XA04C1702

JAERI / ORNL Tests & Analyses on Transient Heating of U_3Si_2-Al Miniplates in Nuclear Safety Research Reactor

by

T. Fuketa* and R. P. Taleyarkhan**
(*)- NSRR Laboratory, JAERI, Tokai, Japan
(**) - Engineering Technology Division, ORNL, USA

May 24-25, 1995

Prepared for Presentation at IGORR-IV, Gatlinburg, TN, USA

This Presentation Will Highlight

- Overview of JAERI-ORNL collaborative work and how it fits in with ANS Severe Accident Program Plan for FCI issue closure
- NSRR tests (with ANS miniplates) during 1993-94 & beyond
- Modeling and analysis framework for:

  - Thermal-hydraulic response
  - Material breakup and dispersion

- Key results of analyses and experiments

Full Papers to be presented at:

1) 1995 Natl. Heat Transfer Conference, Portland, Oregon, USA
2) Nuclear Reactor Thermal-Hydraulics Conf., NURETH-7, NY, USA

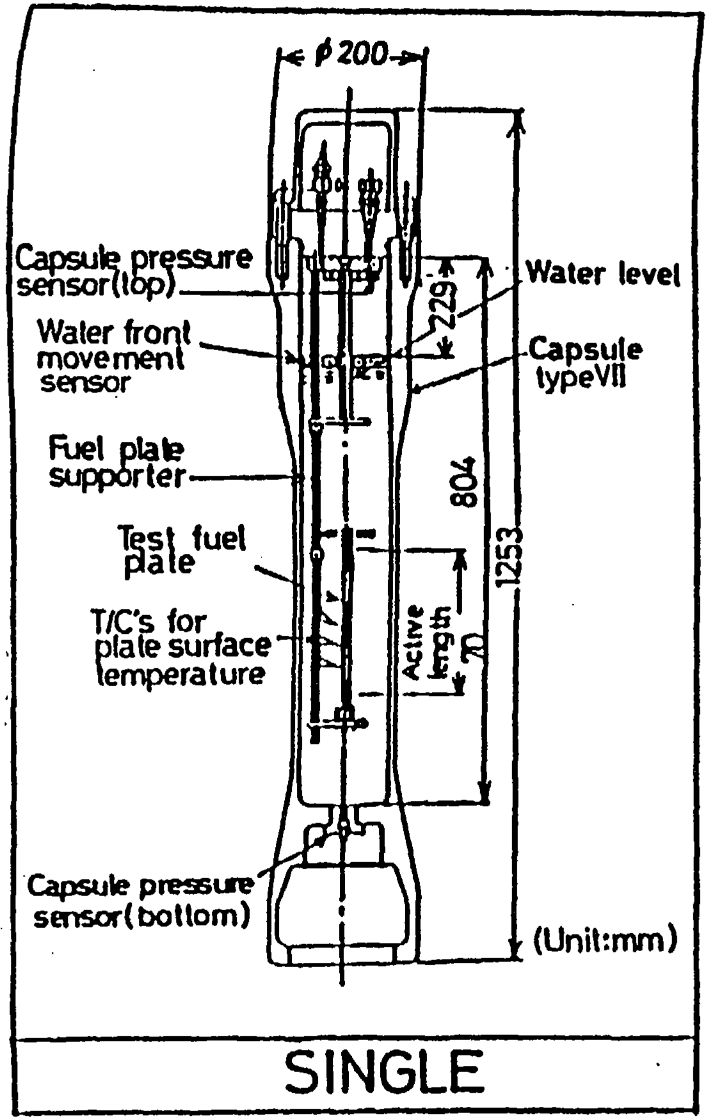


Fig. 2.4 NSRR irradiation capsule type VII prepared for the test of silicide plate-type fuel in experiment 508 series

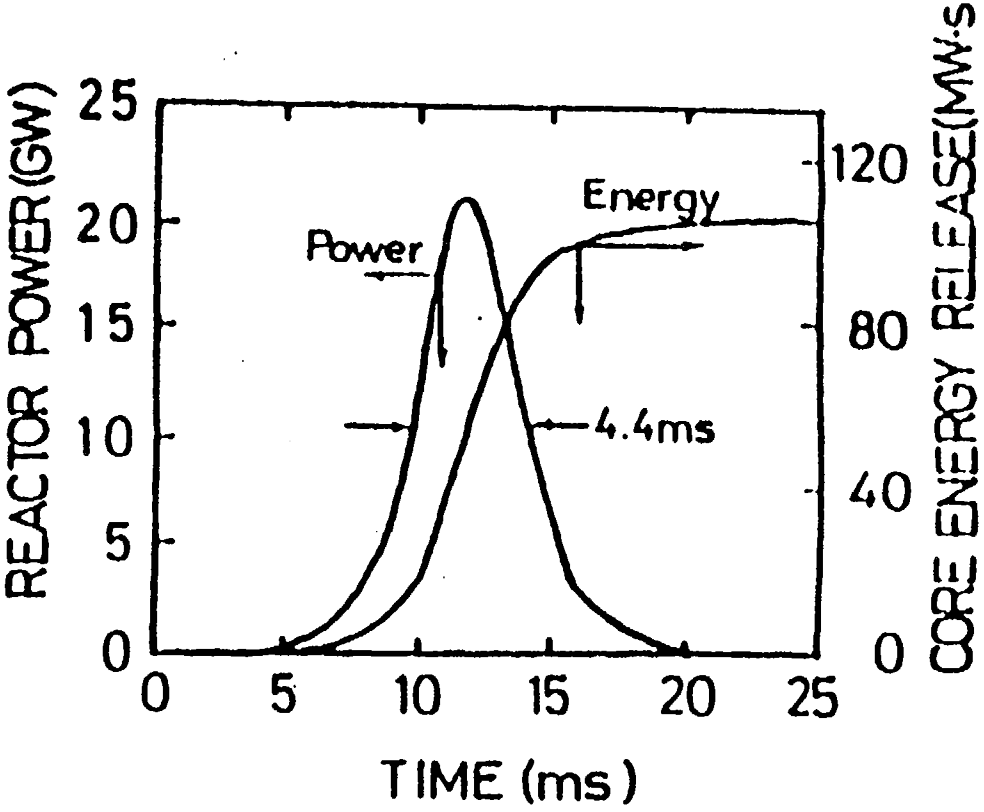


Fig. 2.5 Transient reactor power and core energy release attained in pulsing operation NSRR with $4.67 reactivity insertion

JAERI-ORNL TESTS IN NSRR

o A FEW (KEY) QUESTIONS CONCERNING ISSUE CLOSURE

- What is the likely mechanical behavior of plates during rapid heatup?
- What is the impact of fuel homogeneity on damage thresholds ?
- What are the kinetics of U_3Si_2-Al and Al-H_2O ignition during rapid heatup?
- What are the triggerability and onset requirements for material dispersion ?
- What are the energetics of a resulting (if any) energetic FCI "for ANS fuel" ?

****- How does fuel burnup affect the above outcomes ? ****

o NSRR TESTING & MODELING WORK CAN PROVIDE VALUABLE INFORMATION (esp. for closure of FCI-related issues)

- Plate cracking, bowing and steam explosion onset thresholds
- Impacts of fuel homogeneity and preirradiation on damage thresholds
- Degree and onset of aluminum ignition can be quantified
- Degree of "transient" onset and degree of U_3Si_2-Al exothermic reactions
- Realistic thermal-to-mechanical energy conversion estimates

** This information is obtained with nuclear heating, but, in the absence of external triggers and propagation - aspects to be looked at via out-of-pile testing and appropriate modeling **

Test Summary 1993–1994

Test #	Configuration	Fuel Homogeneity	NSRR Core Energy Release (MJ)	Max. Cladding Surface Temp. (°C)	Post-test Fuel Plate
518-1	Single	Inadequate	27.0	410	Mechanical failure
518-2			40.3	700	Clad melting
518-3		Improved	27.6	N/A	No failure
518-4			21.3	210	No failure
518-5			42.7	600	
518-6	with two dummy plates		27.3	320	
518-7			43.1	610	

OVERVIEW OF MODELING FRAMEWORK

- o HEAT TRANSFER (--> Material response, dispersion and ignition)
  - 3-D HEATING model developed (heatup, melting and freezing)
  - Impact of thermocouples quantified
  - Surface boiling heat transfer correlations for transient heatup
  - Estimates of voiding and heat transfer in enclosed geometries
- o MATERIAL BREAKUP / DISPERSION (--> explosive loads estimation)
  - Multidimensional CTH, PCTH and LS-DYNA3D models of fuel plate
  - 1-D modeling of important effects (strain induced due to thermal expansion, melting, vaporization and void / fission gas expansion)
- o NEUTRONICS (--> Integral thermal energy generated in miniplates)
  - 2-D model of NSRR, with 3-D model of miniplates using MCNP
  - 1-D deterministic neutronic calculations with XSDRNPM (cross-checking)

  *** Future efforts will investigate transient energy deposition profiles, and impact of pre-existing fission products ***

Overview of Neutronic Analysis Results

EVALUATION OF ETA (cal/g/MJ)

- Overall results of MCNP and XSDRNPM evaluations show good agreement with isotopic gamma scan data analyses (** data scatter **)

Fuel Plate	Gamma Scan*	MCNP		XSDRNPM
		Void Thickness(mm)		
		0	4	
ANS	7.71 (9.51)	7.79	7.43	8.1
JMTR	13.98 (17.30)	12.22	13.68	15.4

(*) -- ETA values defined over >> 1s and (1s) of NSRR pulse duration

Notes: 1) Temperature effects (up to 700℃) are less than 1%
2) The above values for ETA represent integral energy deposition

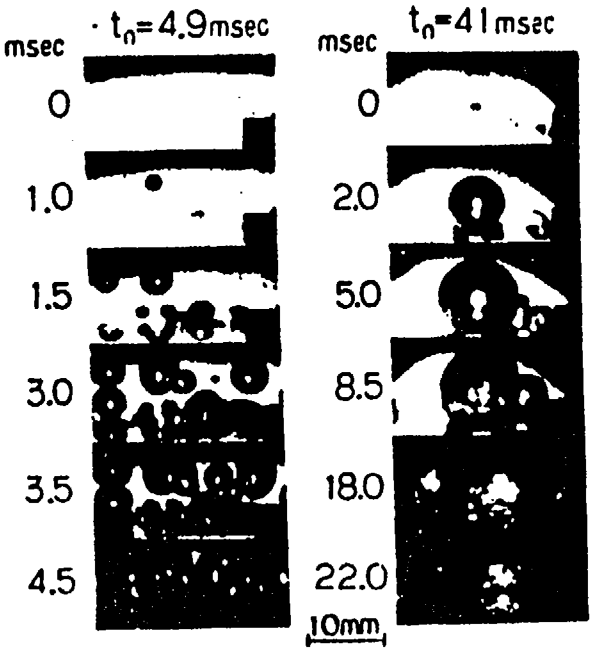


Fig.4 Dependence of bubble pattern on the period in saturated pool boiling.

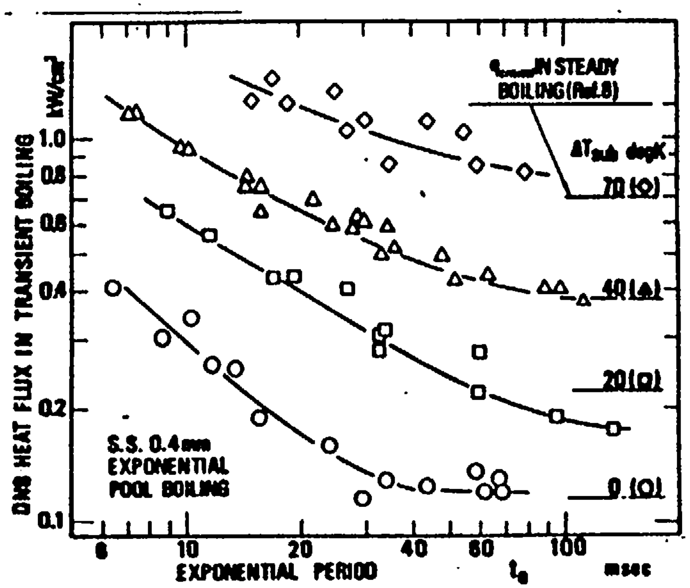
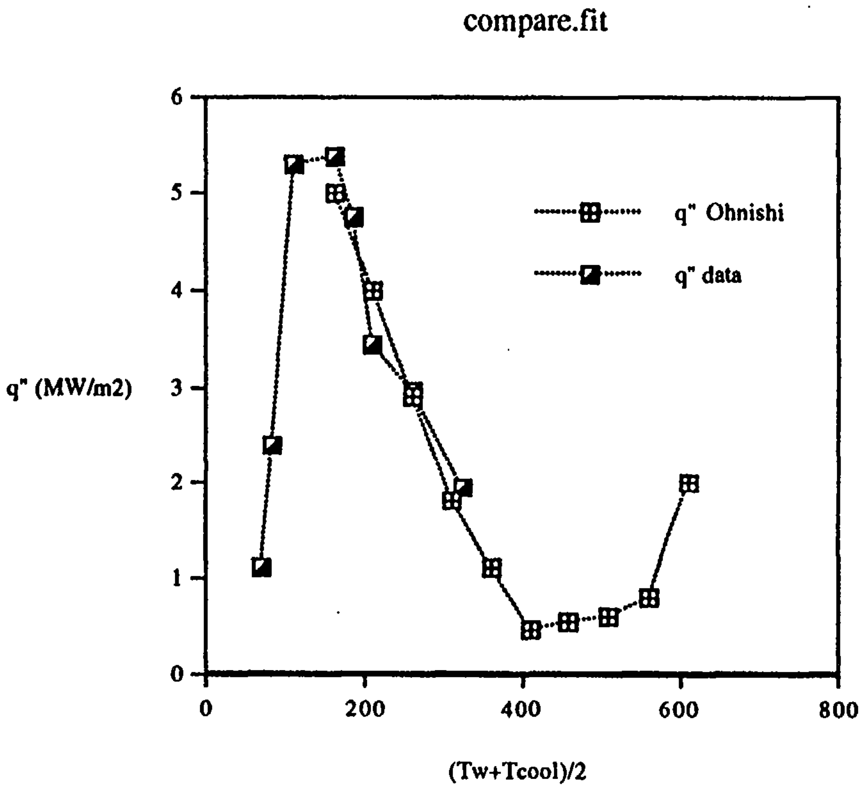
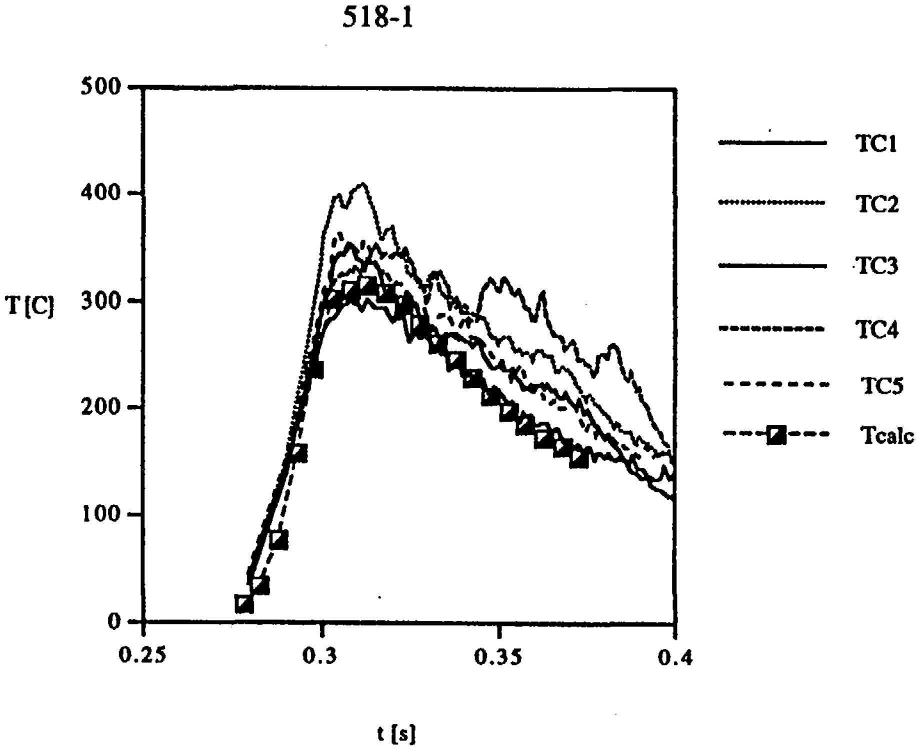


Fig.3 DNB heat flux vs. period.

HIGHLY SUBCOOLED STEADY BOILING

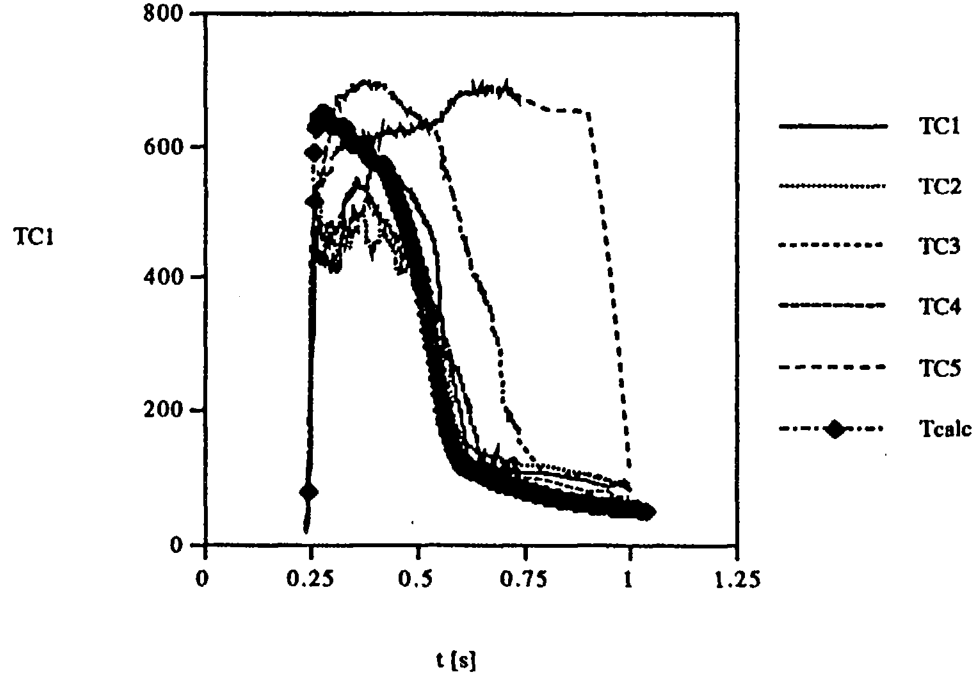


RESULTS OBTAINED FOR TEST #518-1

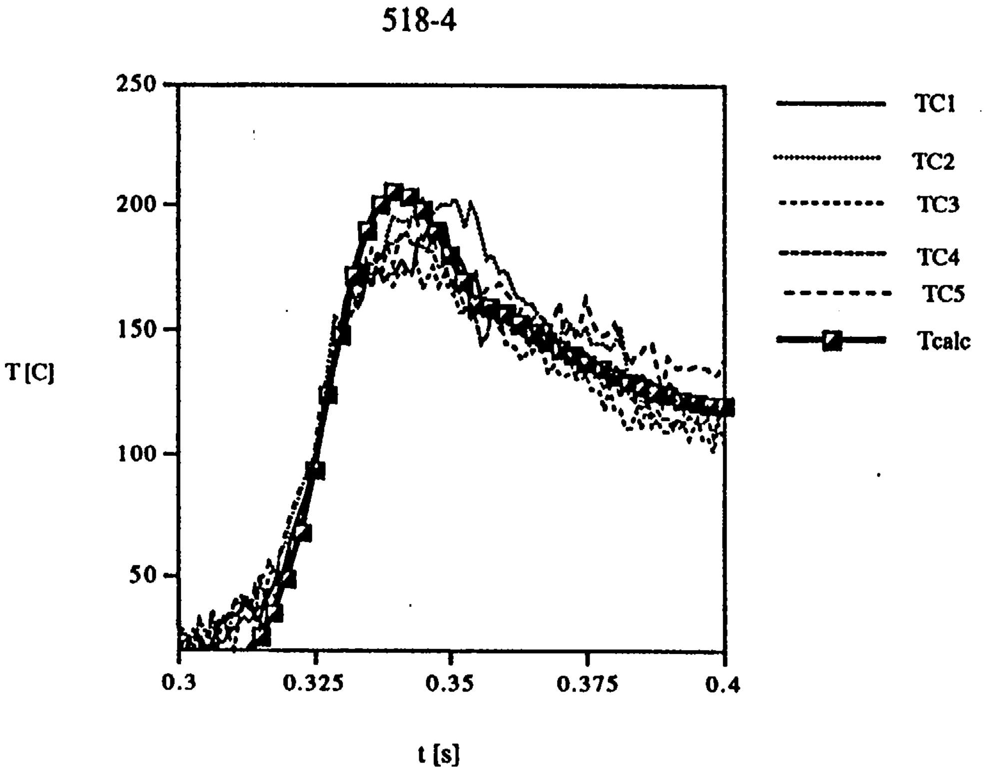


RESULTS FOR CASE 518-2

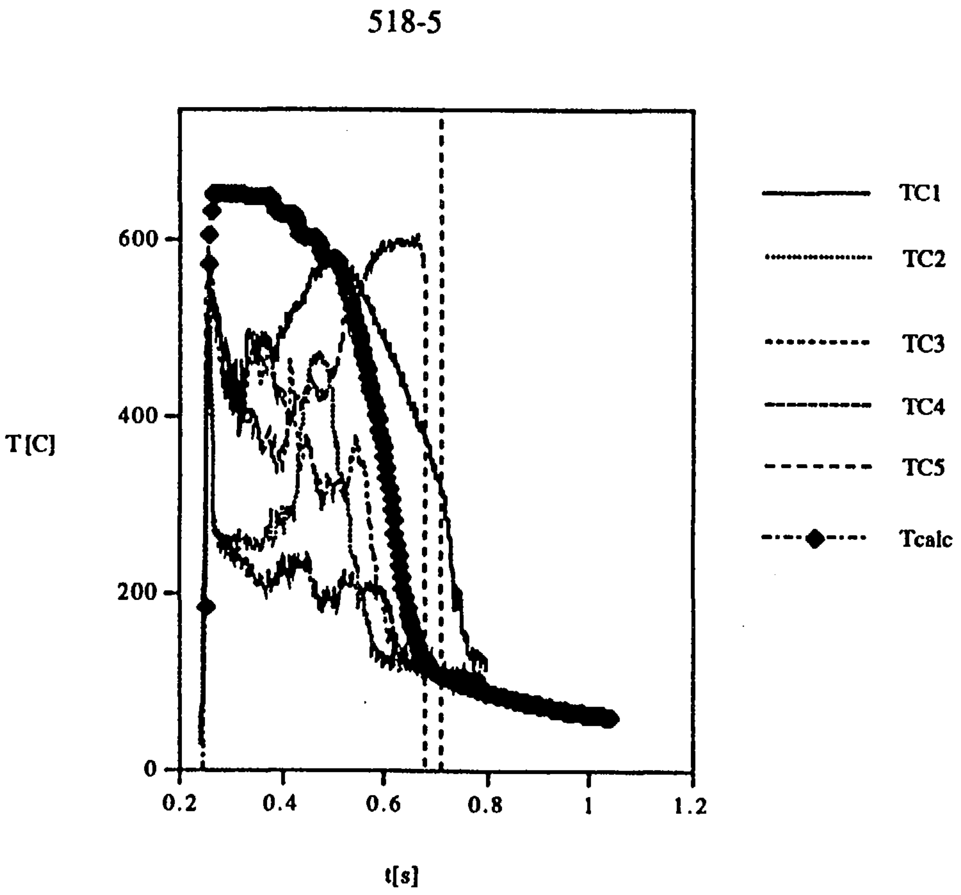
518-2.plot



RESULTS FOR CASE 518-4



RESULTS FOR CASE 518-5



Experimental data base

o TREAT EXPERIMENTS

- x **SL-1 fuel plate tests** (mass composition: 81% Al; 17% U; 2% Ni)
  - - U-Al alloy fuel; no clad; Dimensions: 5mm x 12.7 mm x 12.7 mm cutouts
- x **HFIR fuel plate tests** (mass composition: 59% Al; 41% U_3O_8)
  - - Cermet (U_3O_8) fuel; Dimensions: 25.4 mm x 12.7 mm x 1.27 mm cutouts

o NSRR EXPERIMENTS

- x **JMTR fuel plate tests** (mass composition: 23.3% Al; 76.7% U_3Si_2 --> 4.8 g/cc)
  - - Cermet (U_3Si_2) fuel; Dimensions: 125 mm x 75 mm x 1.27 mm picture frame
- x **ANS fuel plate tests** (mass composition: 63% Al; 37% U_3Si_2 ---> 1.4 g/cc)
  - - Cermet (U_3Si_2) fuel; Dimensions: 125 mm x 75 mm x 1.27 mm picture frame

Experimental data base (cont)

	TREAT Facility	JAERI Facility
Pulse width	0.3 - 1 sec	0.015 - 0.08 sec

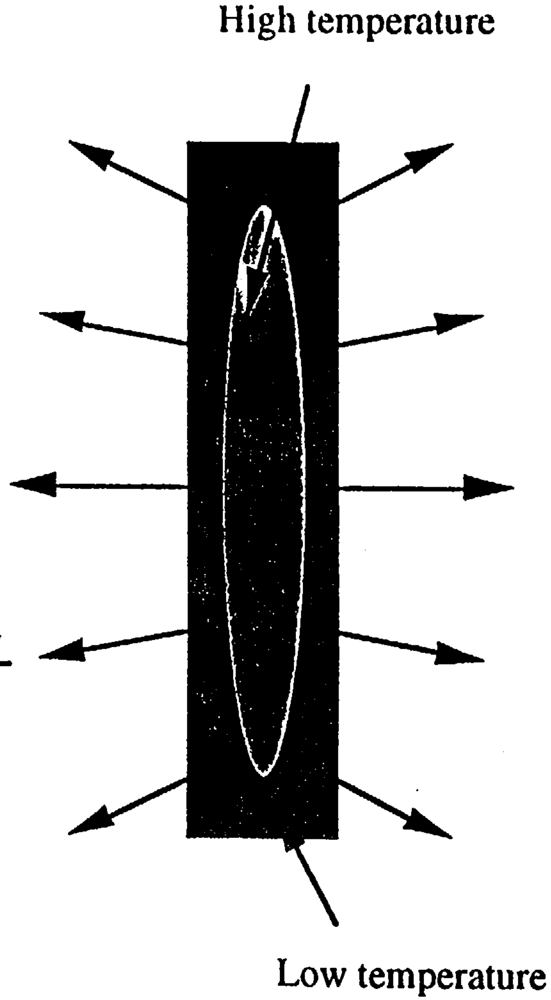
- TREAT Experiments
    - Longer heat up time allows energy to spread
    - Uniform temperature distribution
    - More energy leaves the plate
    - Able to deposit more energy
- JAERI Experiments
    - Shorter exposure time
    - Steeper temperature gradients

- JAERI experiments show that rate of energy deposition affects fuel performance

Dispersion model (cont) Mechanism for accelerating the fuel plate

<u>Dispersion</u> - break up of fuel into small particles by acceleration induced hydrodynamic breakup

- **Thermal expansion of the solid** $\alpha_s \frac{dT}{dt}$
- **Expansion of material while changing phase from solid to liquid** $\frac{\rho_l - \rho_s}{\rho_s} \frac{dx_{s-l}}{dt}$
- **Thermal expansion of material while in liquid phase.** $\alpha_L \frac{dT}{dt}$
- **Expansion of material while changing phase from liquid to vapor** $\frac{\rho_v - \rho_l}{\rho_v} \frac{dx_{l-v}}{dt}$
- **Expansion of gases trapped in the plate (f.p., gas occupying voids)** $\frac{1}{T} \frac{dT}{dt}$



Dispersion model

- **Thermally driven expansion process**
- **Transient temperature change rate and phase change rate affects the expansion process**
- **Finite difference heat transfer model with melting and vaporization was coupled with thermally induced expansion models**

$$k\frac{d^2T}{dx^2}+q'''=\rho c_p\frac{dT}{dt} \qquad T\neq T_m \,\&\, T\neq T_v \qquad k\frac{d^2T}{dx^2}+q'''=\rho h_{sf}\frac{dx_{sf}}{dt} \qquad T=T_m$$

$$k\frac{d^2T}{dx^2}+q'''=\rho h_{fg}\frac{dx_{fg}}{dt} \qquad T=T_v$$

- **Strain rate is defined as the following:**

$$SR=(1-f)\left(\alpha_s\frac{dT}{dt}+\frac{\rho_l-\rho_s}{\rho_s}\frac{dx_{s-l}}{dt}+\alpha_L\frac{dT}{dt}+\frac{\rho_v-\rho_l}{\rho_v}\frac{dx_{l-v}}{dt}\right)+f\frac{1}{T}\frac{dT}{dt}$$

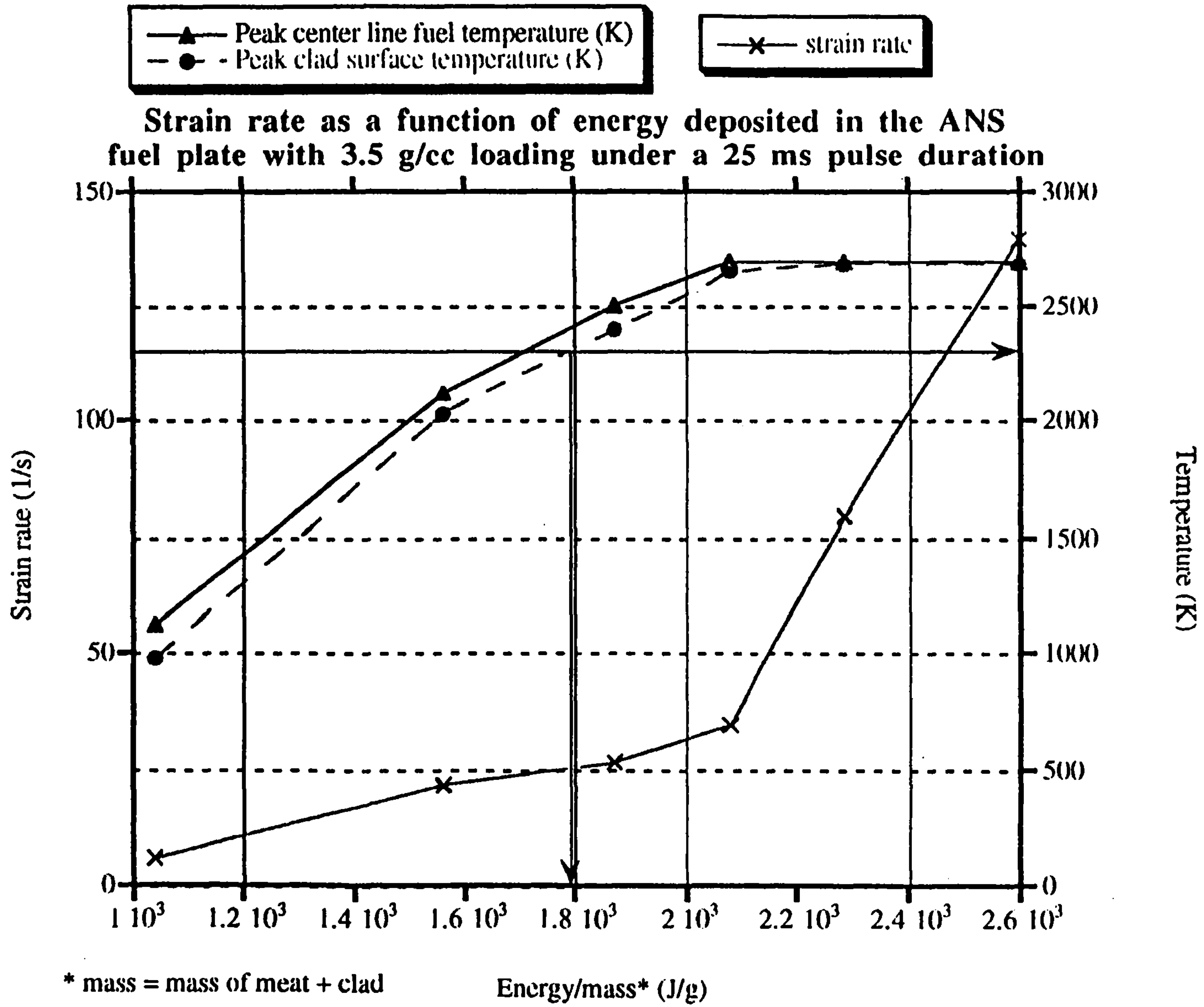
Dispersion model: sources of energy

- Heating caused by nuclear fissioning process
  Follows the shape of thermal neutron flux incident on the fuel plate.
  0.5 - 4.5 MJ/kg of fuel plate
  25 - 400 MW/kg of fuel plate

- Exothermal reaction between U3Si2 and aluminum.
  0.3 - 0.35 MJ/kg of U3Si2 depending on fuel volume fraction
  0 - 100 MW/kg depending on the temperature
  At aluminum melting temperature the reaction is slow.
  At U3Si2 melting temperature the reaction in fast.

- Chemical oxidation reaction between metal and water
  18 MJ / kg of aluminum (0.18 MW/kg - 180 MW/kg)
  - Significant oxidation was reported for tests where surface temperature exceeded melting temperature of the oxide layer
  - Two mechanisms of aluminum oxidation reaction are :
    Vapor phase burning (vapor Al reacting with steam)
    Diffusion of steam though the liquid/solid oxide layer

Dispersion model results (cont)

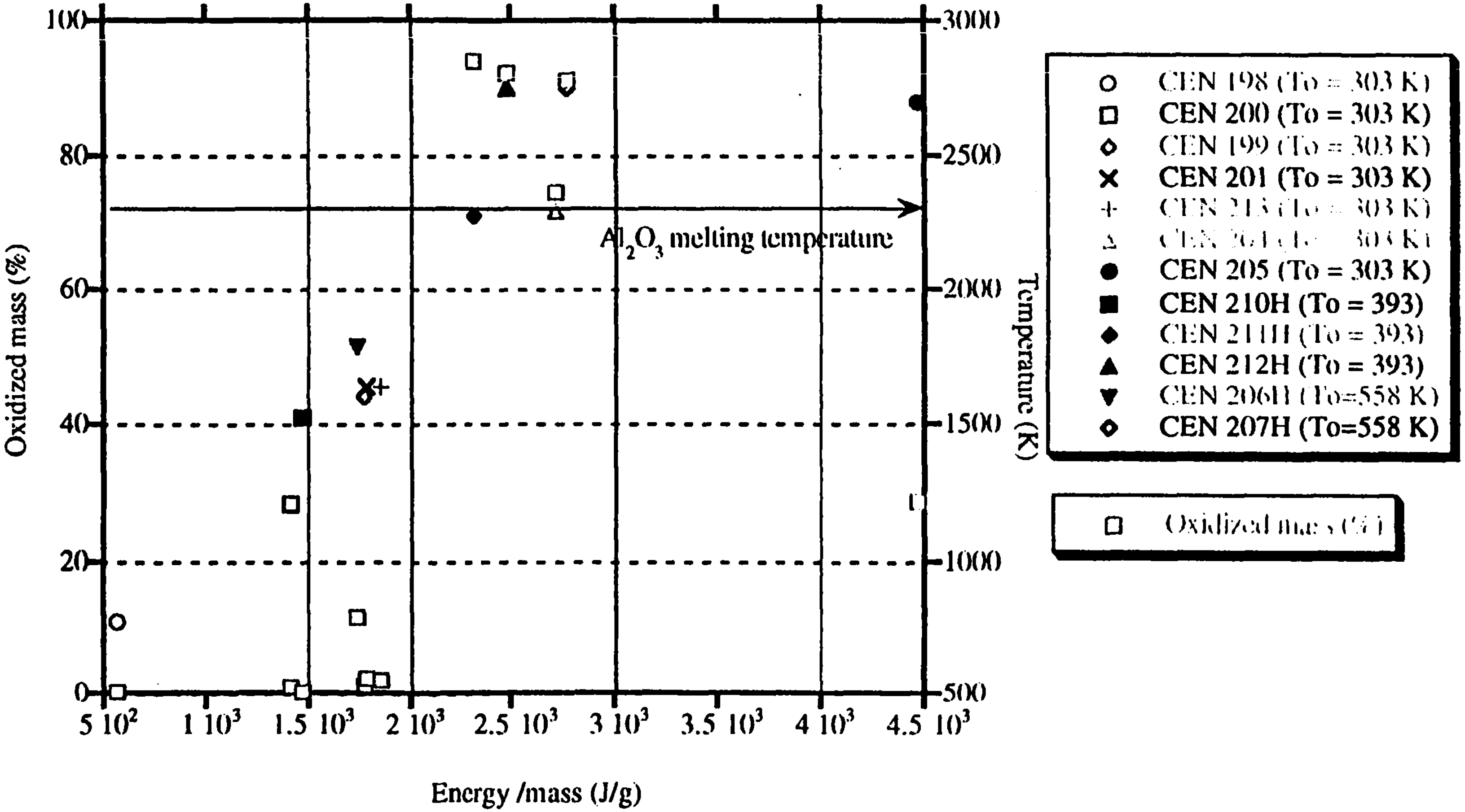


Strain rate as a function of energy deposited in the ANS fuel plate with 3.5 g/cc loading under a 25 ms pulse duration

* mass = mass of meat + clad

Dispersion model results (cont)

Fraction of mass that oxidized compared to the peak clad temperatures reached for different energy depositions in HFIR fuel performed in the TREAT facility



SUMMARY & FUTURE WORK

o PRESENT STATUS OF ANS MINIPLATE SHIPMENTS & NSRR TESTS

- Seven NSRR tests have been conducted (heatup to cracking, bowing & melting; impact of TCs and enclosures investigated)
- Five additional plates have been shipped for testing in FY95

o MODELING & ANALYSES WORK AREAS AT ORNL (** for JMTR & ANS plates**)

- Multidimensional neutronic simulations are in good agreement with data and shall be refined in the future for evaluating transient energy deposition
- Heat transfer and material response simulations have given much useful information on impact of TCs, homogeneity, transient energy deposition, and for estimation of conditions necessary for dispersion and oxidation

o FUTURE WORK WILL INVESTIGATE FOLLOWING AREAS (1994 to 1998):

- Determination of threshold to cracking & evaluation of transient energy inserted
- Impact of higher energy deposition levels on thresholds for steam explosions
- Impact of preirradiation on damage thresholds
- Extension of modeling and analysis framework for reactor safety evaluations

**** Planning for future tests is being jointly conducted ****