P B M R

Radioactivity Releases From PBMR Fuel

Stanley Ritterbusch

Presentation Contents

- **Overview of German experience**
  - Manufacturing and testing experience
  - Comparison of PBMR operating conditions to German data
  - Analysis of German data applicable to PBMR
  - Fuel failure fraction vs. temperature correlation
- **Method of predicting releases of radioactive fission products from the fuel for an accident**
  - Fuel burn-up accrued during normal operation
  - Fuel temperature during transients -- failure fraction
  - Fission product release from fuel spheres

German Experience Overview

- **Manufacturing**
- **Material test reactors**
  - Phase 1 – irradiation and heat-up tests that would be applicable to a variety of reactor designs.
  - Phase 2 – irradiation tests aimed at the HTR-Modul reactor design.
- **AVR test reactor**
  - Fuel design: GLE 4/2
  - Irradiation under in-reactor conditions
  - Accident simulation heat-up

AVR (1967-88)
15 MWe

Overview of Sources of Release Data

- **Releases from PBMR fuel include contributions from**
  - Manufacturing deficiencies
  - Normal operation irradiation
  - Heat-up tests (simulating transients and accidents)

Manufacturing Experience

- **Post-1985 manufacturing –fuel design and manufacturing process was well-established**
- **Burn-leach tests on 528,200 fresh-fuel coated particles measured the quantity of fissionable isotopes not within intact particles**
  - Detects contamination and defective particles
  - Converted to equivalent "failed" particles
- **Results:**
  - Six equivalent failed particles
  - Nominal, calculated failure fraction: 1x10-5
  - 95% one-sided upper limit failure fraction: 3x10-5

German Test Envelope – Normal Operation

Phase	Temperature (^{o}C)	Burn-up (%FIMA)	Fast Neutron Dose E>0.1 MeV (x 10^{25} m^{-2})	Duration (EFPD)
1	880/1320	7.2/15.3	0.1/8.0	232/682
2	903/1140	7.81/10.88	3.2/5.9	565/634

Phase 1: 211,936 coated particles

Phase 2: 145,320 coated particles

Total: 357,256 coated particles
simulating normal operation irradiation

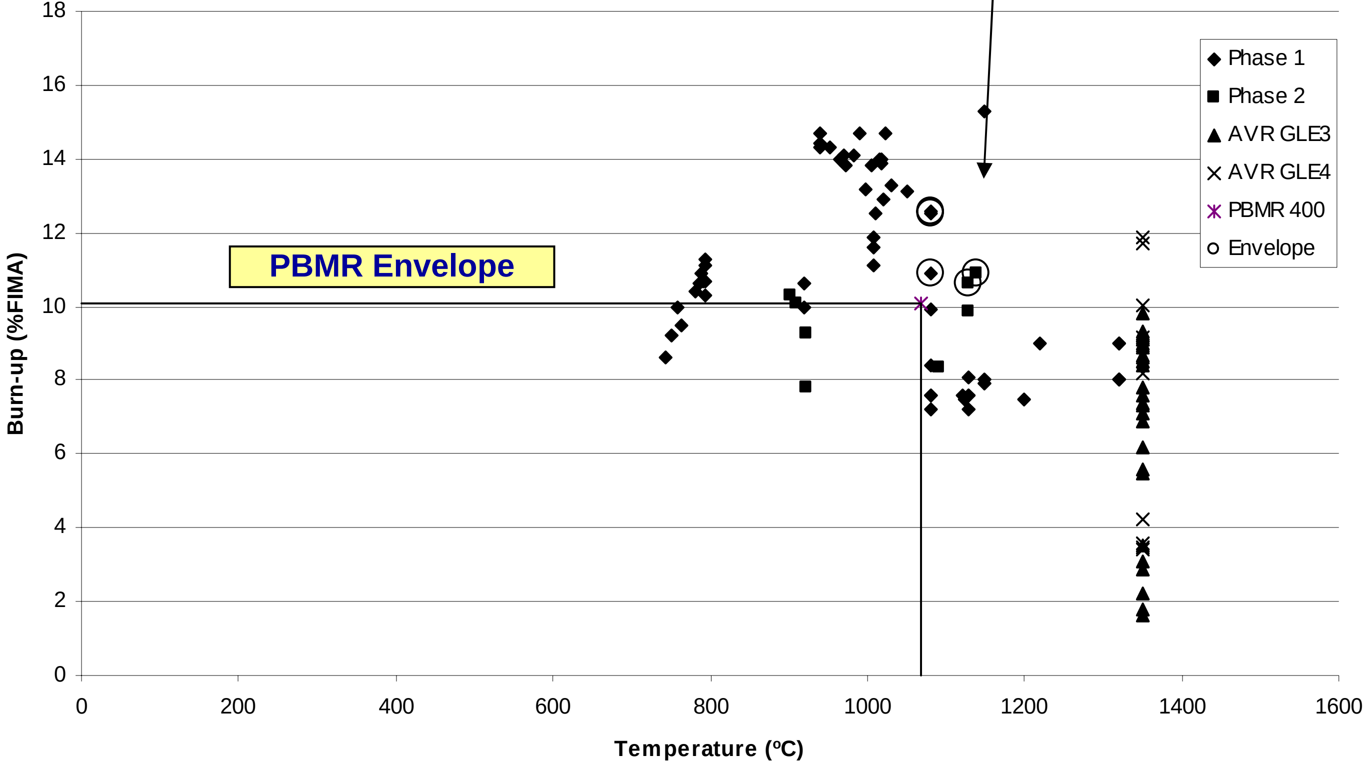
PBMR Nominal Operation Envelope

- **Temperature 1068ºC**
- **Burn-up 10.1% FIMA (maximum)**
- **Fast Neutron Dose 2.72 x 1021 cm-2**
- **Fuel Sphere Power 2.76 kW**

Data may change slightly as analyses are finalized.

Operating Envelope Comparison

Circled data envelope PBMR conditions simultaneously.



Empirical Correlation

- **Fuel failure fraction vs. temperature**
- **Full range of temperatures:**
  - Normal operation (800ºC – 1200ºC)
  - Transients and accidents (1200ºC – 1800ºC)
- **The number of “failed” particles is not counted/ measured directly during a test**
  - Number of “failed” coated particles is deduced from the release-to-birth ratio observed for a nuclide during tests
- **Correlation covers releases during**
  - Normal operation irradiation
  - Transient and accident heat-ups

Sources of Radioactivity Releases

- **Normal operation**
  - Fission product release from coated particles damaged during manufacture
  - Fission reactions in enriched uranium contamination on surface of OPyC layer
  - Fission reactions in trace uranium and thorium contamination in natural graphite matrix material
  - Migration of fission products through coated particle layers

Sources of Radioactivity Releases …

- **Transients and accident heat-ups**
    - Fission product release from coated particles damaged during manufacture
    - Fission product release from coated particles that fail (e.g., opening of a crack) due to higher temperatures
    - Migration of fission products through coated particle layers due to higher temperatures

German Irradiation Data Representative of PBMR Conditions

Test	Sample Number	Irradiation Time (efpd)	Centre Temperature (°C)	Burn-up (%FIMA)	Fast Neutron Dose E>0.1 MeV (x 10^{25} m^{-2})	Number of Coated Particles
HFR-P4	3	351	1010-1082	9.9-14.7	5.5-8.0	19 572
HFR-K3	4	359	1220	9.0	4.9	16 400
HFR-K6	2		1130	10.64	4.6	14 580
	3		1140	10.88	4.8	14 580
	4		1130	9.89	4.5	14 580
Total Number of Coated Particles in selected MTR Tests						**79712**

No failures observed during irradiation

Prediction of Normal Operation "Failures"

- **One-sided, binomial statistical analysis performed for "no observed failures"**

Confidence Level	**Failure Fraction**
50%	8.70×10^{-6}
95%	3.76×10^{-5}

- **Core contains a mix of new and irradiated fuel**
- **Therefore, failure fraction for core-average burn-up is taken conservatively as 50% of that for the fully irradiated fuel spheres**

Total Failure Fraction for Normal Operation

- **Total is combination of “failures” due to manufacturing and irradiation.**

Confidence Level	Failure Fraction Due to Manufacturing Deficiencies	Core Average Failure Fraction Due to Irradiation	Total Failure Fraction During Irradiation
Nominal	1.0E-05	4.35E-06	1.44E-05
95%	3.0E-05	1.88E-05	4.88E-05

50% of values on previous slide

Design Failure Fraction Specification for Normal Operations

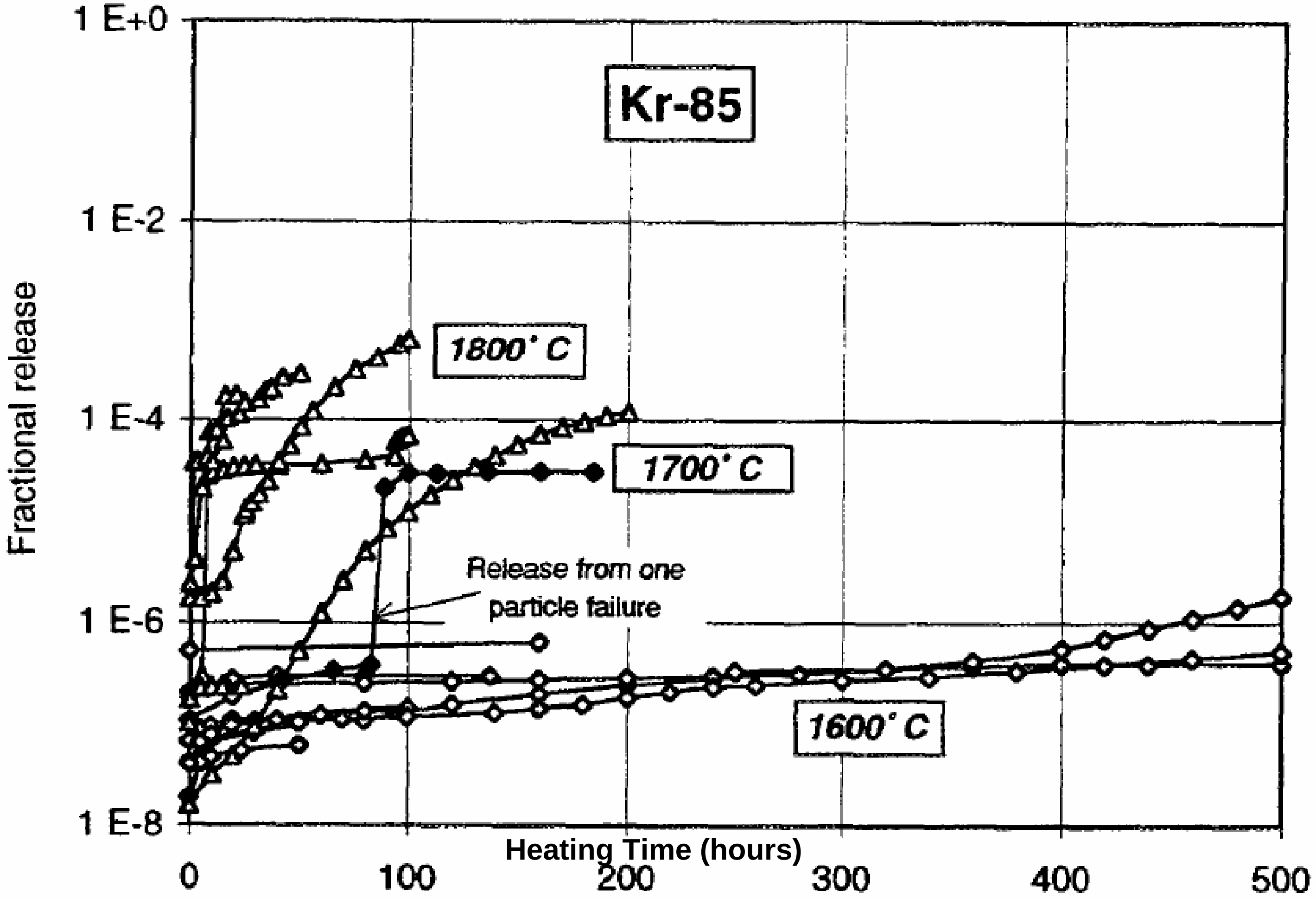
- **For conservatism, the German fuel specification imposed a “free” uranium fraction of 6×10^{-5} as a design limit on fuel sphere manufacturing lots. The same lot limit is used by PBMR.**
- **For the “design” failure fraction, the predicted core-average failure fraction was based on a conservative 97.5% confidence level for fully irradiated fuel.**

Confidence Level	Failure Fraction Due to Irradiation of Manufacturing Deficiencies	Average Core Failure Fraction Due to Irradiation	Total Failure Fraction During Irradiation
Design	**6.0E-05**	**4.63E-05**	**1.06E-04**

Failures During Transients and Accidents

- **Total failure fraction is sum of components from**
  - Normal operation
  - Transient and accident heat-up
- **Heat-up “failures” are based on German data**
  - Releases occur over many hours
  - Release rate depends on the test temperature

Time-at-Temperature Coated Particle Performance for Different Heat-up Tests



German Heat-up Data Used for PBMR

Phase	Temperature (^oC)	Burn-up (%FIMA)	Fast Neutron Dose E>0.1 MeV (x 10^{25} m^{-2})
MTR	794/1120	7.6/13.9	0.2/7.5
AVR	Cycles<1400	1.6/9.8	0.4/2.9

Irradiated Particles Subsequently Heated to Simulate DBA Heat-up:

MTRs: 42,586 particles

AVR: 213,200 particles

Total: 255,786 particles

Summary of Heat-up Test Results

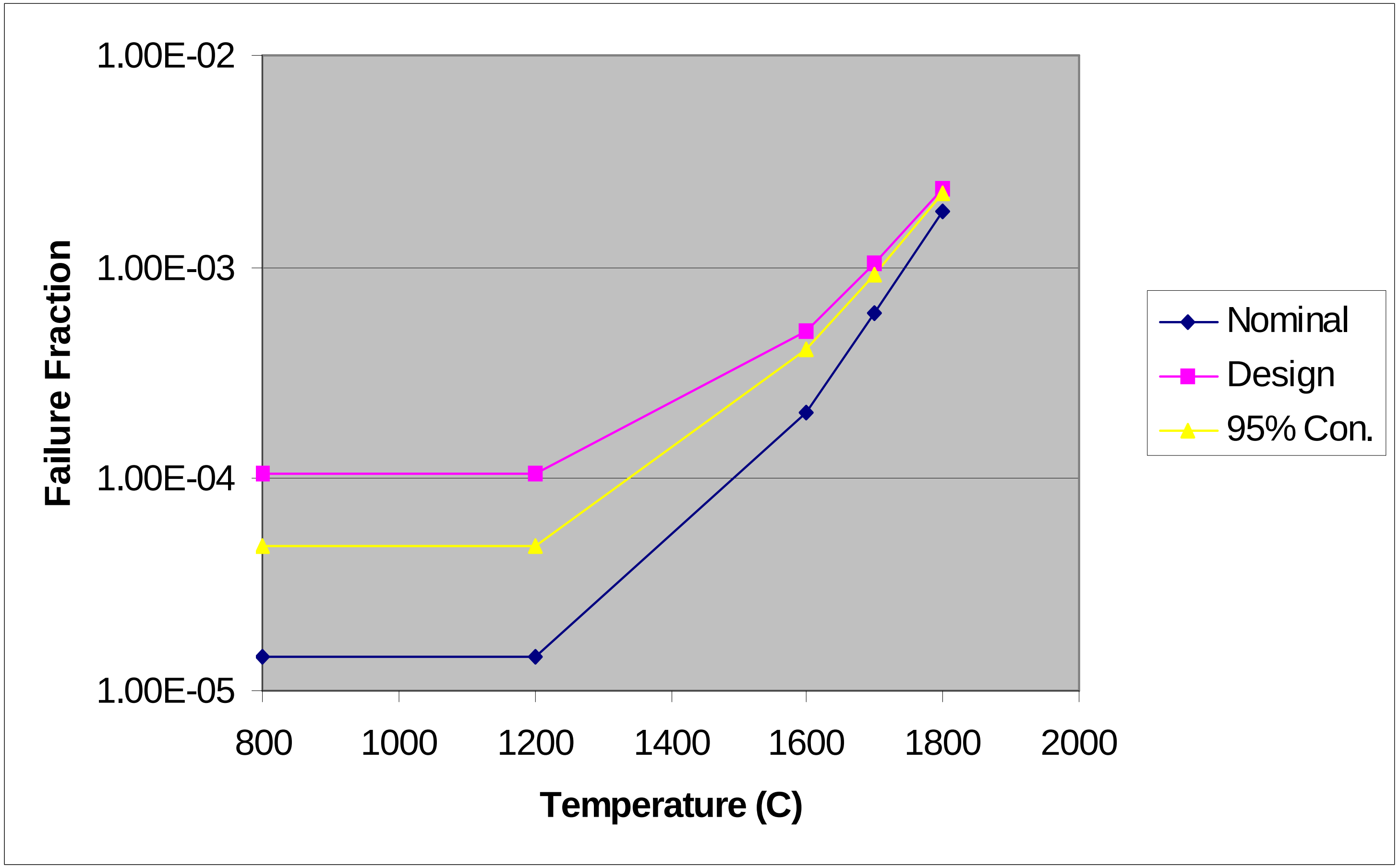
Heating Temperature (°C)	Number of Coated Particles	Number of Failed Coated Particles	Expected Failure Fraction (Average)	95% One-sided Upper Confidence Limit	Design Limit
1 600	86 893	7	8.06×10^{-5}	1.51×10^{-4}	1.66×10^{-4}
1 700	36 062	20	5.55×10^{-4}	8.06×10^{-4}	8.56×10^{-4}
1 800	132 831	108	8.13×10^{-4}	9.54×10^{-4}	9.82×10^{-4}

- **Failure fractions at each confidence level were assumed to be an exponential function of temperature**
  - Based on the statistical distribution of material properties as a function of load on the SiC coating layer
- **The above data were fitted to an exponential correlation**
  - A factor of 2 was added to ensure that the resulting correlation would bound the above data

Fitted Correlation

Temperature (^oC)	Nominal Failure Fraction	95% Confidence Failure Fraction	Design Failure Fraction
800	1.44×10^{-5}	4.88×10^{-5}	1.06×10^{-4}
1200	1.44×10^{-5}	4.88×10^{-5}	1.06×10^{-4}
1600	2.08×10^{-4}	4.11×10^{-4}	5.04×10^{-4}
1700	6.12×10^{-4}	9.31×10^{-4}	1.04×10^{-3}
1800	1.85×10^{-3}	2.21×10^{-3}	2.33×10^{-3}

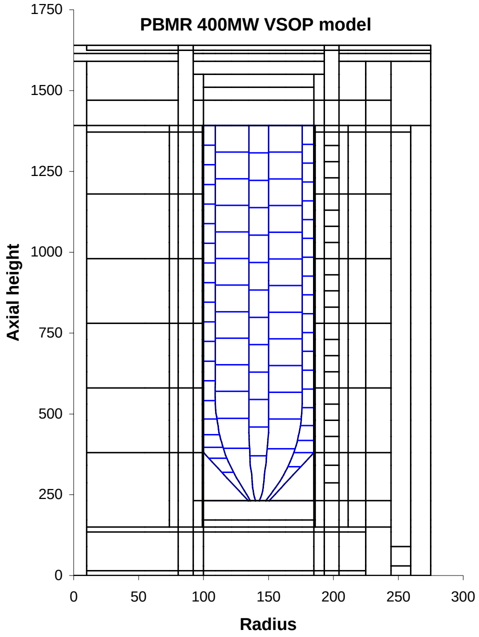
Representative Empirical Correlation of Failure Fraction vs. Temperature



Overview of Use of Release of Fission Products From the Fuel in Accident Analysis

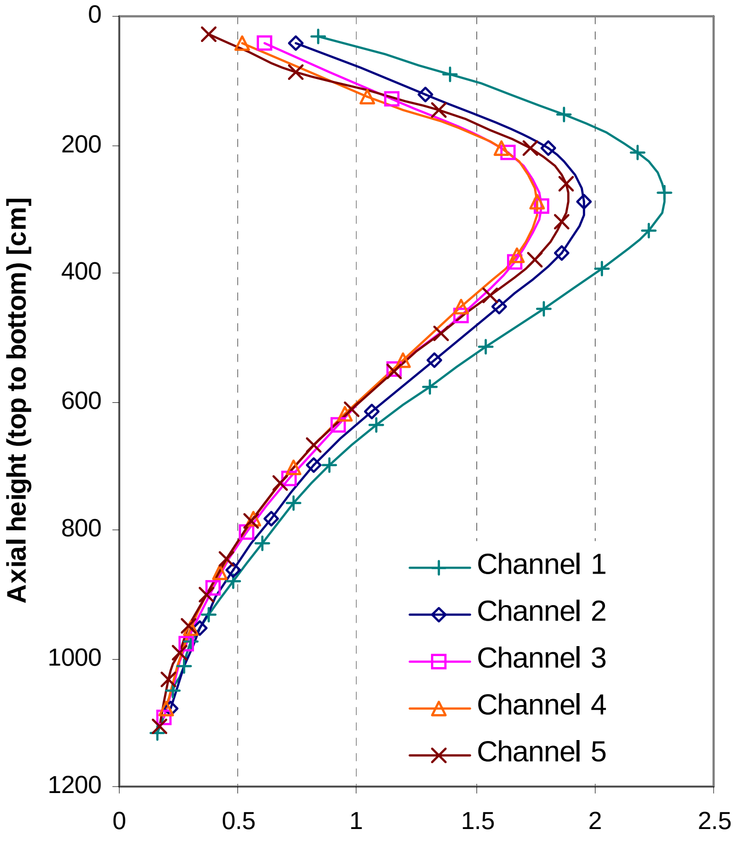
Release Process Overview

- Fission product content of coated particles is based on burn-up accrued during normal operation
  - Flow of spheres through core
  - Steady-state fuel power, burn-up, and temperatures
  - Core divided into radial channels and vertical layers

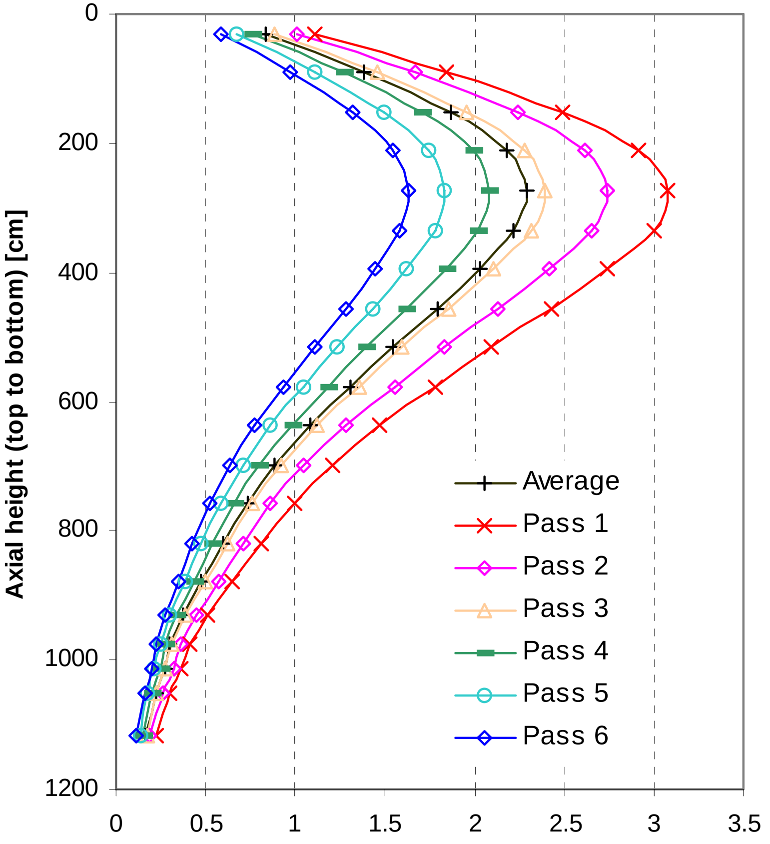


- TINTE used to predict fuel temperatures during transients
- **Temperatures used with the "failure fraction vs. temperature" correlation to predict quantity of failed particles throughout the core**
- **Mechanistic code is used to predict releases from the fuel spheres**

Typical Axial Power Profiles (Normal Operations)



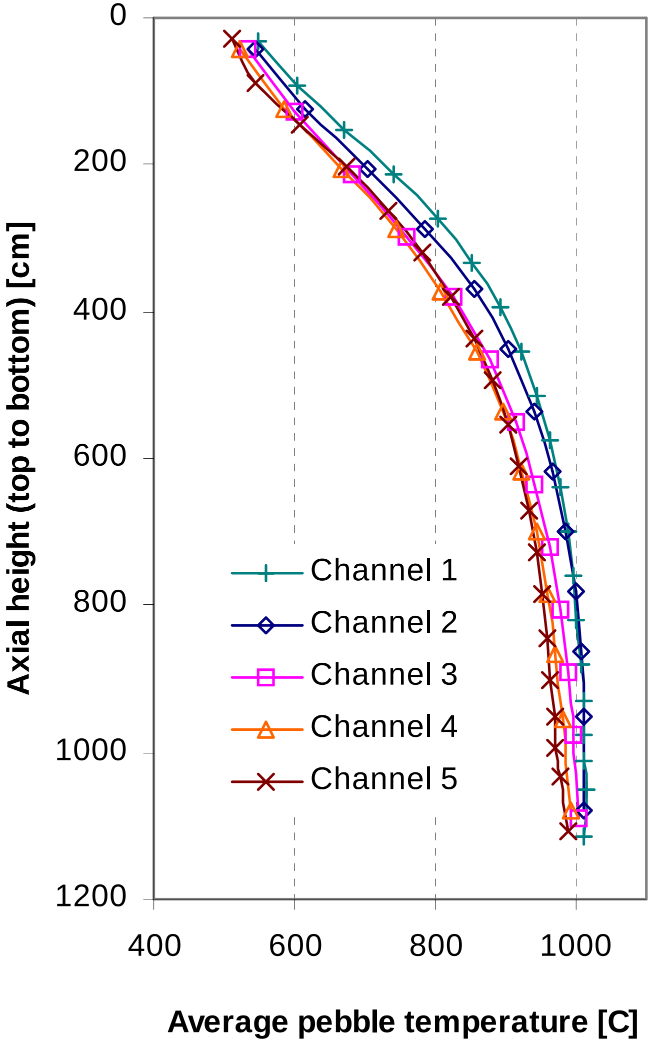
Average power (kW) per sphere for axial position

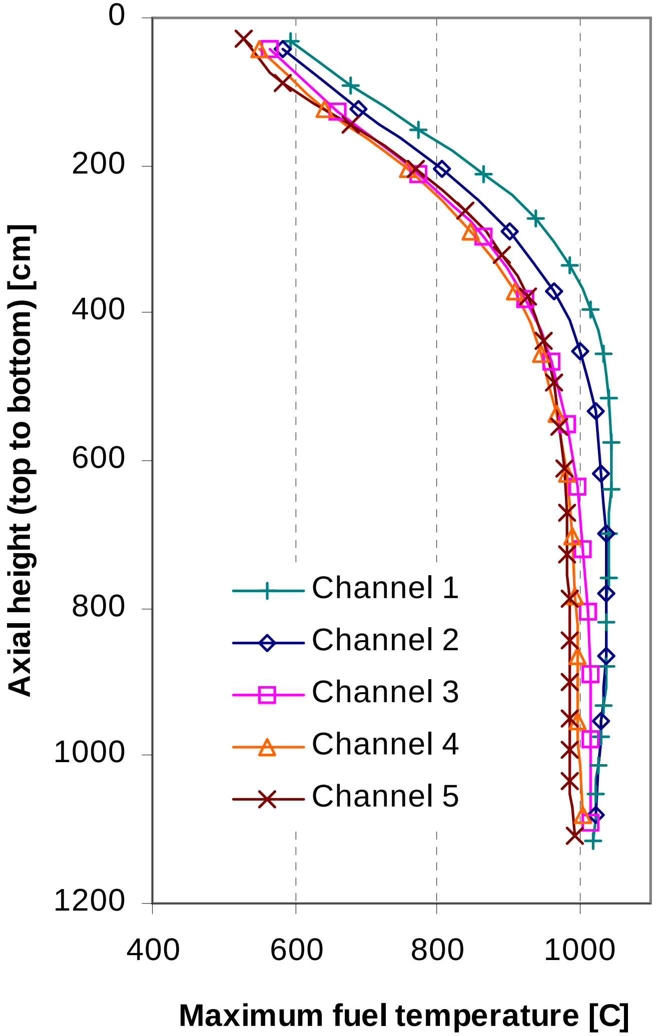


Channel 1- Average power (kW) per sphere for axial position

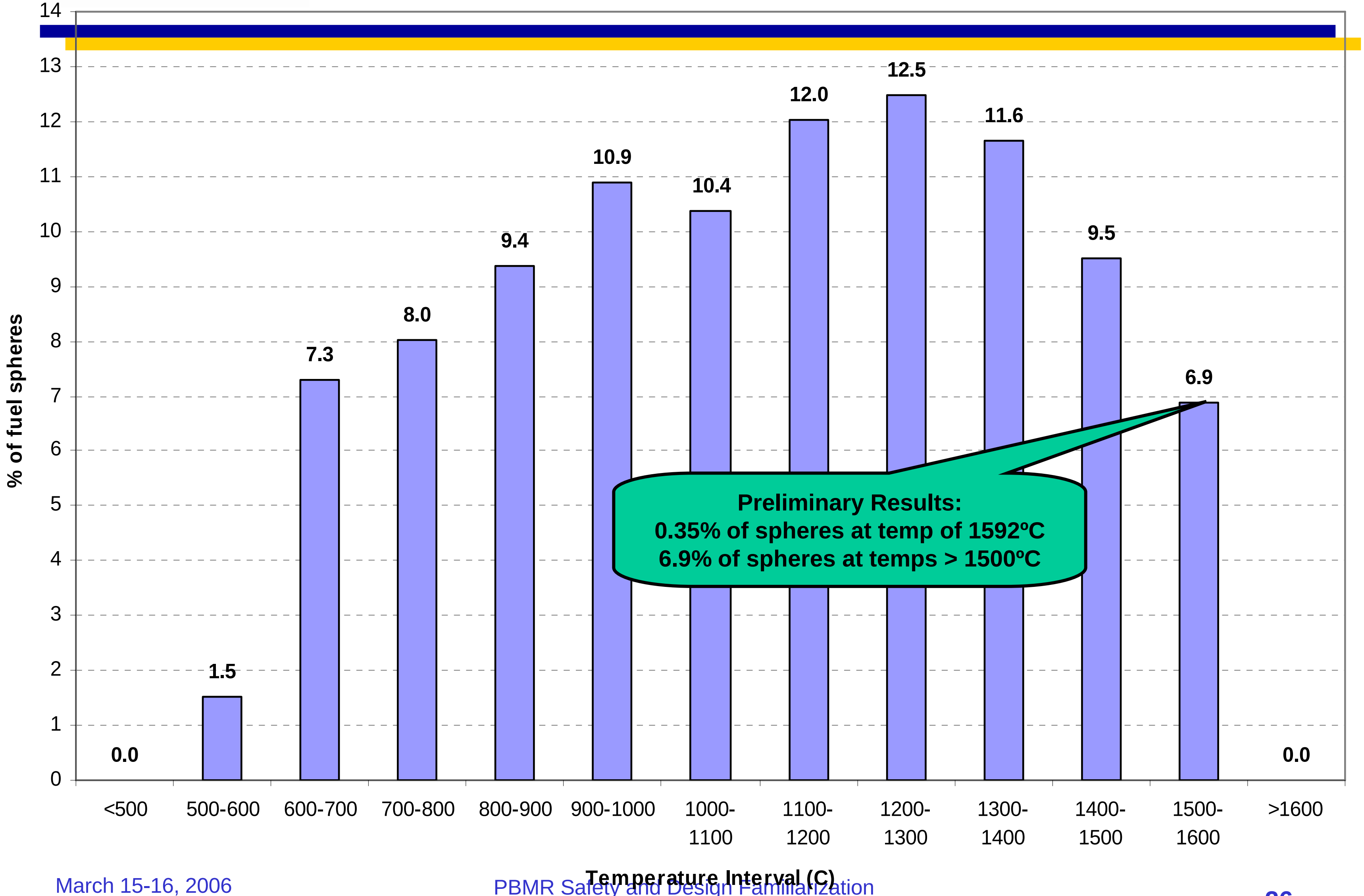
Core average: 0.88 kW/sphere

Typical Fuel Temperature Distributions (Normal Operations)





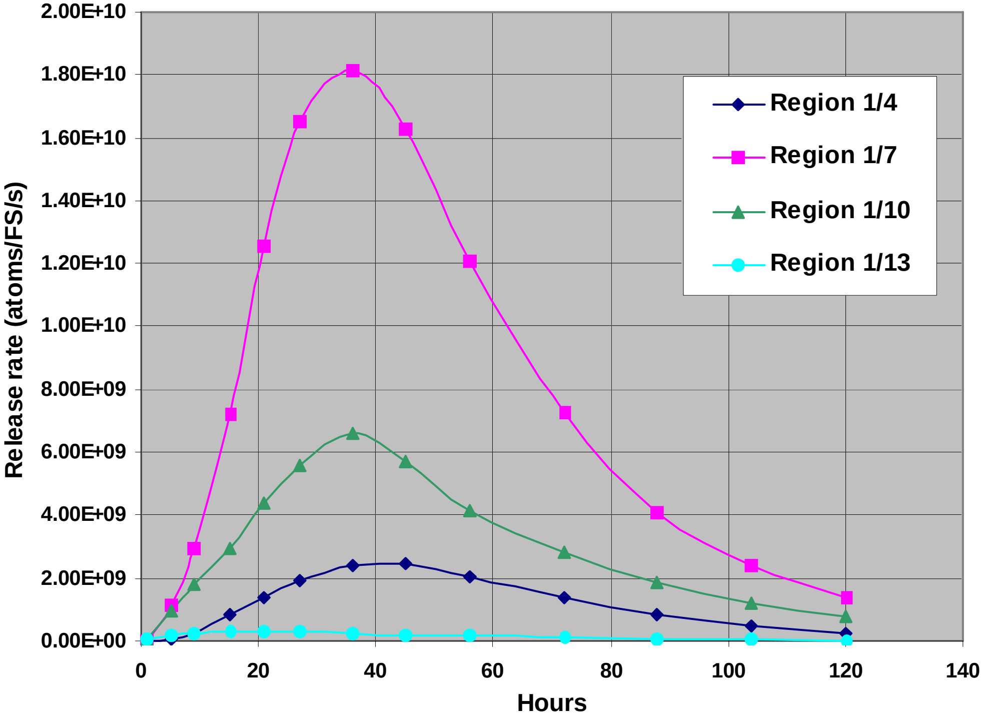
Typical DLOFC Fuel Temperature Histogram at Time of Peak Fuel Temperature



Preliminary Results:
0.35% of spheres at temp of 1592ºC
6.9% of spheres at temps > 1500ºC

Activity Release From Fuel Spheres

- **Inputs: normal operation burn-up, transient fuel temperatures, and failure-fraction correlation**
- **Mechanistic code is used to predict the number of failed particles over the core and the diffusion of fission products to the surface of the fuel spheres**



Cs137 – higher release rate only in limited fraction of core volume

Summary – Activity Release Method

- **Failure fraction as a function of temperature based on manufacturing failures, normal operation irradiation and heat-up test data**
- **Core-wide fuel temperatures during transients used to calculate the fraction of equivalent failed particles in a sphere for the range of burn-ups in the core**
- **Mechanistic model used to predict fission product releases from the spheres**