Safety and security of spent nuclear fuel storage at U.S. nuclear power plants

Frank von Hippel, Princeton University

Meeting #1 of the
NAS Spent Fuel Storage Committee
Board on Radioactive Waste Management,
National Academies of Science
Washington, DC, February 12, 2003
2/7/04

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Outline

What did we do?

Spent-fuel pools

--Probability of loss of coolant

--Probability of a fire if loss of coolant

--Consequences

Dry storage

Nuclear Regulatory Commission (NRC) reaction and our response

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I. "Reducing the hazards from stored spent power-reactor fuel in the United States" *(Science & Global Security 11* (2003), pp. 1-51.

***Robert Alvarez**, Institute for Policy Studies: formerly Senior Policy Advisor to DoE Sec. and Dep. Assist. Sec. for National Security and the Environment, and Senior Investigator for Senate Committee on Governmental Affairs

Jan Beyea, nuclear physicist, consultant on nuclear safety, formerly Chief Scientist and Vice President, Audubon Society

***Klaus Janberg**, formerly Director of Gellschaft für Nuklear Service mbH (Germany's spent-fuel-storage company)

Jungmin Kang, nuclear engineer, Seoul National University

Ed Lyman, Senior staff scientist, Union of Concerned Scientists

Allison Macfarlane, Associate Professor, Earth and Atmospheric Sciences and International Affairs, Georgia Institute of Technology

Gordon Thompson, Executive Director, Inst. for Resource and Security Studies

***Frank von Hippel**, Professor for Public & International Affairs, Princeton Univ.

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II. "Damages from a major release of ^{137}Cs into the atmosphere of the U.S."

(Submitted to *Science & Global Security,* Jan 2004)

Jan Beyea, Ed Lyman and Frank von Hippel

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What did we do?

1. Reviewed 25 years of studies by national-lab & NRC studies

-- *Spent fuel heatup following loss of water during storage* (SAND77-1371, 1979)

-- *Severe accidents in spent fuel pools in support of generic safety issue 82* (BNL-NUREG-52083, 1987)

-- *Value/Impact analysis of accident preventative and mitigative options for spent fuel pools* (NUREG/CR-5281, BNL, 1989)

-- *Safety and regulatory assessment of generic BWR and PWR permanently shutdown nuclear power plants* (BNL-NUREG-52498, 1997)

--*Operating experience feedback report: Assessment of spent fuel cooling* (NUREG1275, 1997)

-- *Technical study of spent fuel pool accident risk at decommissioning nuclear power plants* (NUREG-1738, 2001)

-- *Analysis of spent fuel heatup following loss of water in a spent fuel pool* (BNL-NUREG-52494, 2002)

2. Did our own back-of-the-envelope calculations to check the results

3. Made some policy recommendations

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Probability of uncovering of fuel

1. Hasn't happened (but substantial losses of coolant have)
2. NRC estimated probability from *accident* at about 10^{-6} per pool-year; for 103 U.S. pools = $O(10^{-4})$ per year or 0.3% in 30 years
3. Malevolent acts could increase the probability but **"the possibility of a terrorist attack ... is speculative and simply too far removed from the natural or expected consequences of agency action"**

   --NRC, Dec. 2002

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Spent-fuel-pool overheating accident at Hungary's PAKS-2 nuclear power plant, April 12, 2003

Overheating occurred when a steam bubble developed in a dense-packed underwater fuel-cleaning vessel.
A large fraction of the volatile fission products were released into the pool water.

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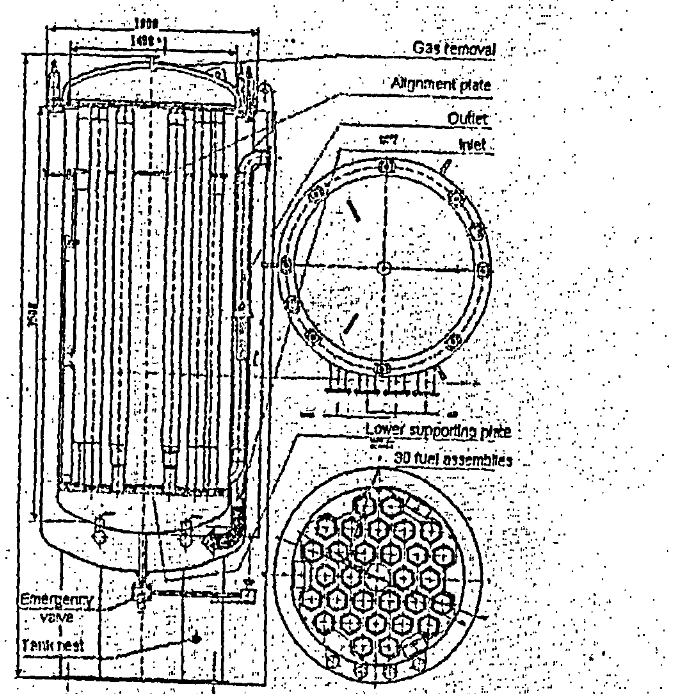
Spent-fuel-pool overheating accident at Hungary's PAKS-2 nuclear power plant, April 12, 2003

Container



Overheating occurred when a steam bubble developed in a dense-packed underwater fuel-cleaning vessel.
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PWR spent fuel pool pools often have spaces beneath them or walls above grade

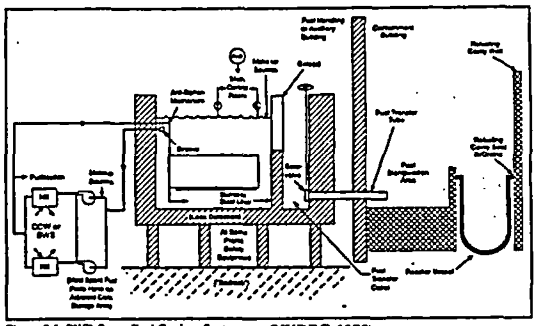

Figure 2.1 PWR Spent Fuel Cooling Systems (NUREG-1275)

In Germany & Switzerland, spent fuel pools are required to be inside containment buildings.

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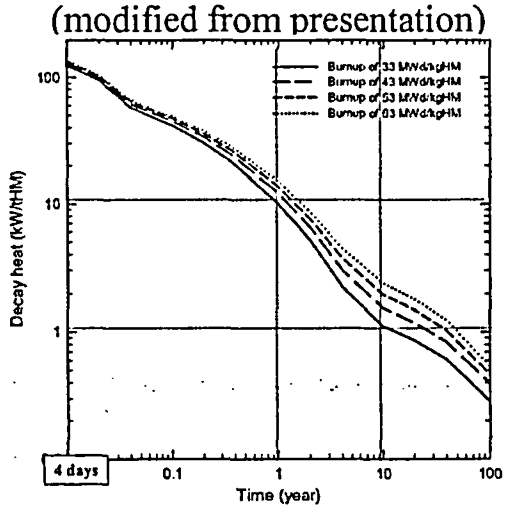
Decay heat

(modified from presentation)



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Scenarios

Drainage: via siphons or transfer tubes below top of stored fuel (NRC staff found 5 pools without weirs in 1997)

Boil down (up to 1 foot/hr.); could be dealt with by emergency water supply.

High-speed turbine shaft or shaped charge; small puncture probably could be dealt with by emergency water supply.

Dropped cask, major source of accident risk; needs more analysis.

Explosion under pool potentially most troublesome.

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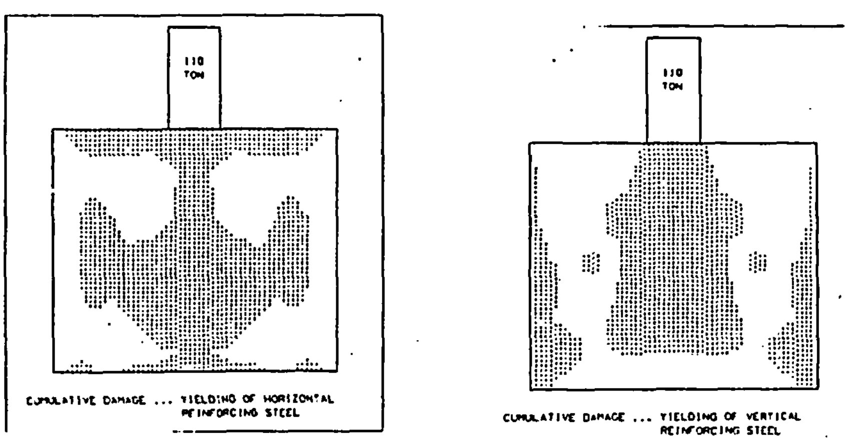
BWR pool wall damage from 6-inch (15-cm) cask drop

[*Seismic failure and cask drop analyses of the spent fuel pools at two representative nuclear power plants* (NUREG/CR-5176, 1989), p. 7-3, Figs. 7-7 and 7-8]



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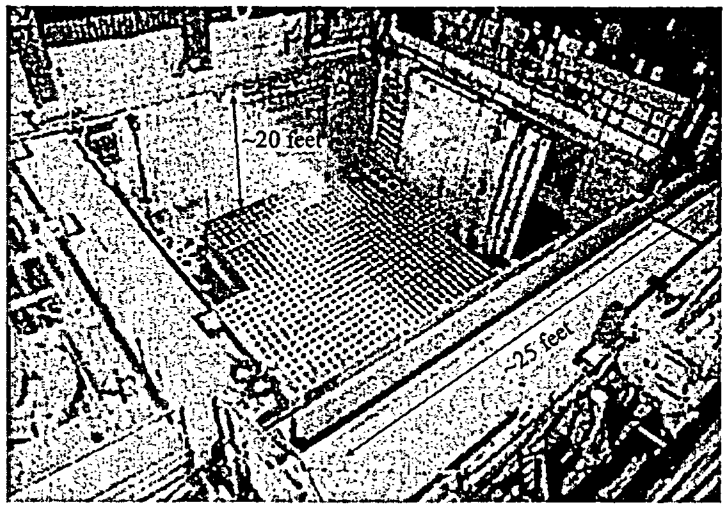

An almost full dense-packed storage pool
(NRC website)

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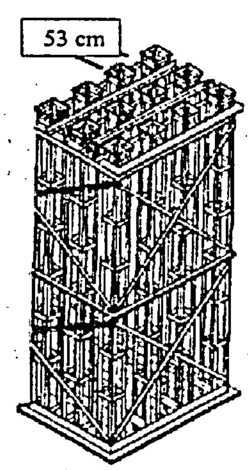
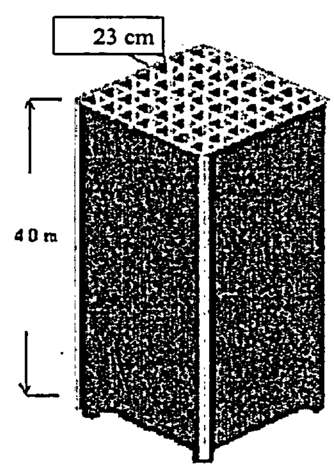
"Open Rack"
Original design



(SAND77-1371)

"Dense-pack"
Current design



(HOLTEC website)

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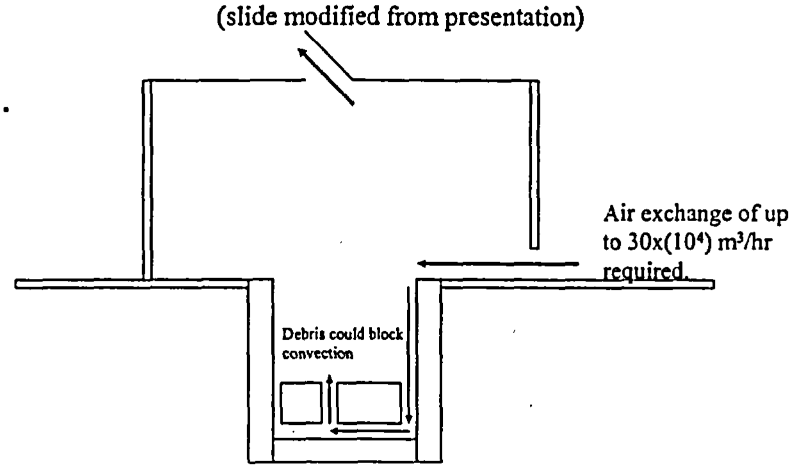
Convective air cooling

(slide modified from presentation)



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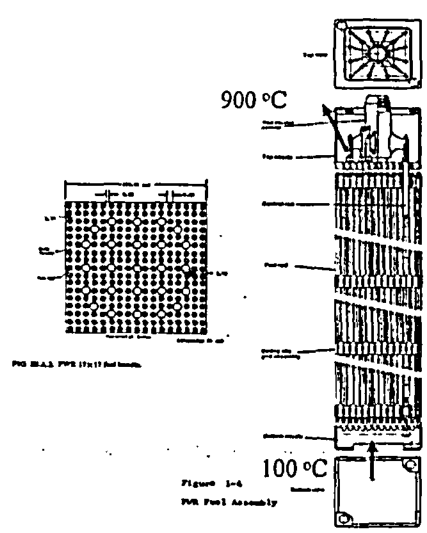
Fuel assembly tight.

Convection velocity 0.3 m/sec (neglecting friction in downcomer and under racks).

Could cool 15 kWt/tU fuel (one year cooling).



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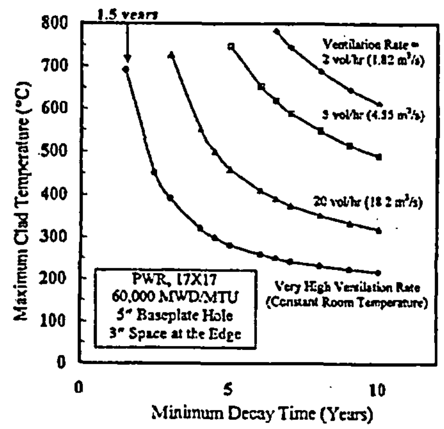
Numerical results (SAND77-1371, 1979)



Things get worse quickly in absence of air exchange with outside -- or if convective flow is blocked by water or debris.

"[I]t was not feasible, without numerous constraints, to establish a generic decay heat level (and therefore a decay time) beyond which a zirconium fire is physically impossible.."
--NUREG-1738 (2001)

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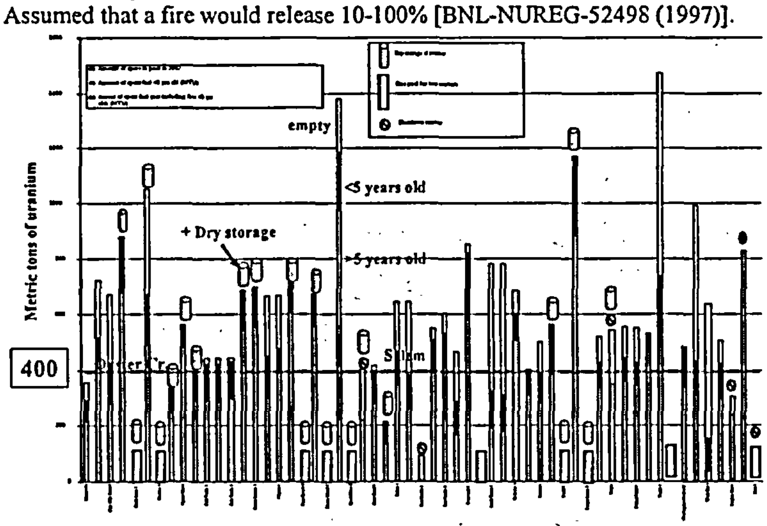
400 tons of spent fuel contains ~ 35 MCi of ^{137}Cs (5x Chernobyl #4 core inventory)
Assumed that a fire would release 10-100% [BNL-NUREG-52498 (1997)].



2003 Inventory in some U.S. spent-fuel pools (est.)

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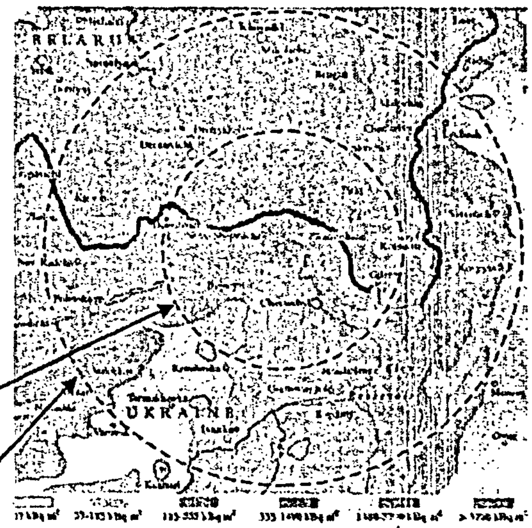
2 MCi of Cs^{137} (30-year halflife) released by Chernobyl

>15 Ci/km²: radiation control area: > 10,000 km² (1/2 of area of NJ)

>50 Ci/km²): >0.7% chance of radiation-caused cancer death from lifetime external radiation ~ 3100 km²

18-mile radius (permanently evacuated)

36-mile radius



[illegible] 50 MCi/km²

Chernobyl releases occurred over 6 days

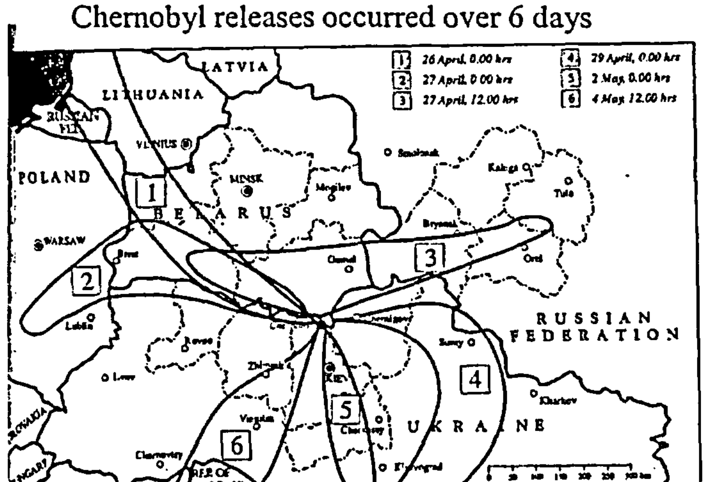


Figure V. Plume formation by meteorological conditions for instantaneous releases on dates and times (GMT) indicated [87].

(UNSCEAR-2000)

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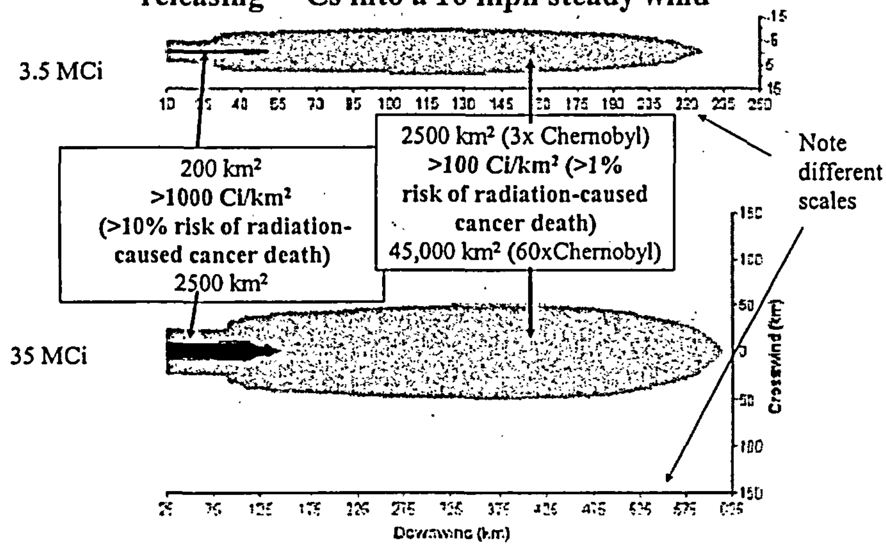
MACCS2 code prediction for smoldering pool fire releasing ^{137}Cs into a 10 mph steady wind



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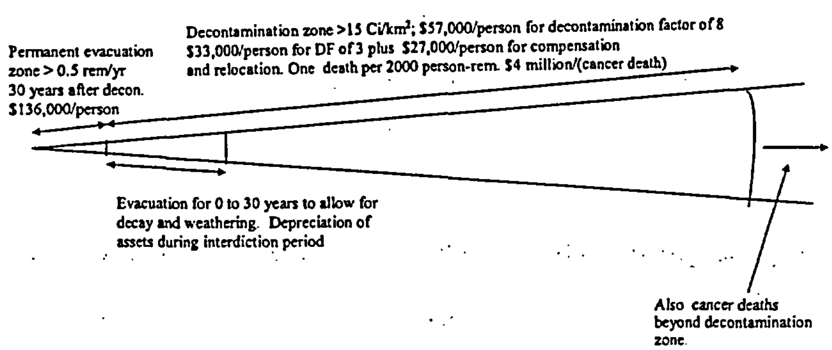
Different zones of damage
(wedge model geometry)



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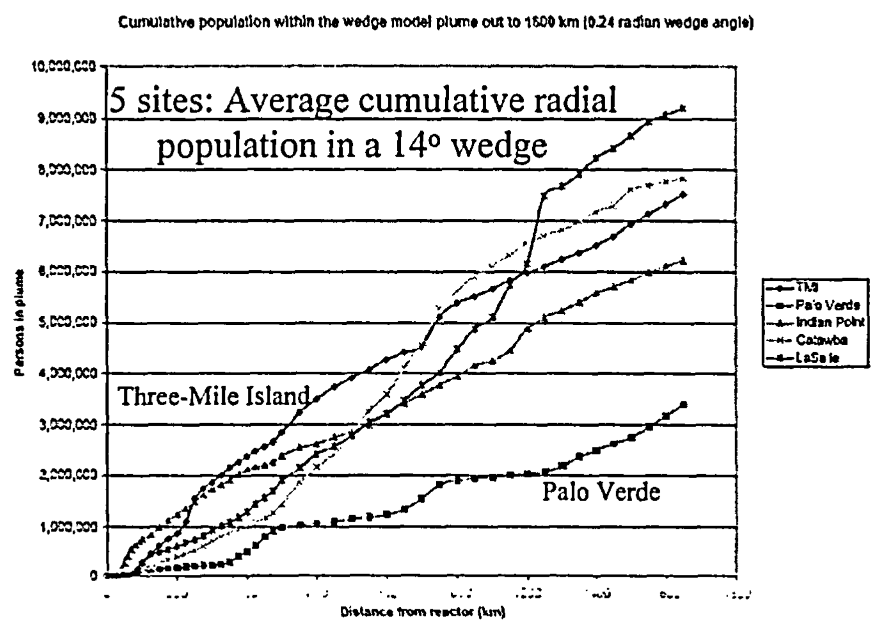

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Damage estimates for 3.5-35 MCi release

Site	Damages ($B)	Cancer Deaths
Catawba	76-547	3100-7700
Indian Point	145-461	1500-5600
LaSalle	54-80	2100-6400
Palo Verde	11-80	600-2000
Three-Mile Is.	171-568	2300-7000
Average	91-347	1900-5700

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Questions

Current NRC policy is to keep 100 dense-packed pools for decades. Should this policy be reconsidered post Sept. 11, 2001?

How much would it be worth to significantly reduce the chance of a spent-fuel fire -- however it is done?

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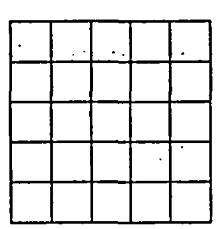
Why reduce storage density?

- Would allow open-rack storage of hottest fuel or
- Removal of one fifth of fuel assemblies could expose at least one side of each to an open channel



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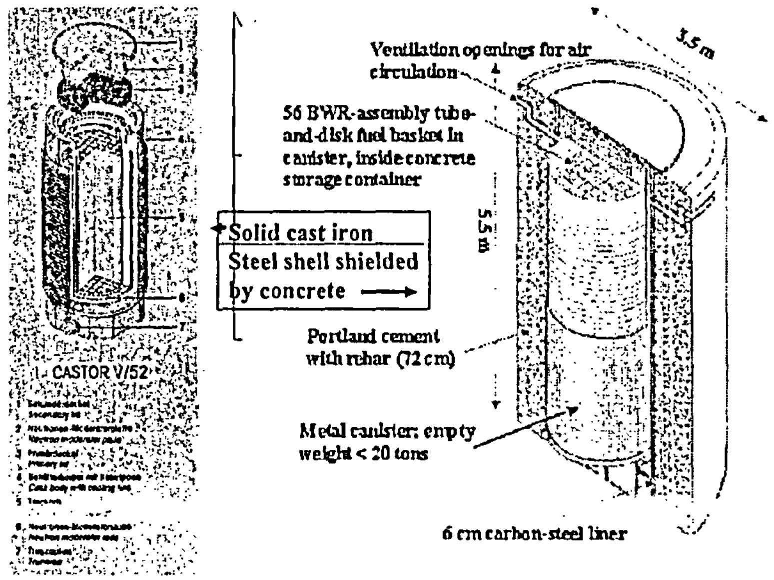
Two types of dry storage casks



Magnitude of the task

45,000 tons of dense-packed fuel currently projected for 2010

9,000 tons with more than 5 years cooling could be stored in about 900 casks

2,400 tons of U.S. spent fuel already stored in 200 dry casks in 2000

Two major U.S. manufacturers say that they could ramp up their combined production to 500 casks/yr

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Cost of dry storage

$1-2 million per cask

=>$1-2 billion for 1000 casks

0.03-0.06 cents per kWh generated from the fuel (less than 1% of retail price of electricity in U.S.)

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Partial unloading of pools may not be enough

Convective air cooling may not work if:

- **Spent-fuel buildings not ventilated**
  --Perforate the sides of the assembly boxes?
- **Debris blocks tops of air channels or fuel assemblies crushed**
  --Install water sprays?

Modeling has to be done of the cooling problem and cooling and recovery strategies in a variety of hypothetical post-attack situations.

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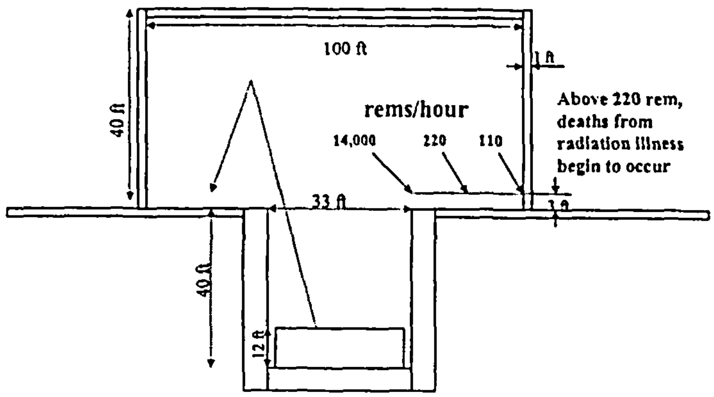
Recovery strategies must take account gamma radiation from dry spent-fuel pool

(simplified circular pool layout, elevation view)



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NRC criticisms of S&GS article

(See www.princeton.edu/~globsec/people/fvhippel.html for full exchange.)

1. **No proof probability of terrorist-caused spent-fuel fires is high enough to justify expense of added dry storage**

--No proof is possible but fault-tree estimates of accidental probability provide a lower bound.

2. **Release of radioactivity is overestimated.**

--NRC believes that fire would not spread to older fuel

--What is the basis of this conclusion?

--In any case, 20 tons of 50 MWd/kgU fuel contain 3 MCi of ^{137}Cs at discharge. A full core contains 7.5 MCi

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Nuclear Regulatory Commission criticisms (cont)

3. Population density overestimated in Brookhaven study

--Correct. We have now done calculations using radial population densities for five specific U.S. sites.

--NRC should publish its own estimates with real wind distributions for population densities projected to 2020.

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Nuclear Regulatory Commission criticisms (cont)

4. Cost of shifting to casks underestimated

-- Spent fuel is being stored in dry storage on a large scale in the U.S., Germany & elsewhere, so good data is available.

-- NRC should publish its own cost estimates

5. Other Criticisms

--Our discussion of turbine-shaft penetration did not take into account the pool liner and water and fuel behind the liner (it did)

--Jet fuel fire would not threaten pool integrity (that's what we say)

--We did not put risks from spent fuel pools in perspective by comparing with terrorist attacks on other facilities (e.g. 747 crash into Rose Bowl game).

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Recommendations

The NAS study group should determine:

1) Where the new NRC staff analyses supercede the 25 years of national lab analyses which our paper reviews.

2) Whether the NRC is justified in refusing to make available for open peer review any parts of its new analyses -- including:

Its model for dense-pack fire spread and ^{137}Cs releases

The population densities it used for consequence estimates

Its estimate of the costs of moving spent fuel to dry storage

See also our recommendations with regard to spent-fuel pool operations and emergency preparations.

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