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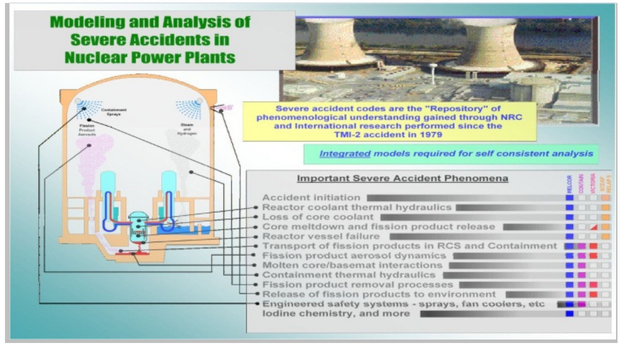

Source Term Prediction
History and Current Practices

Presented at IAEA Source Term Workshop, October 2013
Randall Gauntt
Sandia National Laboratories

All materials from UUR Open Source Reports
SAND2007-7697 "Accident Source Terms…
SAND2010-1633 "Synthesis of VERCORS and Phebus Data

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Outline

- Motivation for this work
- Review of fission product release models
- Assessment of revised release models
  - Phebus FPT-1
  - ORNL VI and French VERCORS
- Examine deposition characteristics affected by release model changes
  - Phebus Circuit depositions
  - Phebus containment deposition
- Revision to model for release from MOX and HBU fuel

Repository of Severe Accident Phenomenology

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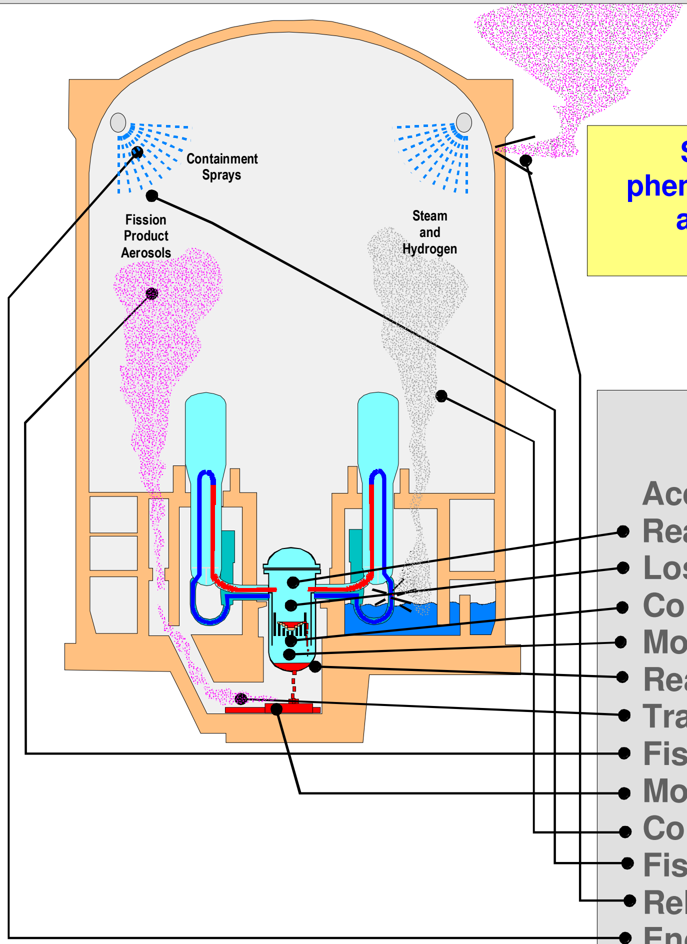
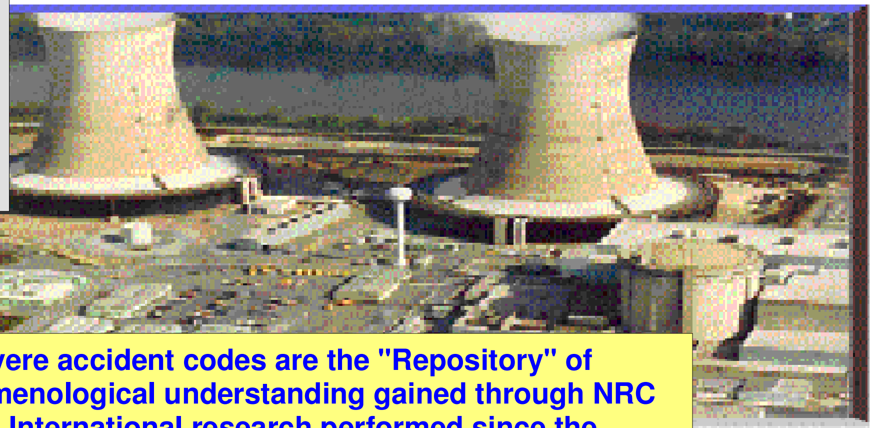
Modeling and Analysis of Severe Accidents in Nuclear Power Plants





Severe accident codes are the "Repository" of phenomenological understanding gained through NRC and International research performed since the TMI-2 accident in 1979

<u>Integrated</u> models required for self consistent analysis

<u>Important Severe Accident Phenomena</u>

Phenomenon	MELCOR	CONTAIN	VICTORIA	IFCI
Accident initiation	■	□	□	□
Reactor coolant thermal hydraulics	■	□	□	□
Loss of core coolant	■	□	□	□
Core meltdown and fission product release	■	□	◩	□
Molten fuel/coolant interactions	■	□	□	■
Reactor vessel failure	■	□	□	□
Transport of fission products in RCS and Containment	■	■	■	□
Fission product aerosol dynamics	■	■	■	□
Molten core/basemat interactions	■	■	□	□
Containment thermal hydraulics	■	■	□	□
Fission product removal processes	■	■	◩	□
Release of fission products to environment	■	■	■	□
Engineered safety systems - sprays, fan coolers, etc	■	■	□	□
Iodine chemistry, and more	■	□	□	□

Motivation for Work

- MELCOR models improved and upgraded as new knowledge arrives from ongoing research
  - Phebus, Quench, Rasplav, Masca, etc
- Code assessment is an ongoing process
  - NRC-RES, International Standard Problems, MELCOR users world-wide
- Fission product release models are 1990 vintage
  - Recent assessments from ISP-46 and Phebus program suggest changes are needed
  - Cs speciation now thought to be CsI and Cs2MoO4 versus CsOH
  - Deposition characteristics suggest lower volatility
- Review reflects recent knowledge gained from assessments

Regulatory Source Term

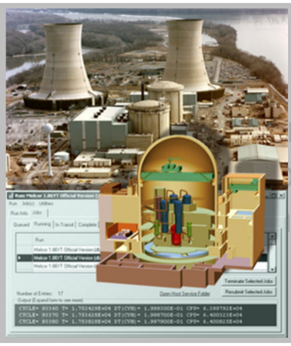
- US regulatory requirements
  - 10 CFR 50 and 10CFR 100
  - Limits on dose to control room and site boundary
  - Consider significant core-melt accident in context of DBA
  - Guidance provided by Reg. Guide 1.183
- Licensee must demonstrate dose limits under design basis events are met by design
  - Can do detailed analysis
  - Safe harbor methodologies outlined in RG 1.183
  - Use alternative regulatory source term
  - Demonstrate adequate containment performance

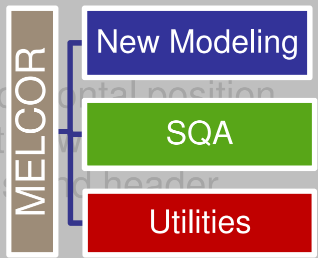
TID-14844 Regulatory Source Term (1962)

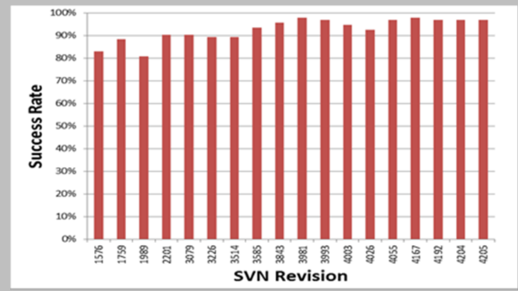
- Characterized as a maximum credible accident
- Assumed significant core-melt accident releases to the *containment*…
  - All noble gases
  - 50% iodine
    - 91% elemental gaseous I2
    - 5% particulate (eg. CsI)
    - 4% organic gaseous
  - 1% particulate
- 10CFR100 Site Boundary Criteria
  - Design leakage rate for intact containment
  - Engineered safety features
- Subsequently replaced by NUREG-1465 source term

NUREG-1465
Alternative Source Term (1995)

- Alternative regulatory source term formulated as an alternative to the out-dated TID-14844 source term *(to containment)*
  - More realistic source term characteristics
  - Defined release phases and durations
  - Iodine recognized as principally aerosol form (CsI)
- AST based on experimental evidence, STCP accident analyses and NUREG-1150 insights gained since mid 1980's
  - Start of risk-informed regulation
  - Intended to be characteristic of likely source term and not bounding or conservative
- Large step in realism since TID and WASH-740







Some Review of Fission Product Release Modeling and Implementation into MELCOR

Fractional Release Models

Diffusion Release Model

Effect of Volatility from Assumed Speciation

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Fission Product Release Modeling - Booth Diffusion Release Model -

$$\frac{\partial C}{\partial t} = D\nabla^2 C$$

$$C(r,0) = C_0 \qquad and \qquad C(a,t) = 0$$

$$J = -D\left(\frac{\partial C}{\partial r}\right)_{r=a}$$

$$F(t) = 6\sqrt{\frac{Dt}{\pi a^2}} - 3\frac{Dt}{a^2} \quad for \quad \frac{Dt}{a^2} \le 0.1547$$

$or,$

$$F(t) = 1 - \frac{6}{\pi^2}\exp\left(\frac{-\pi^2 Dt}{a^2}\right) \quad for \quad \frac{Dt}{a^2} > 0.1547$$

$$D(T) \quad = \quad D_0 \exp\left(\frac{-Q}{RT}\right)$$

- Booth solution solves the diffusion equation where *"C"* is concentration of FP in spherical grain
- Assumes uniform initial FP concentration in grain and zero FP concentration at surface
- Release rate is outward flux at surface
- Release fraction well approximated by simple forms
- Diffusion coefficient is temperature dependent
  - Determined by curve fitting

Fission Product Release Modeling - Booth Release Model, cont. -

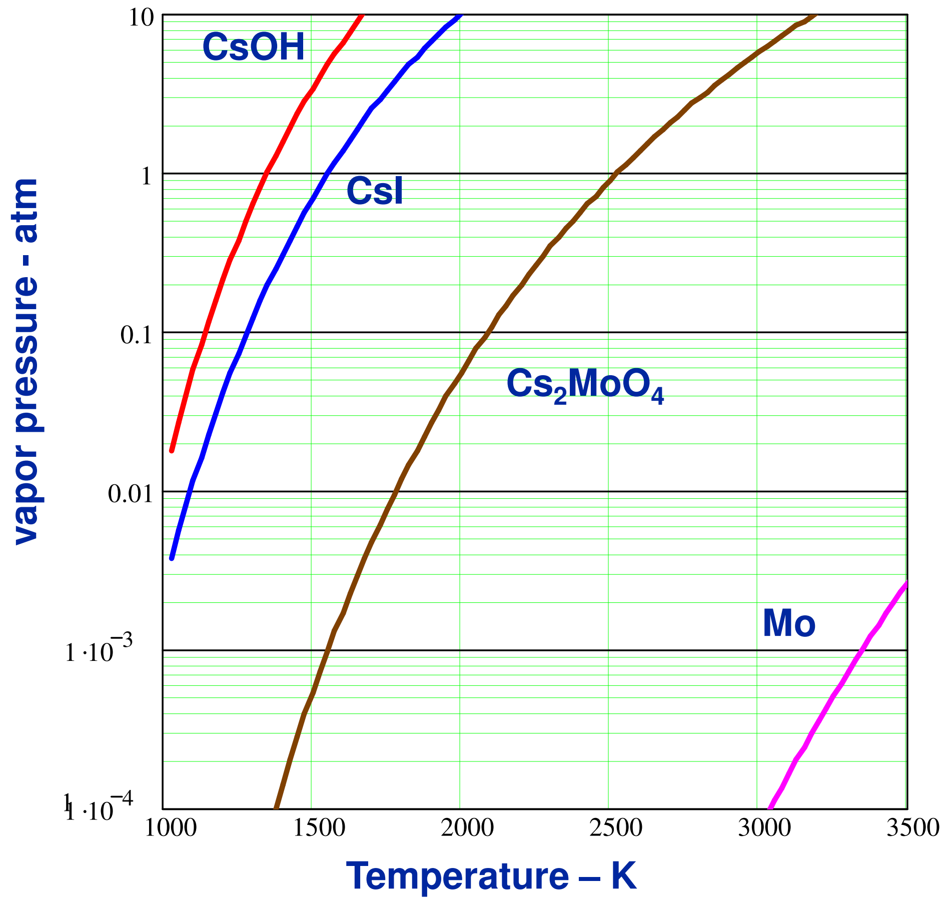
$$RR_{Diff} = \frac{F(t+\Delta t) - F(t)}{F(t)\cdot \Delta t}$$

$$\dot{m}_v = \left[\frac{Nu\mathcal{D}_k}{D_{fuel}}\right]\left(\frac{P_k - 0}{RT}\right)A_{fuel}$$

$$RR_{net} = \left[\frac{1}{RR_{Diff}} + \frac{1}{\dot{m}_v}\right]^{-1}$$

- MELCOR determines diffusion fractional release rate by differencing the release fraction F
- A mass transfer limit by vapor transport is calculated using an analogy to heat transfer
  - Vapor pressure is driving potential
- The net release is estimated by inverse of reciprocal sums
  - Low vapor pressure can limit release
  - Low diffusion rate can also limit release

Vapor Pressures of Some Important Species



- Molybdenum vapor pressure extremely low
- Cs_2MoO_4 considerably higher, but…
- Less volatile than CsOH or CsI
- Modified treatment
  - Cs and Mo treated as Cs_2MoO_4 with respect to volatility
  - CsI left unchanged

Fitting of Booth Parameters

$$F(t) = 6\sqrt{\frac{Dt}{\pi a^2}} - 3\frac{Dt}{a^2} \quad for \quad \frac{Dt}{a^2} \le 0.1547$$

$or,$

$$F(t) = 1 - \frac{6}{\pi^2}\exp\left(\frac{-\pi^2 Dt}{a^2}\right) \quad for \quad \frac{Dt}{a^2} > 0.1547$$

$$\frac{D\,t}{a^2} = \frac{2}{\pi} - \frac{F}{3} - 2\sqrt{\frac{1}{\pi^2} - \frac{F}{3\pi}} \qquad \text{for F} < 0.85$$

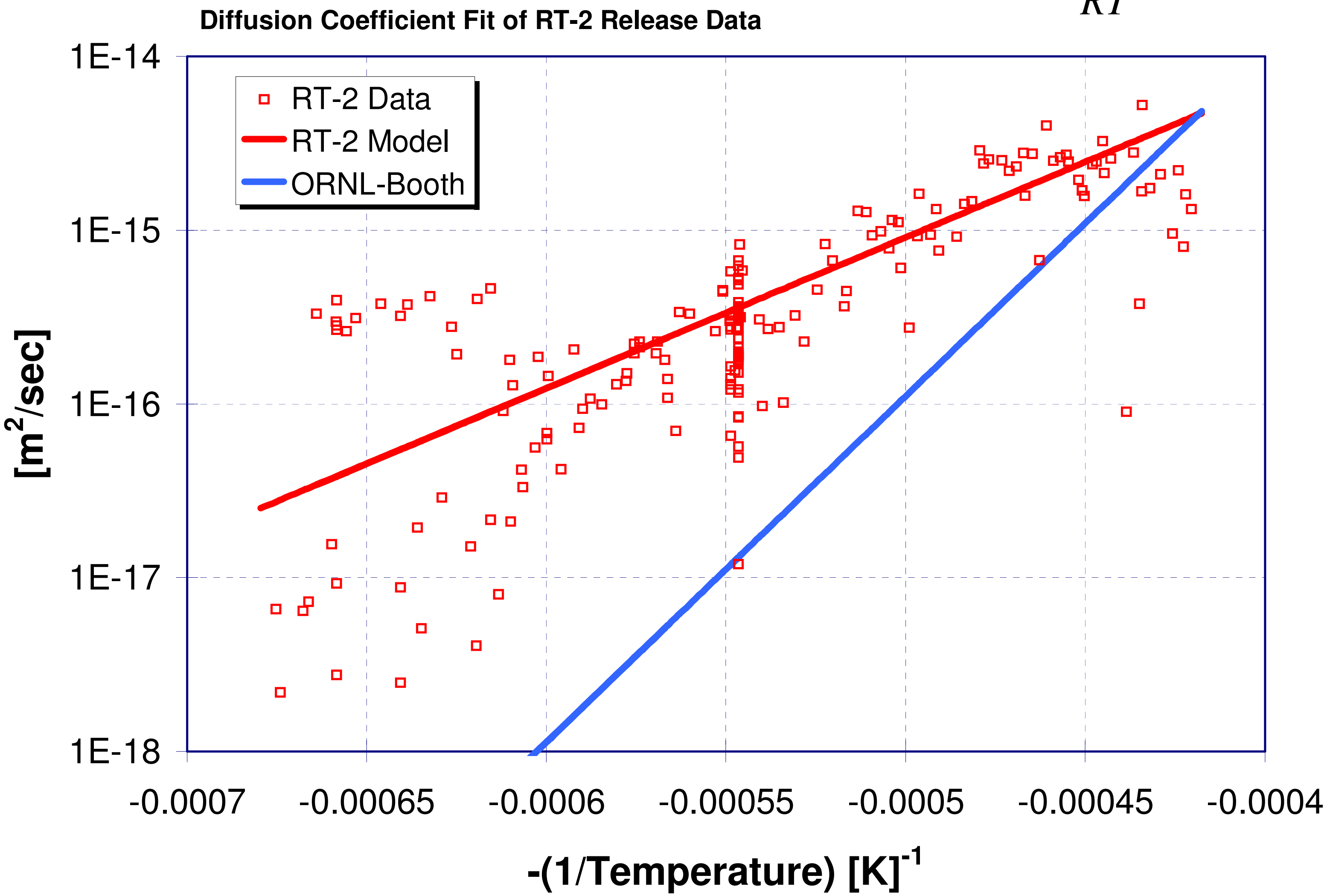
$$\frac{D\,t}{a^2} = \frac{-1}{\pi^2}\ln\left[\frac{\pi^2(1-F)}{6}\right] \qquad \text{for F} > 0.85$$

- Release fractions from Booth model
- Invert solution in terms of “D t”
- Allows plotting of instantaneous “D” as a function of temperature
- Infer a functional form for D(T)

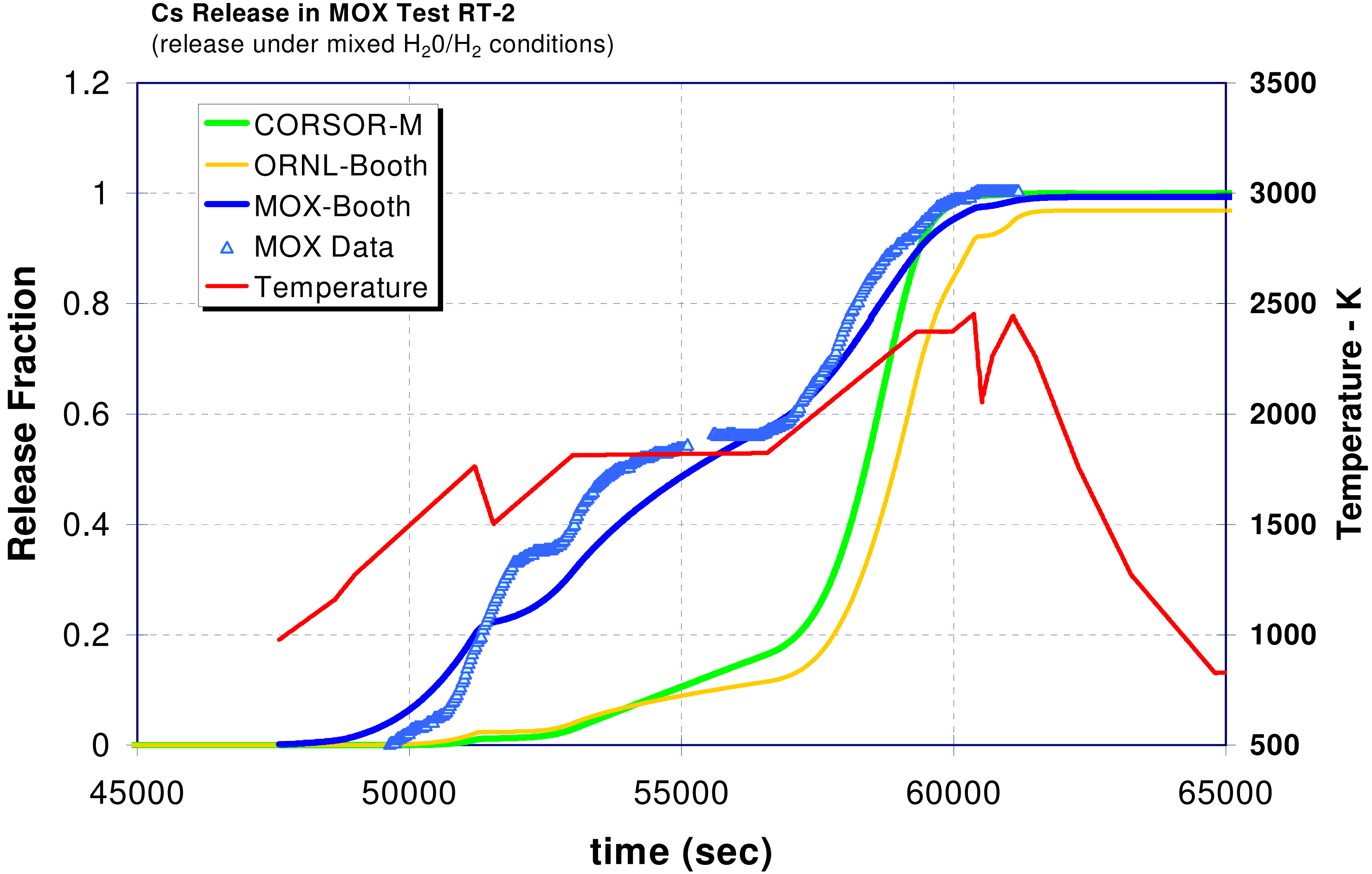
RT-2 MOX Data

$$D(T) \quad = \quad D_0 \exp(\frac{-Q}{RT})$$

$$\ln D = \ln D_0 - \frac{Q}{RT}$$



Booth Model Release Predictions for RT-2 Test



Booth Parameters for Different Data Fits

	CORSOR-Booth	ORNL-Booth	Adjusted ORNL-Booth
Diffusion coeff. D_o	*$2.5x10^{-7}$ m^2/sec*	*$1x10^{-6}$ m^2/sec*	*$1x10^{-6}$ m^2/sec*
Activation Energy Q	$3.814x10^5$ joule/mole	$3.814x10^5$ joule/mole	$3.814x10^5$ joule/mole
Grain radius, a	6 μm	6 μm	6 μm
Class Scale Factors	---	---	---
Class 1 (Xe)	1	1	1
Class 2 (Cs)	1	1	1
Class 3 (Ba)	$3.3x10^{-3}$	$4x10^{-4}$	$4x10^{-4}$
Class 4 (I)	1	0.64	0.64
Class 5 (Te)	1	0.64	0.64
Class 6 (Ru)	*$1x10^{-4}$*	*$4x10^{-4}$*	*0.0025*
Class 7 (Mo)	*0.001*	*0.0625*	*0.2*
Class 8 (Ce)	$3.34x10^{-5}$	$4x10^{-8}$	$4x10^{-8}$
Class 9 (La)	$1x10^{-4}$	$4x10^{-8}$	$4x10^{-8}$
Class 10 (U)	$1x10^{-4}$	$3.6x10^{-7}$	$3.2x10^{-4}$
Class 11 (Cd)	0.05	0.25	.25
Class 12 (Sn)	0.05	0.16	.16

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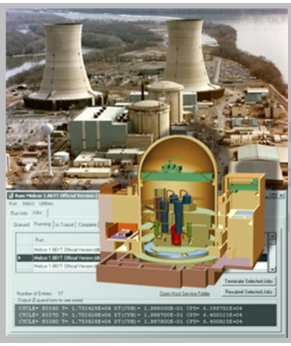

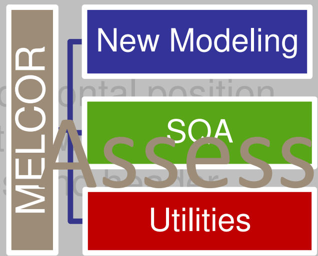

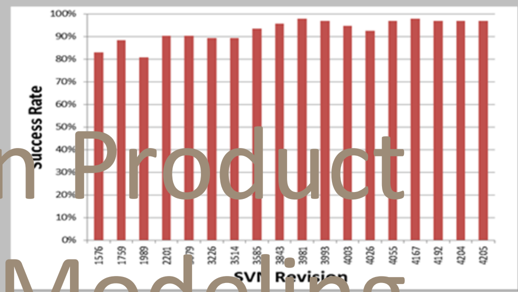

Assessment of Fission Product Release Modeling

Phebus FPT-1

ORNL VI

VERCORS

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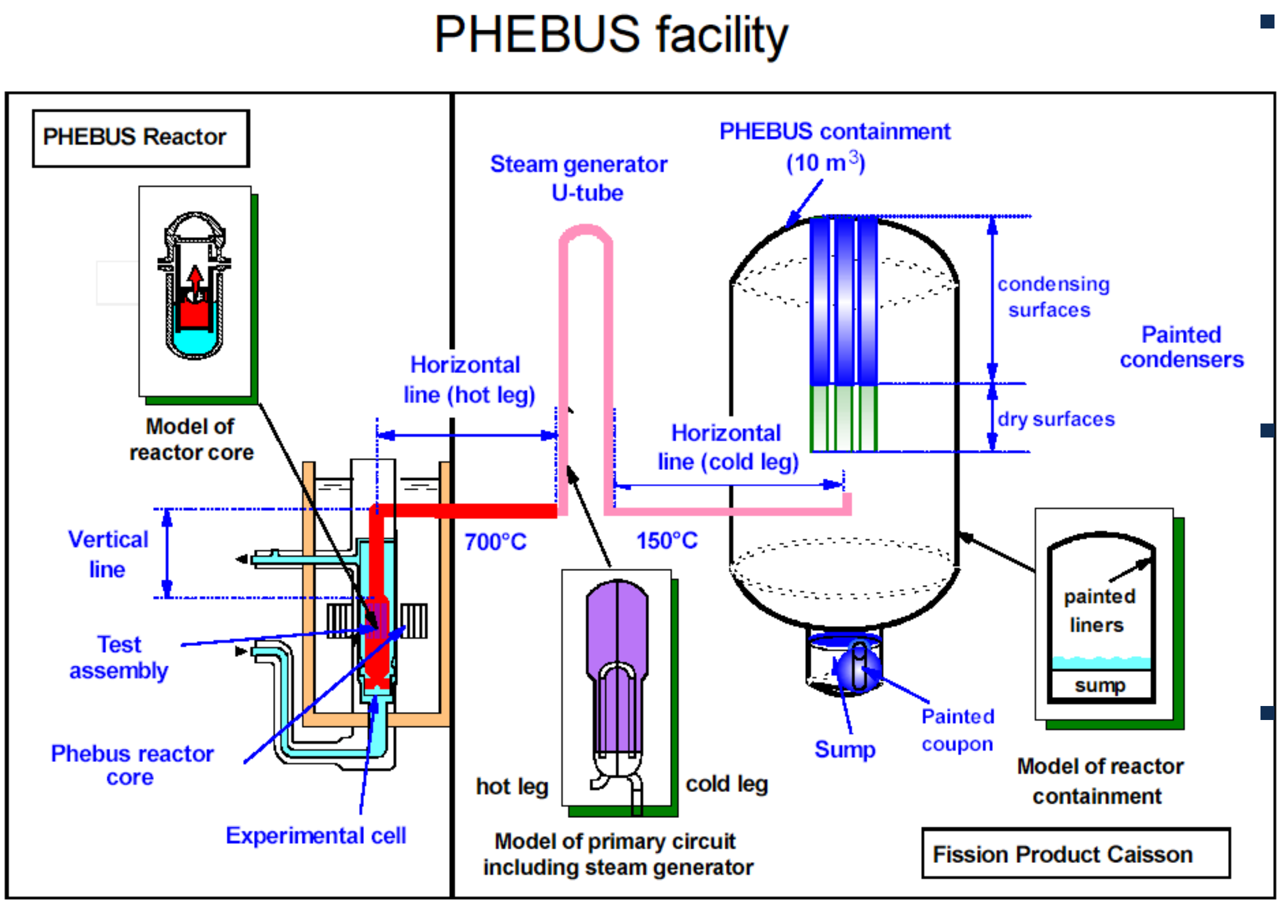
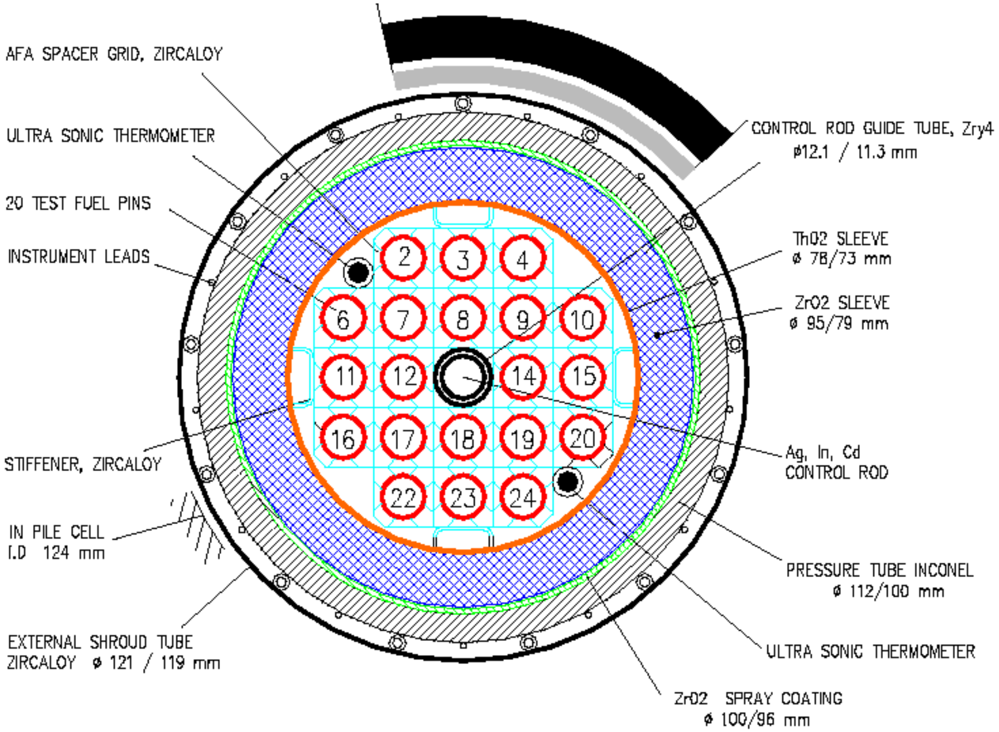
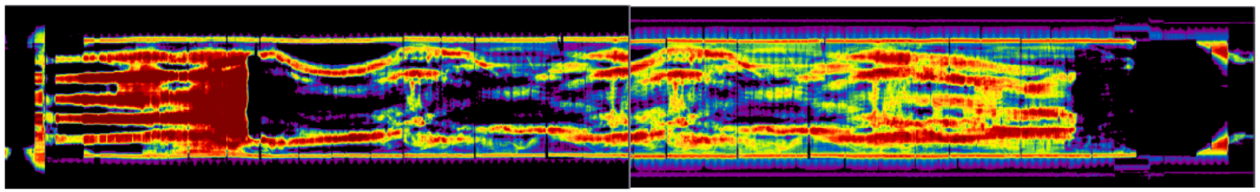
The Phebus Experiment Facility



- Irradiated fuel heated in test package by Phebus driver core
  - Fuel heatup
  - Zr oxidation, H_2
  - Fission product release
- Circuit (700 C) transports FP through steam generator tube
  - Deposits in circuit and SG
- Containment receives FP gas and aerosol
  - Settling
  - Iodine chemistry

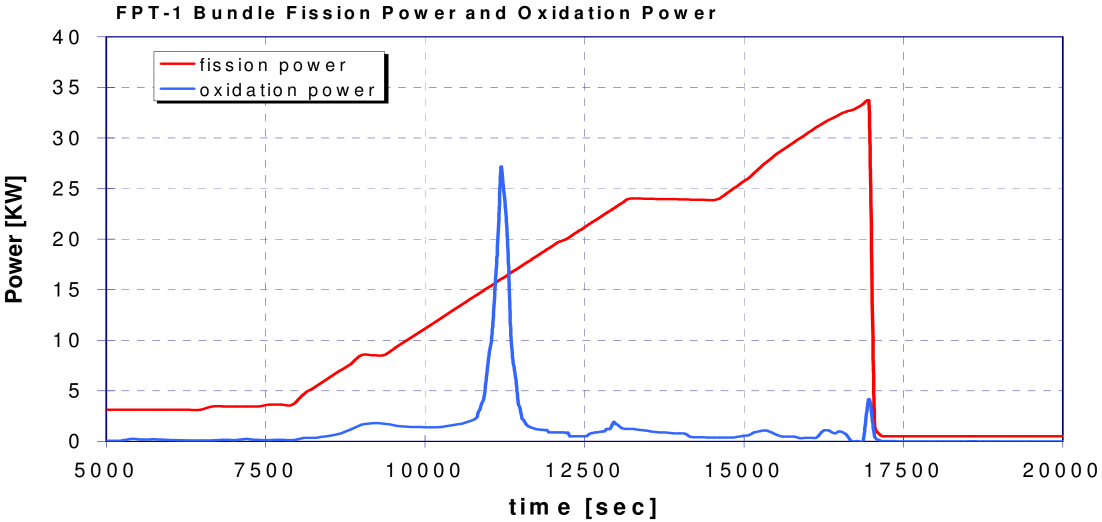
Fuel Rod Test Assembly

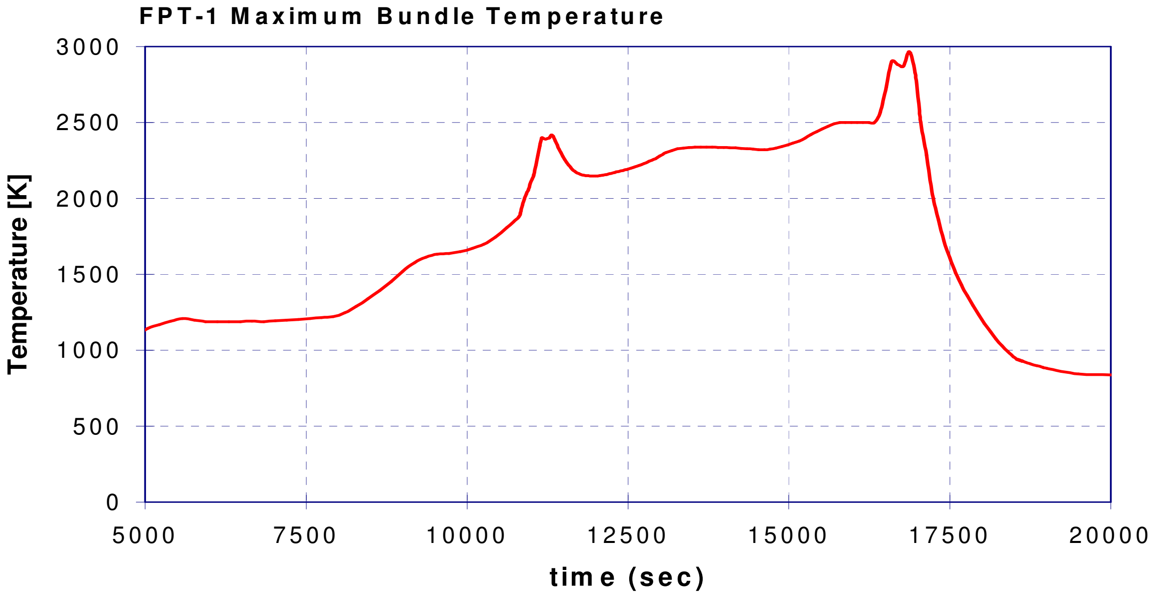




- Irradiated BR-3 fuel
- Ag/In/Cd or B_4C control rod
- Grid spacers
- Fuel damage
  - Zr oxidation
  - U-Zr-O interactions
  - Molten pool

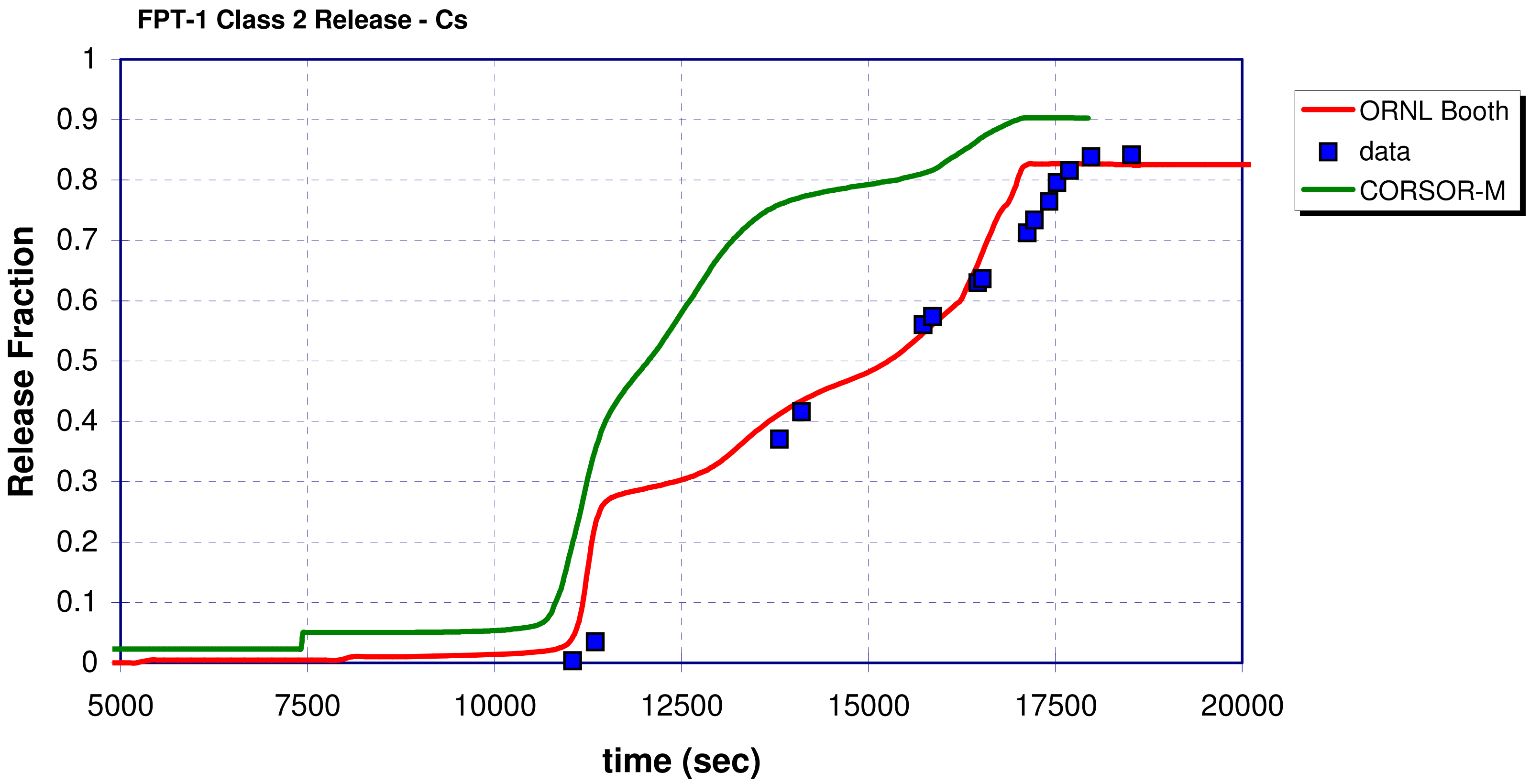
FPT-1 Experiment





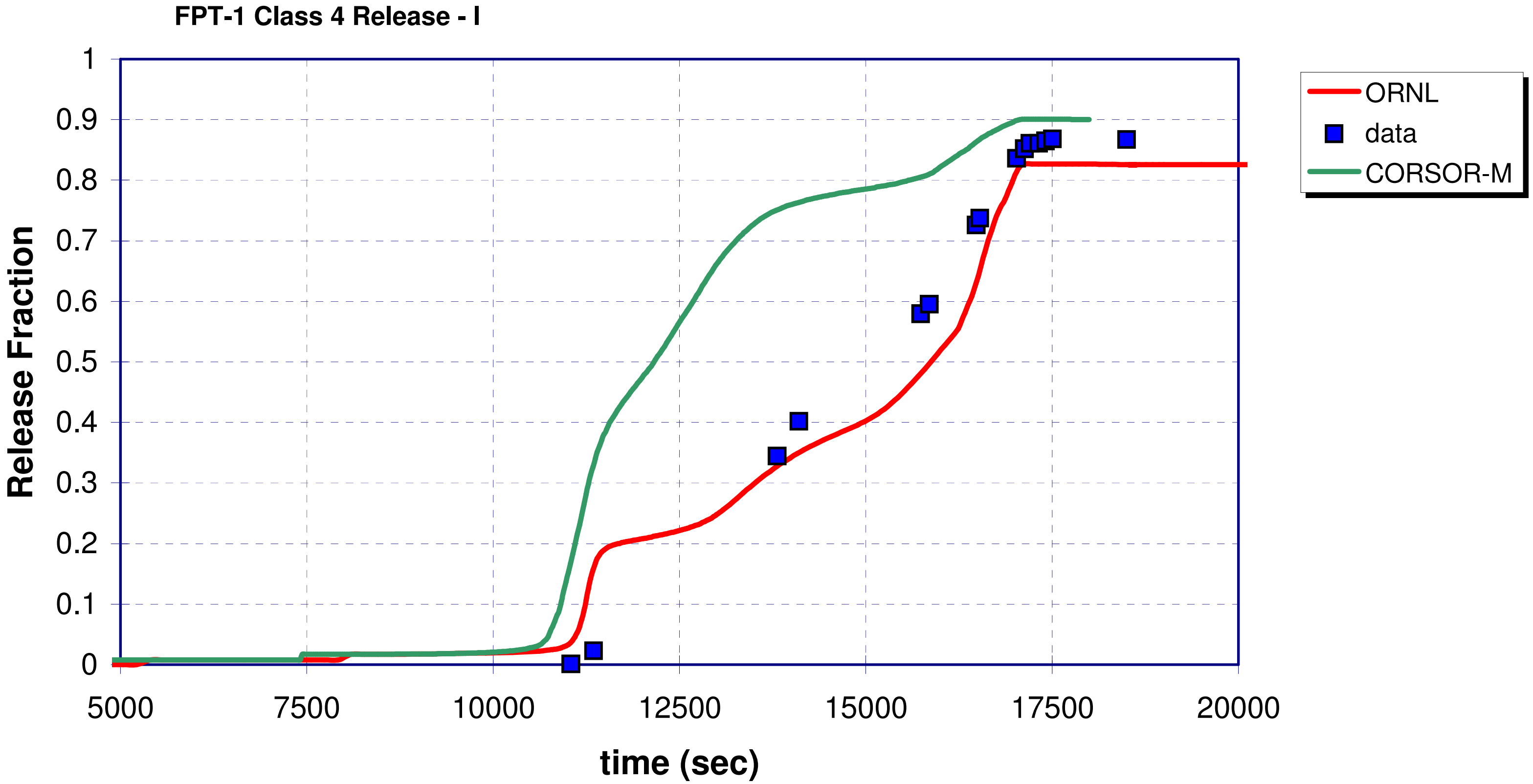
- Power produced by driver core heats fuel and supports heat losses
- Oxidation power drives rapid fuel heating
  - Clad melting
  - Zr-UO_2 liquefaction
- Late-time oxidation produced by relocation of materials

Cs Release from FPT-1 Fuel

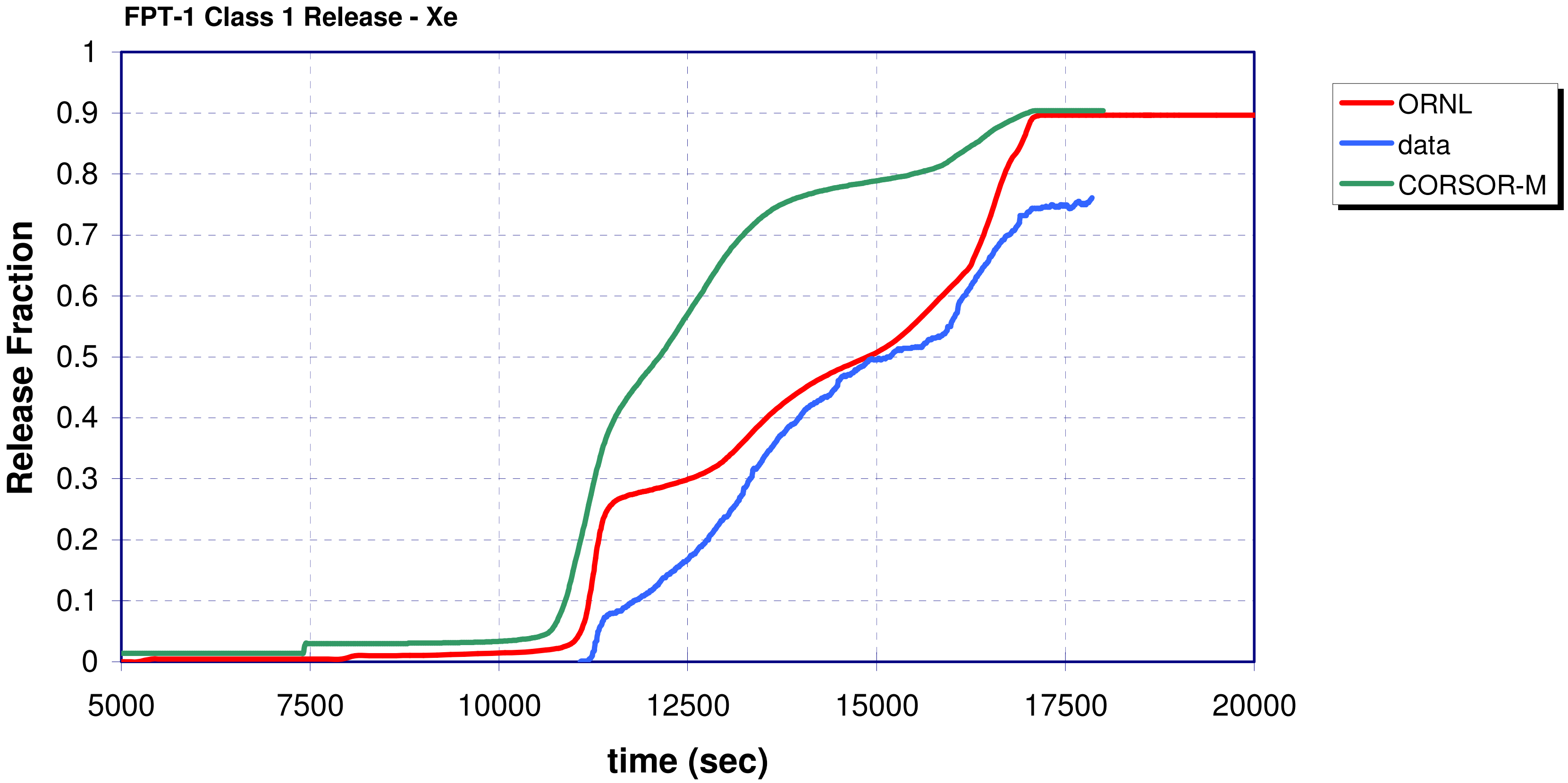


- ORNL Booth model shows improved release kinetics
- CORSOR-M over-predicts early release

Iodine Release

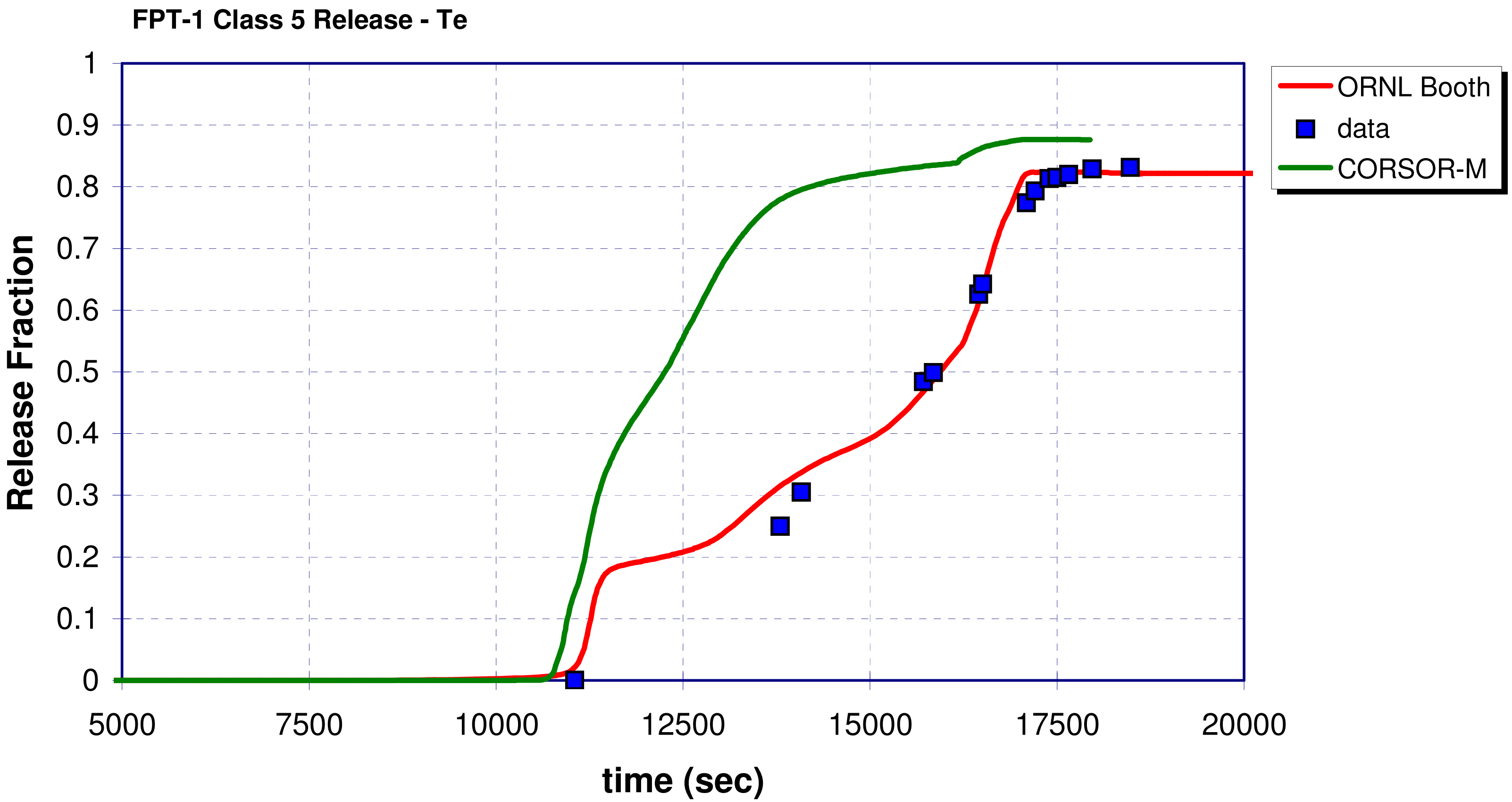


Noble Gas Release



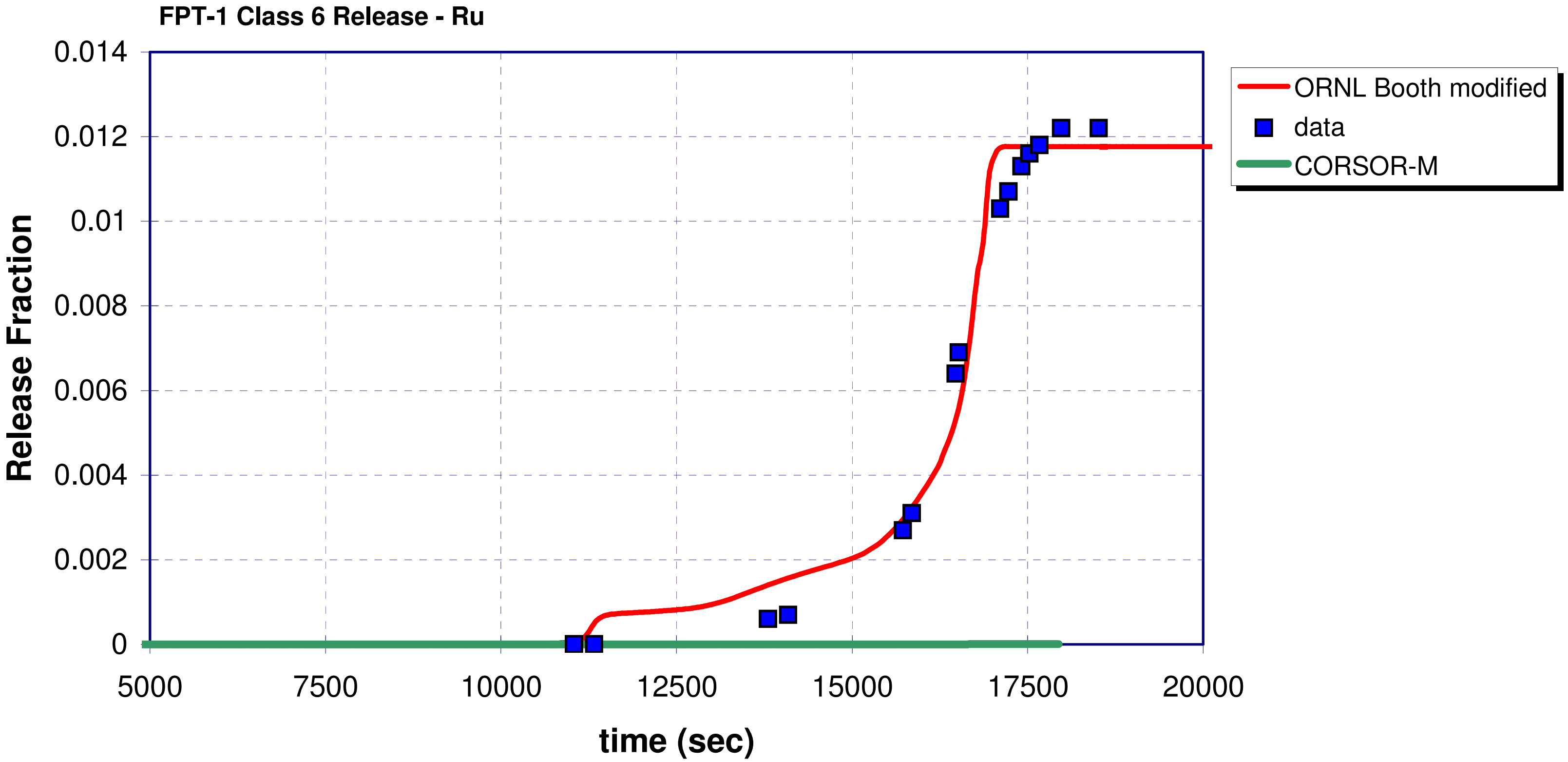
- Similar improvement for Xe

Te Release



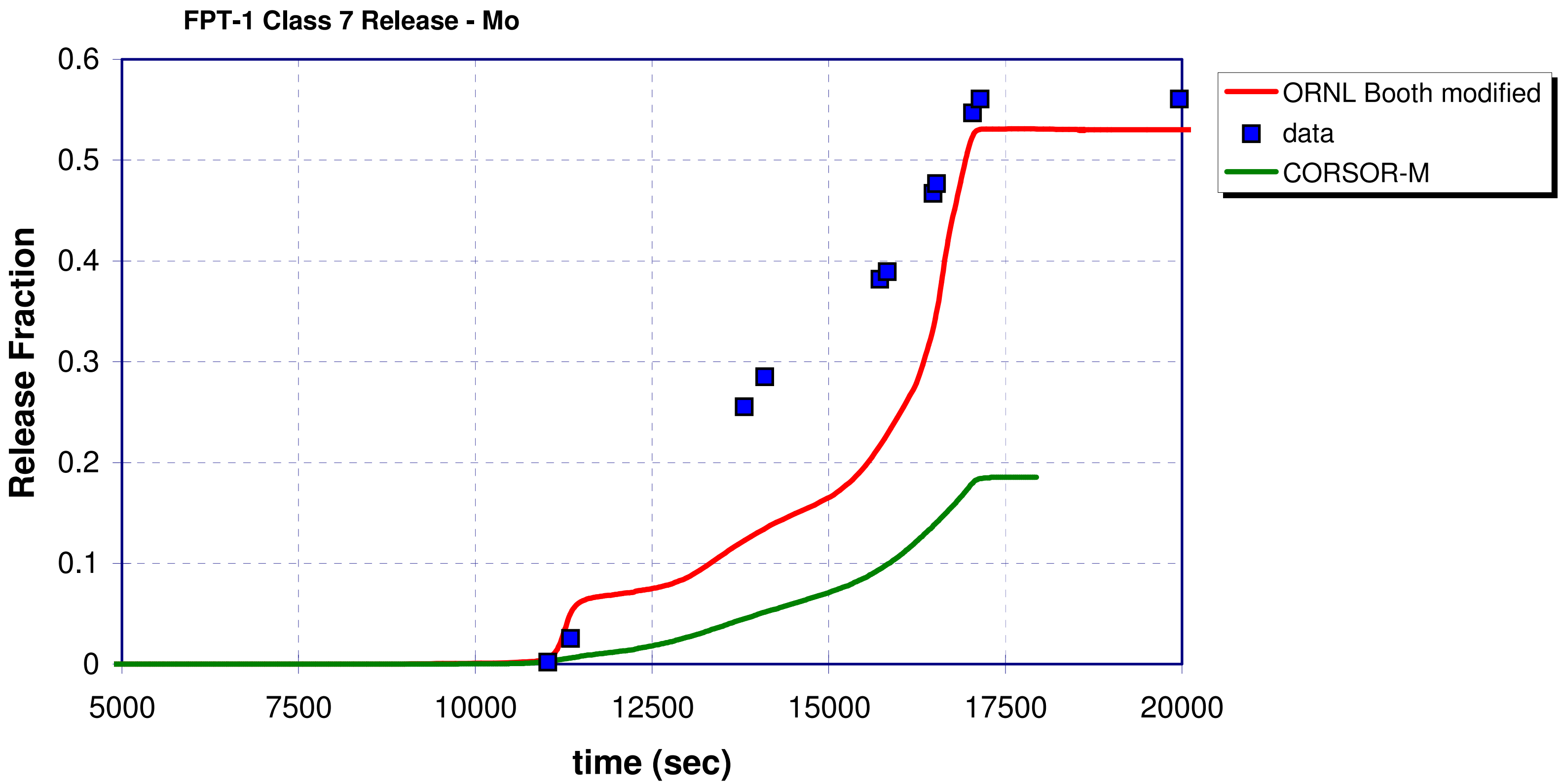
FPT-1 Class 5 Release - Te
Release Fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5000
7500
10000
12500
15000
17500
20000
time (sec)
ORNL Booth
data
CORSOR-M

Ru Release



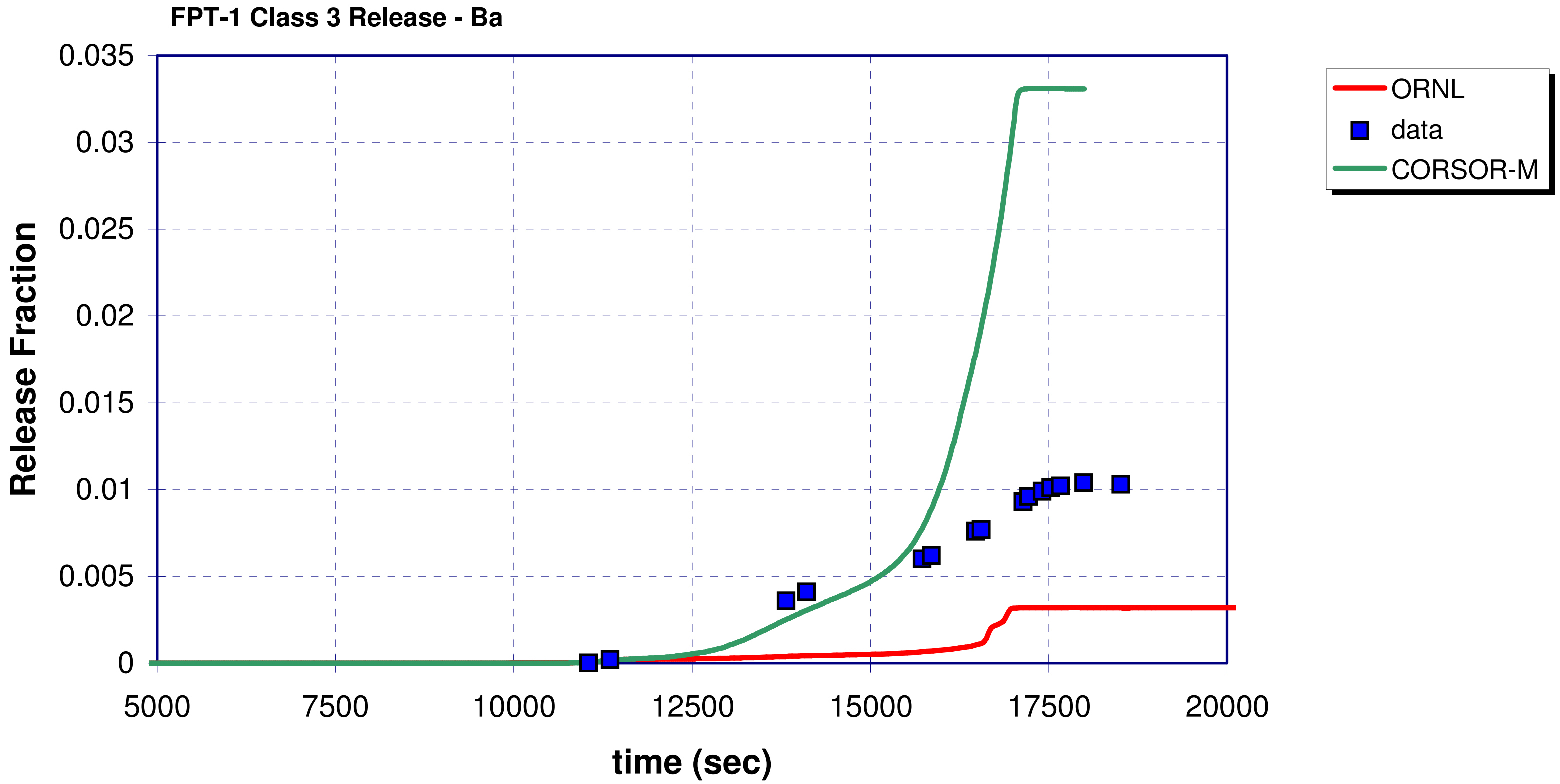
- Ru release compares well with FPT-1
- CORSOR-M seriously under-predicts Ru

Moly Release

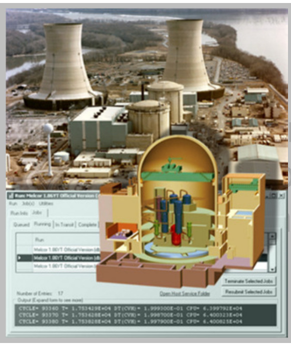


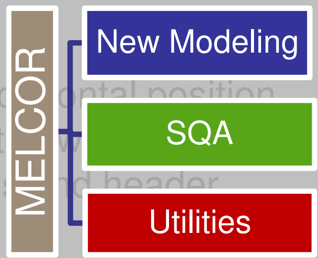
- Implementing volatility of Cs_2MoO_4 and adjustments to Cs-release scaling factor produces agreement with FPT-1

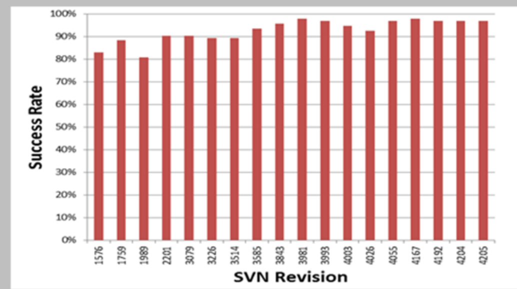
Ba Release Problematic



- Ba release often not as well predicted
- Ba metal versus BaO affected by reducing conditions
  - Ba boils at ~1900K, BaO shows volatility above ~2100K
  - Volatility sensitive to temperature and Red/Ox conditions (Zr strong reducing agent)





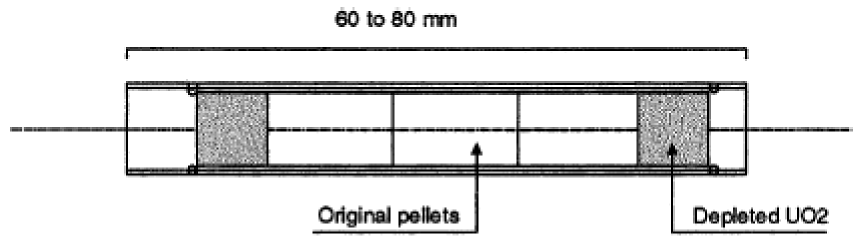


Having produced good comparisons to FPT-1, how do these changes affect comparison to the small scale tests on which original models were developed ?

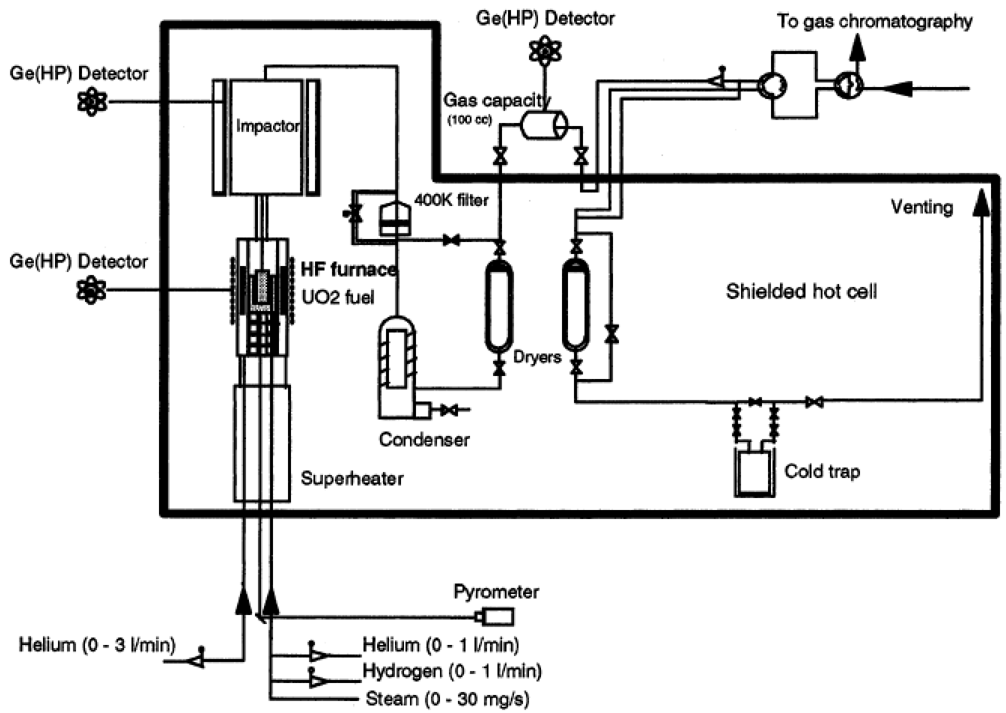
ORNL VI tests

French VERCORS tests

Small Scale Release Tests VERCORS and ORNL VI



G. Ducros et al. / Nuclear Engineering and Design 208 (2001) 191–203



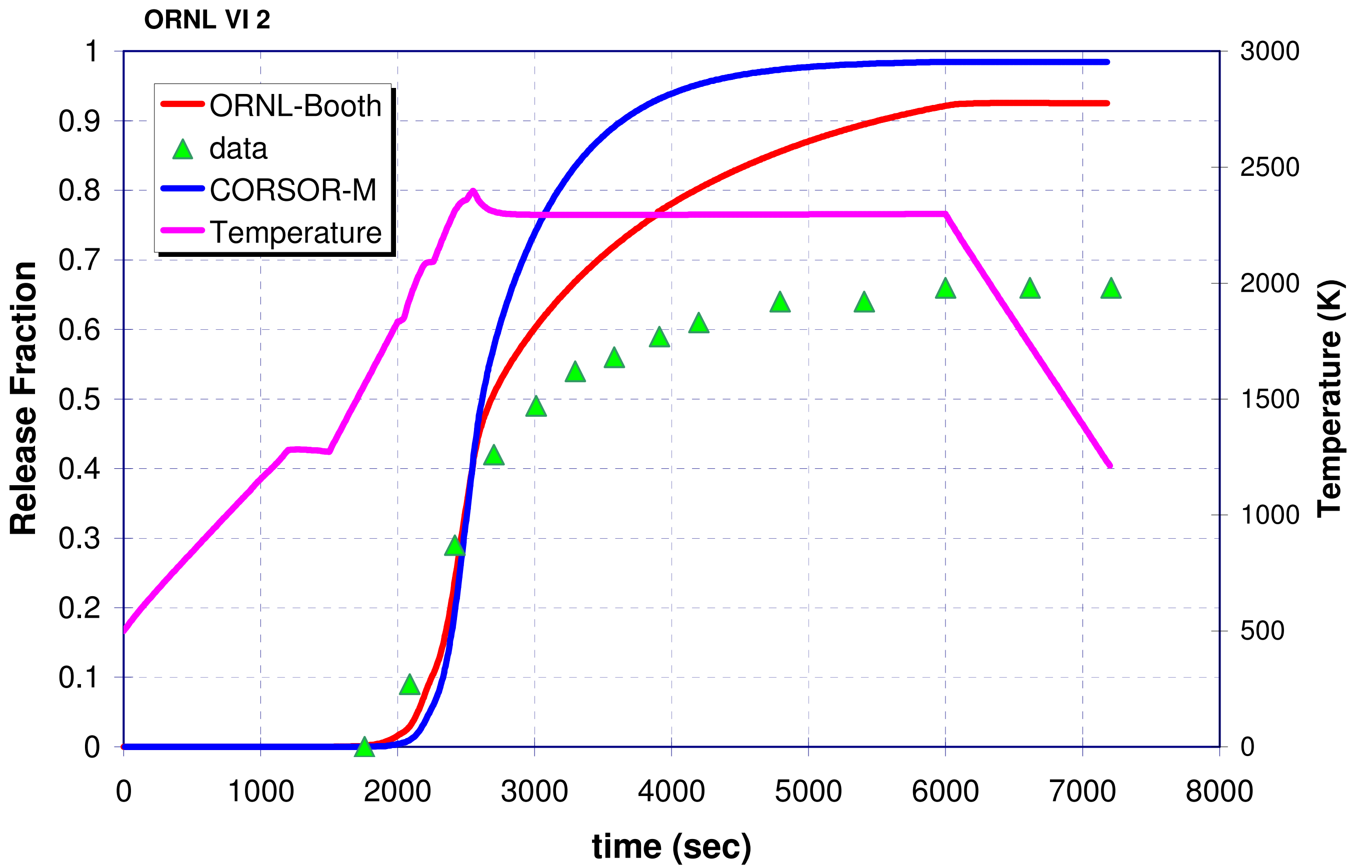
- Small scale tests use only a few pellets
- Conditions are uniform compared to integral tests like FPT-1
- Cladding often fully oxidized prior to release measurements
- Temperature raised in steps with long plateaus

Small Scale Tests Examined

Test	Hydrogen	Steam	Max Temperature
ORNL VI-2	0	1.8 liter/min	2300K
ORNL VI-3	0	1.6 liter/min	2700K
ORNL VI-5	0.4 liter/min	0	2740K
VERCORS 2	0.027 gm/min	1.5 gm/min	2150K
VERCORS 4	0.012 gm/min	1.5 – 0 gm/min	2573K

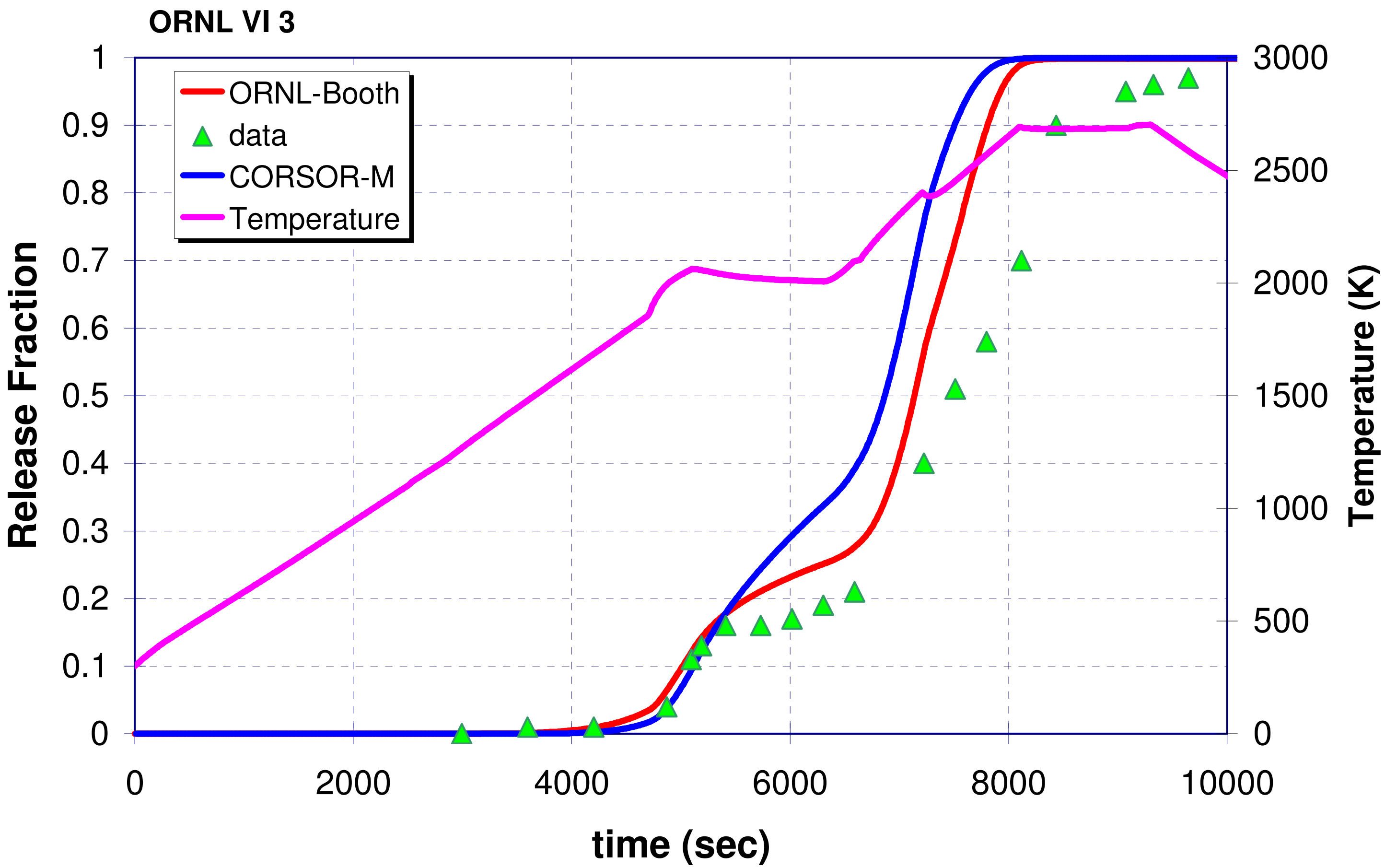
- Different peak temperatures
- Differing oxidizing potentials

Cs Release in ORNL VI-2

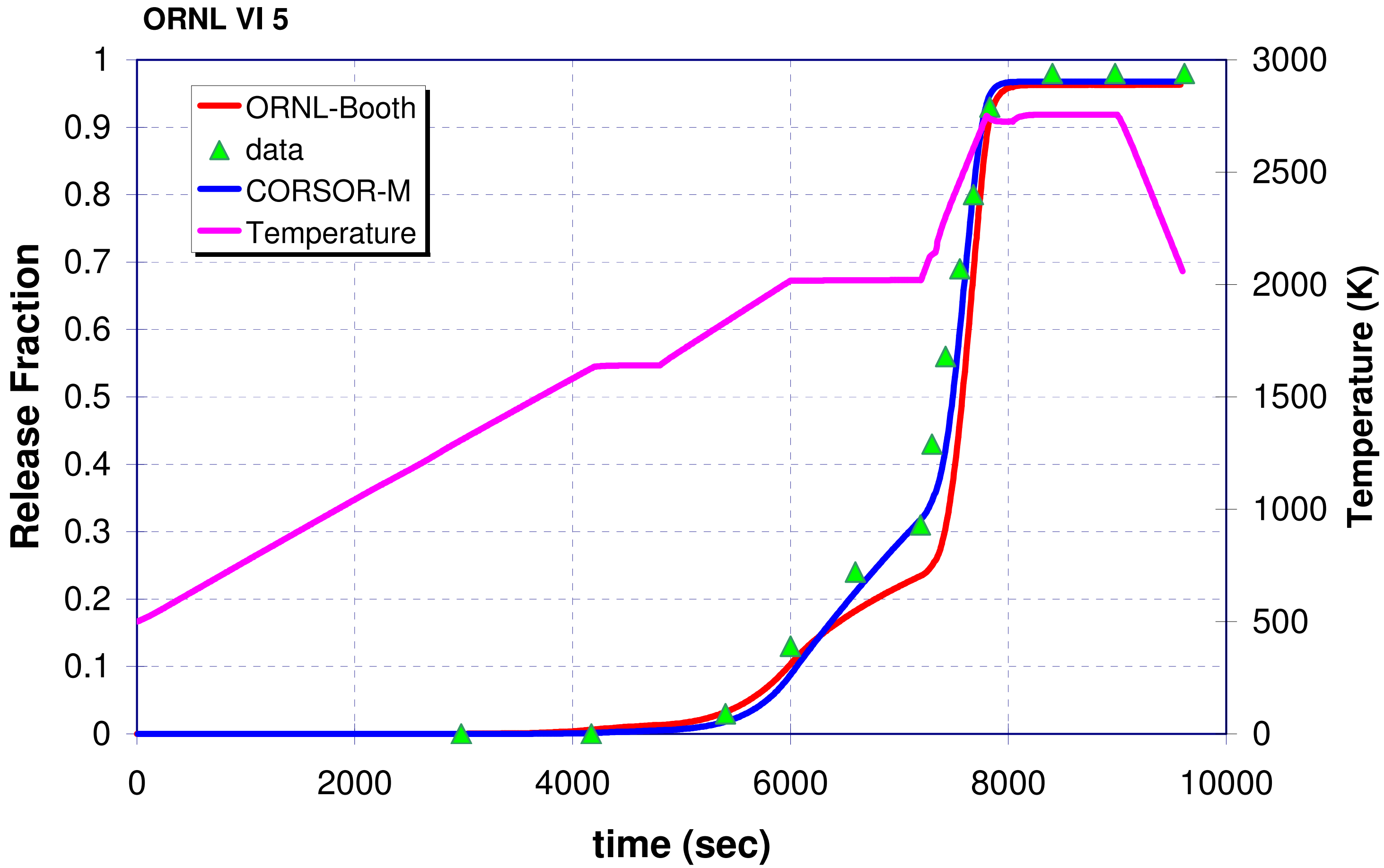


- ORNL-Booth compares better (not terrific however)
- CORSOR-Booth might have done better

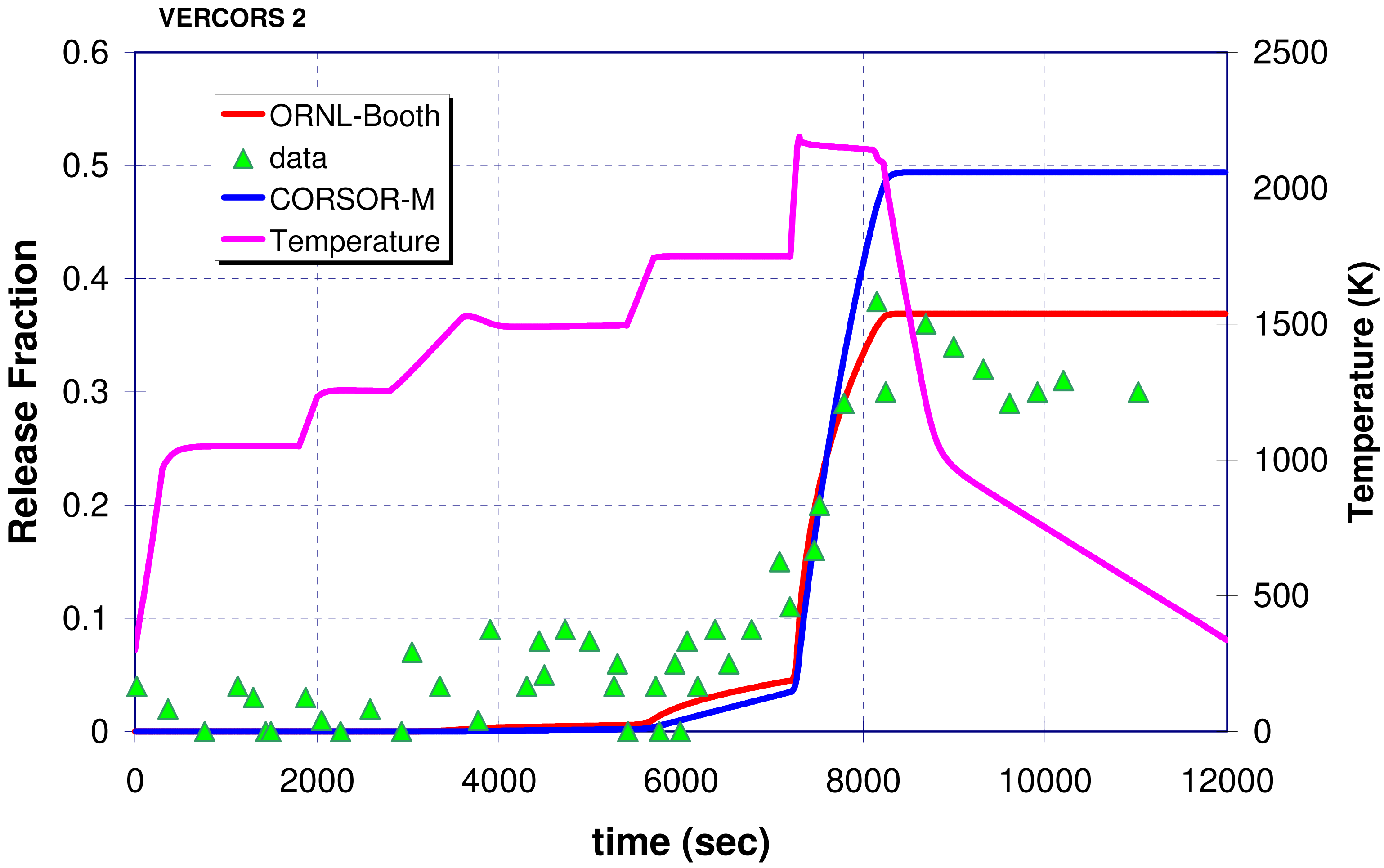
Cs Release in ORNL-VI 3



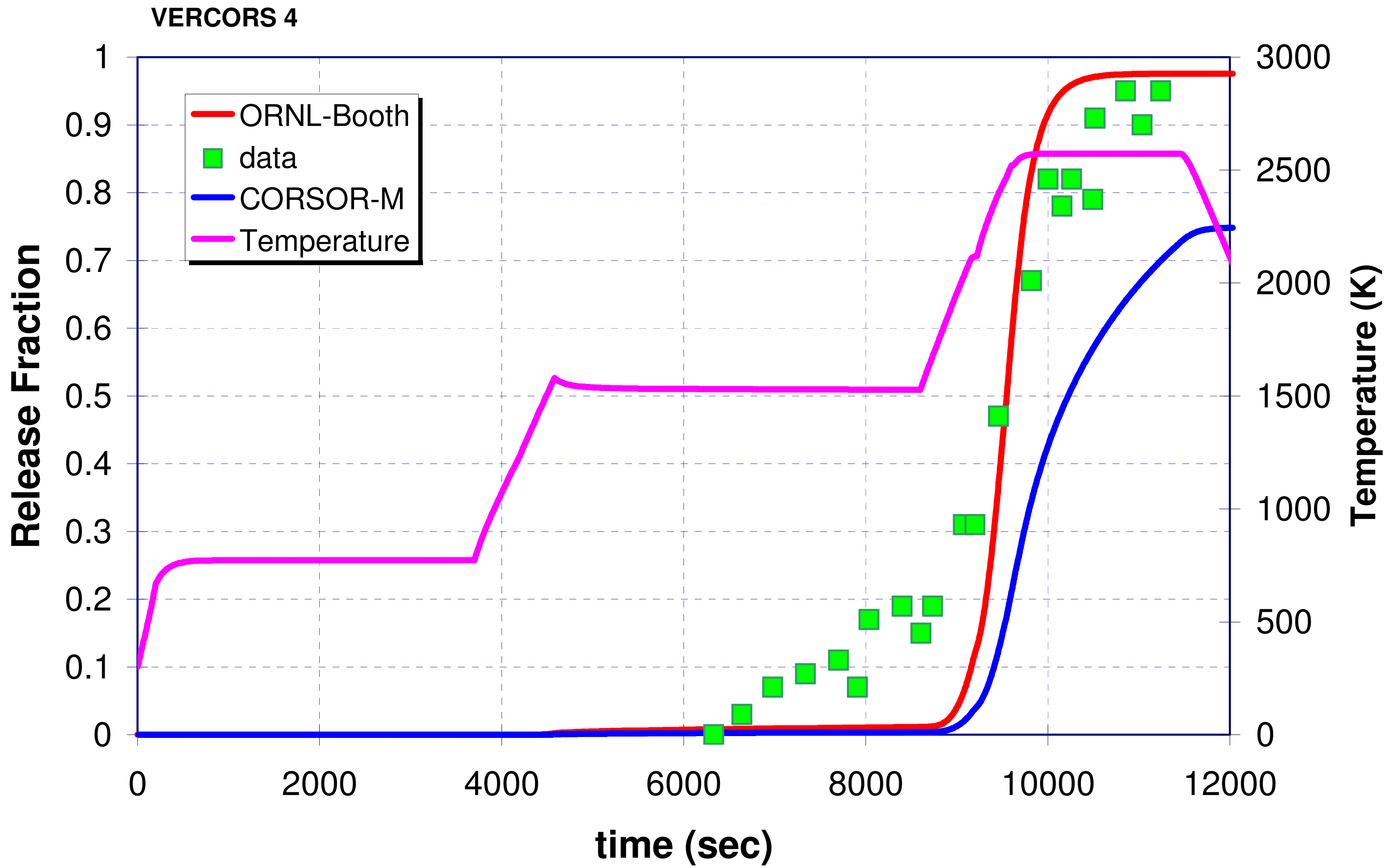
Cs Release in ORNL VI 5



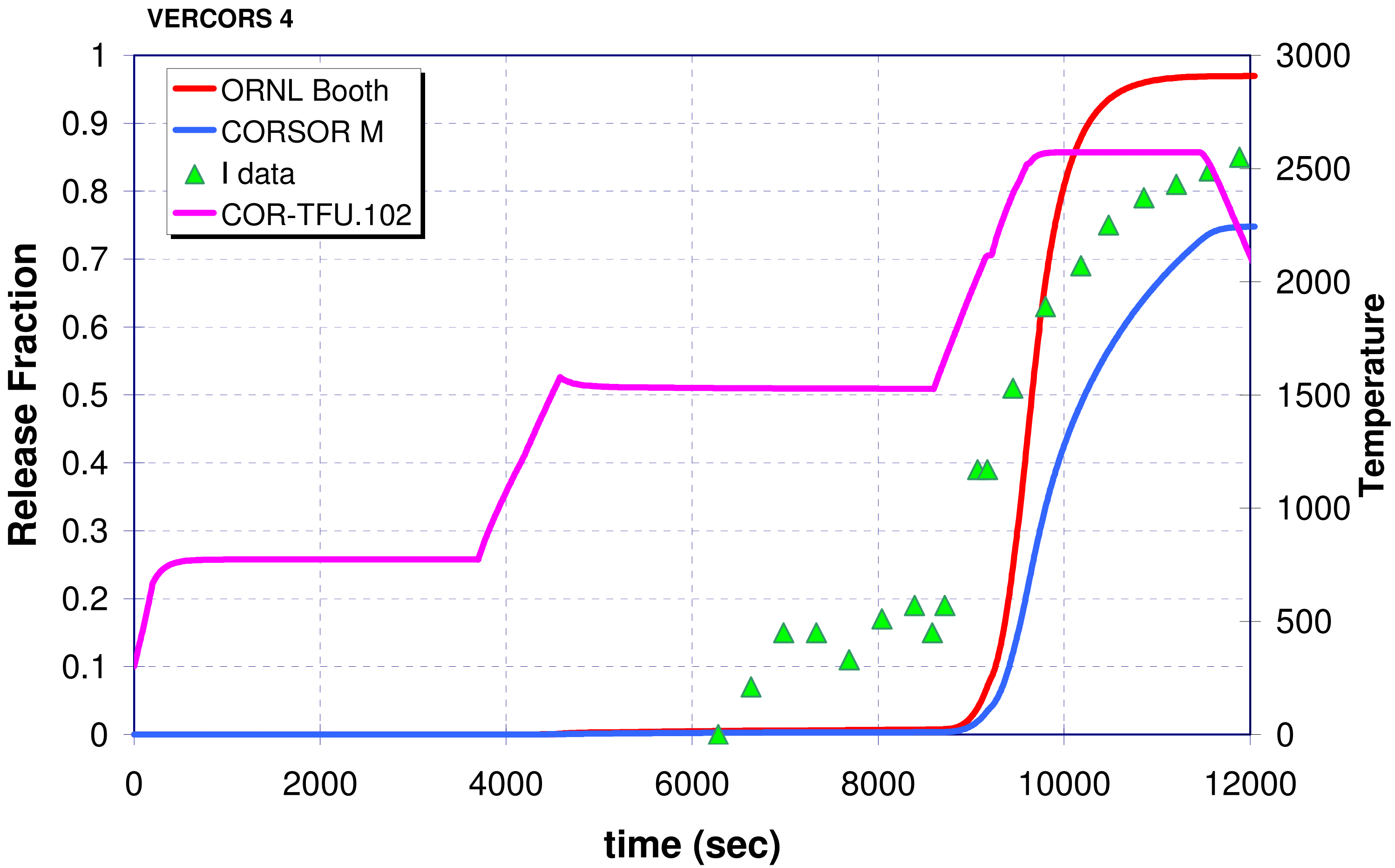
Cs Release in VERCORS 2



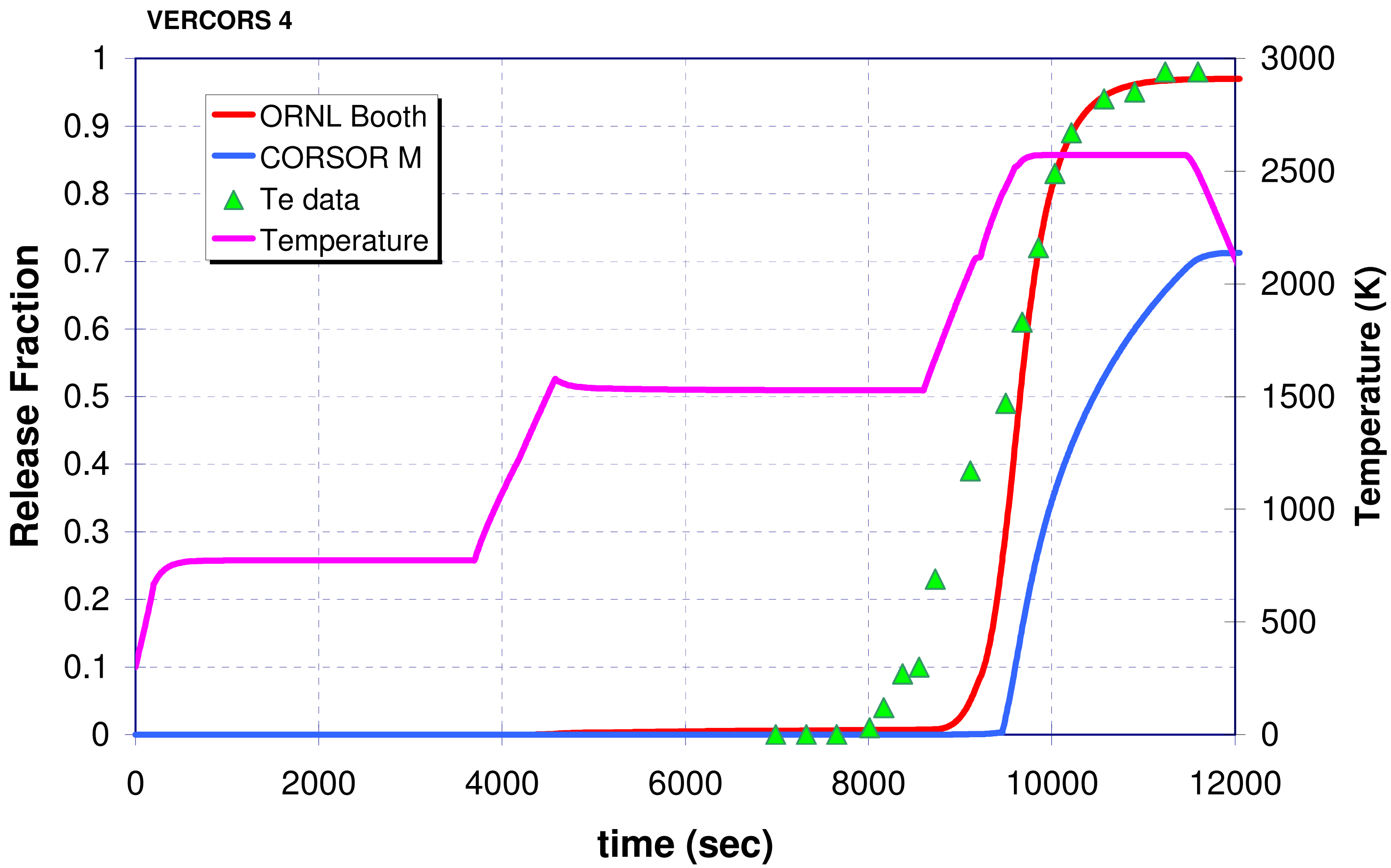
Cs Release in VERCORS 4



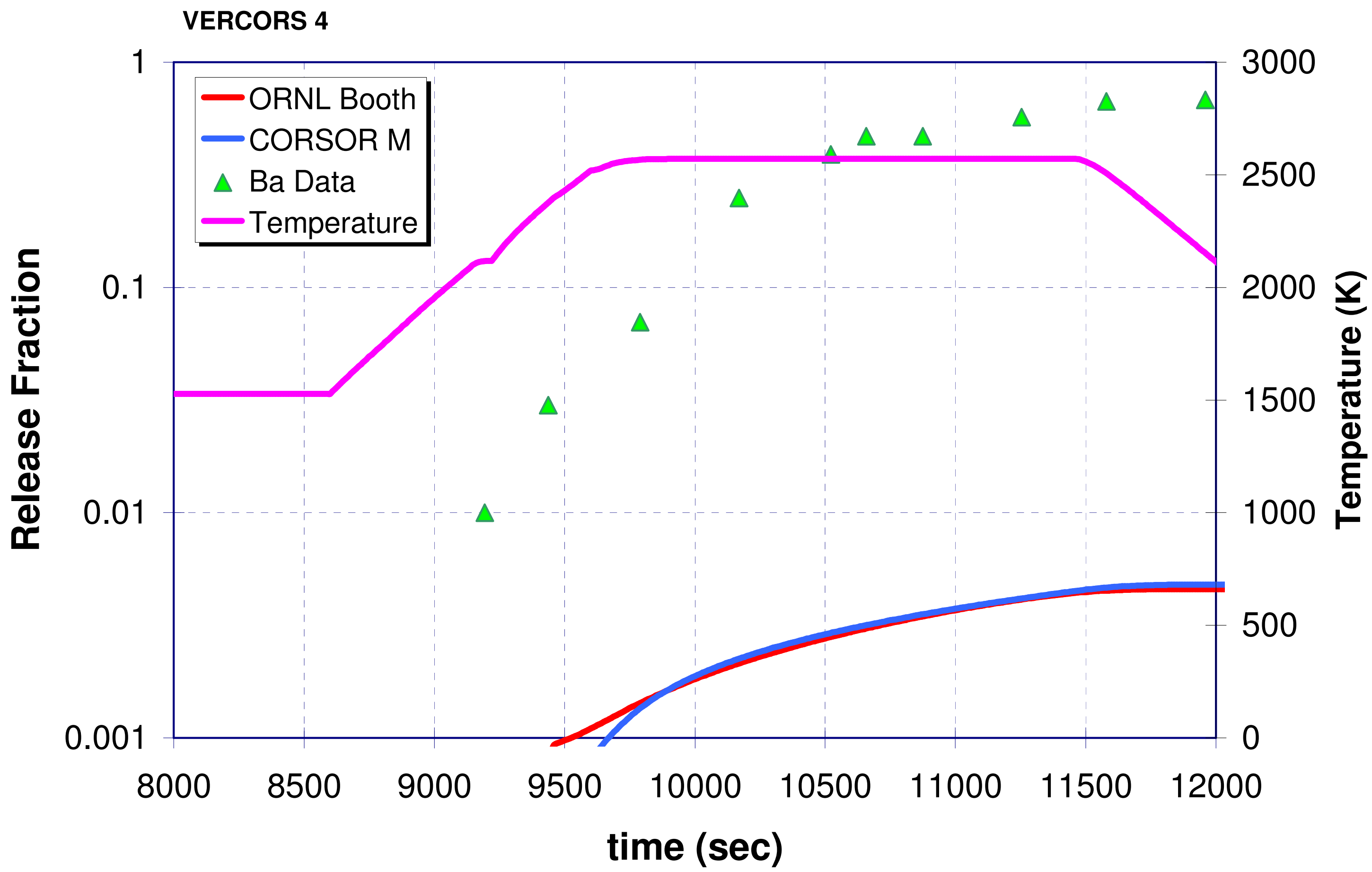
Iodine Release in VERCORS 4



Te Release in VERCORS 4

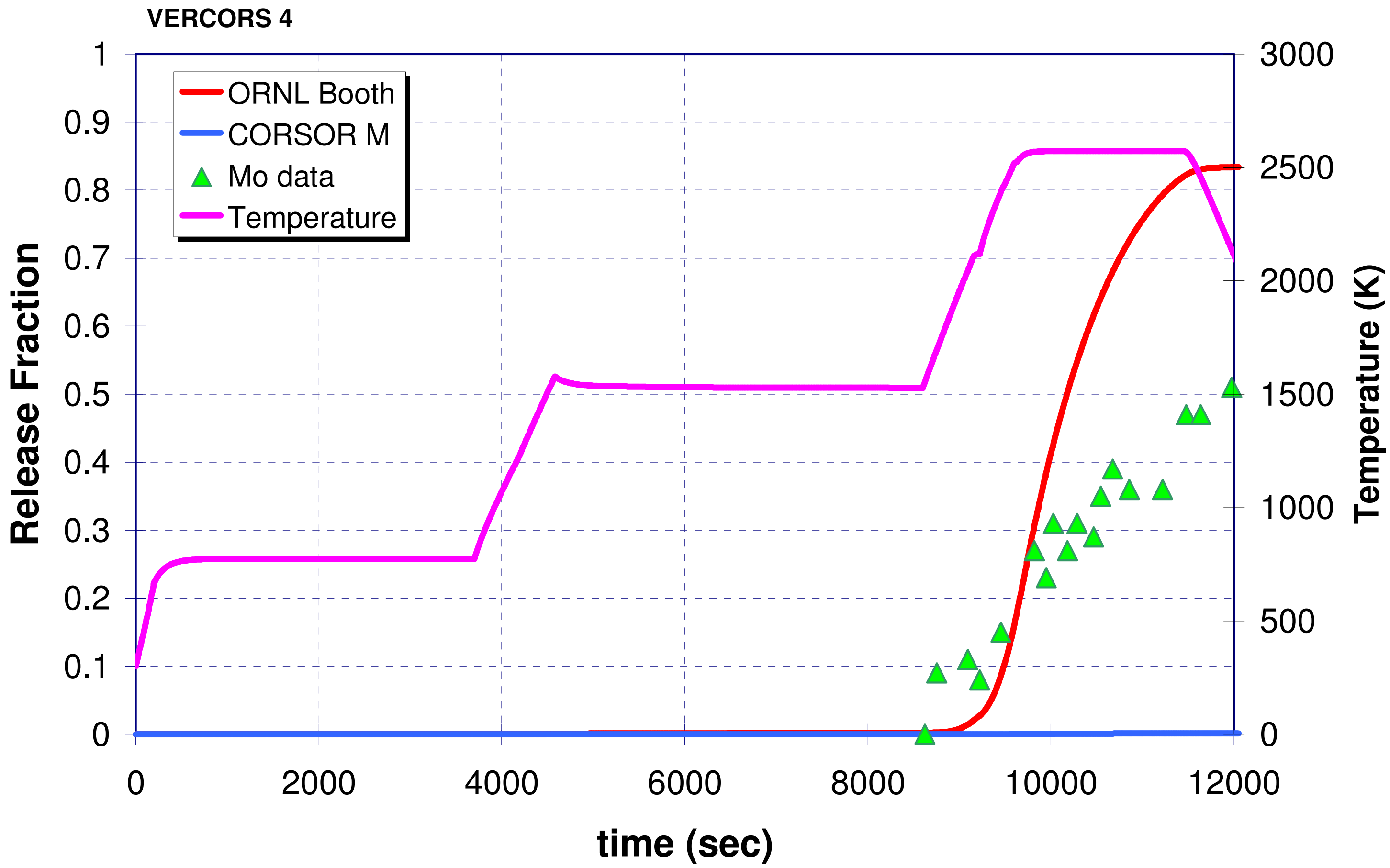


Ba Release in VERCORS 4



- Small scale tests often show enhanced release of Ba compared to integral tests

Mo Release in VERCORS 4



- Present treatment as Cs2MoO4 over-predicts Mo in VERCOR-4, but….
- Still better than CORSOR-M

Conclusions from Release Assessments

- Booth type release treatment provides improved release timing
- ORNL-Booth parameters give significantly improved predictions for FPT-1
- Modifications to Cs and Mo vapor pressure to reflect Cs_2MoO_4 improves Mo release behavior
- Adjustment of Ru release coefficient and vapor pressure produces agreement with FPT-1
- Adjustments to release modeling produces modest improvement in comparisons to small scale tests

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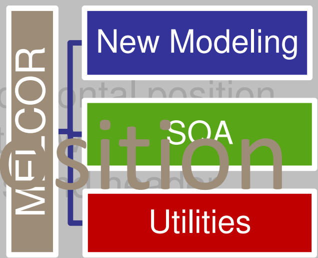

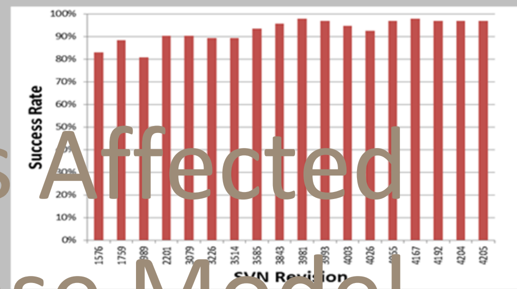

Deposition Characteristics Affected by Release Model

Release model implies speciation and volatility

Can affect deposition

FPT-1 circuit deposition examined

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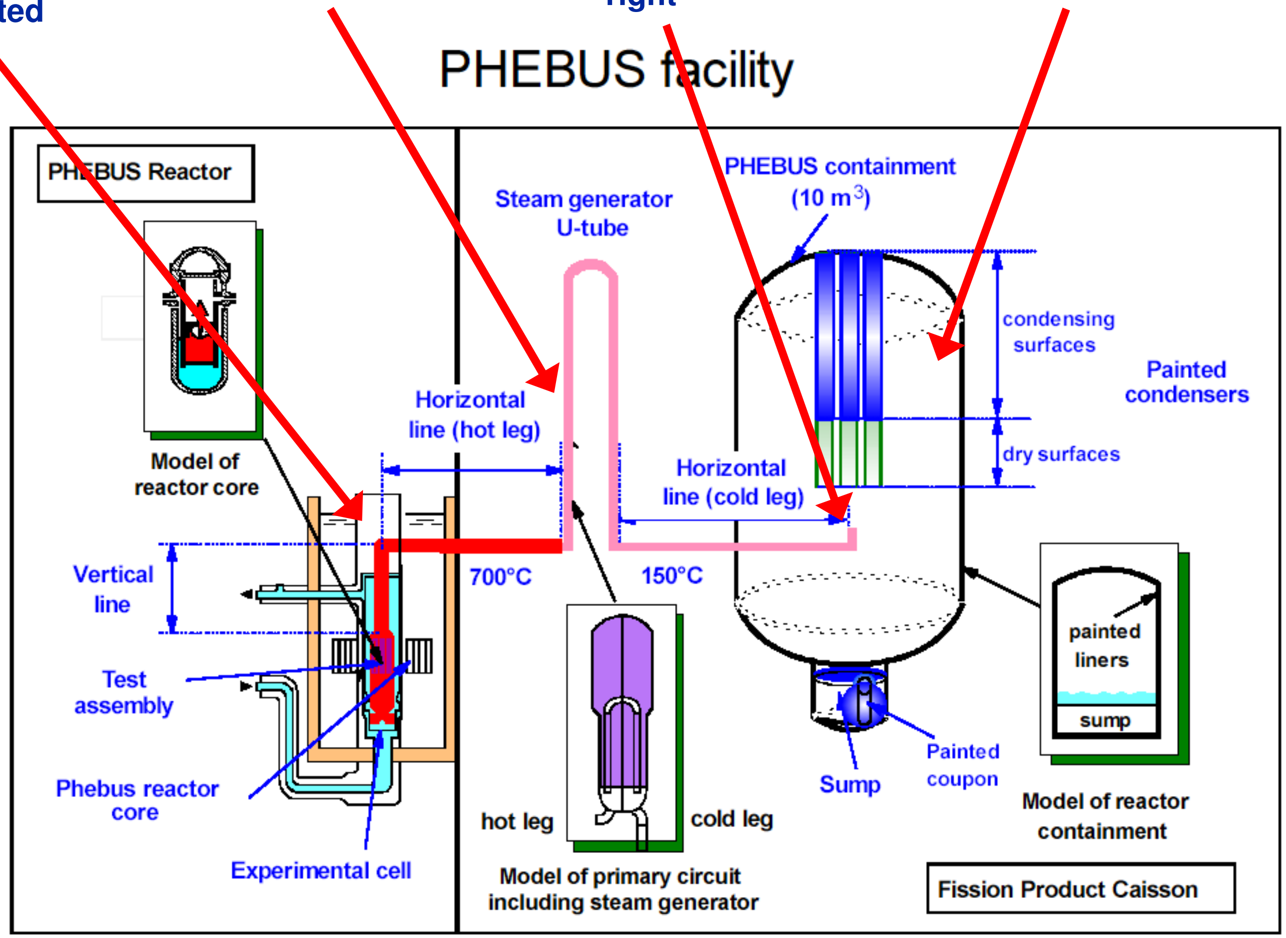
The Phebus Experiment Facility

Plenum and Hot Leg Deposits often under predicted

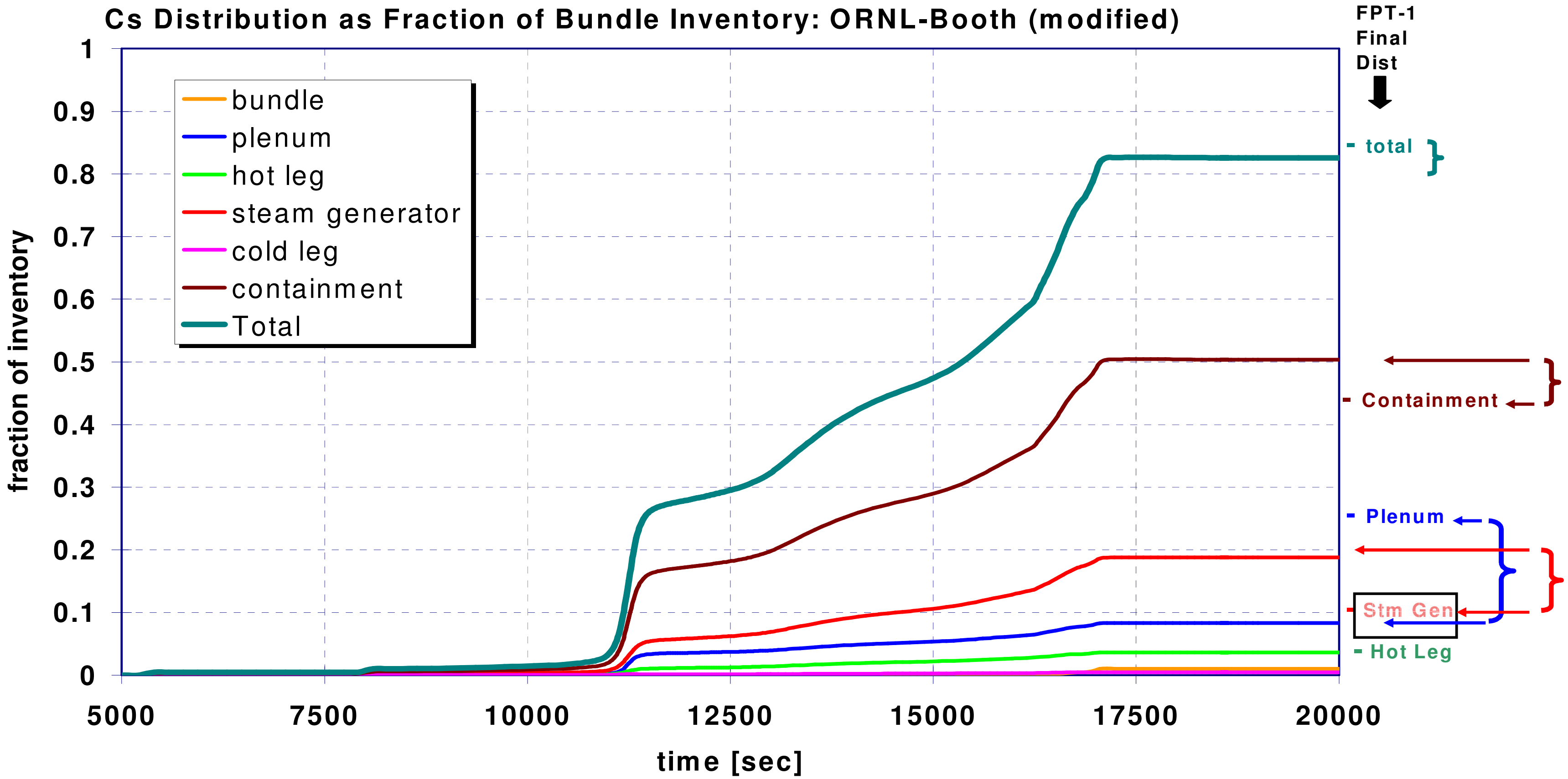
Steam Generator Deposits often over predicted

Fission Product Transported to Containment about right

Containment Aerosol Depletion mainly by Settling and diffusiophoresis

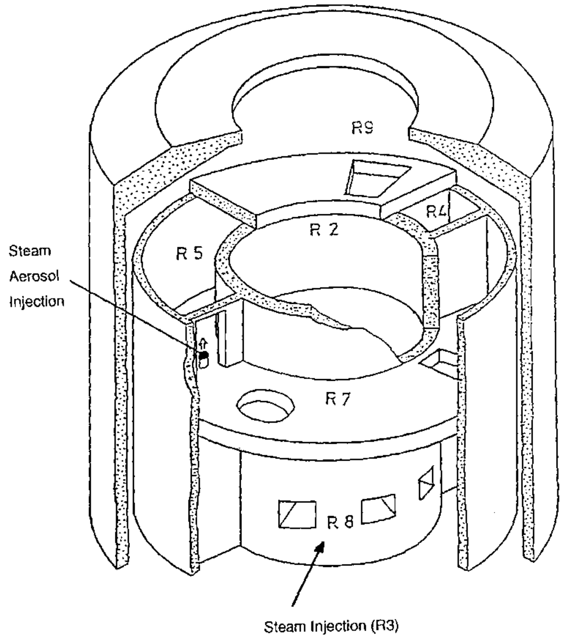


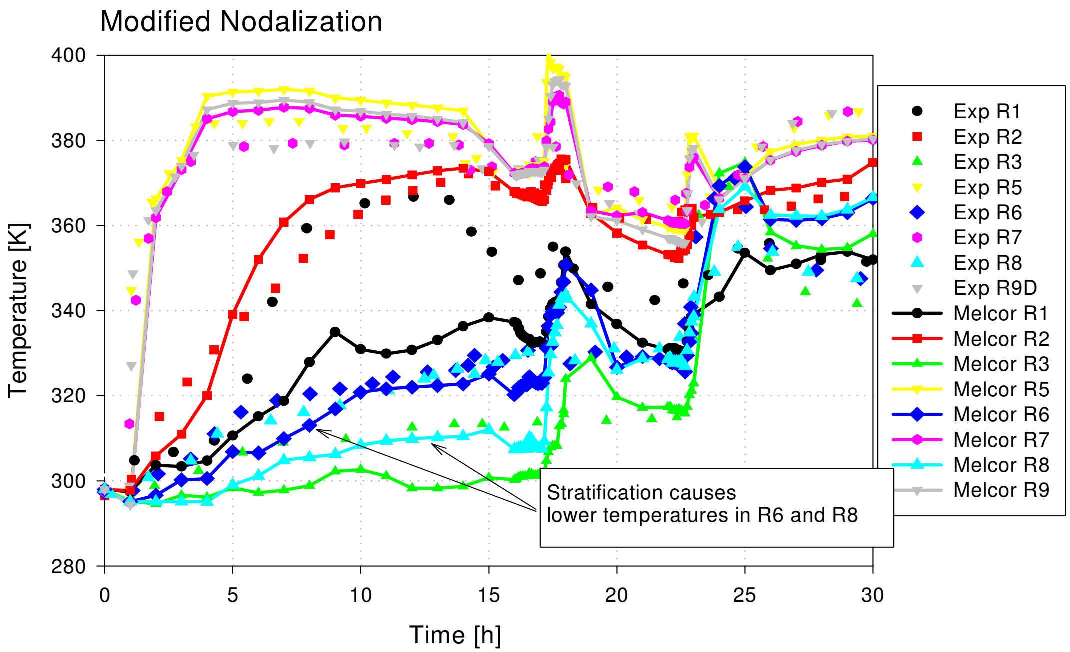
FPT-1 Deposition using ORNL-Booth Release Model



- Cs release from fuel slightly improved
- Overall transport to containment remains about right
- Retention in plenum and hot leg much improved
- Deposition in steam generator also improved

VANAM-M3 Results Comparison





Summary

- Fission product release models updated to reflect current knowledge
  - Volatility of Cs, Mo, Ru adjusted: FPT-1 basis
  - Good comparison to small scale tests
- Changes to release models improved deposition characteristics in FPT-1
- New data emerging from French VERDON tests provide additional source of new information
- Source term predictive technology on fairly sound footing
  - Chemistry and speciation effects for Ba-class more difficult to capture
- Source Term Estimation Technology on pretty good footing overall