Radiological Safety of Spent Fuel Storage and Transport

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ABSTRACT

The debate over expanded commercial nuclear power generation in the U.S. focuses on several issues, but the most emotionally gripping topic involves nuclear safety and the threat of radiological harm. A subset of this topic is the prospective safety of spent fuel storage and transportation. The U.S. is backing away from the use of the Yucca Mountain repository, and, with the solution to spent fuel disposition certainly being extended in time and with the prospect of an expanding use of nuclear power, there are some that wish to elevate concern within the public over radiological safety of spent fuel storage and transport.

With the perseverance and prospective expansion of the radiation-fear issue, a study has been performed to assess the credible radiological outcomes of nuclear events that have historically been the centerpieces of nuclear opposition. Analyses of population radiation doses resulting from worst-case, credible events in the U.S. nuclear fuel cycle have been performed. Such events may be very credibly modeled for realistically conservative outcomes using the same accident profile, release patterns, dispersion characteristics, and population exposures as the accident profile and outcomes from the Chernobyl Nuclear Power Plant Unit 4 (CNPP4) accident. Based upon industry and U.S. Nuclear Regulatory Commission (NRC) published studies, the worst-case radiological event for either spent fuel storage or transport would result from a credible sabotage scenario. Using modeling based on the CNPP4 accident, it is shown that worst-case, credible radiological outcomes for both peak exposures and lifetime population doses are less than what would be considered a significant radiological hazard. More importantly, it is demonstrated that these hypothetical outcomes are well below what are actually produced by at least seven non-nuclear industries each year in the U.S., industries that have existed for decades or centuries and whose radiological characteristics are not regulated.

Finally, such information can be used to inform decision-making about commercial nuclear power growth as a key step towards reducing fears and improving knowledge of various stakeholder parties involved in U.S. energy decisions.

INTRODUCTION

> In 1994, at a Congressional conference on legislative priorities, the Vice President of the United States, Mr. Albert Gore, reportedly called spent fuel transportation a “mobile Chernobyl.”

This reported event, one in a history of events by nuclear energy opponents intended to tarnish the safety record of spent fuel management, has often been quoted and used by those wishing to stimulate, concentrate, and elevate opposition to transport and storage of nuclear spent fuel. However, the concept of a mobile Chernobyl called to this author’s mind the great disparity between the actual results at Chernobyl and what projections would be from modeling such an event using the radiological release and population exposure codes deployed today, not just by anti-nuclear organizations, but by industry itself in its efforts to be very conservative in safety design and analysis of nuclear technology. The population doses and radiological impacts on the 5.2 million people surrounding CNPP4 were researched for 14 years, then reported in detail by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 2000 [1]. Since the publishing of reference [1], The Chernobyl Forum, consisting of the three most affected countries of the former Soviet Union (FSU), as well as the UN, the World Health Organization, the IAEA, and the World Bank, published a follow-up study in 2005 [2] that validated and concurred with the population and individual dose assessments of reference [1]. Thus, UNSCEAR’s assessment retains its full robustness of method and conclusions after an independent, in-depth review.

Using the contents of the reference [1] study, this author developed a realistically conservative approach to, and modeling for, a bounding credible LWR accident and spent fuel storage and transport event. That study, reference [3], demonstrates that both peak exposures and lifetime population doses are less than a significant radiological hazard. It also shows these hypothetical outcomes are well below actual, annual doses to the public from seven non-nuclear industries in the U.S., industries that have existed for decades or centuries and whose radiological characteristics are not regulated. Provided herein is a summary of these comparative results for spent fuel storage and transport events that could credibly produce radiological releases.

BACKGROUND: THE CHERNOBYL ACCIDENT

CNPP4 was a second generation Russian RBMK 1000 reactor, with a 1,000 megawatt electric (MWe) output. On April 26, 1986, a system instability occurred during testing at CNPP4 that produced a huge increase in power and temperature, combined with reductions in coolant flow, resulting in a massive steam explosion that thoroughly disassembled and ejected portions of the reactor's core. With no containment structure, a significant fraction of the CNPP4 core was discharged outside the reactor hall, and the energy of the explosion injected a substantial quantity of fission products and core materials into the upper atmosphere for widespread dispersal.

About 30% of the core was certainly ejected to the environment and atmosphere around the plant, but some assessments show that as little as 77 MtU of the core remained in the reactor hall, so that 60% of the core may have been ejected. Additionally, the core remaining in the reactor hall was open to the atmosphere, so that all core material was exposed to release its radioactivity as nuclear, physical, and chemical processes permitted. Releases continued for about 40 days as emergency workers tried to cover or remove fuel from the surrounding plant property. About 55% of the core's iodine and 34% of the cesium were released over the 40 day period, but weather conditions essentially produced a 360 degree dispersal pattern. Some 5.2 million people within three regions of the FSU received an effective dose equivalent averaging at least 0.5 cSv above background for the first 10 years after the event, as a result of the high-atmosphere injection, protracted release period, and wide dispersal of radionuclides.

Reference [1] and Table 1 show that the post-accident 50 year collective effective dose equivalent (CEDE) in the 3 regions surrounding CNPP4 will be in the range of 10.7 million person-cSv.

Table 1. CNPP4 accident CEDE to inhabitants of the Russian Federation, Belarus, and the Ukraine

Type of Exposure	50 Year CEDE (Person-cSv)
External	~4 million
Internal	~2 million
Thyroid (total country populations)	~4.7 million
CEDE	<10.7 million
Average Annual CEDE: 5.2 Million People	~0.04

POPULATION DOSE MODEL DEVELOPMENT

Reference [1] shows the results of a reactor accident caused by a poor reactor design and no containment structure, and demonstrates there is no comparable accident with a western-style reactor having LWR safety features, a robust containment building, and demonstrated and tested emergency response plans. Therefore, the reference [1] accident details, together with the U.S. industry and NRC research over the last 30 years on limiting releases from current generation LWRs resulting from credible accidents, become very useful in establishing an assessment method that can produce bounding population dose estimates for credible events involving current generation LWRs and spent fuel storage and transport systems in the U.S. There are many features of the CNPP4 accident that are not credible for a U.S. LWR accident or spent fuel storage and transport system event, assuring that incorporating such features into population dose modeling for credible events will result in conservative projections. Just a few of these include: a reactor accident at >>100% power, with instantaneous environmental releases; a huge steam explosion and large dispersion of the core; full core exposure to the atmosphere for 40+ days with a continuous thermal plume of radioactive material spreading to the environment; ejected core material producing secondary fires and ancillary thermal plumes, with extensive additional spread of radioactivity; on-going consumption of local foodstuffs; and protracted evacuations of the affected public.

A model to assess population doses from a current U.S. LWR accident or from a spent fuel storage/transport system sabotage event, reference [3], was developed. The model, termed the *Accident Dose Assessment and Projection Technique from Radionuclide Analysis at Chernobyl* (ADAPTRAC), uses the full CNPP4 experience for event initiation and source term modeling, which are extreme compared to accidents/sabotage involving a U.S. LWR or storage/transport system and bound credible U.S. events. ADAPTRAC relies on the bounding radionuclide dispersion and uptake, exposure measurements and calculations, and exposed population data from the CNPP4 accident for application in the U.S. For population dose projection, ADAPTRAC applies the CNPP4 radionuclide dose contribution fractions to U.S. events, calculating population doses from LWR-fuel-specific radionuclide contents (from NRC and industry research, testing, and modeling contained in the literature, such as references [4] and [5]), assuming the CNPP4 dispersions and population densities over three time periods, taking account of radionuclide quantities and decay for the dose contribution in each period.

BOUNDING CEDE FROM SPENT FUEL STORAGE/TRANSPORT SYSTEM SABOTAGE

Dry spent fuel storage and transportation are among the safest of all industrial activities: as discussed in [6] and [7], tens of thousands of tons of spent fuel have been stored and shipped around the world in many thousands of storage and transportation packages, even traveling tens of millions of miles, without a radiation-induced injury or fatality. Spent fuel and radioactive material packagings have a unique characteristic among all other hazardous material packagings: the need for gamma-ray shielding. Gamma-shielding materials are dense and strong, and since the shielding must remain attached even following accident conditions, it thus provides enhanced robustness with larger structural safety margins than other packages. Figure 1 shows typical spent fuel storage and transport systems deployed in the U.S. today.

Extensive safety analyses and testing have been performed to conclude that casks in a licensed configuration will not release radioactive material under any credible accident conditions, and these analyses and testing have been accepted by the NRC in the package licensing process. Assumptions regarding cask “material failure,” imposed by the application of conservative regulatory codes and standards, help to make a “no release” design possible. An example of conservatism in materials is stainless steel, a predominant material of choice for containment boundaries, which has about 2 orders of magnitude more energy absorption capability before failure than permitted by design codes.

However, the possibility of terrorists acquiring and using very sophisticated military weaponry for a spent fuel storage or transportation system sabotage event is often raised as a specter portending grave population dose consequences. The public’s safety sensibilities are repeatedly gored by the media’s infatuation with this threat that a spent fuel transportation system is a “mobile Chernobyl.” For terrorist-induced, beyond-design-basis (BDB) events, only those that involve the use of high energy density devices (HEDD), commonly called shaped charges or anti-tank missiles, have any real opportunity of compromising cask integrity. The probability, however, of successful deployment of such devices must still be viewed as vanishingly small, since precise placement or delivery of such weapons must be accomplished to achieve a perfect impact condition known as “zero obliquity”.

Over the last three decades, substantial testing and analyses have been performed to bound releases from spent fuel casks following a perfect assault using a HEDD. Robert Luna [8] provides an excellent summary of this testing and offers an analysis of the likely respirable fission product release fractions from the spent

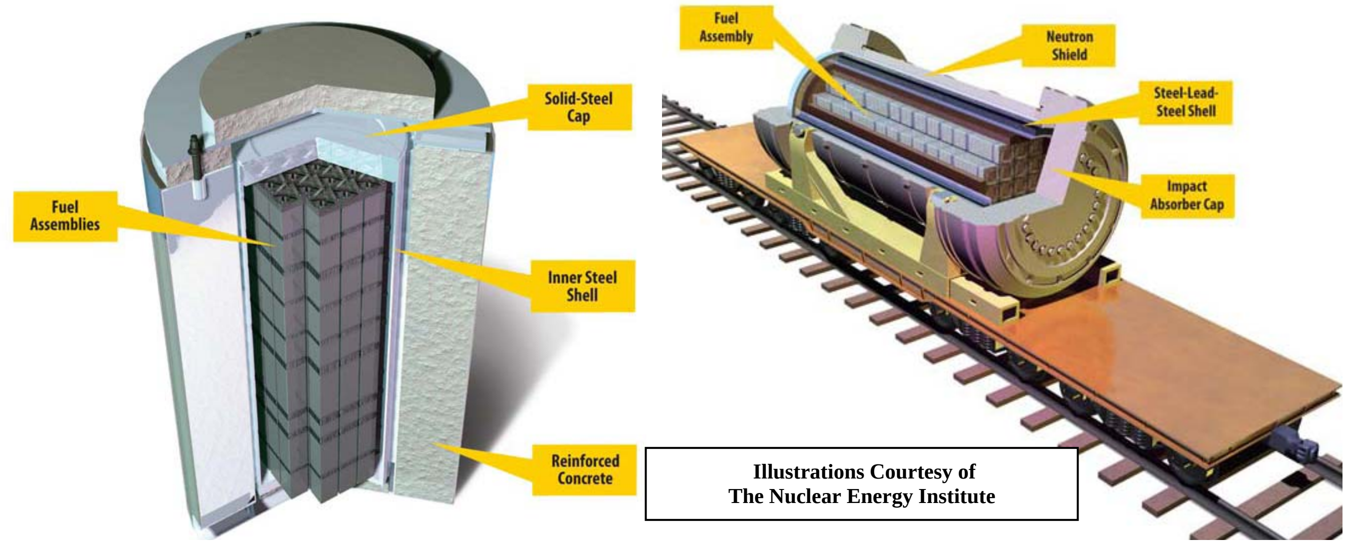

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Figure 1. Concrete, canister-based spent fuel storage system and spent fuel rail transport cask system

fuel system that are supported by testing. Luna has continued to research the release characteristics of spent fuel storage and transport package sabotage events using military weaponry, and this research, as summarized in [9] and [10], combined with the ADAPTRAC modeling approach, may be used to establish a bounding population CEDE for a credible sabotage event involving such packages.

An attack with a HEDD on a spent fuel storage or transport system could result in a situation remotely akin to the CNPP4 event, but with only small quantities of spent fuel ejected into the proximate environment and none injected into the high atmosphere. Therefore, using the Luna research on release fractions for a terrorist attack on a spent fuel storage or transportation system with the ADAPTRAC modeling to calculate maximum population exposures provides a bounding CEDE for a terrorist sabotage attack on a spent fuel storage or transportation system.

A high-capacity spent fuel storage or transport system contains less than 0.06% of the radionuclides in the CNPP4 reactor core. ADAPTRAC modeling uses the reference [1] 50 year post-accident dose distribution for the long-lived radionuclides released from the event, the half-lives of the radionuclides with significant dose participation, and the total involved population, as well as the full application of all the long-lived radionuclide release, dispersal, and exposure pathway conditions that existed at CNPP4. Additionally, all the highly conservative CNPP4 conditions involving ejection into the upper atmosphere, a long term release, wide dispersion, and affected populations are retained. For example, the first two plumes from the CNPP4 release continued for more than 36 hours, covering an area within a 5 km radius having a population density of almost 640 people/ km^2. However, for the 45° dispersion arc of these first two plumes, the effective population density within that 5 km distance and 45° arc was more the 5,000 people/ km^2. The plume duration, combined with the very high population density within the early dispersion arcs, makes the CNPP4 dispersion characteristics very conservative for application of ADAPTRAC to a HEDD attack on a spent fuel storage or transport system in the U.S.

The radionuclide release fractions resulting from a HEDD attack on a spent fuel system for use in ADAPTRAC are taken from references [9] and [10], but are increased by a factor of 6 due the assumption of using a very modern spent fuel storage or transportation system with a 100 psig pressurized canister for the spent fuel, based on discussions with Mr. Luna regarding test results for such pressurized systems. The spent fuel released and ejected from the spent fuel system would amount to almost 16 kg having total radioactivity of about 0.12 PBq.

Table 2 shows the ADAPTRAC projected 50-year population CEDE resulting from a bounding HEDD attack on a rail-size, spent fuel storage or transportation system, with a dense, proximate general population in the initial downwind plumes. Using the CNPP4 experience described in reference [1], the peak dose to an emergency worker, as well as to the most highly exposed member of the general public, would be less than 0.3 cSv. Such a transportation or storage system sabotage event would result in no deaths and no health threats from radiation exposure (references [11] and [12]). The population CEDE for 5.2 million people, even with the worst case CNPP4 accident assumptions fully operative, is quite small.

Table 2. CEDE for maximum credible HEDD attack on spent fuel storage or transportation system

Type of CEDE	Year 1 (person-cSv)	Years 2 – 10 (person-cSv)	Years 11 – 50 (person-cSv)	Totals (person-cSv)
External CEDE	800	1,200	1,300	3,300
Internal CEDE	700	1,300	200	2,200
Thyroid CEDE	0	0	0	0
Totals	1,500	2,500	1,500	5,500
Average Annual Dose to Individual (cSv)	0.0003	0.00005	0.000007	0.00002

COMPARATIVE POPULATION DOSES FROM NON-NUCLEAR INDUSTRIES

Many non-nuclear industries expose workers and the public to ionizing radiation levels above background, resulting from reconfiguring, redistributing or dispersing naturally occurring radioactive material (NORM, primarily potassium (^{40}K) and isotopes from the uranium, thorium, and actinide primordial series within the earth's crust). Technology enhanced natural radiation (TENR) results from NORM and from people being in closer or less-shielded proximity to natural radiation due to human actions. TENR is produced by long-standing human activities and may be reduced only by controlling such activities. More information may be found in references [3], [13], and [14].

People receive radiation from NORM radionuclides continually, both internally and externally, throughout their lives. The relative risk from inhaling, ingesting, or being exposed externally to the radiation from man-made radionuclides like plutonium (^{239}Pu) and cesium (^{137}Cs) has been compared to that for NORM radionuclides in references [3] and [13] using cancer mortality risk coefficients. This shows many NORM radionuclides are more hazardous then man-made radionuclides.

Seven non-nuclear industries were selected (out of many) for comparison of their population radiation doses with those from spent fuel storage and transport system sabotage, as detailed in reference [3]: aviation, agriculture, building design/construction, potable water supply, construction material, tobacco supply, and medical diagnostics. Each non-nuclear industry is briefly summarized below.

Aviation: Flying causes a reduction in the natural shielding against galactic cosmic radiation provided by the atmosphere's gases and particulate matter, meaning that there is more cosmic radiation available to interact with human bodies. People that fly in commercial, private, corporate, or military aircraft receive increased exposure to ionizing radiation from outer space.

Agriculture: Soil contains an abundance of NORM. Left untended, soil is self-shielded by dense natural foliage. Clearing, plowing, tending, weeding, watering, and harvesting lower density crops result in exposure to TENR for workers and those in close proximity to farms: by removing the shielding of the natural foliage otherwise covering the fields; by loosening and aerating the soil, which reduces its self-shielding and increases the soil surface area and diffusion paths for radon (^{222}Rn) and thoron (^{220}Rn) radioactive gases; and by providing a large source of both radioactive wind-borne dust and radon and thoron gases.

Use of fertilizers, having even higher concentrations of NORM radionuclides, also contributes to TENR.

Building design/construction: The industry that designs and constructs buildings for human occupancy is also responsible for the air quality within. Radon and its four daughters are present in soil and get "trapped" in buildings after leaking into occupied spaces, resulting in major contributions to public radiation exposure. Indoor radon levels are often more than 50 to100 times the natural outdoor levels, significantly increasing the radiation exposure of U. S. populations.

Potable water supply: The potable water supply industry delivers water to homes and businesses for drinking and cooking. Water originates from terrestrial sources and many radionuclides become dissolved or suspended in the water delivered to homes or businesses. When consumed, the ingested radionuclides deliver TENR to the occupants, thereby increasing radiation doses to people.

Construction materials: Stone, concrete, brick, tile, cinder block, and asphalt often contain high NORM concentrations due to human activities and can produce increased radiation exposure to people who live or work in or around buildings, roads, sidewalks, or other structures. Construction materials also result in elevated TENR exposure to people who work close to shopping or business districts with an abundance of masonry buildings, paved streets, sidewalks, plazas, and parking facilities.

Tobacco supply: The supply of tobacco is predominantly directed towards the production and consumption of cigarettes. Tobacco leaves contain radioactive material (particularly high levels of lead-210 and polonium-210) that substantially remains with the leaves during the cigarette production process. Inhaling tobacco smoke delivers to the lungs and other body organs these radionuclides, which are largely retained in the body and contribute to a large CEDE for smokers.

Medical diagnostics: Medical diagnostics use advanced, radiation-based procedures to perform non-curative investigations of patient symptoms. The use of advanced technologies to perform medical diagnostics, such as computerized tomography (CT), has grown by a factor of 5 to 6 since the 1980s. Patient and population doses from medical diagnostics are unregulated by federal or state governments.

Table 3 and Figure 2 provide a summary of the analysis results of these non-nuclear industries from reference [3], showing both single year and lifetime (50 year) CEDE. Over the next 50 years, assuming a growth in U.S. nuclear capacity to 300 reactors and operation of a spent fuel repository, two spent fuel storage and transport system CEDE scenarios are shown: one with 50 years of no successful sabotage breach events, and one with 10 successful credible sabotage events over the 50 years.

Table 3. Comparisons of CEDE for non-nuclear industries with spent fuel storage and transport

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 Spent Fuel Storage and Transport. Supporting growth to 300 reactors over next 50 years; 2 scenarios: A and B	<0.00008 million	<0.002 million	A. Without Breach Events: <0.008 million B. With 10 Credible Breach Events: <0.07 million

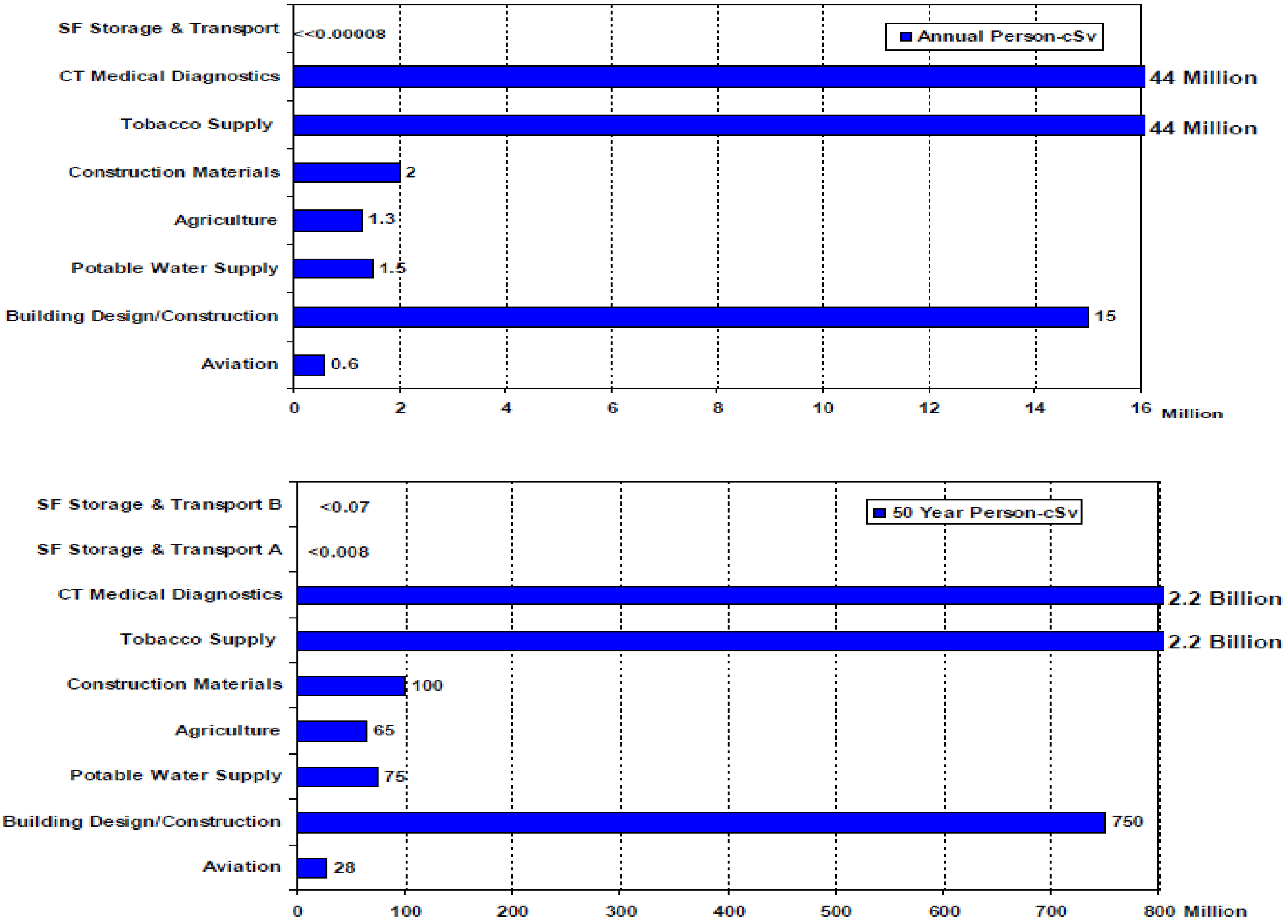

Figure 2. Comparative annual and 50 year CEDE for selected industries

CONCLUSIONS

1. Conservative modeling based upon and benchmarked to detailed, validated results of the world's worst reactor accident shows that spent fuel storage and transport cannot credibly result in significant public radiological impact, even assuming successful sabotage of storage and transport systems.
2. Currently, each of the seven non-nuclear industries assessed herein produces substantially higher annual population doses from ionizing radiation than does any event or set of events that can occur with spent fuel transport or storage. These non-nuclear industries together produce far more population dose than spent fuel transport or storage over any time period, by orders of magnitude.
3. A large fraction of the U. S. public receives annual CEDE from non-nuclear industries having unregulated public radiological impacts that well-exceed worst-year population doses from any hypothetical spent fuel transport or storage event, and this has occurred for decades, if not centuries.
4. This assessment shows that spent fuel storage and transport in the U.S. offer no credible, significant threat of population radiation doses even approaching the normal population radiation doses resulting from a number of other industries. It also shows that <u>nothing can credibly happen with spent fuel storage and transport to cause any significant radiological harm to any member of the U.S. public.</u>
5. One use of this assessment is for educating stakeholders on the comparative safety of spent fuel storage and transport. Opinions about the value of such use may vary, but an indicator of its value might be to consider the public/political response if the population doses from spent fuel storage and transport and those from non-nuclear industries, shown herein, were reversed.

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