, all-engulfing jet fuel fire on the tipped-over VCC and enclosed canister shows the fuel temperatures remain below their accident limits and that the confinement of the used fuel is not compromised.

The specific comparative advantages of this armored canister system design are as follows:

- The VCC is a cylindrical structure that tends to “shed” (reduce) direct impact loads and make direct missile impact with the canister virtually impossible. This is opposed to large flat surfaces that fully absorb impact loads, leading to more extensive failure.
- The VCC offers thick steel canister armoring, physically and structurally surrounding each canister.
- The VCC armoring does not collapse under impact; it retains its structure and offers the means for remote up-righting without the need for recovery personnel to deal with collapsed rubble surrounding the canister.
- The VCC, under impact, will not trap jet fuel, unlike a hardened over-structure; this could result in fires producing furnace conditions within the over-structure, resulting in structural failure of load-bearing members. Such failures of load-bearing, structural members of concrete/steel over-structures in the presence of hydrocarbon fires have occurred in other disasters, such as the collapse of the World Trade Center (WTC) buildings following the events of September 11, 2001, and at the “Macarthur Maze” fire in Oakland, California, USA, in April, 2007. This is discussed more fully below.

Additional Hardening

While over-structure additions to harden each storage system may offer some measure of threat resistance for used fuel dry storage systems, there may be a significant down-side to their use. NAC and others have performed studies of the safety of dry storage casks under a variety of aircraft impact scenarios. Each study has shown that aircraft impacts cannot cause the used fuel canisters to fail and release radioactivity. Further, the jet fuel from impacting aircraft is widely dispersed, burn times of the jet fuel around the casks are short, and recovery from such an event, while presenting some difficulties, is not likely to be overly protracted and would not likely result in large operator exposures to radiation, owing to the limited number of casks involved, the generally localized nature of the impact and fire damage, and the shielding offered by the VCC design.

Whenever it is proposed that used fuel storage casks be placed within individual over-structures with the intention of making the storage "safer", such concepts seem to have arisen without an appropriate event-cycle evaluation to determine the overall impact on those affected or involved. For aircraft attacks on dry storage facilities, the use of over-structures to protect the storage casks offers no discernible safety improvement for the general public or for recovery staff because, even without the over-structure, a large aircraft impact with a cask cannot cause a release of radioactivity. However, the over-structure has air inlet and outlet features for cooling, and unless the over-structure has extraordinary design features (at an extraordinary cost), the over-structure may permit the ingress and trapping of potentially substantial quantities of aviation fuel. After the impact, then, with the resultant burning of the aviation fuel, hardening over-structures may become ovens or furnaces that reflect and generalize high temperatures on the over-structure load bearing members.

Since such high temperatures in the over-structure will not directly cause a release of radioactivity from the dry storage system, there is no real threat to the general public or plant operations personnel from this. However, there could be greater thermal damage to a cask’s concrete shielding and, for the over-structures, to their load-bearing members. Gaining access to the casks in an individual system over-structure for evaluation purposes may be much more difficult. Therefore, the recovery process from such an event may be compromised because the casks could be much more difficult to access and assess, and the over-structure remaining around the casks may be of questionable stability. Further, the casks could be covered with rubble (including gravel in some concepts), raising questions about system thermal performance. As a result, quickly determining what has happened and what must be done may not be readily possible, remaining over-structures could interfere with people and equipment, recovery may be more complex and time consuming, recovery staff may receive higher radiological exposures in the recovery, and there could be more serious injuries to personnel from unstable over-structures that remain. Depending on the BDB event, then, the hardening approach may result in greater concerns for personnel during the recovery process than would leaving the casks at an outdoor ISFSI, and with no improvement in public health and safety.

The case for the substantial reduction in structural stability of over-structures as a result of aviation fuel fires was first highlighted following the WTC events of September 11, 2001. Engineers now believe that both WTC buildings could likely still be standing if the burning aviation fuel had not greatly weakened the structural steel load-bearing members of some floors of the buildings, causing both buildings to experience a “pancake” collapse. Further concern over such scenarios has arisen as a result of NRC investigations of recent fire events that could, in some circumstances, involve used fuel casks. One such investigation involved what has been called the MacArthur Maze fire, in which a maze of elevated highways experienced a fire caused by a gasoline truck tanker accident directly beneath an elevated highway span. The fire resulted from the combustion of almost 8,600 gallons of gasoline in the truck tanker and lasted only 17 minutes. However, as a result of the weakening of the steel and concrete load-bearing members of the elevated highway span, the span collapsed on the burning tanker truck beneath it. This event was outside, in the open air, and peak temperatures on bridge structural members were in the range of 980 to 1,020 degrees C. The NRC research program of this accident is contained in the NRC report NUREG/CR-6987, Analysis of Structural Materials Exposed to a Severe Fire Environment, February 2009.

Other NRC research on a fire that might involve used fuel casks has been reported for the Baltimore Howard Street Tunnel Fire, in which a train had an accident in a tunnel in Baltimore, Maryland, USA, in July 2001 that produced a non-petroleum-based hydrocarbon fire of several hours duration, resulting in very high temperatures of the tunnel structure and the railcars surrounding the burning car. The NRC research on the Baltimore tunnel fire is contained in the NRC report NUREG/CR-6886, Rev 2, PNNL-15313, Used Fuel Transportation Package Response to the Baltimore Tunnel Fire Scenario.

These research reports by the NRC raise concerns that a large aircraft impact with a facility containing hardened over-structures that are well-ventilated for used fuel storage system heat removal could produce a situation in which significant quantities of burning aviation fuel might be trapped in an over-structure. Large aircraft carry about 57,000 gallons of aviation fuel. Hardened over-structures can have flat walls that absorb some or all of an aircraft impact, as well as multiple openings to allow air ingress and egress for storage system cooling. The MacArthur Maze experience shows that open-air burning conditions can produce collapse of heavy steel and concrete structural members in 17 minutes of burn time. Within a closed over-structure having excellent air supply with very effective ceiling/roof insulation characteristics due to thick concrete surfaces, such collapse may be possible in less than 17 minutes. Another key consideration is that MacArthur Maze resulted from 8,600 gallons of gasoline. Large aircraft carry much more aviation fuel, so that less than 15% of the aircraft fuel capacity needs to enter the over-structures to produce a collapse threat potential.

With respect to the potential for an explosives attack on used fuel storage systems at an ISFSI, other alternatives than hardened over-structures are available. For these sabotage scenarios, effective national and local security systems and effective security forces are the three legs of the primary deterrence triad. As discussed above, NAC concrete system designs are robust because of the rebar cages in the concrete and the thick armor plate outboard of the canister. Cask system geometry (a cylindrical structure with the canister buried deep inside 2 - 3 feet of concrete, rebar, and steel) makes the system a poor target, and the need for a missile or explosive to achieve a nearly perfect strike (zero obliquity) makes the design resistant to successful attack. The DOE has estimated that a successful missile attack on a cask system has a probability of less than one in a million, and it is more easily defended against than a large aircraft attack. Plant designs in the U.S. already use missile defense elements that are common in the military. Further, the use of a berm can provide excellent protection, especially if the berm incorporates redundant fence elements in its design. Even with a highly improbable successful attack, thanks to effective security systems and security forces, however, the use of a hardened over-structure may make the job of recovery more hazardous to operations personnel, with essentially no increased public safety. This is the real health and safety concern.

BDB Event Outcomes: Standard for Acceptability

Much of the desire for hardening seems to arise from a fear of a very large radiological risk to the public, should some sabotage event cause a breach in a storage (or transport) system. Fortunately, such a radiological risk is comparatively small. The DOE, as part of its Final Supplemental Environmental Impact Statement for Yucca Mountain (DOE/EIS-0250F-S1), conducted a full analysis of the collective doses resulting from a sabotage event using a high energy density device (HEDD), i.e., a military weapon that produces a breach in a transport packaging. The DOE analyses used conservative codes and modeling, and included the results from nuclear packaging sabotage testing over the last three decades. The DOE reported the results for both high and low density surrounding populations: the worst case is 47,000 person-rem for high density populations, and 92 person-rem for low density populations. Since the storage and transport packaging designs have similar penetration resistance, the low population density numbers from DOE's analyses might be taken as representative of population doses that would result from dry storage (since population densities around commercial nuclear power plants are less than 150 people per km^2). Other models to project population doses using conservatively realistic methods with high population densities show population doses less than 10,000 person-rem. However, none of these population dose outcomes would produce any definable radiation injury or death, and, when any of these population exposures are converted to risk by applying credible sabotage probabilities, the comparative risk is extremely small.

The critical question may then become: what is a reasonable, objective standard for society to judge the acceptability of such BDB hypothetical population doses? What is a good standard to use as an assessment tool for determining the public's comparative radiological risk to a BDB event? A credible standard would seem to arise, or be derived from, society's decisions over the last 5 decades regarding non-nuclear industries' exposure of large populations to doses from radionuclides that are at least as hazardous as those in used fuel: these non-nuclear industries are not regulated to control their population dose characteristics. Non-nuclear industries such as aviation, agriculture, building design/construction, potable water supply, construction material, tobacco supply, medical diagnostics, many resource extraction industries, and fossil fuel combustion, among others, produce lognormally distributed, annual and 50 year collective effective dose equivalents (CEDE) and peak individual doses well above what is credible from nuclear fuel cycle events. Figure 2 shows a comparative assessment of population doses from non-nuclear industries with used fuel storage and transport. Establishing a comparative standard for hypothetical dry storage and transport BDB event population dose outcomes based on actual population doses from non-nuclear industries, doses that are typically unregulated, unmonitored, uncontrolled, unreported, and undisputed, seems to be an imminently objective method of determining if society faces a serious risk from such hypothetical BDB events, compared to other radiological exposures it routinely accepts. Of course, DB event outcomes would still comply with the established legal, regulatory, and licensing requirement acceptance criteria. There is no intent to loosen or reduce industry responses to, or regulatory requirements for, DB events. The industry must remain focused on demonstrably safe technology arising from rigorous requirements and a high level of safety culture.

Conclusion

In conclusion, an over-structure enclosure, such as HOSS, for hardening of a dry storage system is likely to be an expensive undertaking, quite possibly exceeding the cost of the storage overpacks. Additionally, the up-front costs associated with site modifications, dry storage system re-analysis or re-design, re-licensing costs, and reduced capabilities for storing used fuel may be substantial. What seems clear from the preceding discussion is that there is little or no discernable benefit from hardening of used fuel dry storage systems on public health and safety, but there is a potential liability from hardening as a result of its impact on recovery staff safety due to furnace effects and structural collapse. The expected outcome of an event cycle evaluation would seem to show very little benefit from hardening, with a strong possibility for liabilities to be higher, causing the benefit-cost ratio for hardening to approach zero and maybe, in fact, to become negative. The reasonable conclusion is that further hardening of dry storage systems is not meritorious because it does not produce a clear, discernible enhancement of either public or worker health and safety under BDB conditions. Appropriate safety and security may be best achieved, then, not by further hardening, but by maintaining an effective, tiered deterrence/resistance approach: effective security systems, national and local; effective security forces; and the continued use of conservative, robust and resistant technology.

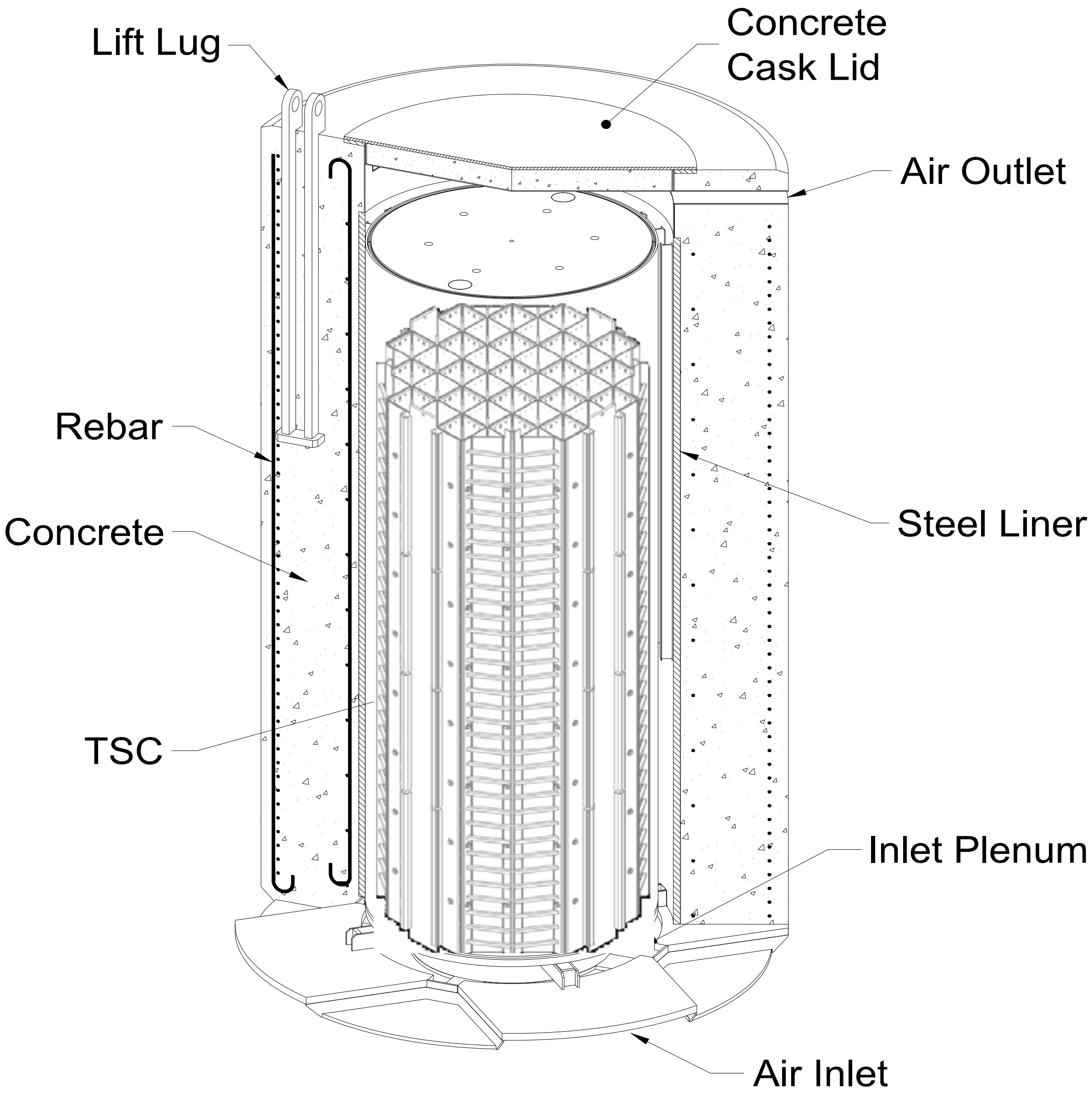

Figure 1 NAC International Dry Storage System with Vertical Concrete Cask (VCC)

Industry	Current Annual CEDE (Person-cSv)	Estimated Previous 50 Year CEDE (Person-cSv)	Projected 50 Year CEDE (Person-cSv)
Aviation	>0.6 million	>12 million	>28 million
Building Design/Construction	>15 million	>430 million	>750 million
Potable Water Supply	>1.5 million	>38 million	>75 million
Agriculture	>1.3 million	>52 million	>65 million
Construction Materials	>2 million	>78 million	>100 million
Tobacco Supply	>44 million	>3 billion	>2.2 billion
CT Medical Diagnostics	>44 million	>1 billion	>2.2 billion
Total for 7 Non- Nuclear Industries	>108 million	>4.6 billion	>5.4 billion
Commercial Used Fuel Storage and Transport, supporting growth to 300 reactors over next 50 years	<0.00008 million	<0.002 million	No Breach Events: <0.008 million 10 Breach Events: <0.07 million

Figure 2 Comparisons of CEDE for Non-Nuclear Industries with Used Fuel Storage and Transport