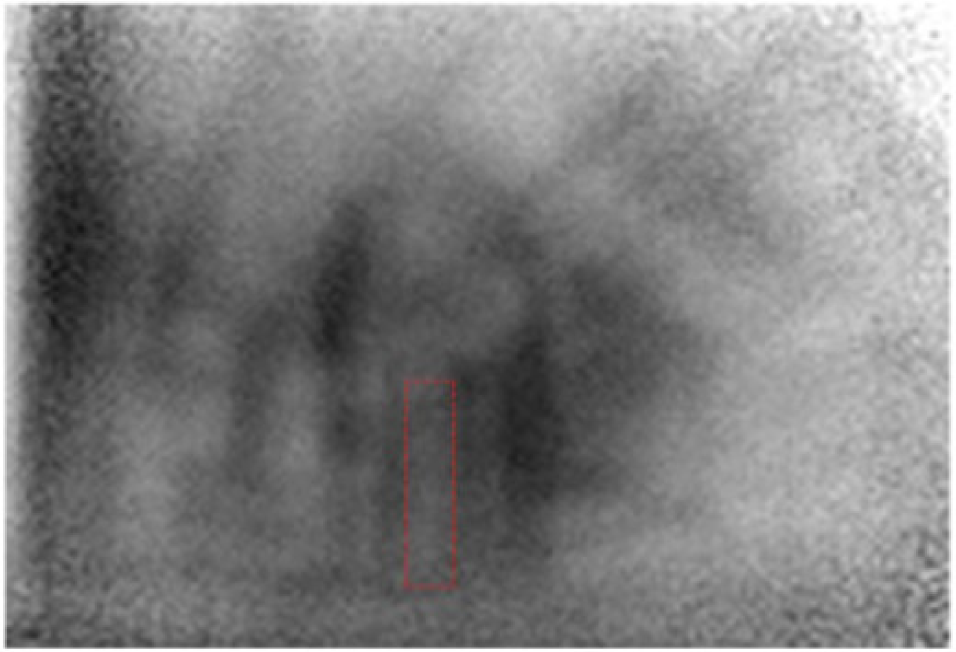
Post-accident neutrino detection



Applied Antineutrino Physics 2024

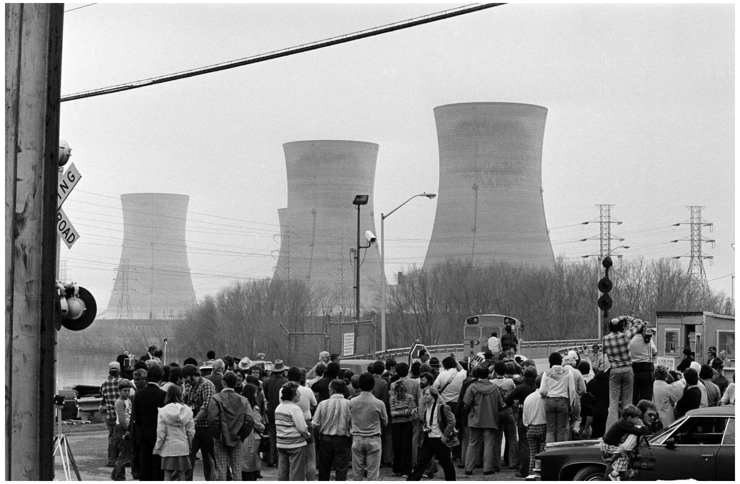
28 – 30 October, 2024, Aachen, Germany

Patrick Huber
Center for Neutrino Physics
Virginia Tech

Image credit: Fujii, *et al.*,Progress of Theoretical and Experimental Physics, Volume 2020, Issue 4, April 2020, 043C02

Post-accident neutrinos?

Broadly identified as potential use case by NuTools



Three historic cases:

Three Mile Island (1979)

Chernobyl (1986)

Fukushima Daiichi (2011)

This and the following is work in collaboration with B. Cogswell and A. Glozer, in preparation

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Chernobyl - 1986

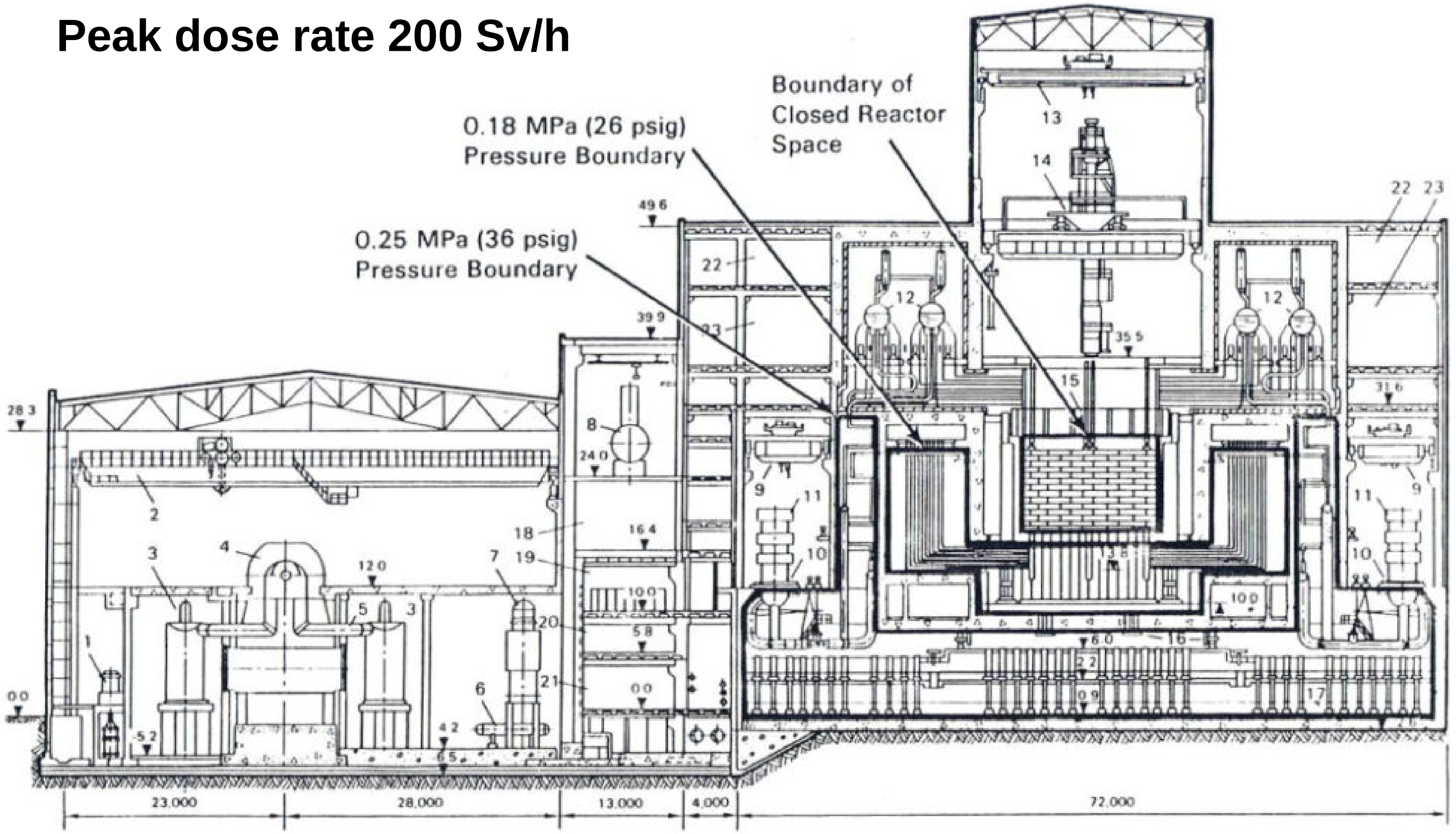
RBMK reactor, water-cooled, graphite-moderated, no reactor pressure vessel, no secondary containment

Large fraction of core inventory was dispersed, i.e. **all fission fragments** contribute to the gamma radiation field

Very large core, very large building → **closest approach about 50m**

Vague concerns about ongoing criticality – hence boron-laden sand was dropped on the open reactor

Peak dose rate 200 Sv/h



1 - First-stage condensate pump; 2 - 125/20-t overhead travelling crane; 3 - Separator-steam superheater; 4 - K-500-05/3000 steam turbine; 5 - Condenser; 6 - Additional cooler; 7 - Low-pressure heater; 8 - Deaerator; 9 - 50/10-t overhead travelling crane; 10 - Main circulating pump; 11 - Electric motor of main circulating pump; 12 - Drum separator; 13 - 50/10-t remotely controlled overhead travelling crane; 14 - Refueling mechanism; 15 - RBMK-1000 reactor; 16 - Accident containment vavles; 17 - Bubbler pond; 18 - Pipe aisle; 19 - Modular control board; 20 - Location beneath control board room; 21 - House switchgear locations; 22 - Exhaust ventilation plant locations; 23 - Plenum ventilation plant locations

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Three Mile Island & Fukushima Daiichi

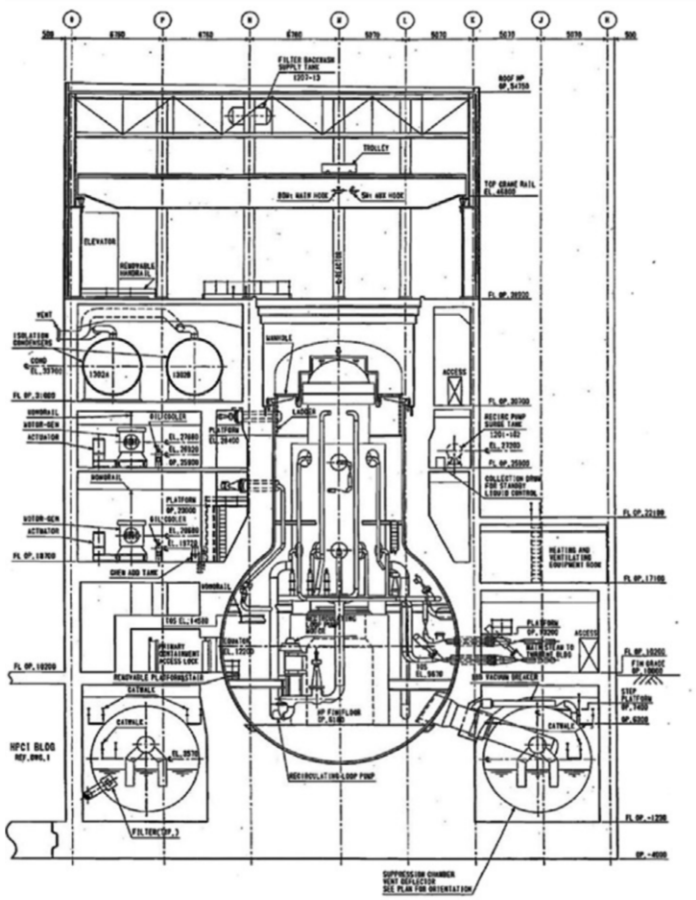
Both reactors are light-water moderated and cooled

Both have pressure vessels and secondary containment

Only **volatile fission fragments** are dispersed and contribute to gamma radiation field

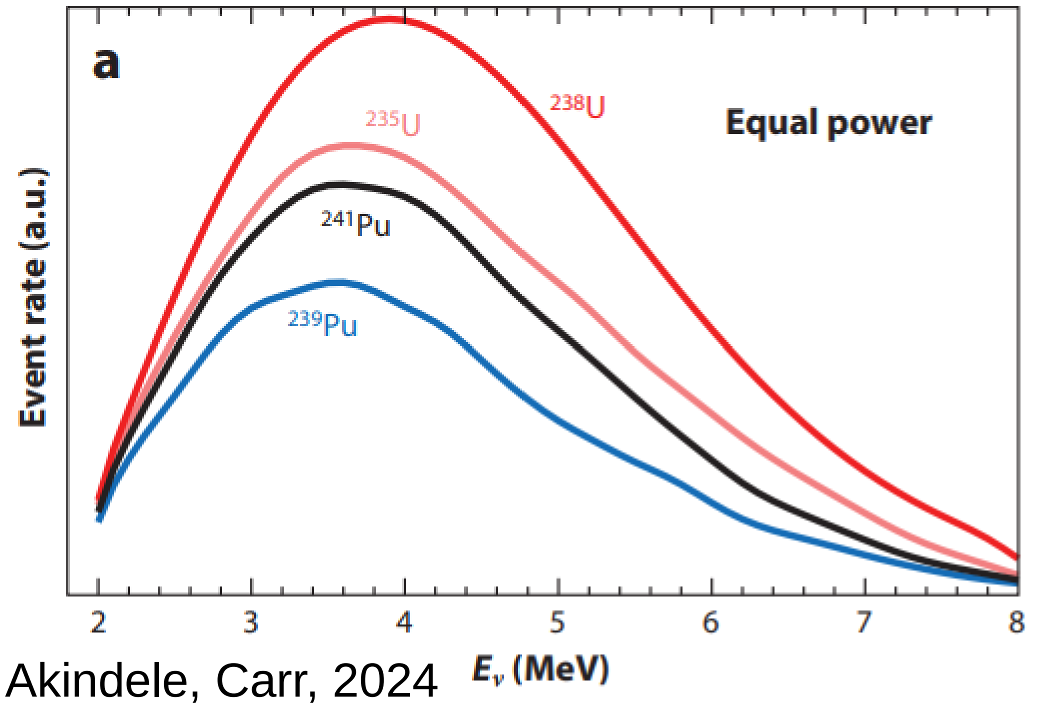
Compact cores, compact containment structures → **closest approach 25m**

Specific concerns that emergency cooling with unborated water could lead to **re-criticality**



Peak dose rate 0.4 Sv/h

Neutrino Signatures

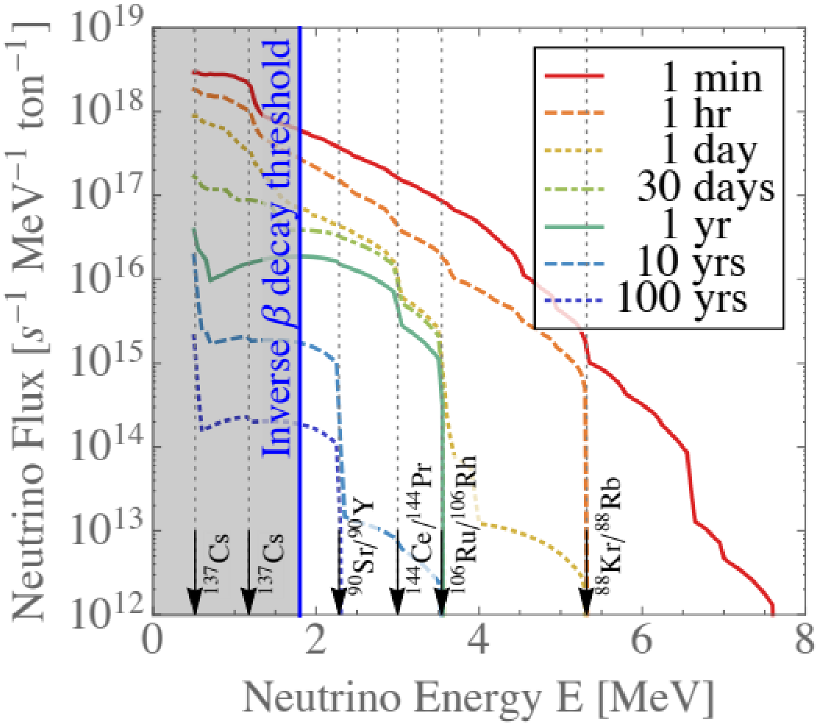


Akindele, Carr, 2024

Prompt signature directly tracking fission rate
→ is fission happening right now?

This talk!

Brdar, Huber, Kopp, 2017



Delayed signature tracking location of core
→ where is the material which was fissioning?

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Re-criticality at TMI

As of March 31, 1980, the damaged core of TMI-2 is subcritical as verified by the single remaining excore source range neutron detector.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

8005130498
P

APR 0 4 1980

MEMORANDUM FOR: William J. Dircks
Acting Executive Director for Operations

FROM: Robert J. Budnitz, Director
Office of Nuclear Regulatory Research

SUBJECT: IMPLEMENTATION OF RECOMMENDATIONS OF SPECIAL TASK FORCE ON THREE MILE ISLAND CLEANUP

Reference: Your memorandum of March 6, 1980, same subject

Enclosed is the report "A Further Evaluation of the Risk of Recriticality At TMI-2," which you requested be prepared in the referenced memorandum.

TABLE III. FISSION PRODUCT INVENTORIES GENERATED DURING CRITICALITY EVENTS

	TRANSIENT (PULSE) CRITICALITY	SUSTAINED CRITICALITY			CUR[illegible] T[illegible] INVENTORY
		CASE A	CASE B	CASE C	
Energy Generation Rate (MW)	2772	27.7	27.7	277	-
Fraction of Core Which is Critical	0.1	1.0	1.0	1.0	-
Time at Power (MIN)	1	60	60	600	-
Total Energy Generated (MJ)	$1.7x10^4$	$1x10^5$	$1x10^6$	$1x10^7$	-
Fission Products Generated (Ci)					
Krypton	$5.1x10^3$	$3.2x10^4$	$3.2x10^5$	$3.2x10^6$	$1.0x10^5$
Xenon	$7.1x10^3$	$4.4x10^4$	$4.4x10^5$	$4.4x10^6$	$2.3x10^{-3}$
Iodine	$8.4x10^3$	$5.1x10^4$	$5.1x10^5$	$5.1x10^6$	$2.2x10^{-1}$
Cesium	$6.4x10^3$	$3.9x10^4$	$3.9x10^5$	$3.9x10^6$	$1.2x10^6$
Others	$9.0x10^4$	$5.3x10^5$	$5.3x10^6$	$5.3x10^7$	$4.0x10^7$
TOTAL	$1.2x10^5$	$7.0x10^5$	$7.0x10^6$	$7.0x10^7$	$4.1x10^7$*

19

Only **one piece of equipment** still functioning to assess criticality in real-time.

Only case C will lead to relevant off-site radiation releases and will take 24h to mount an intervention.

10% of full reactor power, over 24h

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Re-criticality at FD

Nuclear Engineering and Technology
Volume 55, Issue 9, September 2023, Pages 3241-3251

Original Article

Analyses on the recriticality and sub-critical boron concentrations during late phase of a severe accident of pressurized water reactors

Yoonhee Lee, Yong Jin Cho, Kukhee Lim

ELSEVIER
Annals of Nuclear Energy
Volume 99, January 2017, Pages 495-509

Investigation of the recriticality potential during reflooding phase of Fukushima Daiichi Unit-3 accident

Piotr Darnowski, Kacper Potapczyk, Konrad Świrski

The New York Times

In Nuclear Crisis, Crippling Mistrust

TOKYO — On the evening of March 12, the Fukushima Daiichi nuclear plant's oldest reactor had suffered a hydrogen explosion and risked a complete meltdown. Prime Minister Naoto Kan asked aides to weigh the risks of injecting seawater into the reactor to cool it down.

At this crucial moment, it became clear that a prime minister who had built his career on suspicion of the collusive ties between Japan's industry and bureaucracy was acting nearly in the dark. He had received a confusing risk analysis from the chief nuclear regulator, a fervently pro-nuclear academic whom aides said Mr. Kan did not trust. He was also wary of the company that operated the plant, given its history of trying to cover up troubles.

Mr. Kan did not know that the plant manager had already begun using seawater. Based on a guess of the mood at the prime minister's office, the company ordered the plant manager to stop.

By Norimitsu Onishi and Martin Fackler
June 12, 2011

No instrumentation available due to station blackout

Uncertainty on core state confuses decision making

Based on volatile core inventory event of concern

10% of full power for 24h

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Radiation shielding goal

Current detectors operate in the natural gamma radiation field of **1E-7 Sv/h**

This defines the **maximum shielding** requirement but puts no extra burden on detector performance or operation

Segmented detectors with a clean neutron tag should tolerate much higher gamma radiation fields.

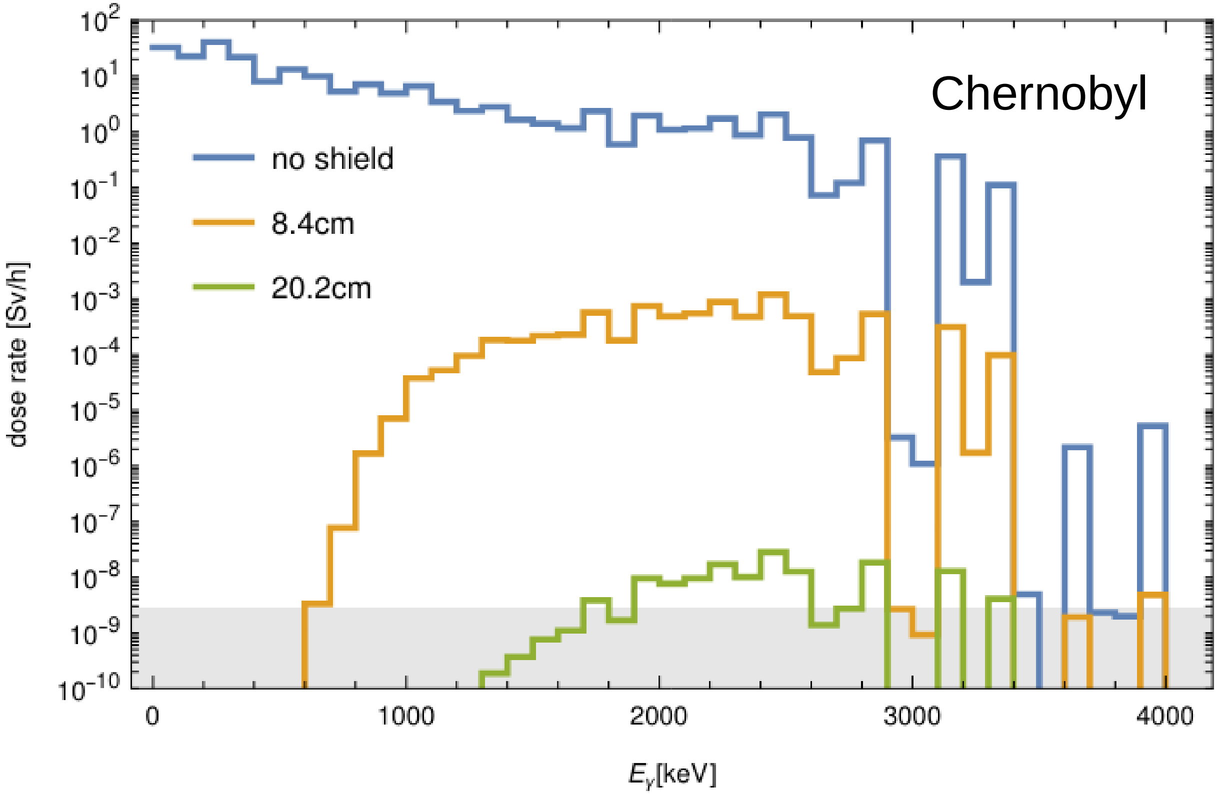
1) Energy cut to remove singles (few MeV) efficiency!
2) 1 GHz data rate for DAQ **0.02 Sv/hr**
3) 2 gamma pileup (evading 1) 20 Sv/hr
4) 2 gammas creating long event to mimic neutron 0.1 Sv/hr

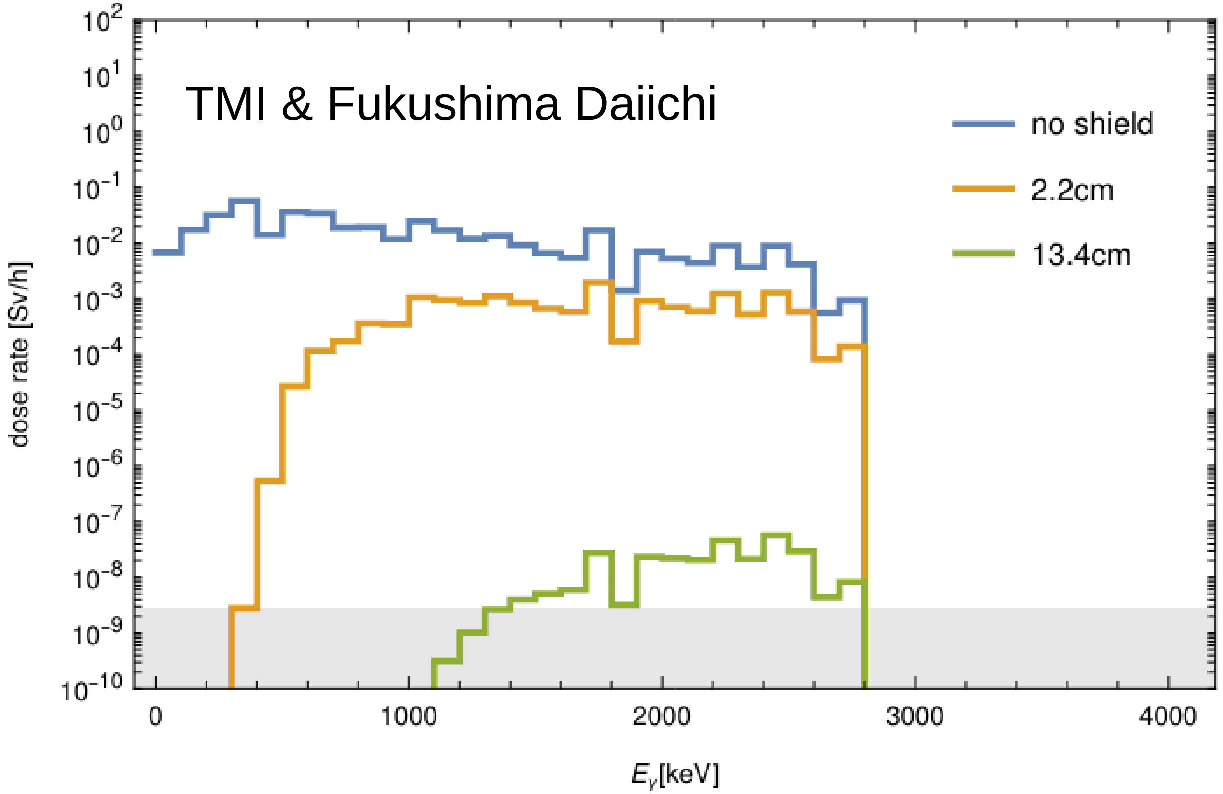
DAQ rate is the limiting factor with a corresponding occupancy of time/volume segments is about 1E-4

This defines a **minimum shielding** requirement but the energy cut will reduce signal efficiency

NB: We will neglect the impact of gamma shielding on neutron backgrounds from muon spallation.

Radiation simulation & shielding





- Isotopic composition from fuel burnup computed with SCALE (45 GW d/t, 4% enriched)
- Gamma dose rates from ENSDF
- Gamma attenuation for depleted uranium from NIST tables

Orange – minimal shield, green – maximal shield

System Mobility

For a given carrying capacity there is a maximum volume which can be shielded, hence detector mass.

$$M = \underbrace{\left[(l+2d)^3 - l^3\right]\rho_s}_{\text{mass of shield}} + \underbrace{l^3\rho_d}_{\text{mass of detector}}$$

This assumes zero-thickness photo sensors…

NB: Both vehicles can be airlifted

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Possible detector masses

	Chernobyl		TMI/FD	
actual dose rate [Sv h^{-1}]	200		0.4	
target does rate [Sv h^{-1}]	1×10^{-7}	2×10^{-2}	1×10^{-7}	2×10^{-2}
required reconstructed energy cut [MeV]	0	4.0	0	2.8
signal efficiency of energy cut [%]	100	27	100	60
required shield thickness [cm]	20.2	8.4	13.4	2.2
detector mass [t] for a gross mass 15 t	0.2	1.3 (0.4)	0.6	6.3 (3.8)
detector mass [t] for a gross mass 30 t	0.8	3.8 (1.0)	1.8	14.7 (8.9)

Resulting sensitivity

Chernobyl – 50 m

gross mass [t]	15		30	
detector mass [t]	0.2	1.3 (0.4)	0.8	3.8 (1.0)
0.1 neutron bkg.	670	580	**330**	**290**
0.2 neutron bkg.	900	820	530	460
0.5 neutron bkg.	1520	1500	1000	730
1.0 neutron bkg.	2450	2190	1570	1050

TMI/FD – 25 m

gross mass [t]	15		30	
detector mass [t]	0.6	6.3 (3.8)	1.8	14.7 (8.9)
0.1 neutron bkg.	**100**	**50**	**80**	**30**
0.2 neutron bkg.	**140**	**70**	**130**	**50**
0.5 neutron bkg.	**280**	**120**	**250**	**80**
1.0 neutron bkg.	380	**170**	**270**	**120**

95% detection probability with 5% false positive rate within 24h data taking, numbers in MWt of average fission power released. MAD-style neutron background and efficiency (plus energy cut)

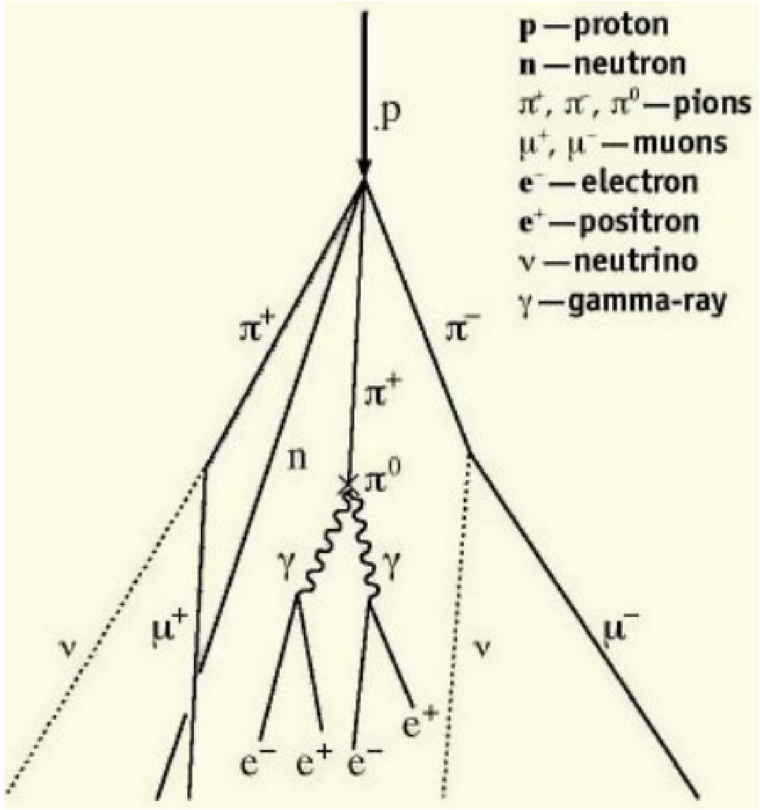
Further thoughts on shielding

High energy dose rate dominated by lanthanides which stick to the ground.

Volatiles are either noble gases which do not accumulate near the reactor or cesium that also sticks to the ground.

Radiation field not isotropic – bulk from below and the sides

Muons and neutrons come from above, mostly



Tank armor varies in thickness from 300-700mm and is not isotropic

Graded, anisotropic shields are commonly used

- high-Z high-density on bottom and sides
- low-Z low-density on top

Needs real simulation and design, but may allow to keep neutrons under control.

Summary

- Re-criticality has been a real-world concern in actual nuclear accidents – conventional instrumentation is insufficient
- 10% of full power for 24 hours delineates adverse off-site effects
- Radiation environment is severe but manageable with a range of strategies – depends on detailed detector performance
- Despite the difficult environment, it seems possible to deploy ton-scale neutrino detectors on a short time scale on a mobile platform
- The achievable sensitivity is encouraging for light-water reactors – majority of reactors globally

Acknowledgements

Dr. Bernadette Cogswell

Addison Glozer

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

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