THE DANGERS OF USING MOX (PLUTHERMAL) FUEL

Edwin S. Lyman
Senior Scientist
Union of Concerned Scientists
Washington, DC USA

July 2015

Summary

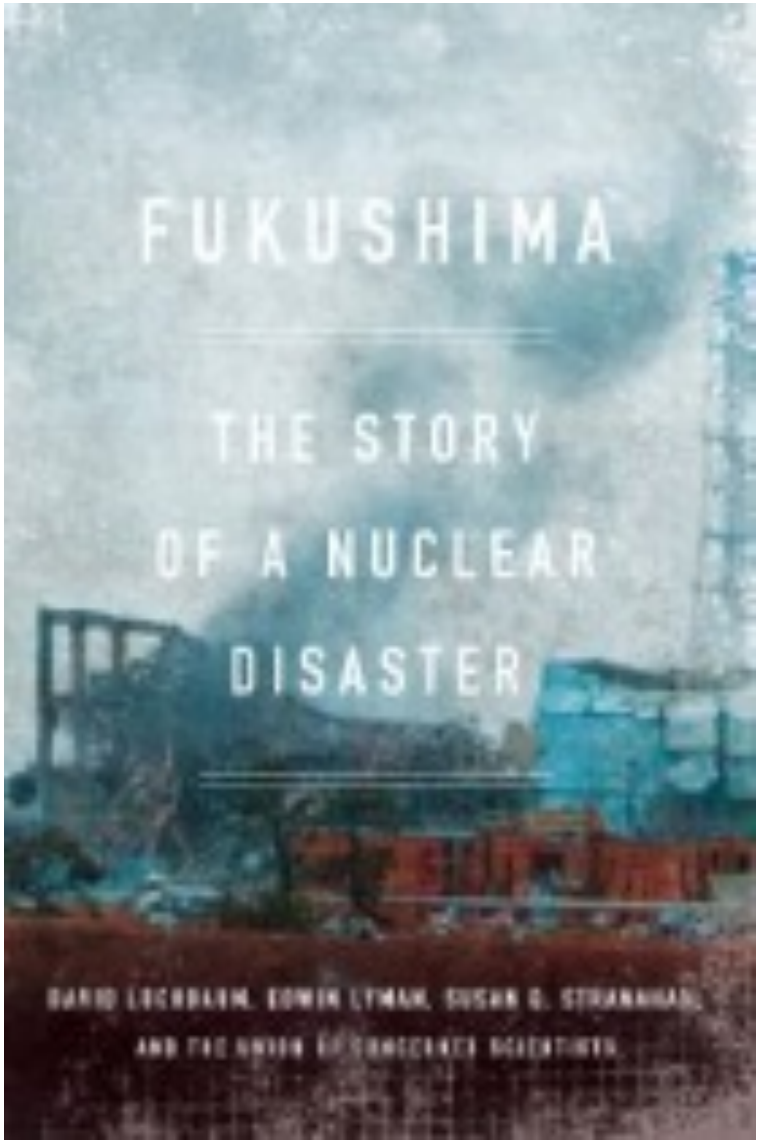
- Using MOX (pluthermal) fuel in reactors will increase
  - the likelihood of a severe nuclear accident (like Fukushima)
  - the public health consequences of a severe nuclear accident (cancer cases)
  - the economic impact of a nuclear accident (cleanup cost of contaminated areas)
  - the cost and danger of spent fuel storage
- There are many unanswered questions about MOX fuel safety; more research is needed
- The Nuclear Regulation Authority should heed the lessons of Fukushima and not permit the use of MOX fuel in Japan, given the lack of information

FUKUSHIMA:
The Story of a Nuclear Disaster

David Lochbaum
Edwin Lyman
Susan Q. Stranahan

The New Press (2014)

To be published in Japanese by Iwanami Shoten (October 2015)



A lesson of Fukushima

- Calculations of the probabilities of severe nuclear accidents are highly uncertain, especially for accidents initiated by natural events (e.g. earthquakes, floods)
- It is crucial to have generous safety margins and “defense-in-depth” in order to provide a cushion to hedge against uncertainty
- The NRA says that its regulatory philosophy is based on “thorough application of the defense-in-depth concept”

MOX fuel lowers safety margins

- After Fukushima, if nuclear plants are to be restarted in Japan, it is crucial to increase safety margins and reduce uncertainty in safety analyses
- However, use of MOX fuel generally decreases safety margins and increases uncertainty

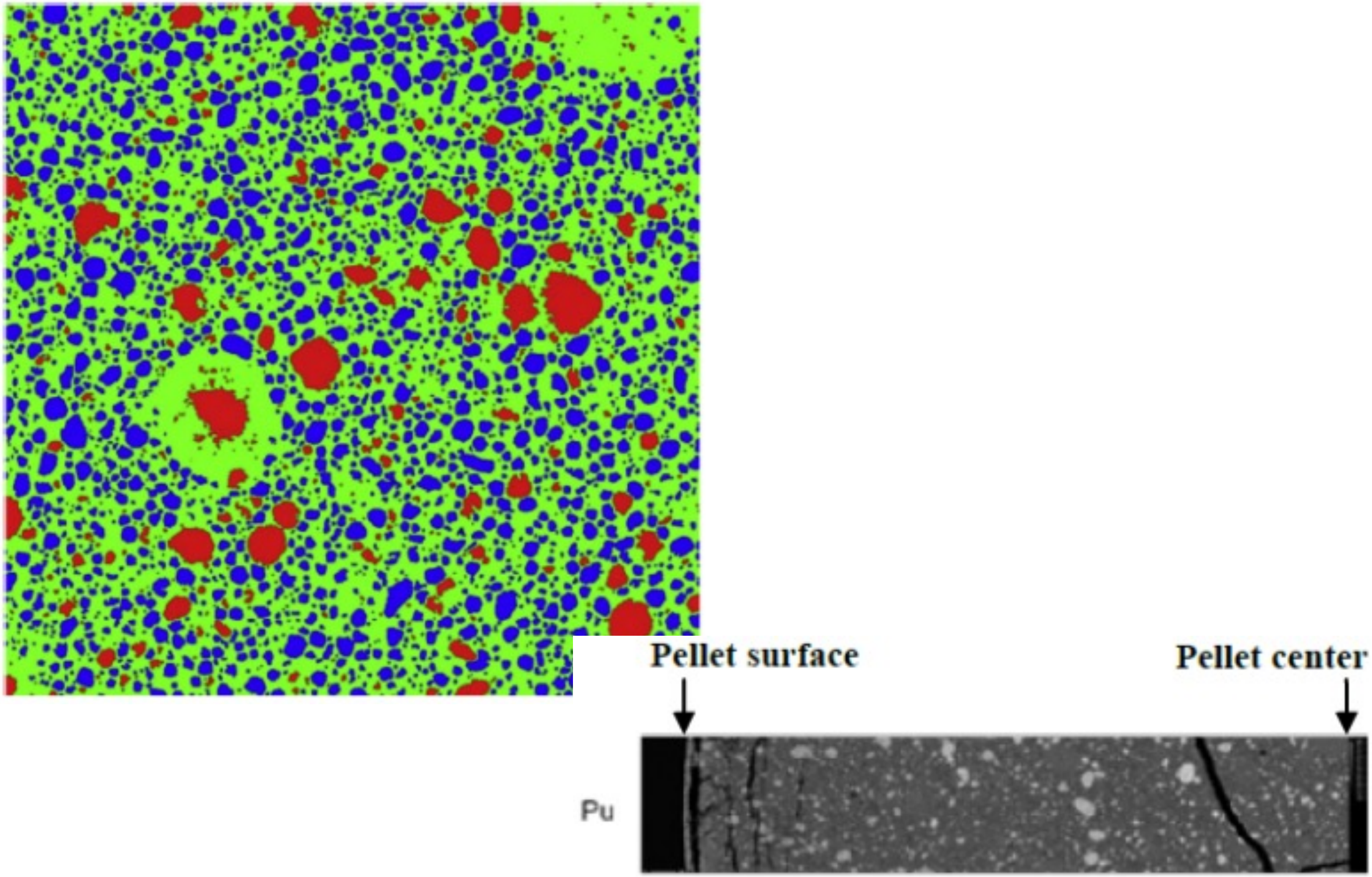
What is MOX fuel?

- Light-water reactors (LWRs) like Ikata 3 normally use fuel consisting of “low-enriched” uranium (LEU) dioxide ceramic pellets clad in a tube made of a zirconium-based metal alloy
  - Uranium-235 content less than 5%
- Mixed-oxide (MOX) fuel is composed of a mixture of uranium and plutonium dioxides
  - Plutonium content less than 10%

MOX versus uranium

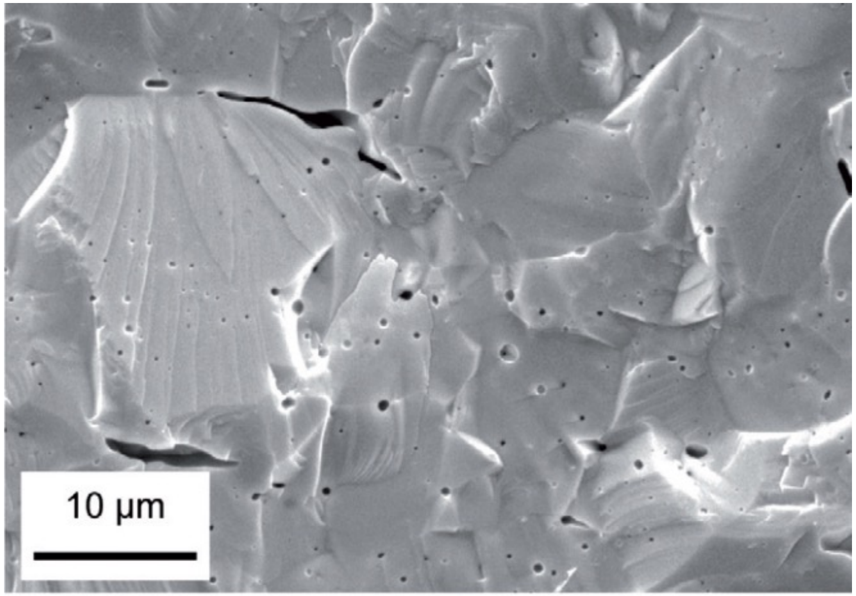
- Uranium dioxide fuel is a relatively homogeneous material
- MOX, in contrast, contains a mixture of two elements that have different physical, chemical and neutronic properties
  - MOX fuel typically has a heterogeneous microstructure with plutonium dioxide clusters
  - This microstructure has a number of negative effects on fuel properties during both normal operation and accidents

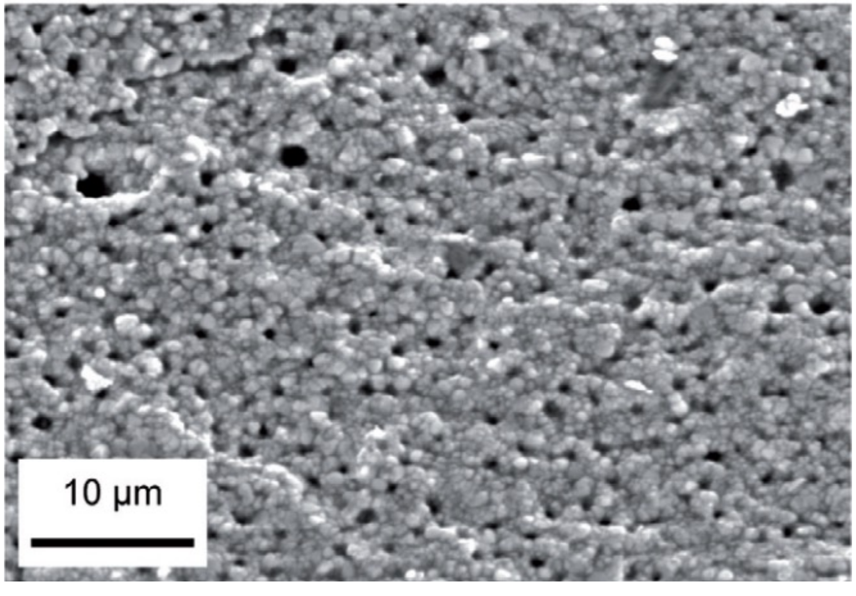
Plutonium clusters (Pu spots)



The RIM effect

- High-burnup uranium fuels (> 40 GWD/t average) undergo a major structural change: the RIM effect
  - High porosity region containing fission gas at the grain boundaries: can destabilize the fuel in a power excursion
- In MOX fuel, the Pu spots experience the RIM effect after a shorter time in a reactor (> 30 GWD/t average) because they experience very high local burnups


10 µm

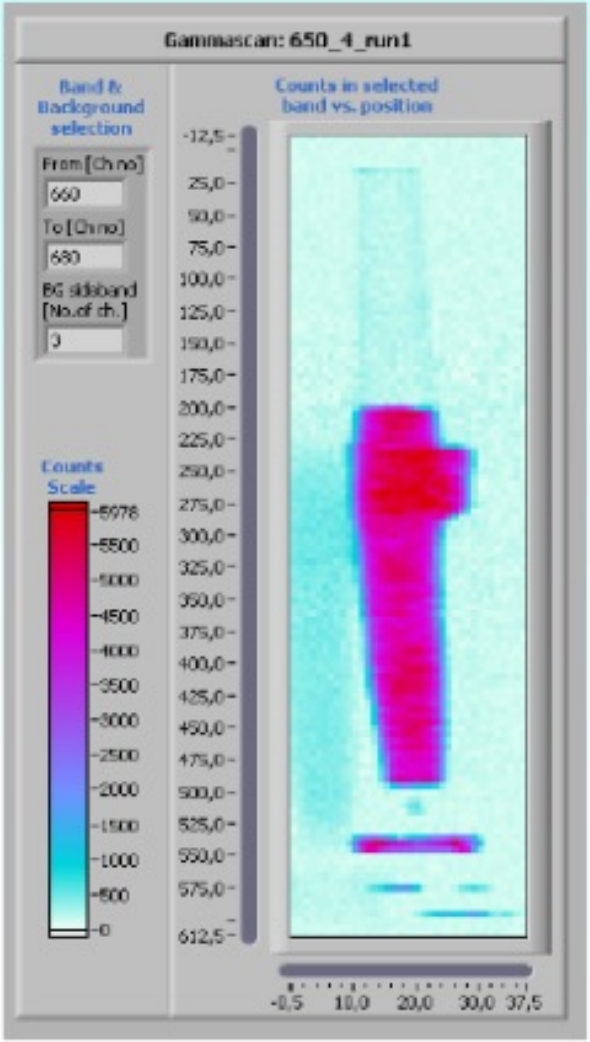

10 µm

Fission gas release

- Fission gas accumulating in the pores of the RIM structure can be rapidly released if the power of a fuel rod changes
- This is a safety issue because
  - Fission gas can increase internal rod pressure and cause reopening of the fuel-cladding gap
  - The movement of the gas can cause the fuel pellets to swell and fragment
  - the gas and swollen pellets can exert pressure on the fuel cladding, possibly causing it to rupture
- MOX fuel releases more fission gas than uranium fuel because more of the fuel has a RIM structure
- MOX fuel also generates more helium gas from decay of plutonium and other actinides than uranium fuel: also contributes to rod internal pressure

Fuel-cladding gap closure

- It is important for safety that the gap between fuel and cladding closes as the fuel is irradiated
- If the gap reopens
  - The thermal conductivity of the fuel decreases and the center of the fuel may get too hot
  - If there is a loss-of-coolant accident, the fuel may be more likely to fragment and “relocate” (Halden reactor tests)



Gammascan: 650_4_run1

Band & Background selection

From [Ch no] 660

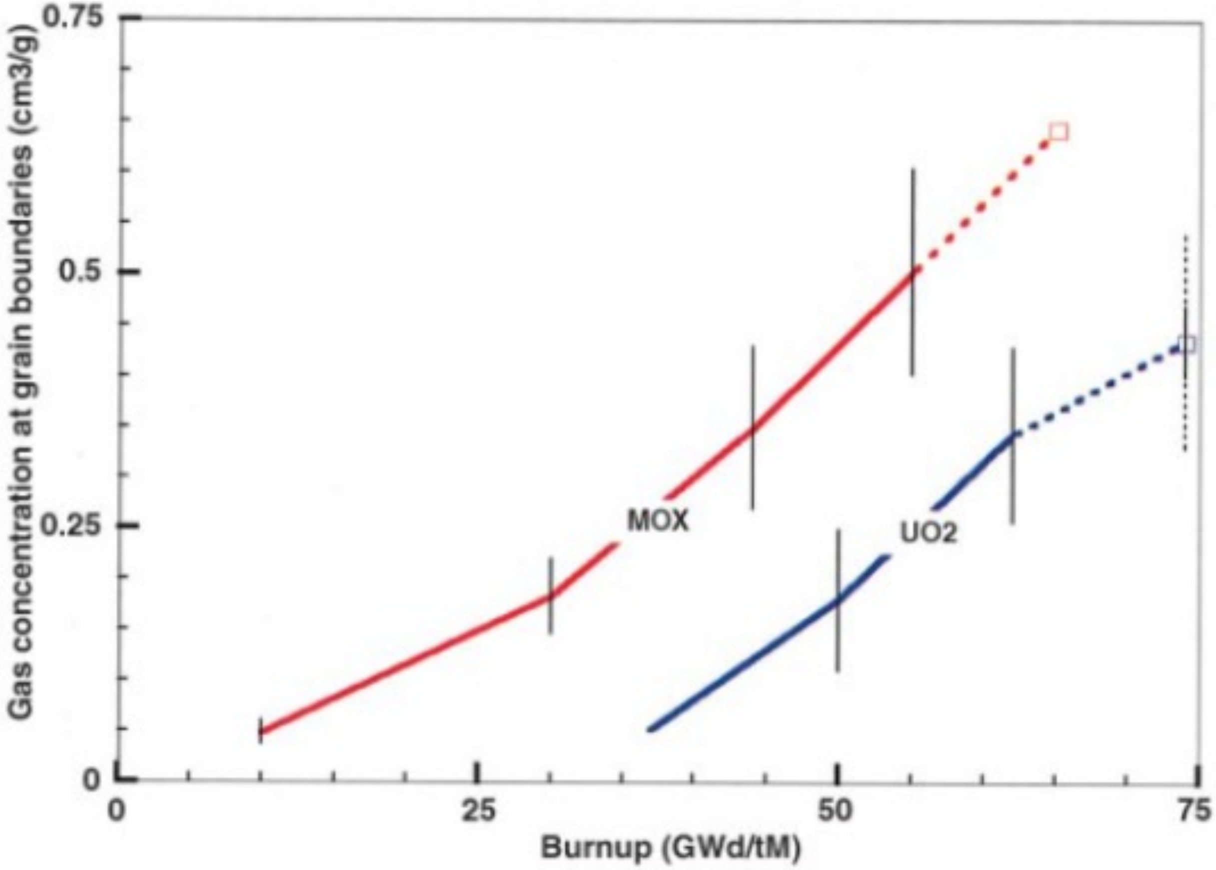
To [Ch no] 680

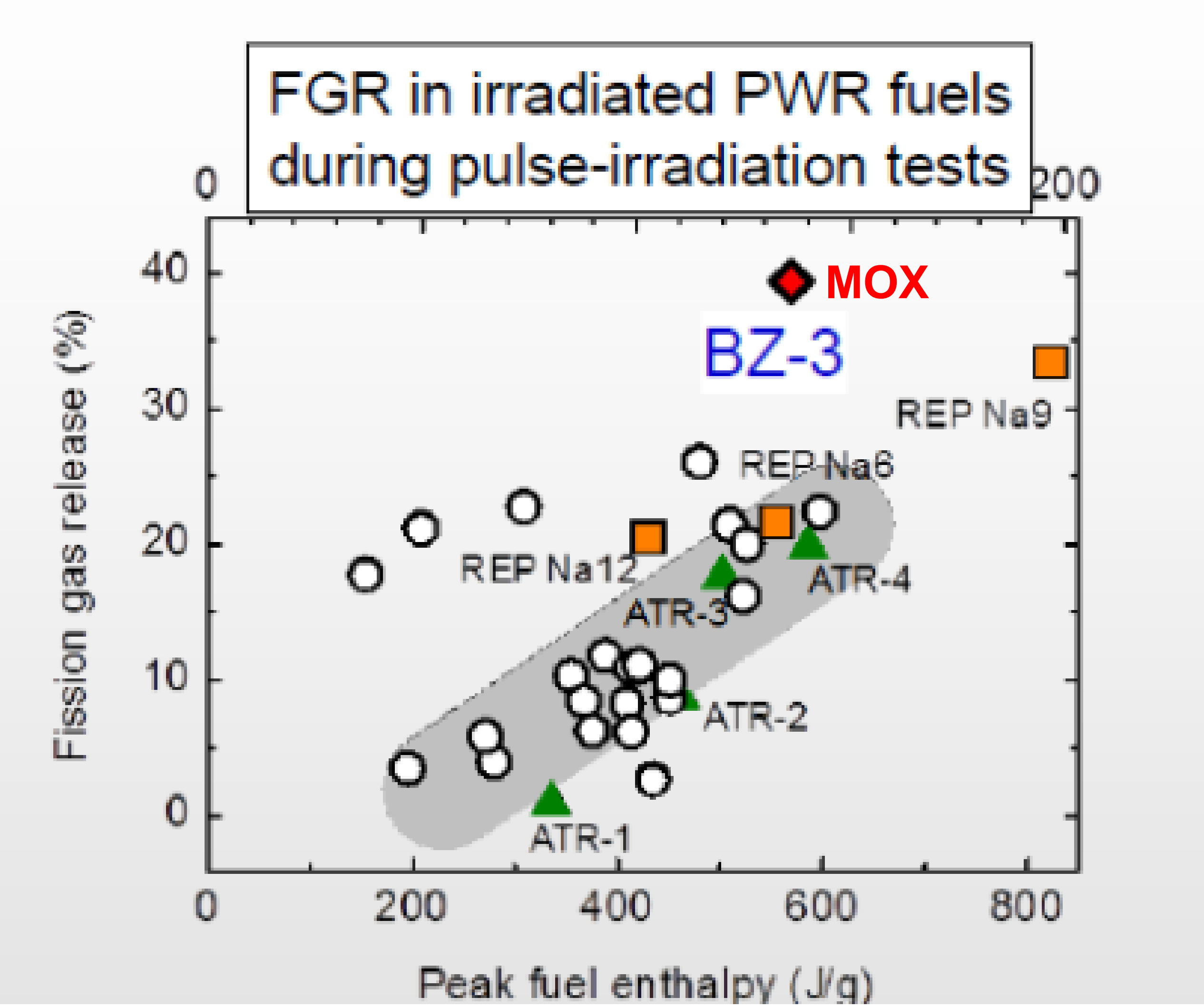
BG sideband [No.of ch.] 3

Fuel relocation in Halden reactor experiment

Figure 10

Fission gas concentration at grain boundaries increases with burnup and is higher in MOX than in UO_2 fuel.




FGR in irradiated PWR fuels
during pulse-irradiation tests
0
200
40
30
20
10
0
MOX
BZ-3
REP Na9
REP Na6
REP Na12
ATR-4
ATR-3
ATR-2
ATR-1
Fission gas release (%)
0
200
400
600
800
Peak fuel enthalpy (J/g)

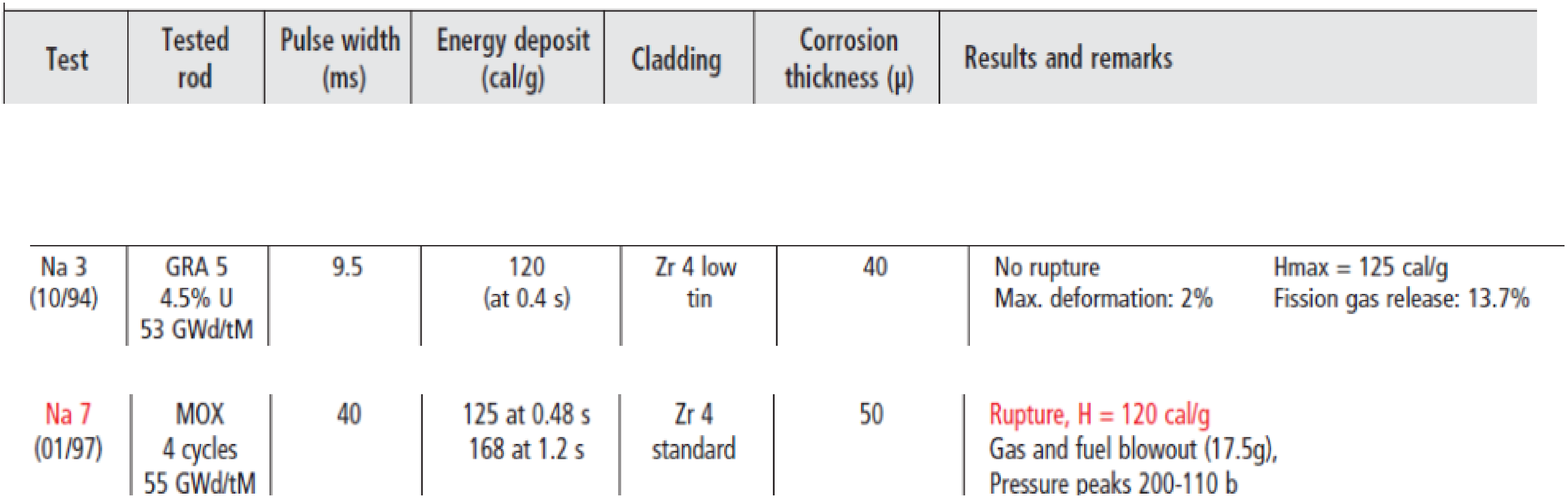
Increased probability of accidents

- The use of MOX in light-water reactors can increase the likelihood that certain accidents can occur compared to an all-uranium core
  - The reactor power can change more rapidly
  - Control rods are less effective
  - The heterogeneous fuel structure can increase the chance that fuel rods will rupture and block coolant channels if a transient occurs

Reactivity transients

- If a control rod becomes loose and is ejected from a reactor core, the power can increase rapidly
- Fuel rods near the ejected control rod can heat up
- The CABRI test series in France demonstrated what can happen to fuel rods that experience reactivity transients
- The tests showed that MOX fuel can fail at lower burnups than uranium fuel to such transients because of the greater fission gas release

CABRI test: uranium vs. MOX



Test	Tested rod	Pulse width (ms)	Energy deposit (cal/g)	Cladding	Corrosion thickness (µ)	Results and remarks
Na 3 (10/94)	GRA 5 4.5% U 53 GWd/tM	9.5	120 (at 0.4 s)	Zr 4 low tin	40	No rupture Max. deformation: 2% Hmax = 125 cal/g Fission gas release: 13.7%
Na 7 (01/97)	MOX 4 cycles 55 GWd/tM	40	125 at 0.48 s 168 at 1.2 s	Zr 4 standard	50	Rupture, H = 120 cal/g Gas and fuel blowout (17.5g), Pressure peaks 200-110 b

Fuel dispersal in CABRI REP-Na7

Enhanced accident releases

- The VERCORS test series in France found that MOX fuel tends to release more semi-volatile fission products (like cesium-137) faster than uranium fuel under heatup conditions typical of loss-of-coolant accidents

Loss of coolant accidents (VERCORS tests)

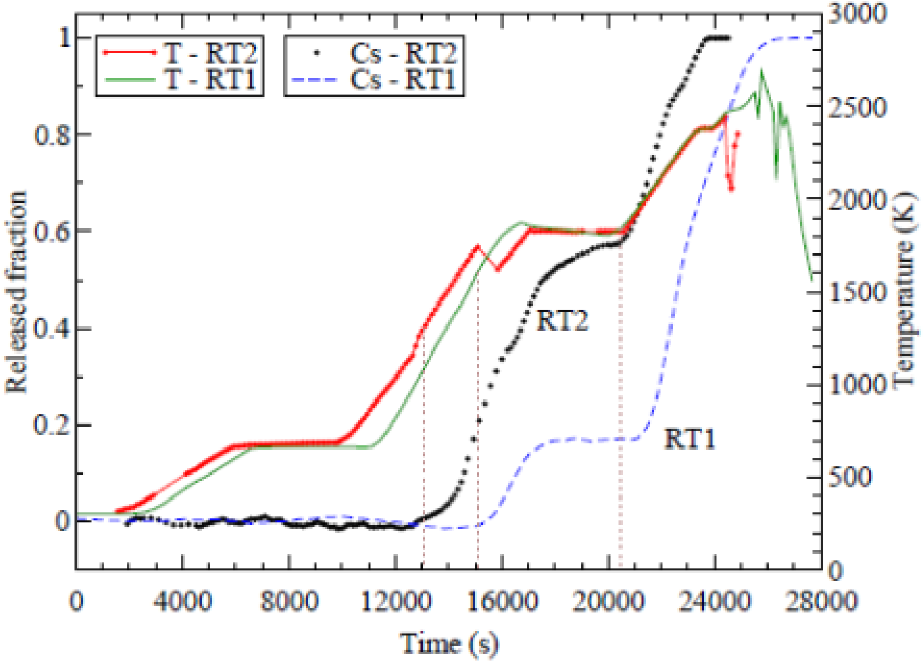


Figure 10: Comparison of caesium release kinetics in RT1 (UO_2 fuel) and RT2 (MOX-AUC fuel).

Uncertainties

- There are many uncertainties regarding how MOX fuel will behave in severe accidents
- Experiments are taking place around the world to study these issues
  - VERDON (MOX source terms and impact of degradation in air)
- Some issues are not being studied because of unavailability of funding
  - MOX fuel relocation in a LOCA
- Some test results are not yet publicly available

Increased consequences of accidents

- MOX fuel in a reactor core has a greater quantity of plutonium and other highly radiotoxic actinides (americium, curium) than a uranium core
- In a severe accident that releases a significant fraction of actinides, the impact on public health and the environment will be greater for a core with MOX fuel than an all uranium core
- The magnitude of the increase will depend on the MOX core loading and the actinide release fraction (RF)

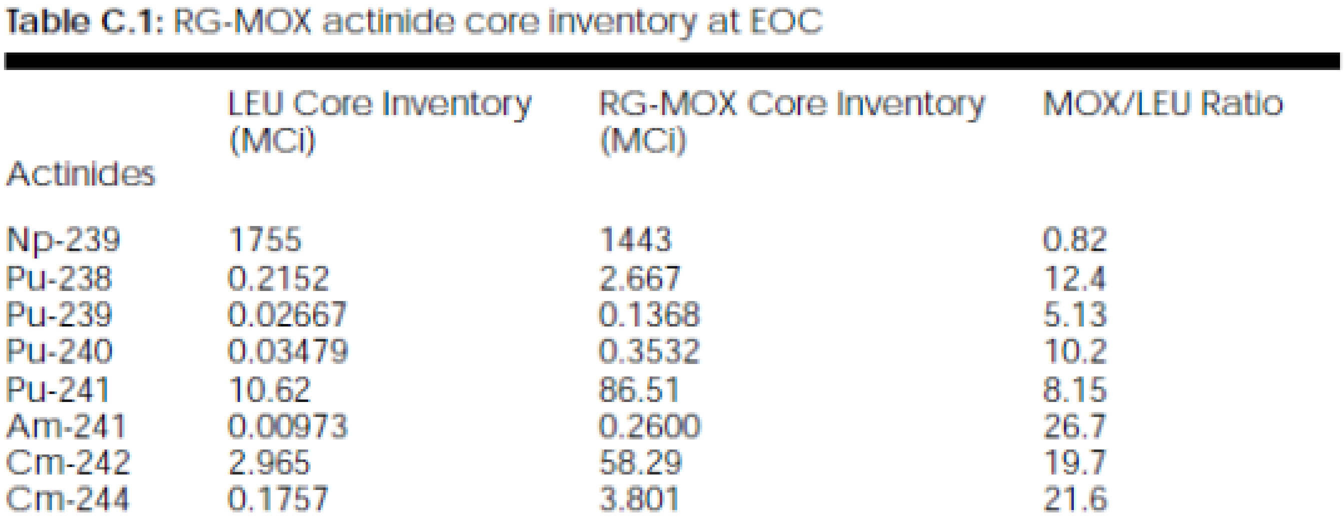


Table C.1: RG-MOX actinide core inventory at EOC

Actinides	LEU Core Inventory (MCi)	RG-MOX Core Inventory (MCi)	MOX/LEU Ratio
Np-239	1755	1443	0.82
Pu-238	0.2152	2.667	12.4
Pu-239	0.02667	0.1368	5.13
Pu-240	0.03479	0.3532	10.2
Pu-241	10.62	86.51	8.15
Am-241	0.00973	0.2600	26.7
Cm-242	2.965	58.29	19.7
Cm-244	0.1757	3.801	21.6

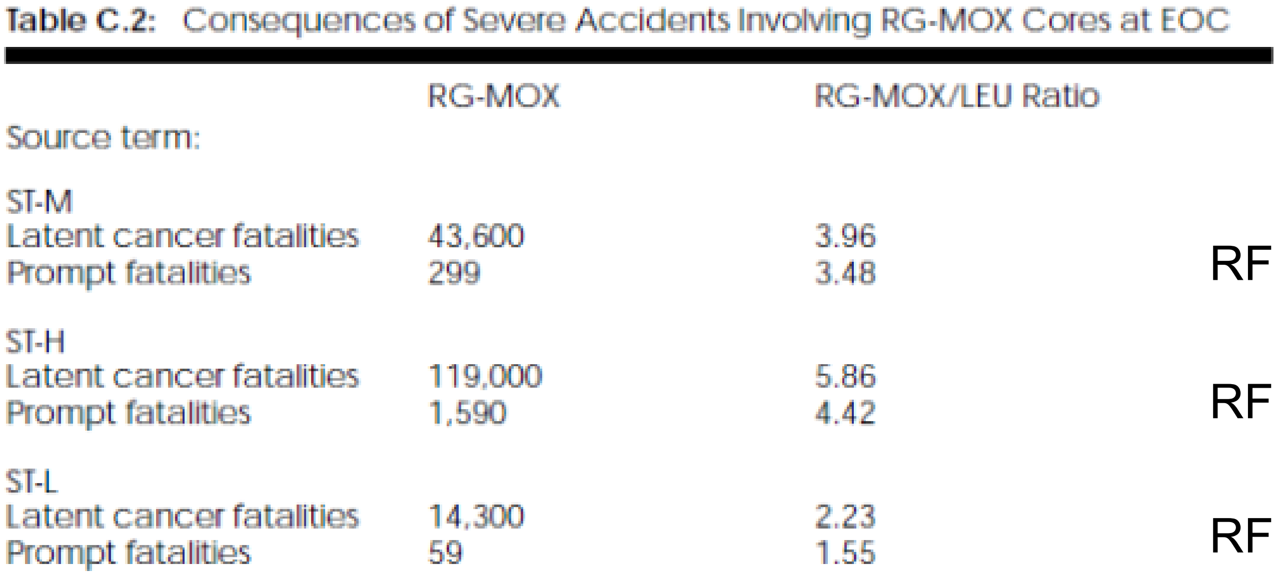


Table C.2: Consequences of Severe Accidents Involving RG-MOX Cores at EOC

Source term:	RG-MOX	RG-MOX/LEU Ratio
ST-M		
Latent cancer fatalities	43,600	3.96
Prompt fatalities	299	3.48
ST-H		
Latent cancer fatalities	119,000	5.86
Prompt fatalities	1,590	4.42
ST-L		
Latent cancer fatalities	14,300	2.23
Prompt fatalities	59	1.55

Full-core MOX

RF=1.5%

RF=6%

RF=0.3%

Actinide release fractions

- There is very little information about the release fractions of plutonium and other actinides, especially from MOX
    - *"MOX fuel* was explored very little (two RT [VERCORS] tests and two tests from the Japanese VEGA programme) and further investigation will be necessary, especially because of its specific microstructure which promotes releases."
- VERCORS tests (France) found plutonium release fractions *lower* than uranium (0.3—1%)
- VEGA tests (Japan) found plutonium release fractions *higher* than uranium (on the order of 1%)
    - VEGA test MOX fuel was more homogeneous than French-supplied MOX fuel and therefore was not representative
- Many more tests needed to resolve these issues

Increased consequences

- At Fukushima Daiichi 3, MOX fuel was only about 6% of the core; it is unlikely that this small amount made a significant difference
- But for Ikata 3 and Takahama 3 and 4, up to one-fourth of the core will be MOX
- For this core loading, the number of cancer deaths will **double** for an actinide release fraction of 1.5%, and increase by 50% for an actinide release fraction of 0.3%, compared to an all-uranium core

Spent fuel pool risk

- Spent fuel loss of coolant accidents (LOCAs) can result from
  - An accident that ruptures the pool liner
  - A terrorist attack
- High-density storage significantly increases the risk (probability times consequences) of a spent fuel fire caused by a loss-of-coolant accident (LOCA) relative to low-density storage
- Only high-density scenarios generate sufficient hydrogen for an explosion

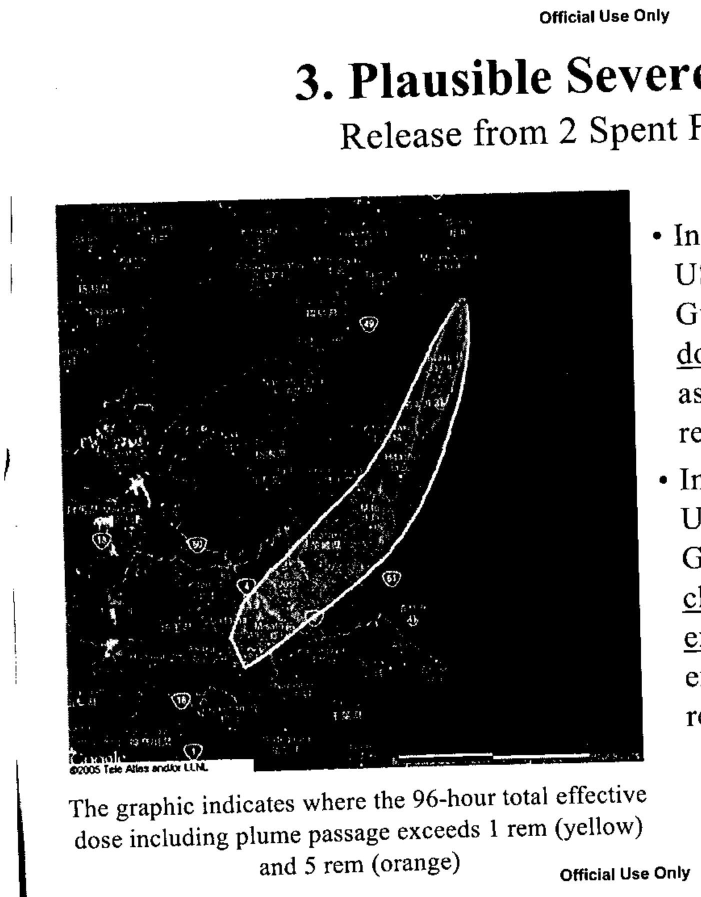
Spent fuel pool fires

- If water is drained from a spent fuel pool, the fuel assemblies will be exposed to air and/or steam
  - When Zircaloy cladding reaches 800-900°C, it can burn, increasing the heatup rate
  - The fire can propagate to cooler assemblies
  - A large fraction of the fission product inventory (mainly Cs-137) can be released
  - Spent fuel burning in air can release more plutonium and other actinides than in a steam environment
  - The structures housing spent fuel pools are not leaktight and are vulnerable to hydrogen explosions if sufficient hydrogen is generated

A mock spent fuel assembly after a fire test

From March 25, 2011 Department of Energy document

(Freedom of Information Act release to UCS)



Official Use Only

3. Plausible Severe Release

Release from 2 Spent Fuel Pools

- In this hypothetical scenario, the US EPA Protective Action Guidelines for the total effective dose MAY be exceeded in Tokyo, as well as at locations closer to the release point.
- In this hypothetical scenario, the US EPA Protective Action Guidelines for both the adult and child thyroid dose will NOT be exceeded in Tokyo, but are exceeded at locations closer to the release point

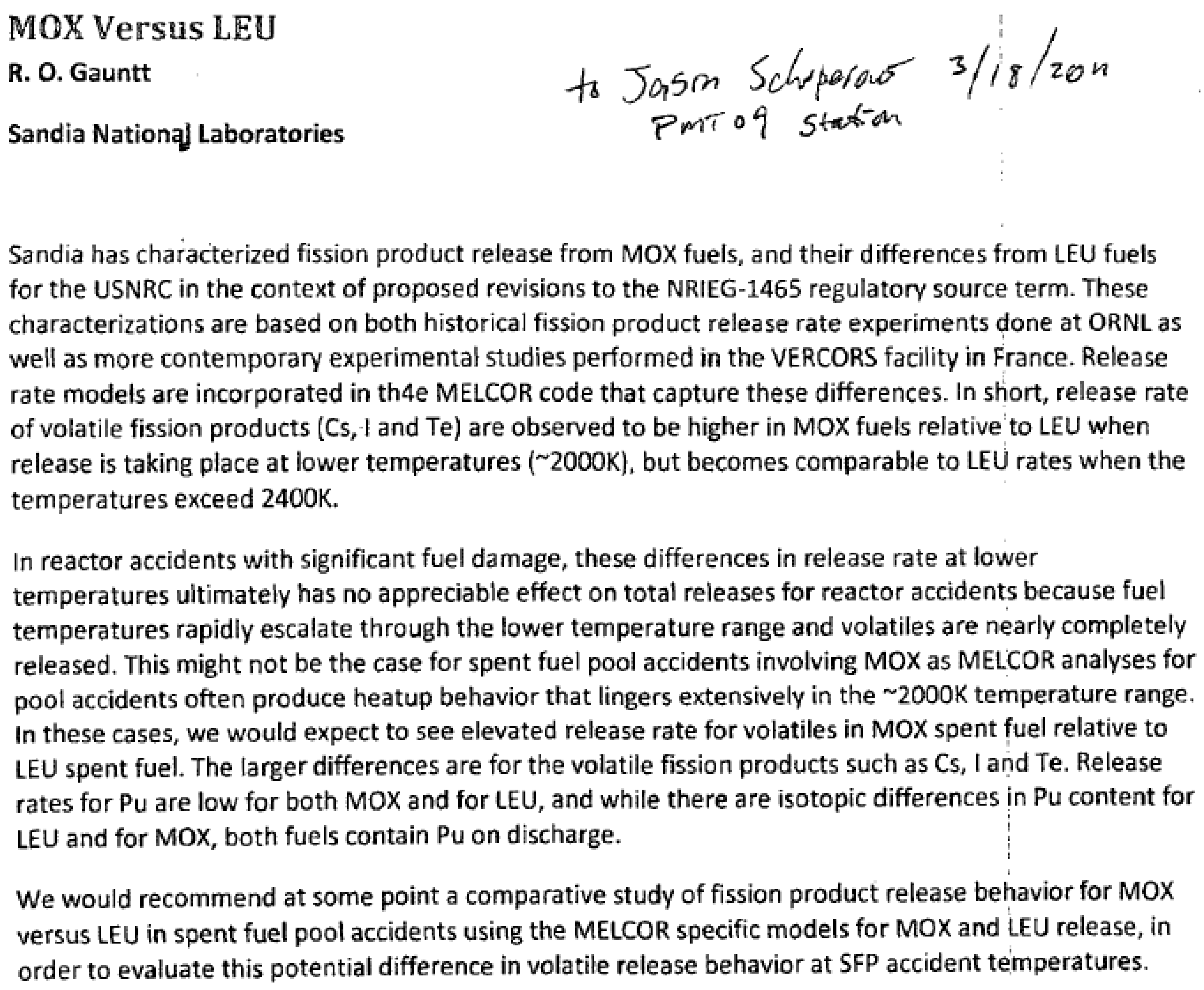
The graphic indicates where the 96-hour total effective dose including plume passage exceeds 1 rem (yellow) and 5 rem (orange)

Official Use Only

Assumed Cs-137 release: 16 MCi (590 PBq)

MOX spent fuel

- The presence of spent MOX fuel in pools can affect the risk of a pool LOCA:
  - Decay heat of MOX spent fuel assemblies is greater than that of uranium spent fuel at times greater than one day after discharge
  - Greater inventories of plutonium and other actinides in MOX fuel could increase source term, especially for degradation in air
  - Spent MOX fuel may release volatile fission products (iodine, cesium, tellurium) at a greater rate than uranium spent fuel at the temperatures typically encountered in spent fuel pool fires (1800-2000 K)



MOX Versus LEU

R. O. Gauntt

Sandia National Laboratories

to Jason Schaperow 3/18/2011
PMT 09 Station

Sandia has characterized fission product release from MOX fuels, and their differences from LEU fuels for the USNRC in the context of proposed revisions to the NRIEG-1465 regulatory source term. These characterizations are based on both historical fission product release rate experiments done at ORNL as well as more contemporary experimental studies performed in the VERCORS facility in France. Release rate models are incorporated in th4e MELCOR code that capture these differences. In short, release rate of volatile fission products (Cs, I and Te) are observed to be higher in MOX fuels relative to LEU when release is taking place at lower temperatures (~2000K), but becomes comparable to LEU rates when the temperatures exceed 2400K.

In reactor accidents with significant fuel damage, these differences in release rate at lower temperatures ultimately has no appreciable effect on total releases for reactor accidents because fuel temperatures rapidly escalate through the lower temperature range and volatiles are nearly completely released. This might not be the case for spent fuel pool accidents involving MOX as MELCOR analyses for pool accidents often produce heatup behavior that lingers extensively in the ~2000K temperature range. In these cases, we would expect to see elevated release rate for volatiles in MOX spent fuel relative to LEU spent fuel. The larger differences are for the volatile fission products such as Cs, I and Te. Release rates for Pu are low for both MOX and for LEU, and while there are isotopic differences in Pu content for LEU and for MOX, both fuels contain Pu on discharge.

We would recommend at some point a comparative study of fission product release behavior for MOX versus LEU in spent fuel pool accidents using the MELCOR specific models for MOX and LEU release, in order to evaluate this potential difference in volatile release behavior at SFP accident temperatures.

Pu downblending and disposal: a safer option than MOX

- WIPP: an operating geologic repository for transuranic (TRU) waste near Carlsbad, New Mexico
- The U.S. has already disposed of 4 MT of excess plutonium in WIPP
- Projected cost to dispose of 34 MT of Pu in WIPP as $17 billion --- 3 times cheaper than MOX
- WIPP was operating successfully until it was shut down in February 2014 after a waste drum released plutonium into the repository
- However, it is projected to resume operations in 2016

Japan’s contribution

- In the past, Russia opposed disposition of the entire U.S. surplus plutonium stockpile without changing its isotopic composition
- The U.S. could import Japanese plutonium stored in Europe for blending with weapons-grade plutonium prior to downblending; The U.S. could pay Japan billions for this material and it would still cost less than continuing with the MOX program
- About 10-20 tonnes of reactor-grade Pu would be needed
- WIPP could likely accommodate the Pu from Japan

Conclusions

- Use of MOX fuel in Japanese nuclear reactors will decrease safety and increase uncertainty
- The NRA does not have enough information to make informed decisions on the safety of MOX fuel: many more experimental results are needed
- Direct disposal of plutonium in a geologic repository can be done safety and securely: this has been demonstrated in the U.S.
- This strategy could provide a safer disposition path for a large fraction of Japan’s own surplus plutonium than MOX