SOURCE TERMS

Sodium Fires & Aerosol Behavior

I. Aerosol Generation (Pool Fires)
II. Current Code Predictability

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Background

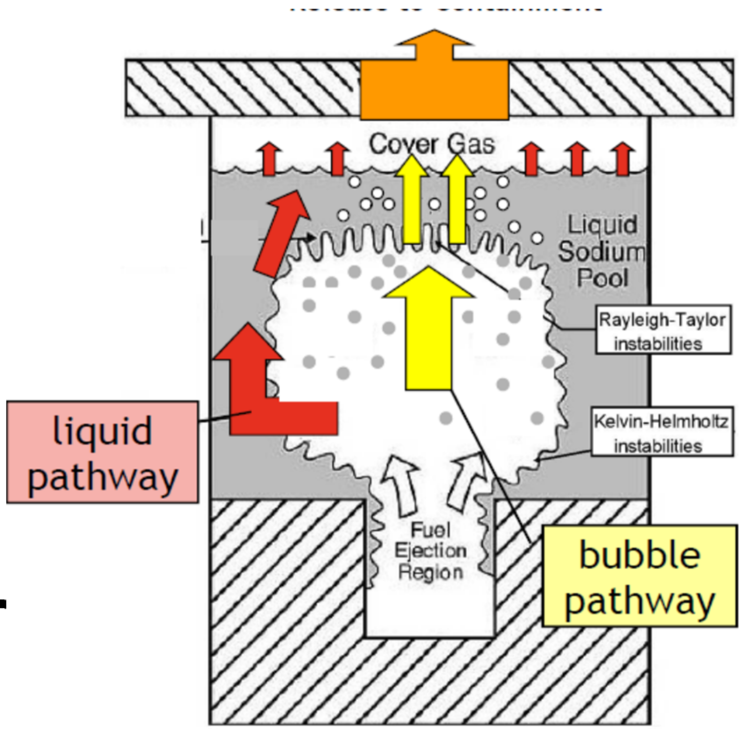
BDBA Scenario

$\uparrow T_{fuel}$, $\uparrow P_{rod}$

Core disruption

FCI

RN in large bubbles



RN absorption in Na

Background

Major Sources

- *"The bubble pathway"*
- *Na-concrete interaction*
- **Sodium fires**
- *Vaporization of CMs*

A fission product "carrier"

Highly volatile species ← **Na** → *Highly reactive species*

Radioactive & Chemical hazard

Aerosol Generation
(Pool Fires)

- ***Na Fires: Generic Analysis.***
- ***Aerosol Release & Transport.***

Na-Fires: Generic Analysis

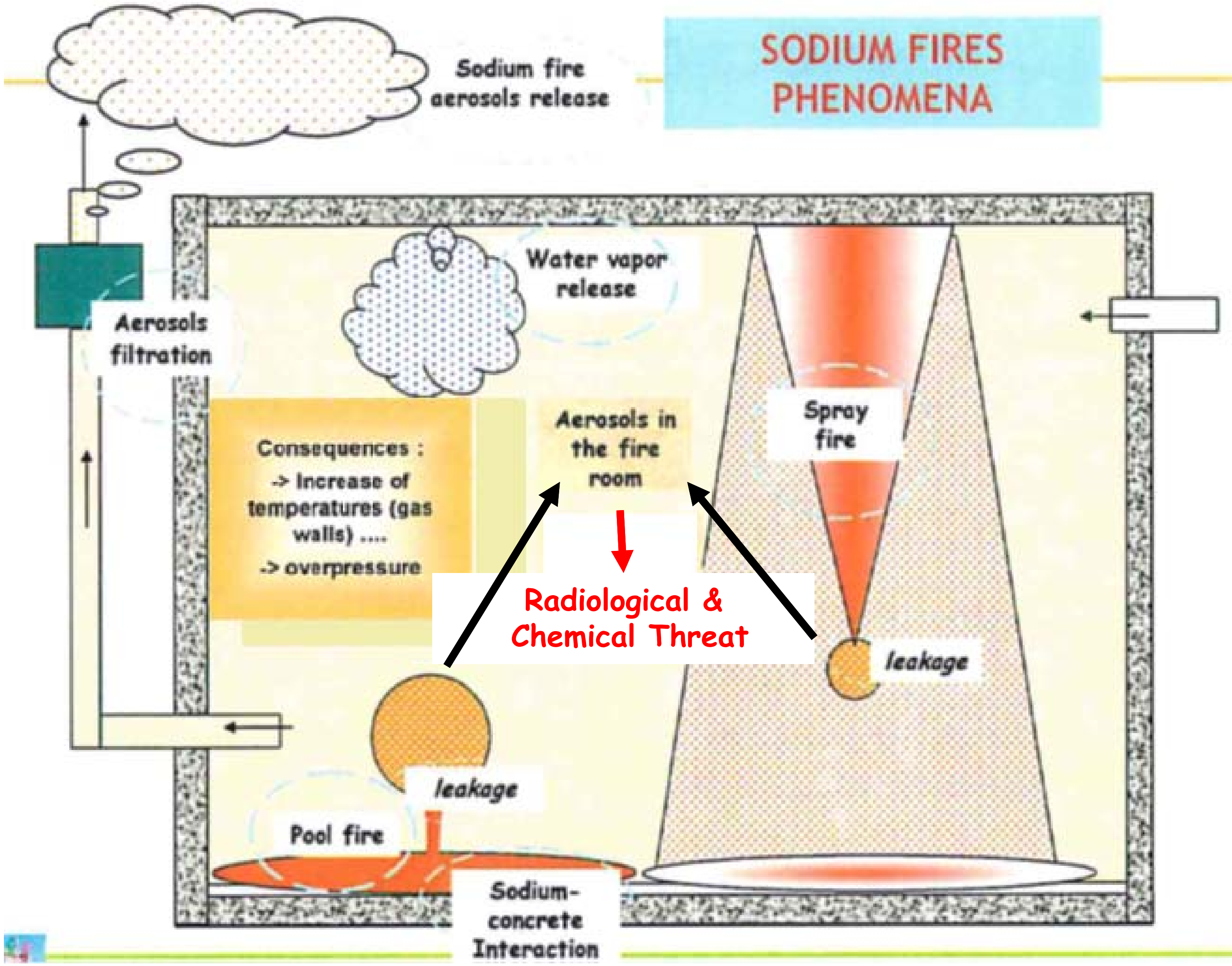
The Safety Issue

- ***Sodium spills & fires pose a threat to plant safe operation***
  - ***Thermal loads (P & T)*** – *sensible heat + combustion thermal energy.*
  - ***Na_xO_y – based particles*** – *radiological and chemical threat.*
  - ***RN partitioning & transport*** – *radiological threat.*

- ***Na-fire studies:***
  - *Mangold & Tidball (1952); Charak & Smith (1965).*
  - *Atomics Intl. (1971); Hilliard et al. (1979).*
  - *Cherdron & Jordan (1980); Cherdron et al. (1985).*
  - *Lhiaubet et al.(1990); Malet et al. (1990); Souto et al. (1994).*
  - *Subramanian & Baskaran (2007); Subramanian et al. (2009).*
  - *…*

- ***Na-fire codes:***
  - *SOFIRE(Beiriger et al., 1973); CONTAIN-LMR (Murata, 1993).*
  - *SPM (Miyake, 1993); SOPA (Lee & Choi, 1997).*
  - *SPHINCS (Yamaguchi & Tajima, 2003).*

Na-related Phenomena

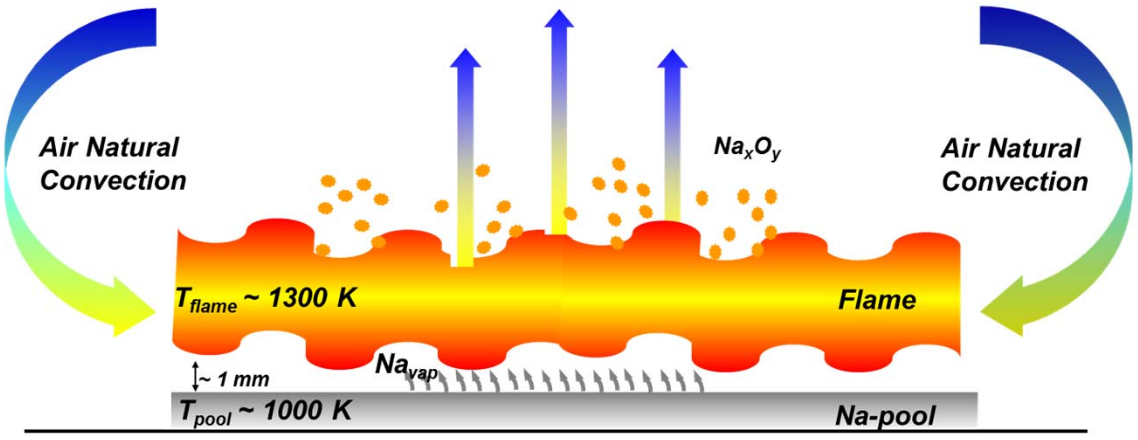


Casselman, 2009

Configurations

Pool Fires

(Large breaks; ~10^2 kg/s)
(Low P spill)

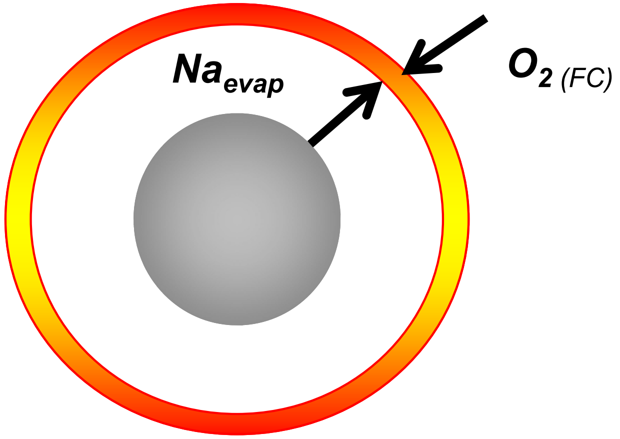


Surface reaction vs. **Gas-phase reaction**
(623 – **723 K**)

Newman, 1983

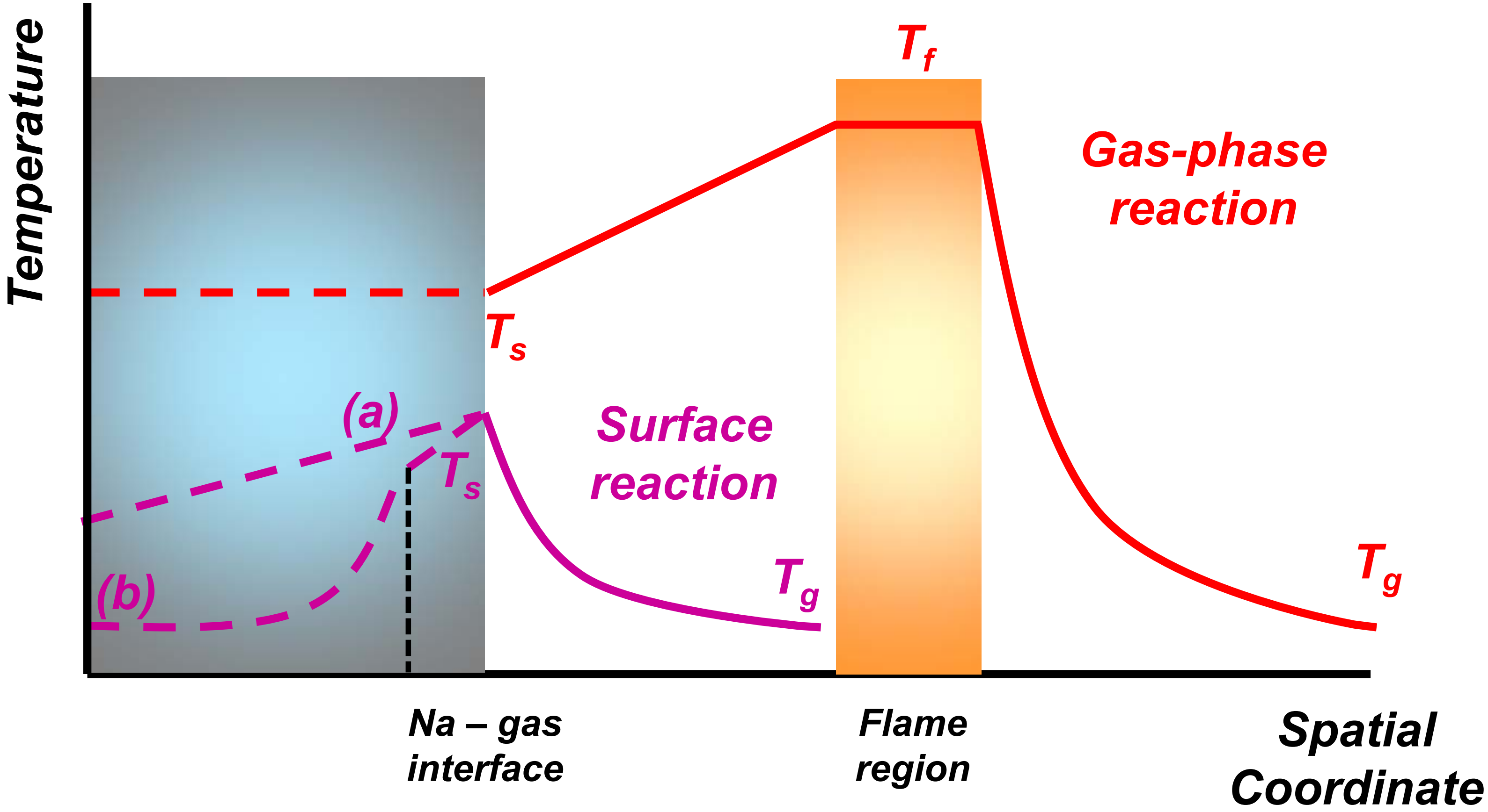
Spray Fires

(Smaller breaks; ~10^0 kg/s)



Jet hydrodynamics!
(jet fragmentation)

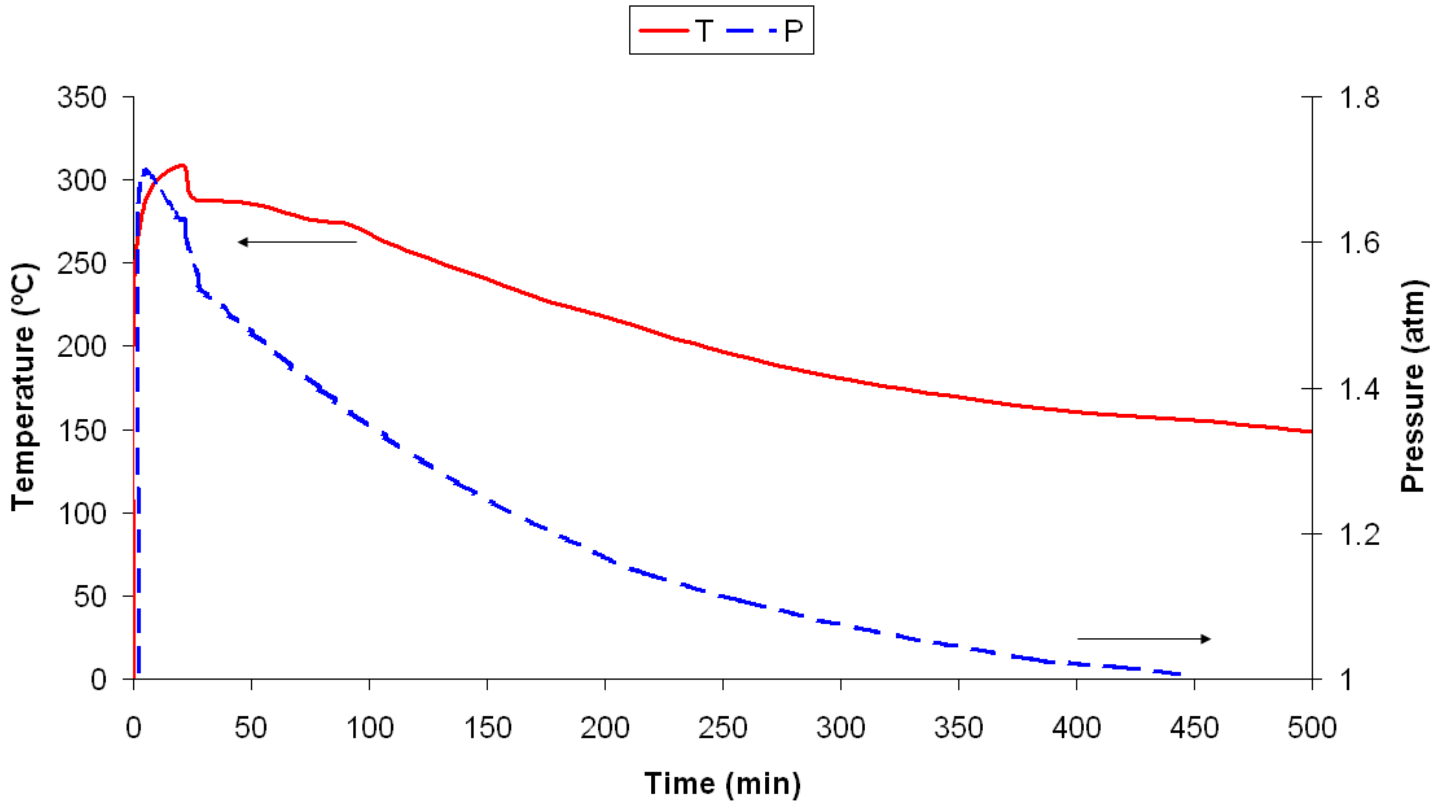
The Thermal Profile



Reactions & Products

- $2 \cdot Na + 1/2 \cdot O_2 \rightarrow Na_2O$ — $\Delta h \sim 9.0$ MJ/kg — $T_m = 1132$ ºC, $T_b = 1950$ ºC
- $2 \cdot Na + O_2 \rightarrow Na_2O_2$ — $\Delta h \sim 11.0$ MJ/kg — $T_m = 460$ ºC, $T_b = 657$ ºC
- $Na + H_2O_v \rightarrow NaOH + ½ \cdot H_2$ — $\Delta h \sim 4.1$ MJ/kg
- $Na_2O + H_2O_v \rightarrow 2 \cdot NaOH$ — $\Delta h \sim 4.2$ MJ/kg
- $Na_2O_2 + H_2O_v \rightarrow 2 \cdot NaOH + ½ \cdot O_2$ — $\Delta h \sim 11.3$ MJ/kg
- $2 \cdot NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$ — $\Delta h \sim 3.6$ MJ/kg

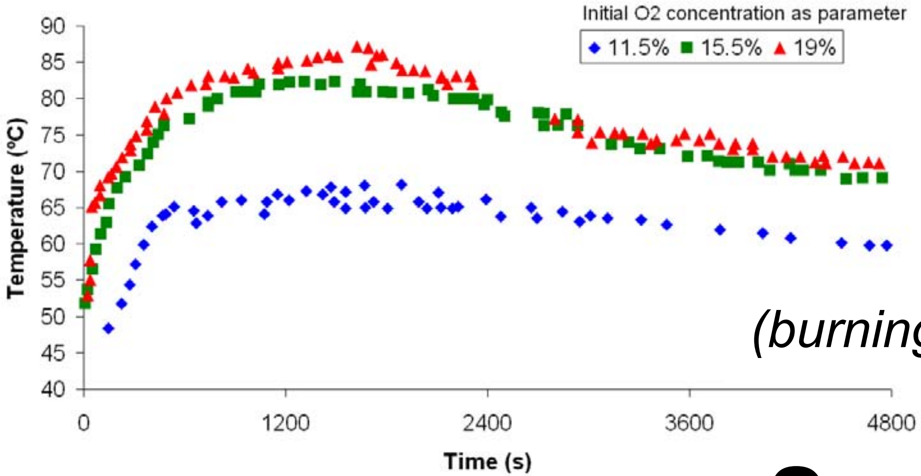
Pool Fire

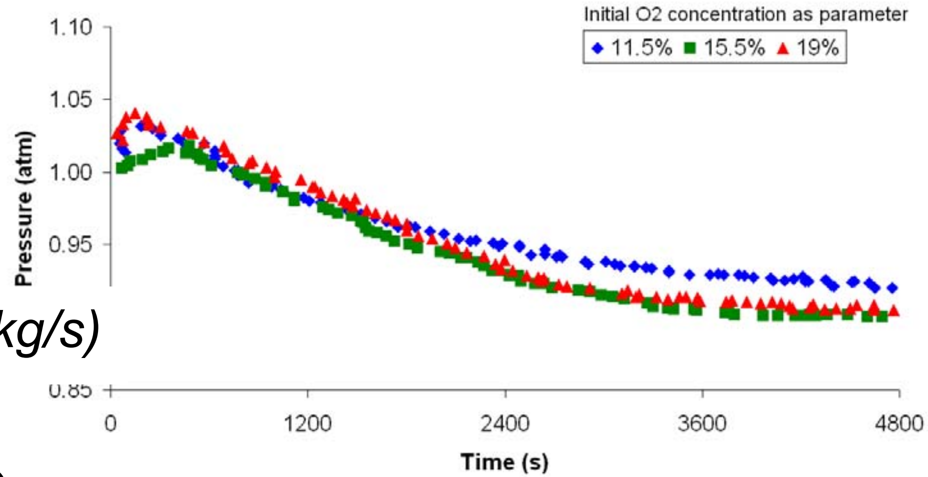


Chiao, 1994
(CONTAIN-LMR)

Natural circulation → Quasi-homogeneous atmosphere

Pool Fires vs. Spray Fires

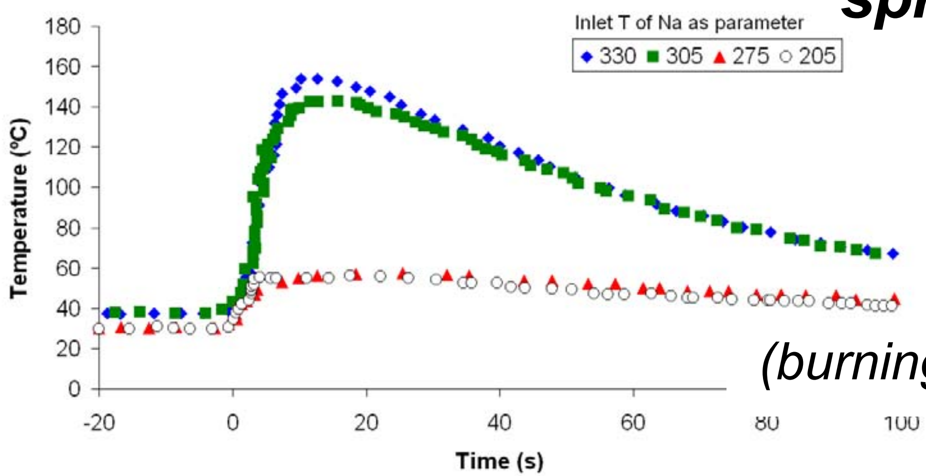


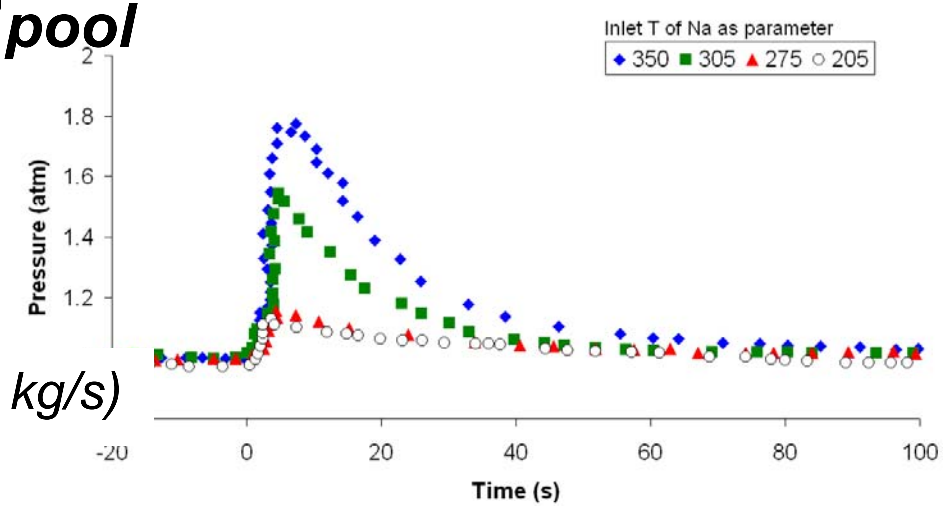


Pool

(burning rate ~ 0.1 kg/s)

$$S_{spray} >> S_{pool}$$



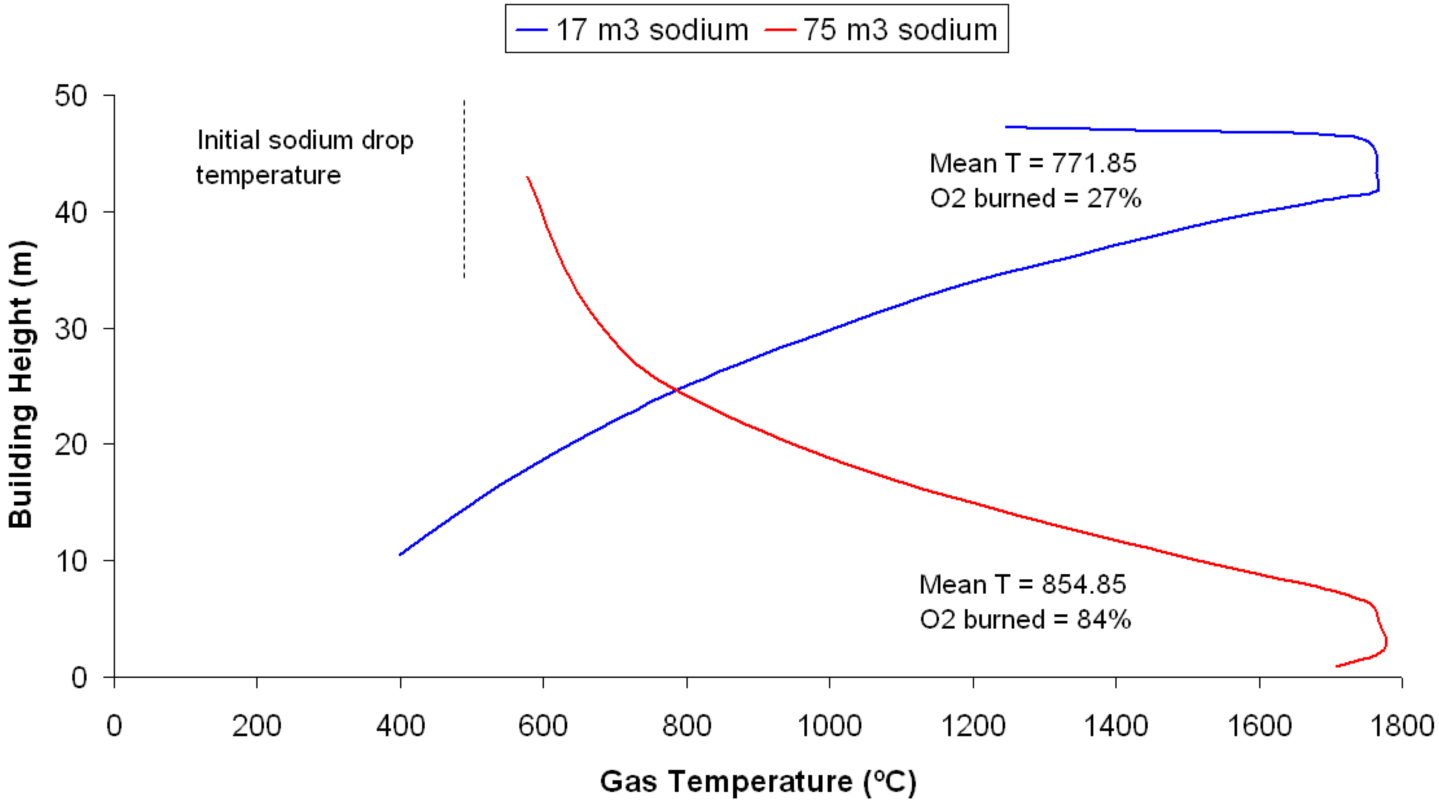


Spray

(burning rate ~ n·10 kg/s)

Bae et al., 1994

Spray Fires



Heisler, 1979 (SOMIX)

Highly non-uniform atmosphere → Large thermal gradients

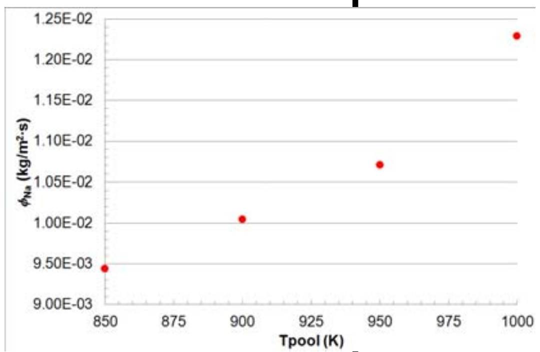
Take Aways

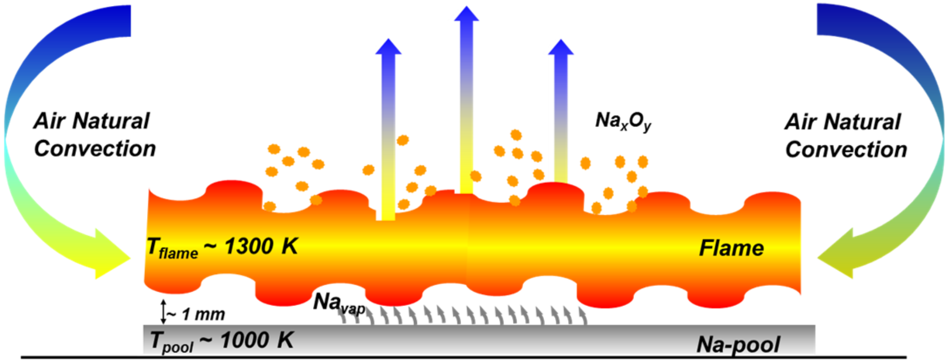
- ***Therm. & mech. loads of pool/spray fires are largely different.***
- ***Spray therm. & mech. loads are notably higher and faster.***
- ***Even in the case of sprays, $P_{max} < P_{limit}$.***
- ***Sprays involve large thermal gradients.***
- ***$t(P_{max}) \neq t(T_{max})$ in pools*** *(burning rate vs. heat removal rate).*

Aerosol Release & Transport

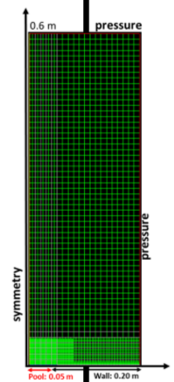
Particle Generation: Phenomena

Na Supply
(Evaporation Model)

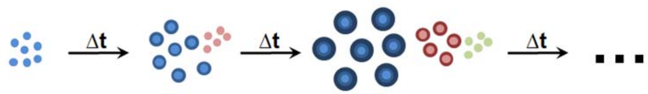


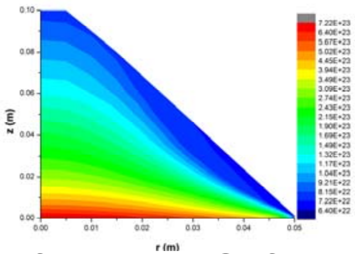


O_2 Supply
(3D Convective Modeling)

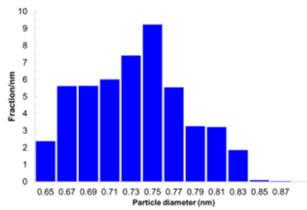


Formation of Na_xO_y Vapors
(Na – O_2 chemical reactions)



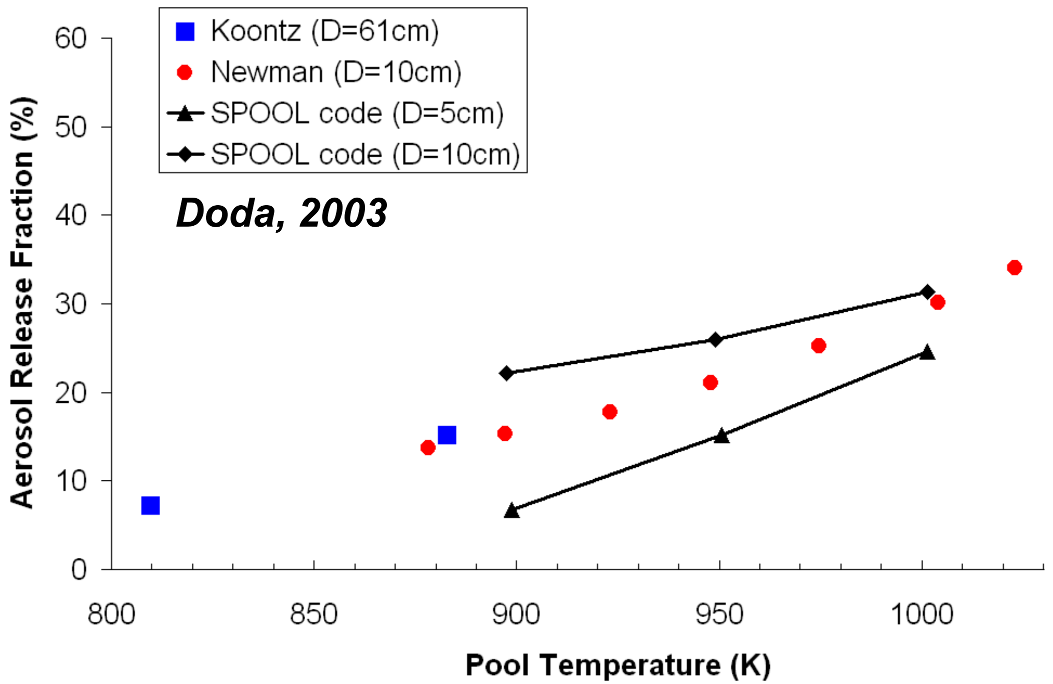


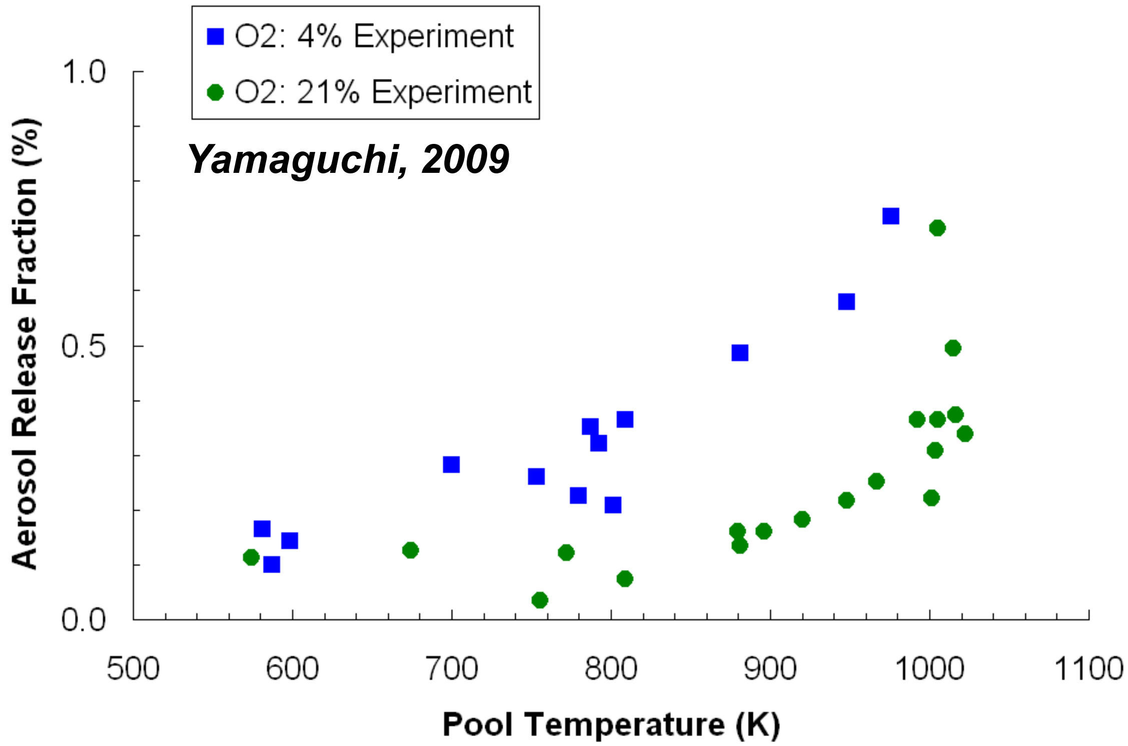
Generation of Primary Particles
(Nucleation & Growth models)



García, 2016

Aerosol Release





$$N = c_1 \cdot \dot{m}_{vap} \cdot d_{pool}^{c2} \cdot X_{O2}^{c3}$$

Aerosol Size

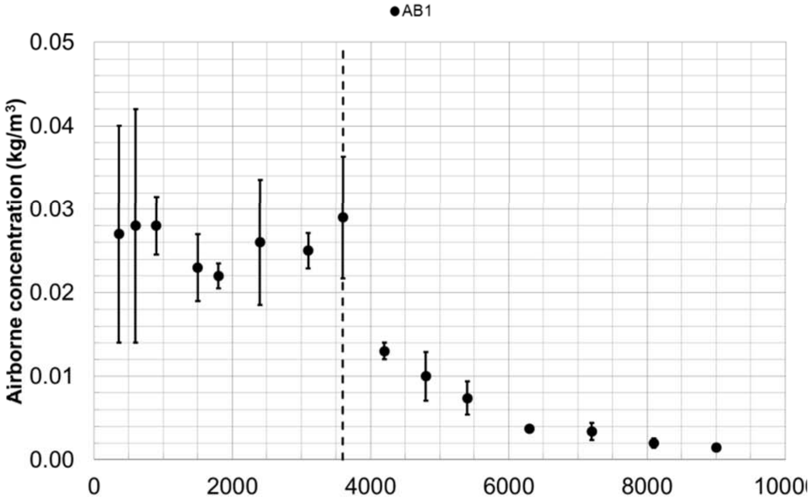
NEA, 1979

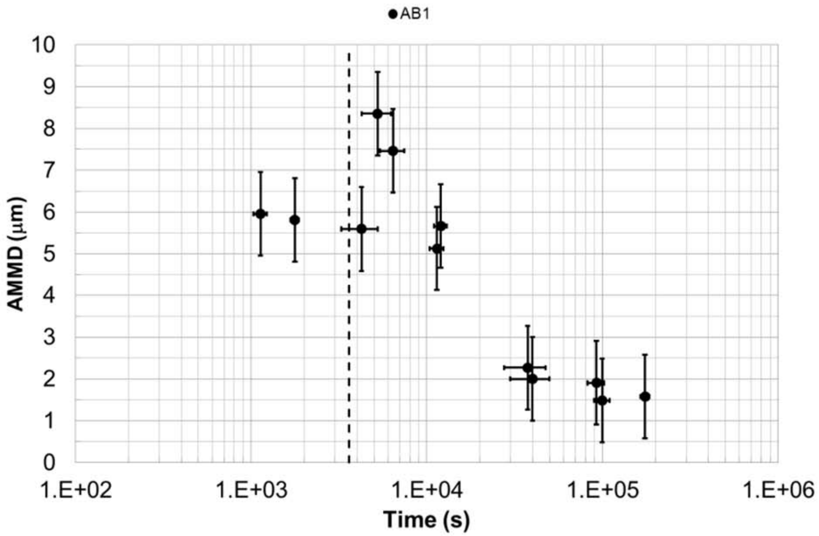
Reference	Material	Primary particle diameter, µm
Allent & Briant	Mixed UO_2, PuO_2	Log-normal, bimodal, (σ_g=1.35)
		0.003-.01
Chatfield	Pu, Na	0.02 maximum
Castleman	Mixed UO_2, PuO_2	Log-normal, 0.004-.004, σ_g=2.0
	PuO_2	0.1, (σ_g=1.9)
	UO_2, N_a	0.2-0.6
Morrison et al.	Clad & bare UO_2	0.002-0.1
Kelly et al.	UO_2	<0.005-0.02
Jordan et al.	UO_2	d_g=0.073 (σ_g=1.85)
Kres	UO_2, U_3O_8	0.014-0.034
Kitani	U_3O_8	d_g=0.037 (σ_g=1.6-2.2)
	U_3O_8	d_g=0.07(σ_g=1.93)
Schikarski	Clad mixed	<0.08
	Oxide fuel	
	Na_2O	0.1-0.4
Hilliard et al.	Na_2O_2, NaOH	0.1-0.5
Parker et al.	UO_2, U_3O_8	d_g=0.034

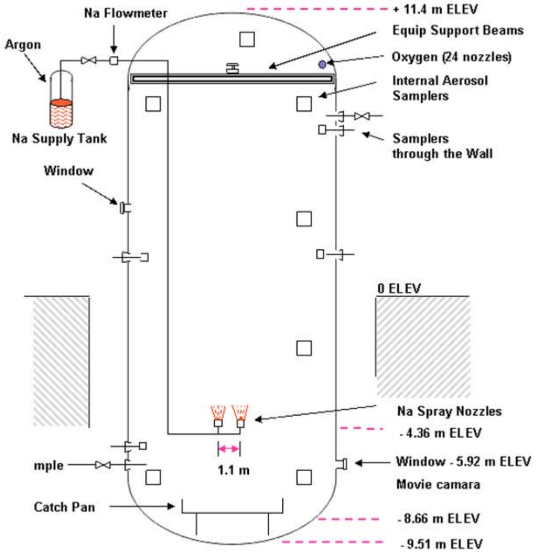
AMMD ~ 0.5 -1.0 µm (GSD ~ 2)

Cherdron, 1985
Jordan, 1988
Subramanian, 2007

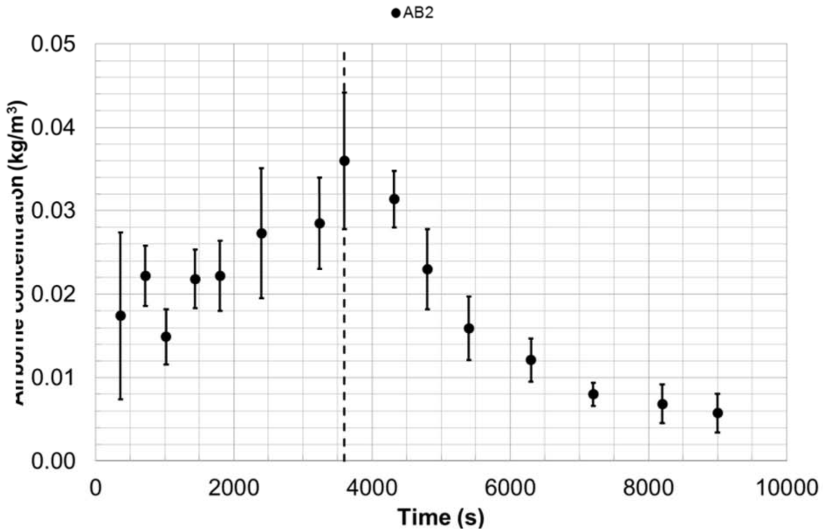
Aerosol Evolution (I)

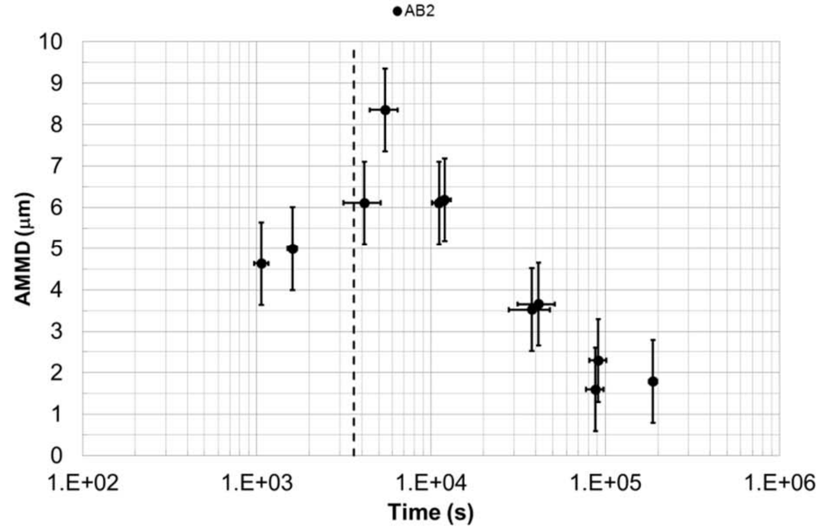




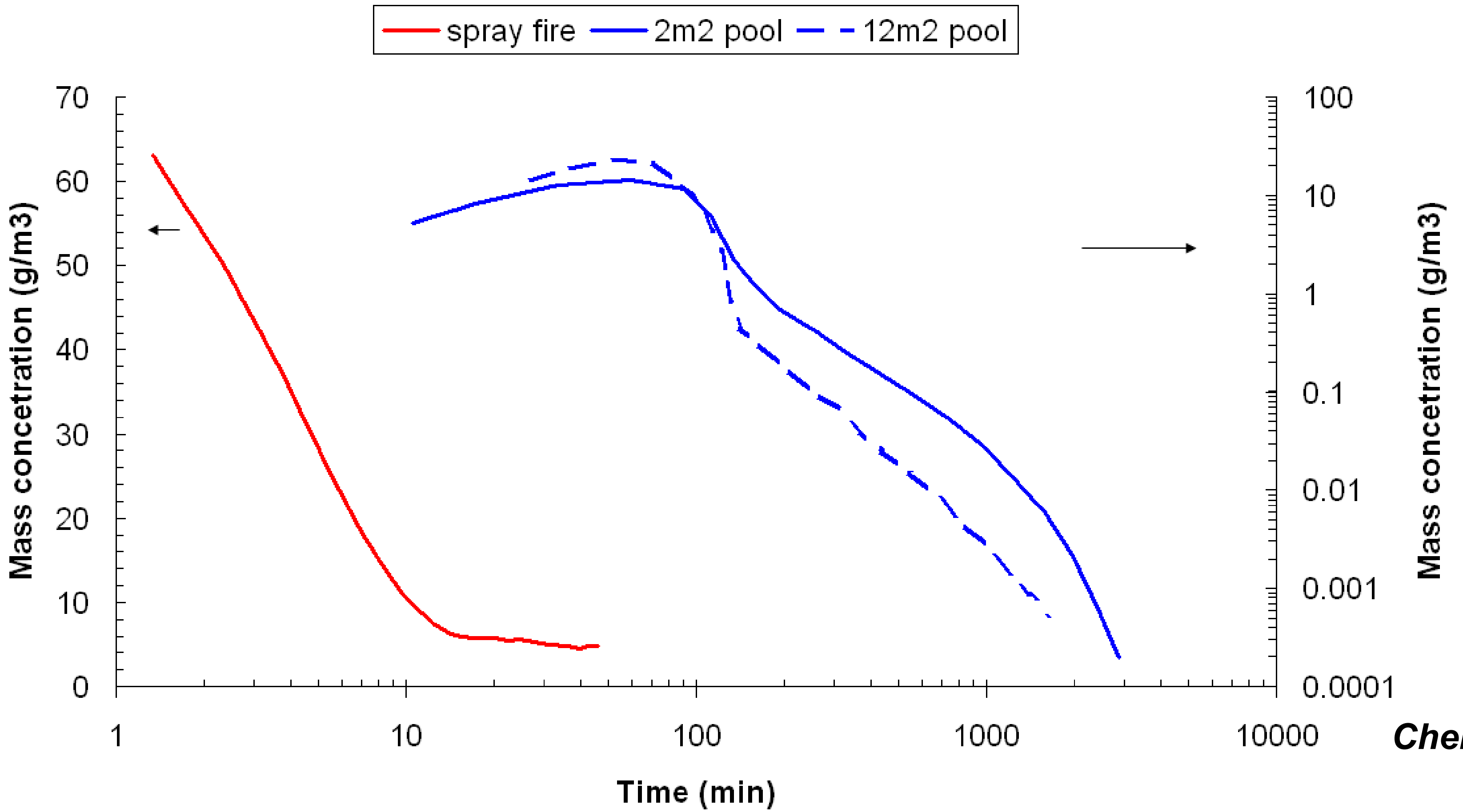


Hilliard, 1977
McCormack, 1979





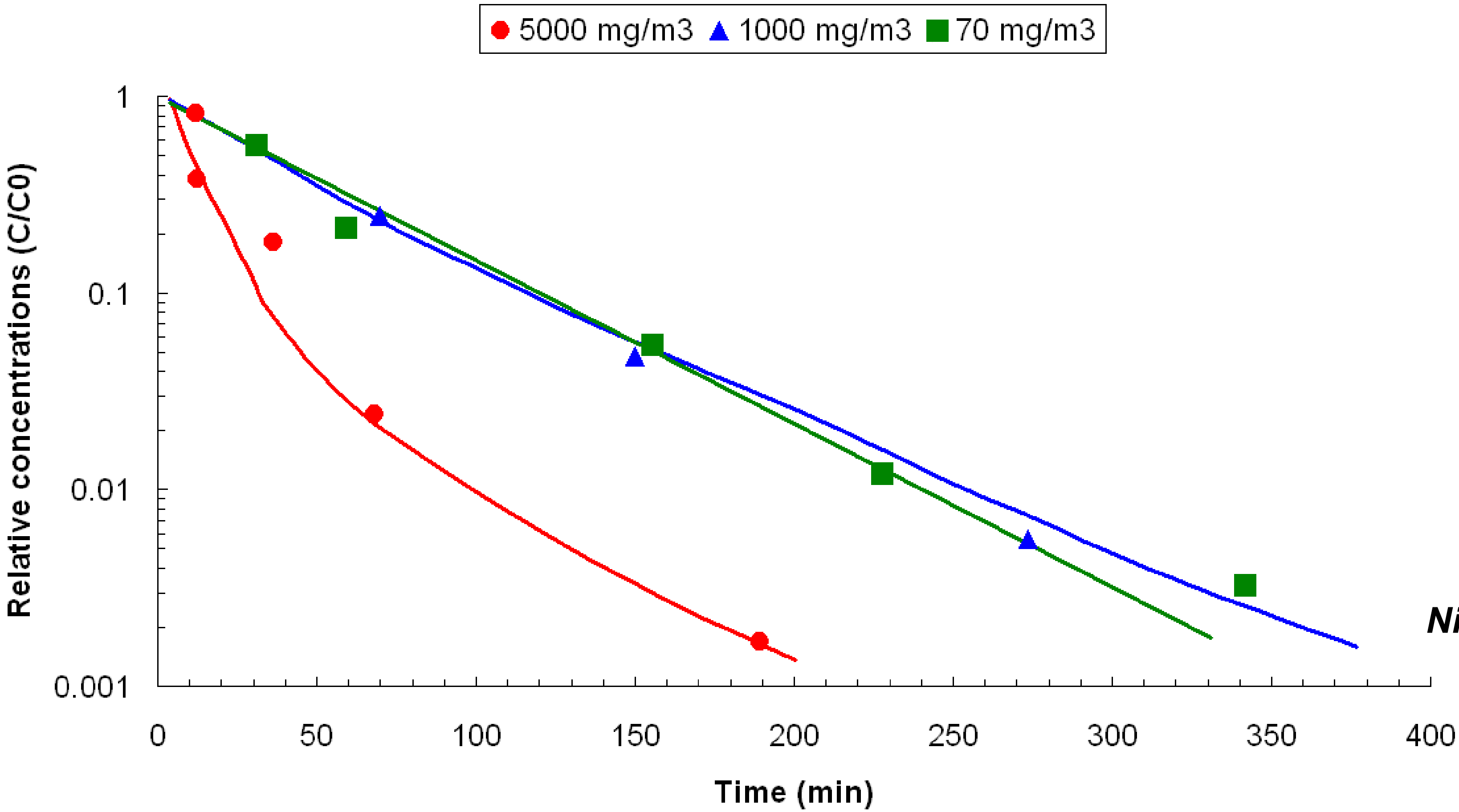
Pool vs. Sprays



Cherdron, 1985 (FAUNA)

- *Much lower concentration!*
- *100 times slower depletion!*

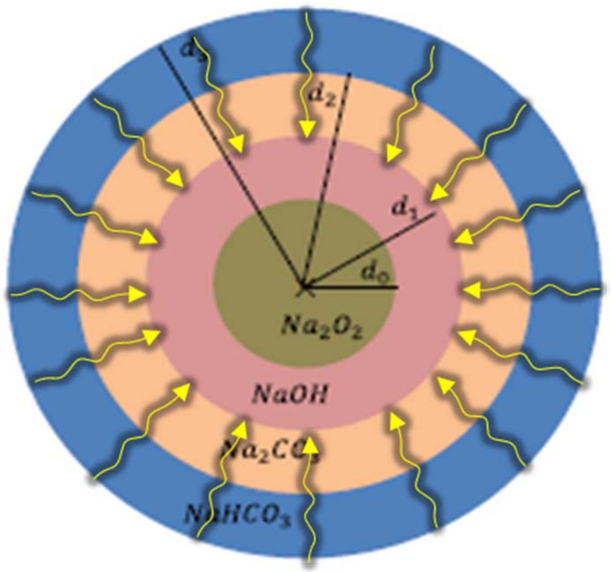
Interaction Processes



Nishio, 1977

Na_xO_y Particle Chemistry

- $Na_2O + H_2O_v \rightarrow 2 \cdot NaOH$ $\Delta h \sim 4.20$ MJ/kg
- $Na_2O_2 + H_2O_v \rightarrow 2 \cdot NaOH + ½ \cdot O_2$ $\Delta h \sim 11.28$ MJ/kg
- $2 \cdot NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$ $\Delta h \sim 3.6$ MJ/kg
- $Na_2CO_3 + H_2O + CO_2 \rightarrow 2 \cdot NaHCO_3$ $\Delta h \sim 3.6$ MJ/kg



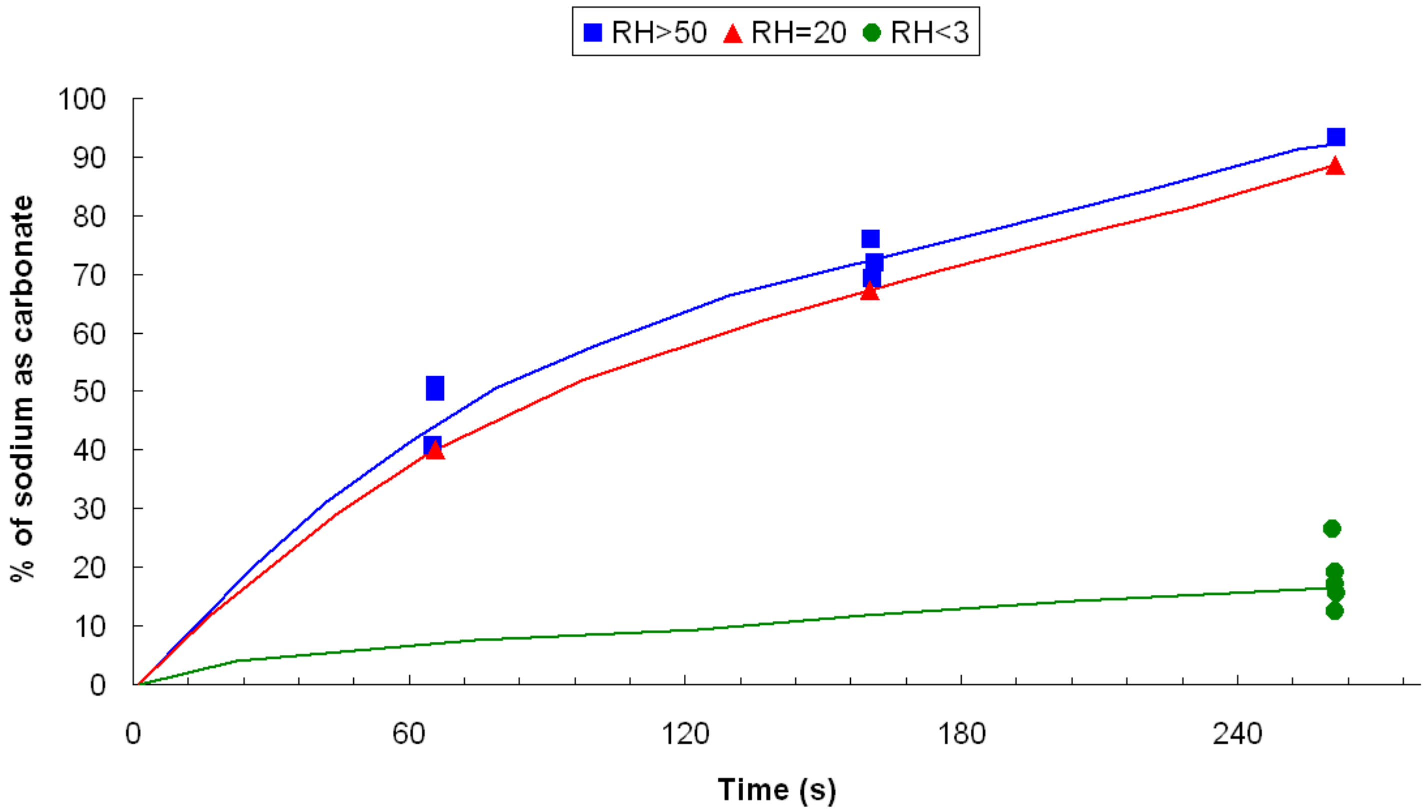
$$W_i = \frac{2\pi c_i D_i^* d_i d_p f}{d_p - d_i}$$

$$D_K^* = \frac{194\, e^2\, d'}{6\,\tau\,(1-e)}\sqrt{\frac{T}{M}}$$

Cooper, 1980
Mathé, 2016

Aerosol Chemical Speciation

Na_2O, Na_2O_2 → (1-10 s) → NaOH → ($\sim 10^2$ s) → Na_2CO_3



Cherdron, 1985

Take Aways

- ***Large amounts of aerosols may be generated****.*
- ***Sprays burning produces higher aerosol concentrations****.*
- ***Airborne residence time depends on conditions*** *([particles]).*
- ***Aerosol aging is a key process*** *(non-radiological effects).*
- ***Failure of components & plugging of filters.***

Current Code Predictability

- ***Na Containment Database.***
- ***Analytical Modeling.***
- ***Results and Discussion.***

Herranz et al. (2018), "Progress in modeling in-containment source term with ASTEC-Na", ANUCENE 12, 84-93.

Herranz et al. (2017), "In-containment source term predictability of ASTEC-Na: Major insights from data-predictions benchmarking", NED 320, 269-281

Herranz et al. (2013), "Benchmarking LWR codes capability to model radionuclide deposition within SFR containments: An analysis of the Na ABCOVE tests", NED 265, 772-784.

Take Aways

- *Scarcity of available experimental data (fundamental & integral).*
- *Single node approximation good enough.*
- *Codes capture the trends, but through heavy parametrization!*
- *Data uncertainties hinder specific Na-models insights.*

Major Model Needs
in Na Source Term Analysis

- ***Particle generation*** *from pool and* ***spray*** *fires.*
- ***RN partitioning*** *between gas and condensed phases.*
- ***Chemical reactivity*** *of RNs and Na compounds.*

- ***Validation*** *of any modeling through SETs and ITs.*

SUMMARY

- ***Na fires are a distinguishing feature of SFRs.***
- ***Na-fire aerosols dominate radiological and chemical threat.***
- ***Na-fires are major source of aerosol generation.***
- ***Na-based aerosol physics is similar to LWR aerosols***
- ***Particle chemistry is essential to estimate SFR risk.***
- ***Scarcity & uncertainties of experimental data!***
- ***"ST Codes" capture the trends*** *through heavy parametrization!*
- ***FP radiological impact dominated by Cs.***

Thank you for your attention!
Any questions?