ODS Alloy Development

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Goal: Facilitate the Exploitation of ODS Alloys

Barriers:

- Joining
- Highly-directional properties: for tubes, transverse strength << axial
- Unusual mechanical behavior; strain-rate sensitivity/mode of failure
- Cost

Options:

- Unconventional joining approaches
- Innovative processing to obtain the desired microstructure
- Improved quantification of alloy properties and characteristics so that there are no surprises

Scientific approach:

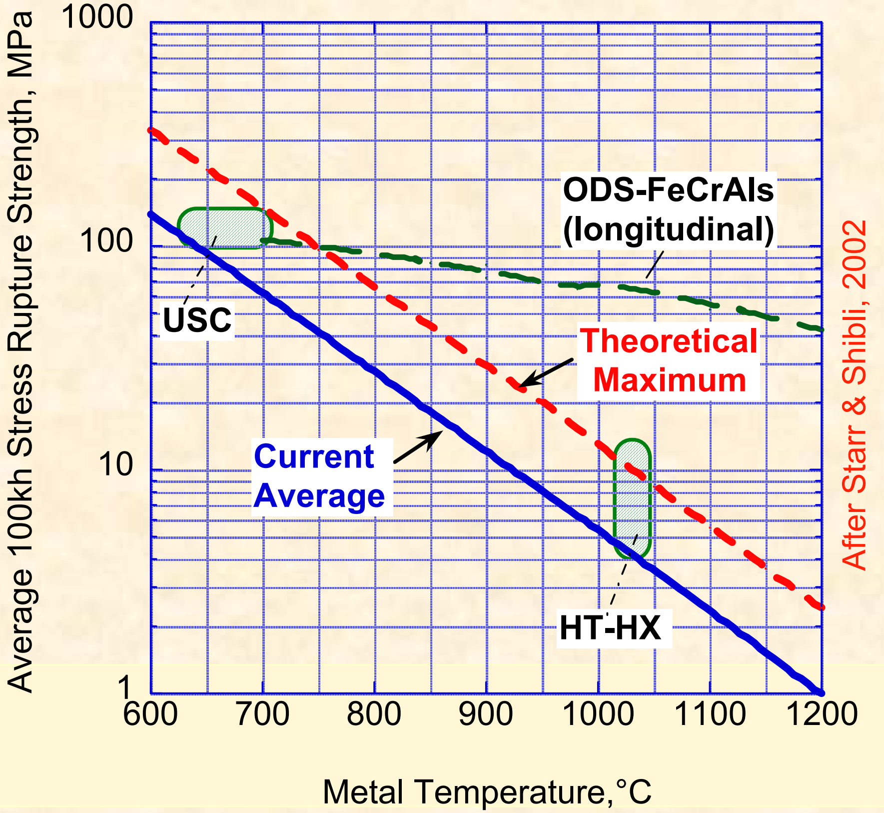
- Understand and quantify all available routes for joining
- Develop mechanistic understanding for understanding how to control the alloy microstructure; and of the oxidation behavior

Why ODS Alloys?

- Creep strength to temperatures > conventional high-temperature alloys
- Potential for use to temperatures where typically ceramics are considered
- Excellent oxidation resistance
- Resistance to sulfidation; steam oxidation
- **Current Focus:** ODS-FeCrAl alloys

Related work:

- Special Metals Inc: ODS tubing
- European COST programs
- SBIR at MER Corp.
- ARM programs:
  - Foster Wheeler
  - UCSD
  - U. Liverpool
- ORNL: 'nano-clusters'



Alloys of Interest

Alloy	Composition, weight percent					Remarks
	Fe	Cr	Al	other	RE	
ODS-Fe_3Al	Bal	2.2	15.9	Ti,Si	Y_2O_3-Al_2O_3	ORNL development
MA956	Bal	20	4.5	Ti	Y_2O_3-Al_2O_3	Special Metals Inc.
MA956H	Bal	21.6	5.7	Ti,Si	Y_2O_3-Al_2O_3	956 modification
PM2000	Bal	20	5.5	Ti	Y_2O_3-Al_2O_3	Plansee
ODM751	Bal	16.5	4.5	Ti	Y_2O_3-Al_2O_3	Dour Metal
Kanthal APM	Bal	20	5.5	Ti,Si	'ZrO_2-Al_2O_3'	oxidation comparator

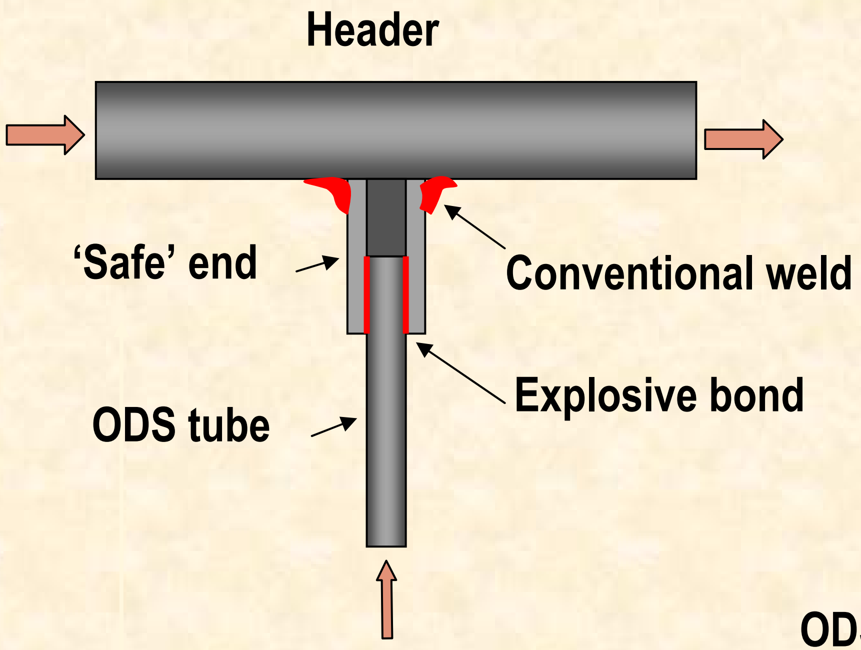
Presentation Content

- Joining
- Temperature limits
  - fireside/steam-side compatibility
- Mechanical properties
  - transverse (hoop) strength
- ODS-specific issues
  - strain-sensitivity/mode of failure

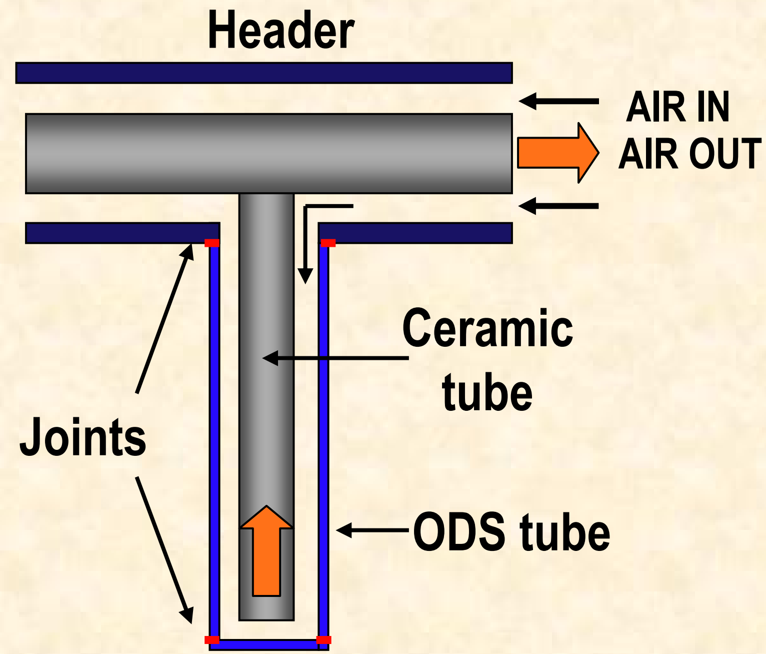
Joining of ODS Alloys

- **Joining must avoid**
  - redistributing the Y_2O_3 dispersed phase
  - changing the grain structure size/shape/orientation
- **Challenges:**
  - *fusion processes*: probably a last resort
    - brazing in COST-522 program
  - *friction/inertia welding:* distortion of microstructure
  - *diffusion bonding*
    - TLP: successfully demonstrated on other ODS
    - plasma-assisted diffusion bonding: MER Corp
  - *others:*
    - explosive bonding: successfully demonstrated (COST-501)
    - pulsed magnetic welding
    - mechanical--threading + brazing

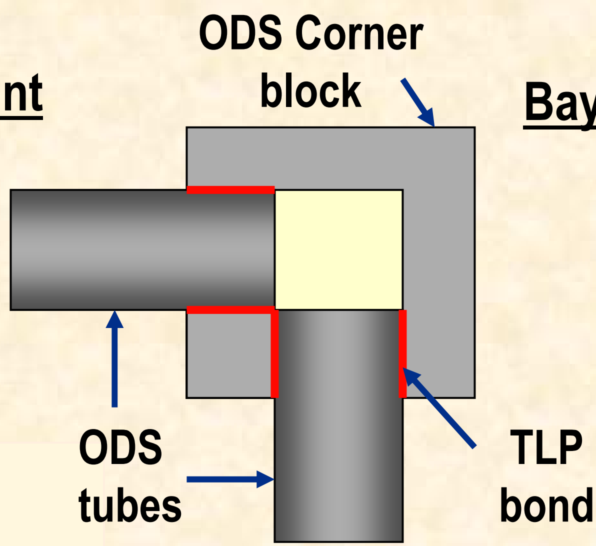
Tested Configurations for ODS Joints



British Gas 'Harp' Joint

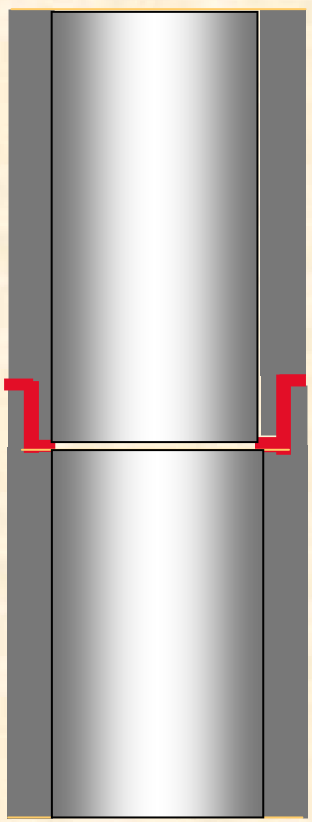


Bayonet tubes (COST-522)

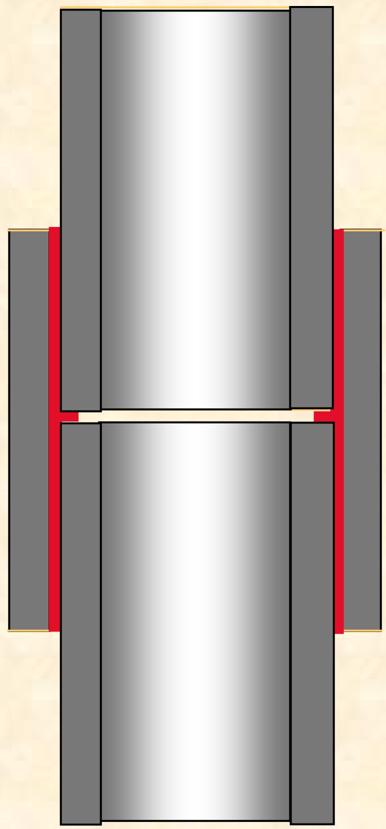


TLP joint: HiPPS program

Other Possible Configurations for ODS Joints

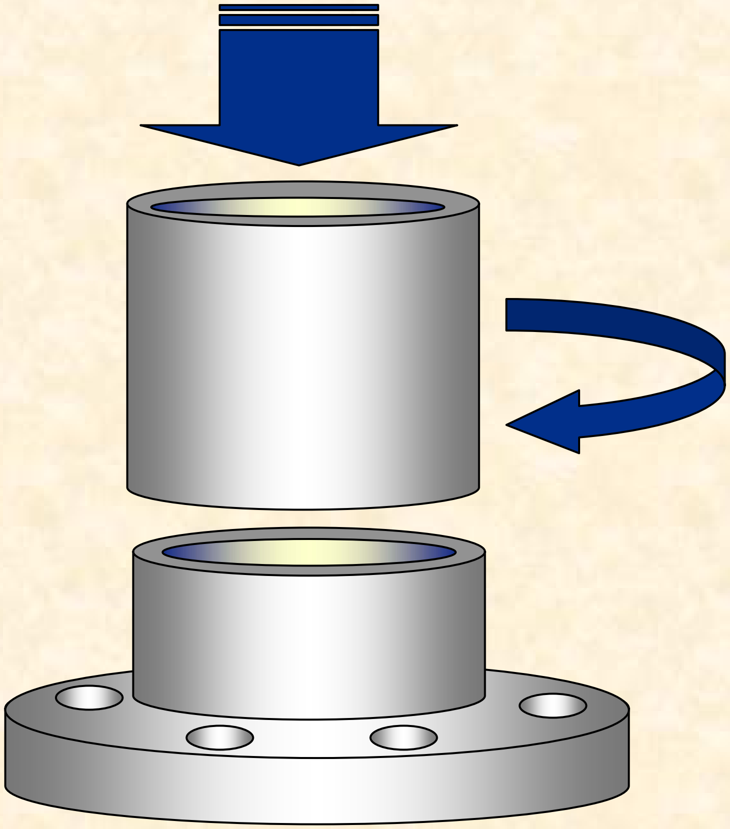


Threaded & brazed



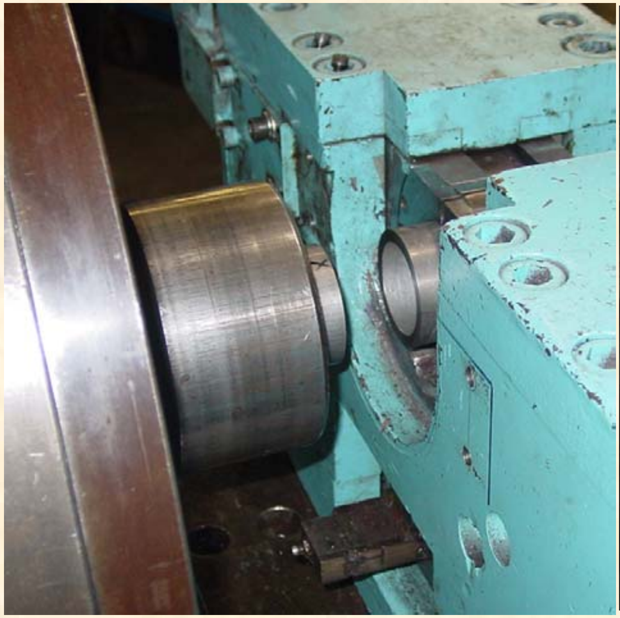
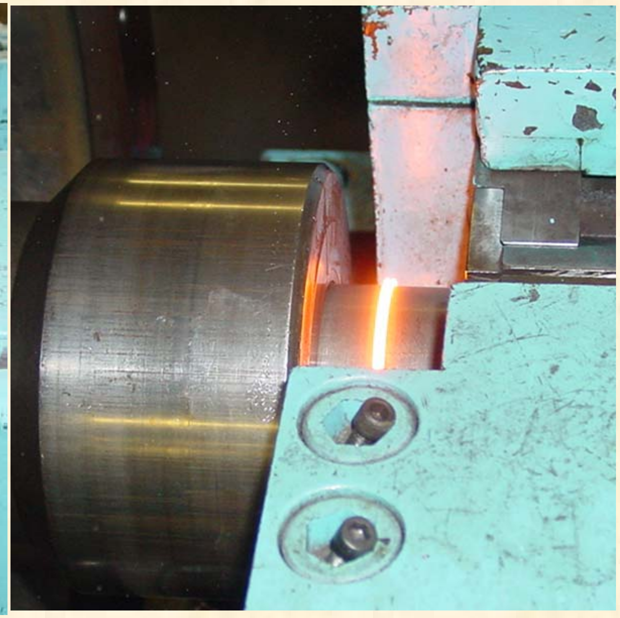
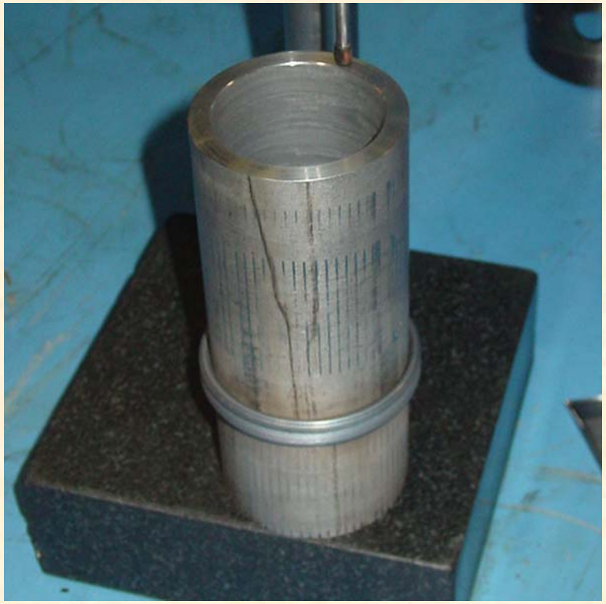
Overlapped and brazed

Reinforced joints



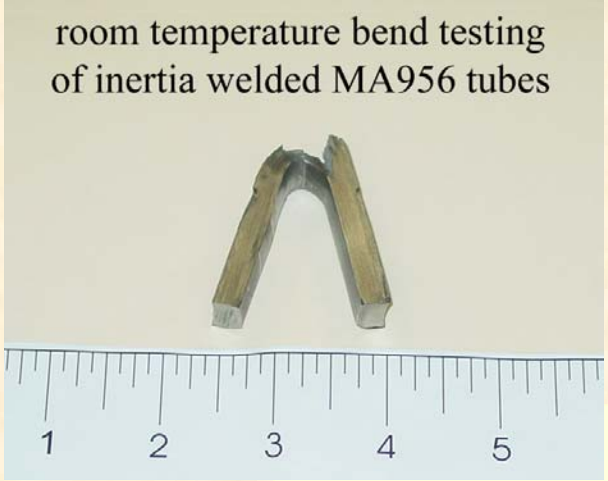
Inertial welded tube-to-flange joint

Inertia welding of MA-956 tubes

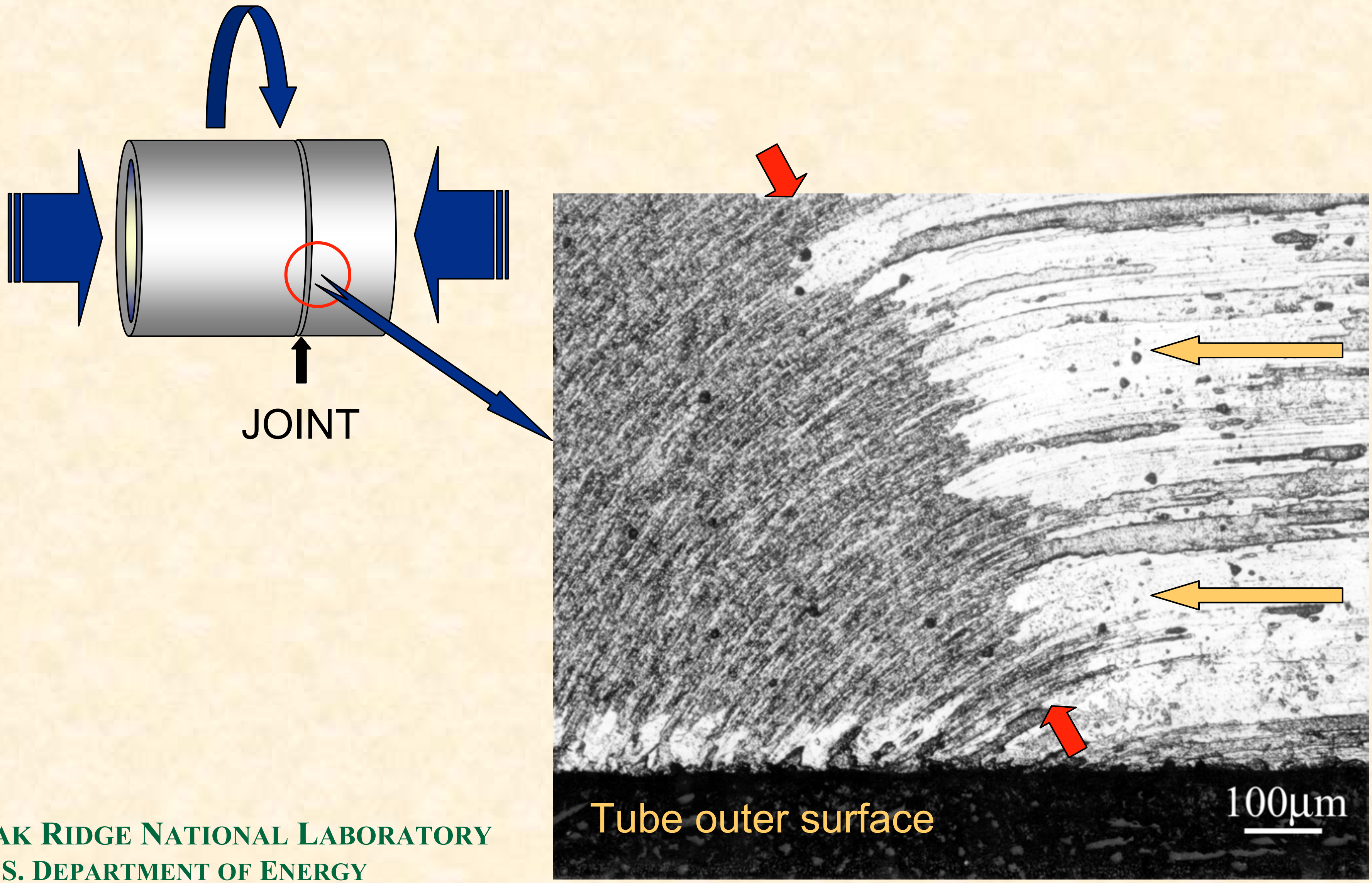




B. Kad/Interface Welding

- 63.5 mm diam. x 7 mm wall thickness, unrecrystallized MA-956 tube
- mechanically robust joints have be produced in using inertia welding
- process window was determined based on the integrity of the joint in bend tests in coupons cut from joined tubes
- reproducibility of joining parameters is excellent



Very sharp demarcation of deformed microstructure after inertia welding

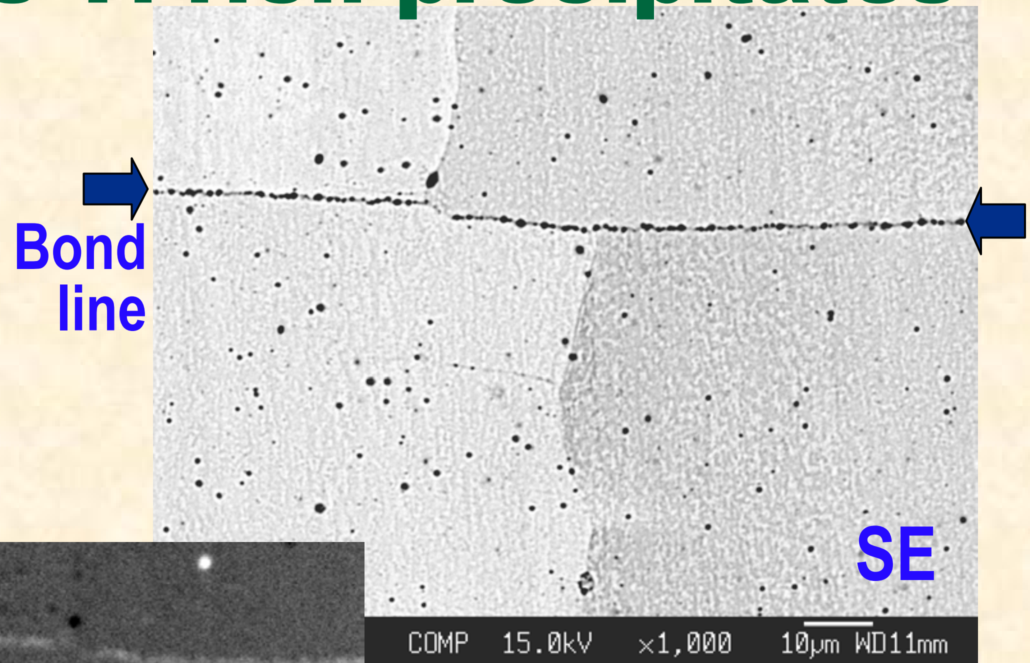


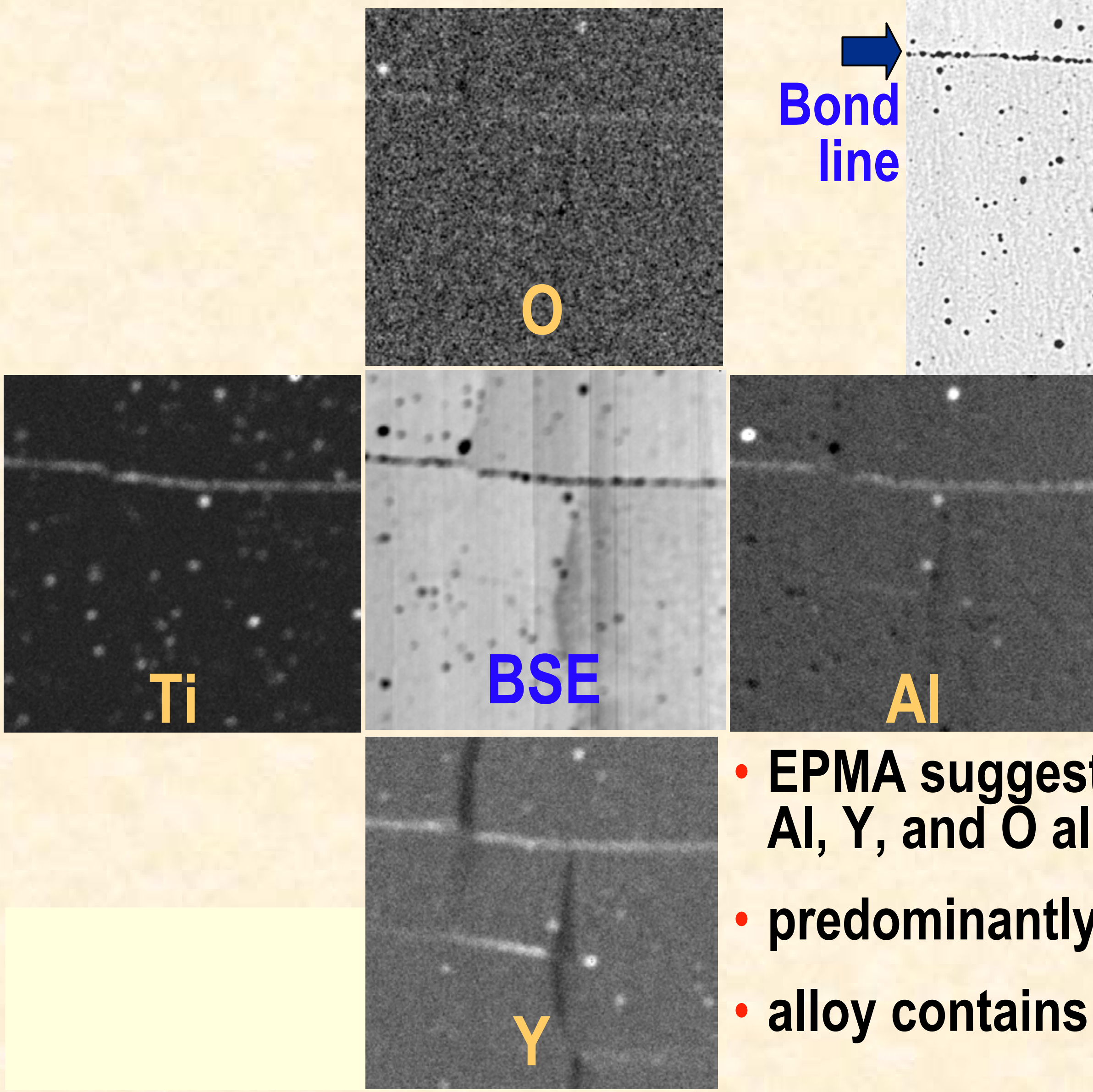
B. Kad, 2003

Plasma-Assisted Diffusion Bonding

- MER Corp-SBIR-II
- 'clean' joint
- thin joined zone
- apparent grain continuity

Bond-line exhibits Ti-rich precipitates





- EPMA suggests an accumulation of Ti, Al, Y, and O along the bond line
- predominantly Ti
- alloy contains approx. 0.5 %Ti

UT-BATTELLE

TEM indicates discrete particles

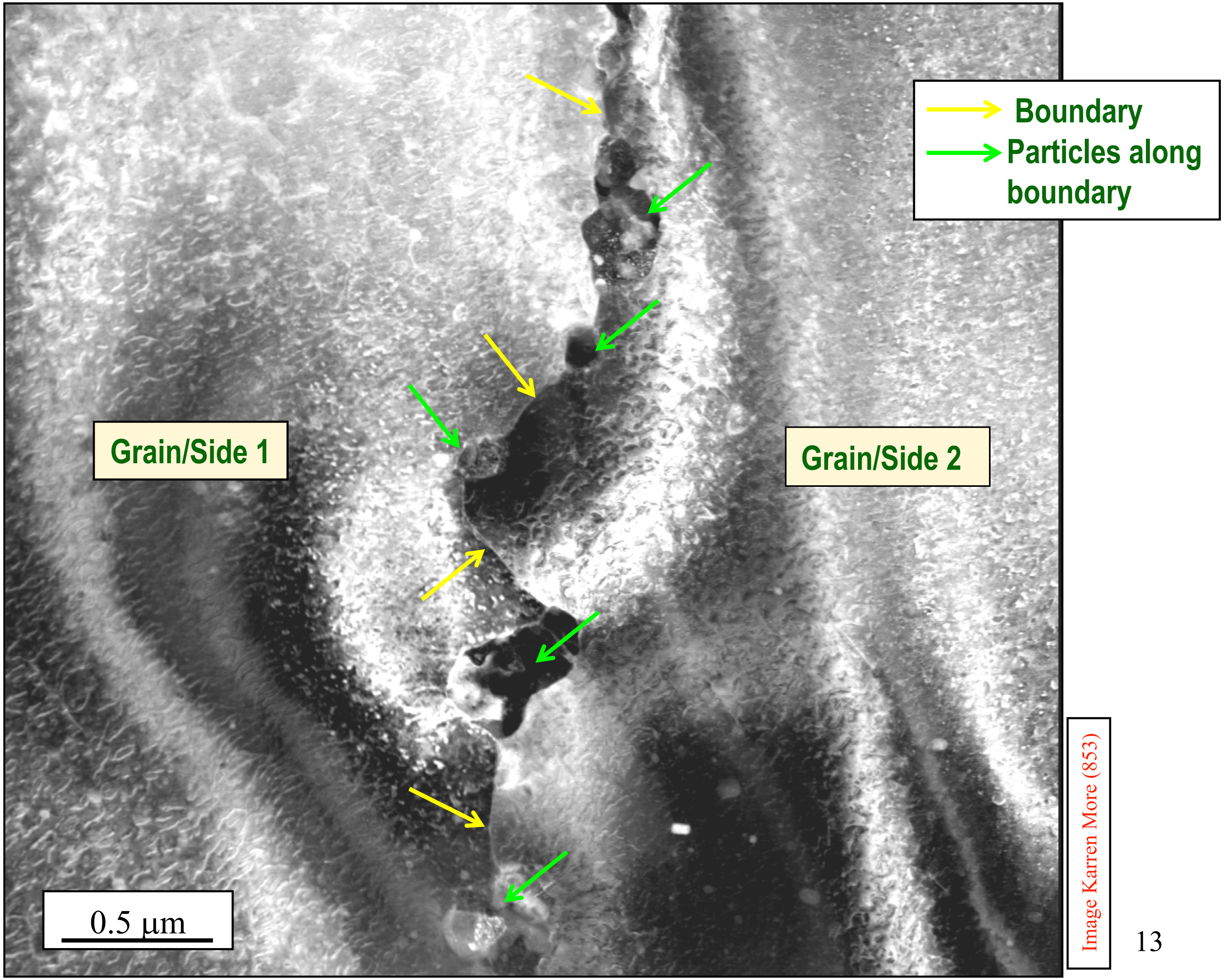
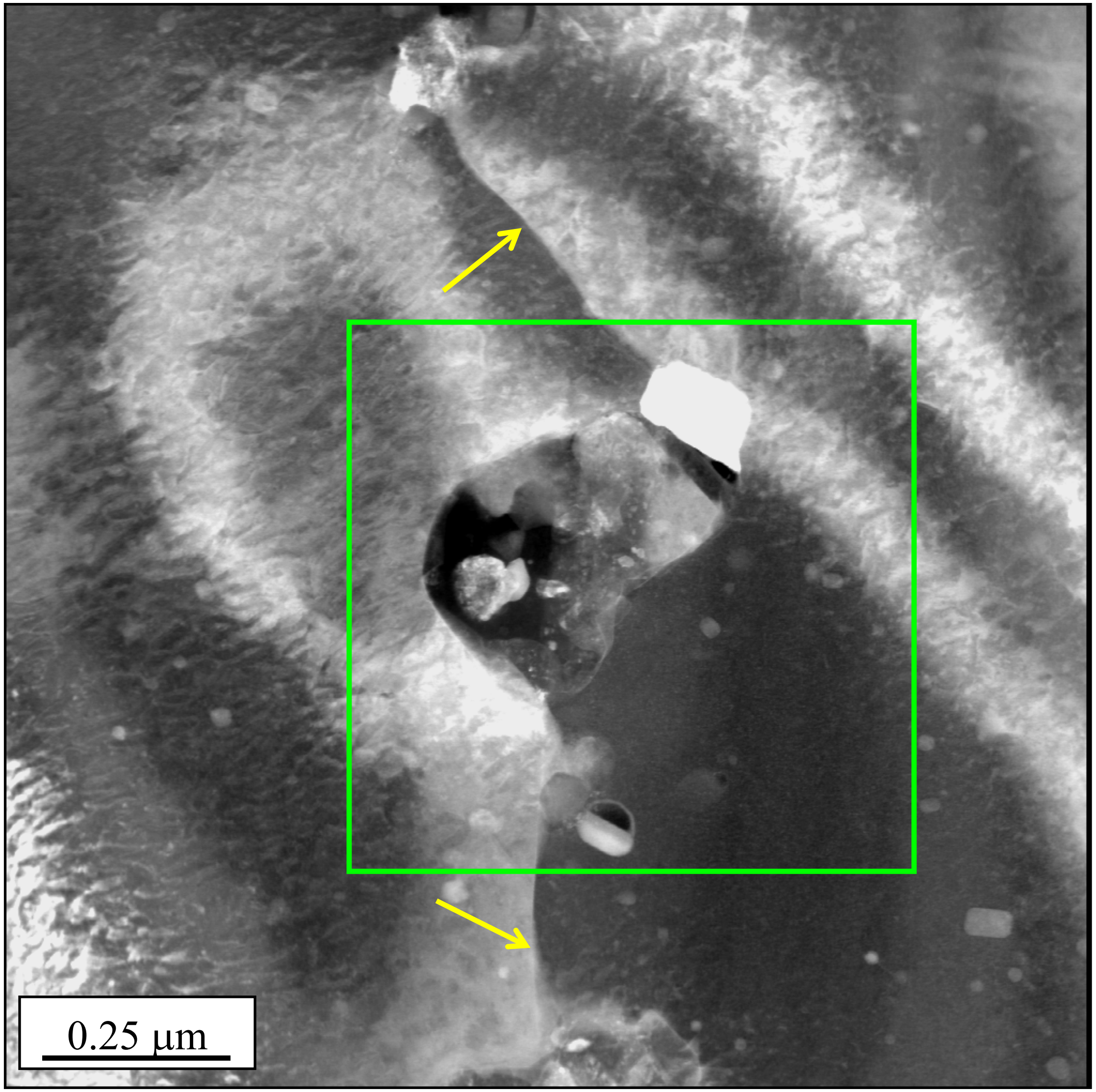
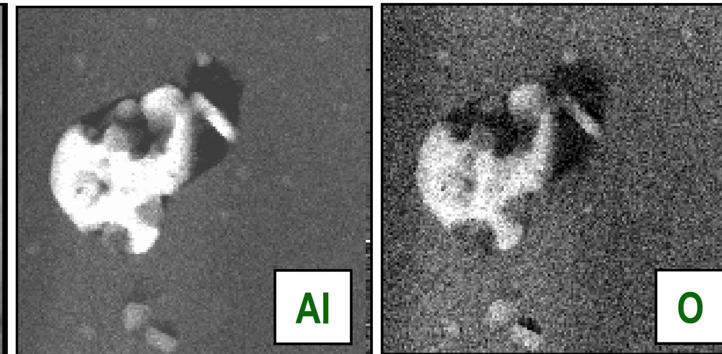


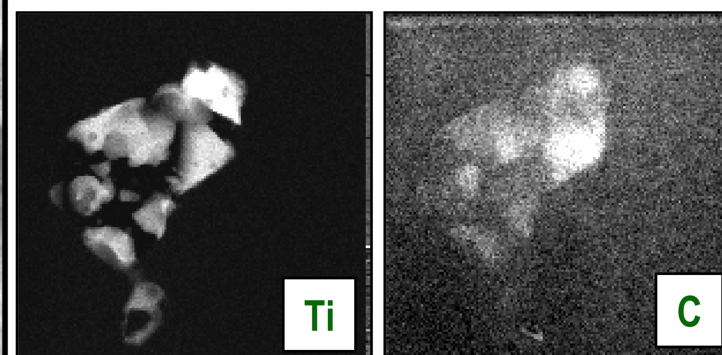
Image Karren More (853)

Particles are TiC and Al_2O_3





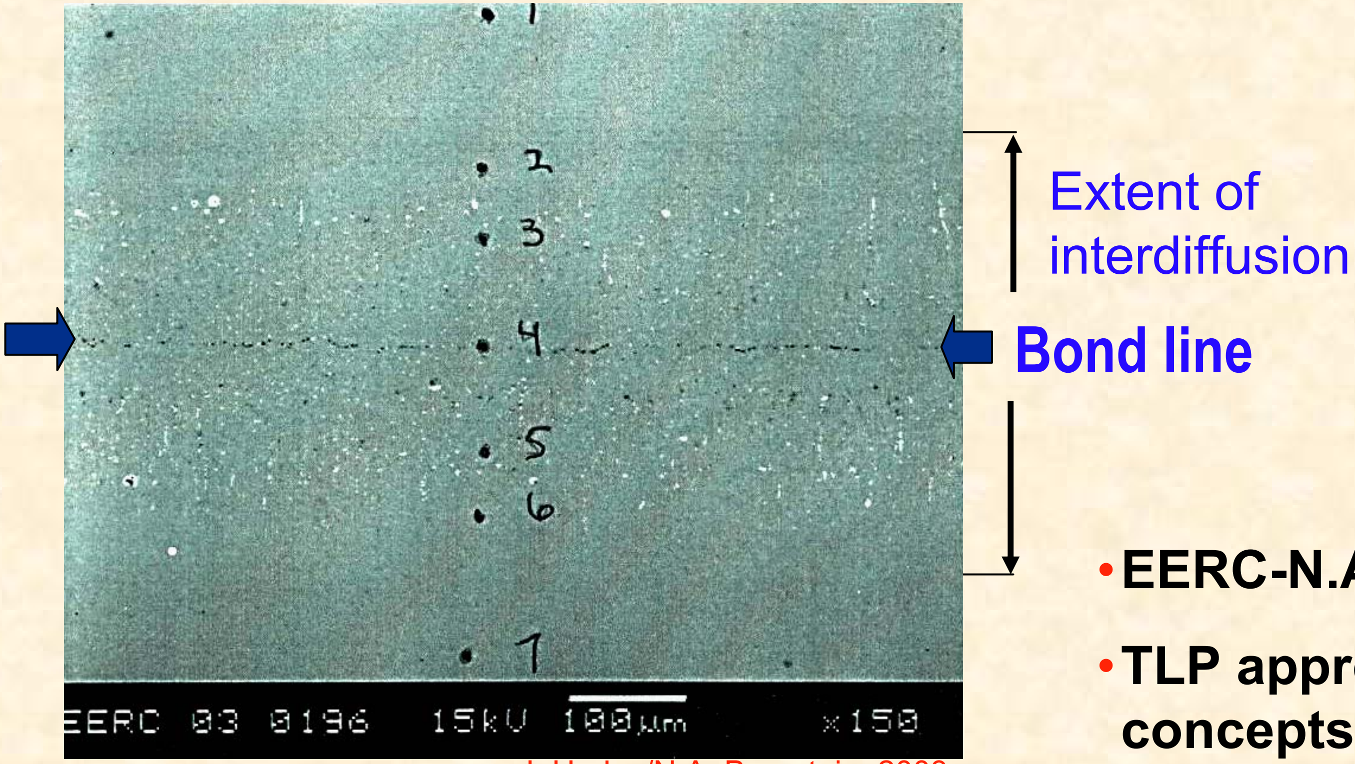
Al_2O_3 particles at boundary



TiC particles at boundary

Image Karren More
(858 + maps 859…)

TLP Joining: Collaborative Effort



J. Hurley/N.A. Bornstein, 2003

- **EERC-N.A. Bornstein-ORNL**
- **TLP approach based on concepts demonstrated for HiPPS joints**
- **special considerations for application to an alumina scale-forming alloy**
- **proof-of-concept TLP alloy**

Temperature Limits

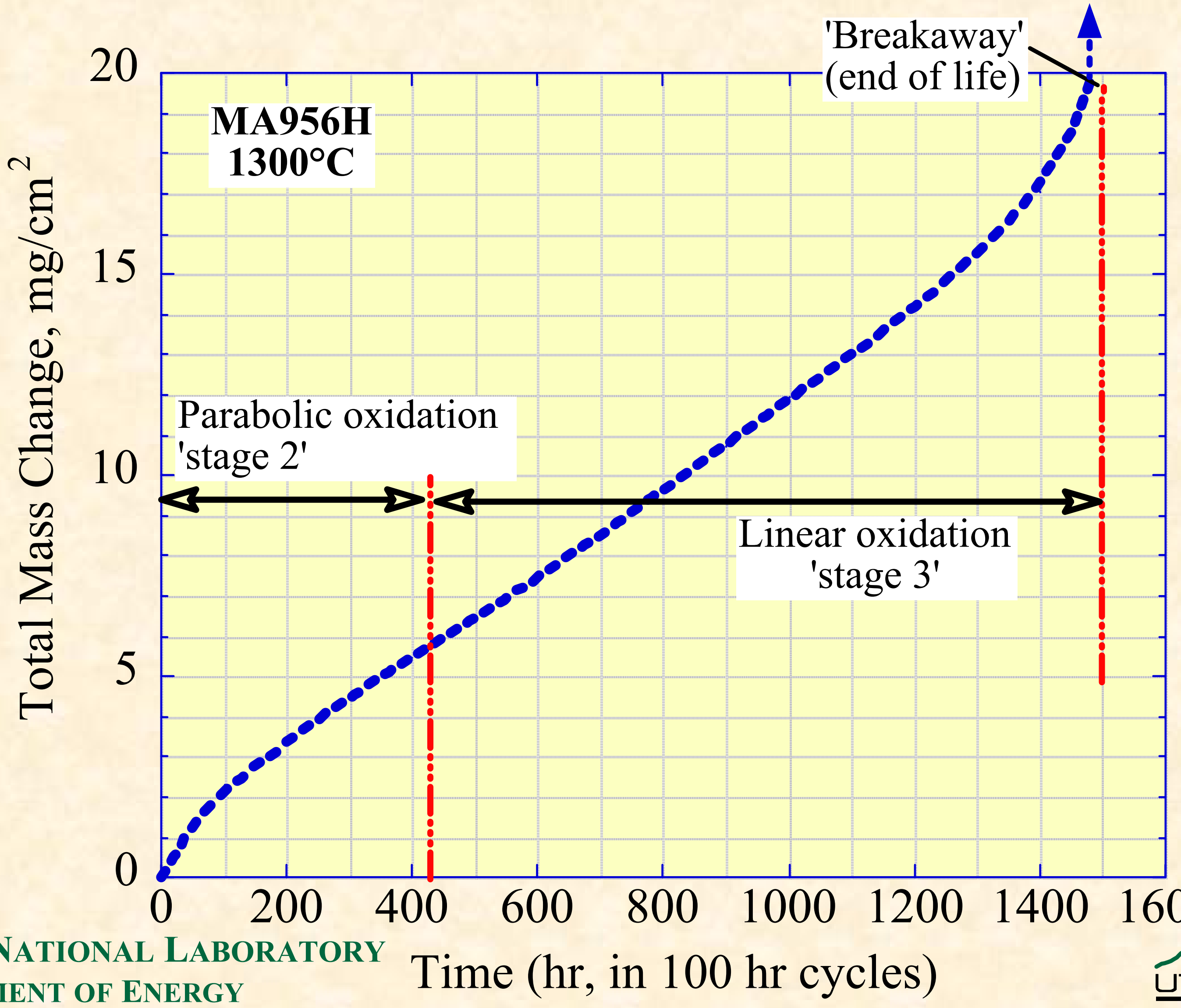
The basis for modeling the oxidation-limited lifetimes of these alloys is relatively straightforward, since:

- they form essentially Al_2O_3 scales that are uniform in thickness
- there is negligible internal attack (life can't be equated to section thinning)
- the Al concentration gradient in the alloy is flat until very near the end of life

As a result, it is possible simply to equate the oxidation lifetime to the rate of consumption of the available Al to form the alumina scale:

Life = Al available for oxidation/oxidation rate

The oxidation kinetics of these alloys have a characteristic form



Current Model

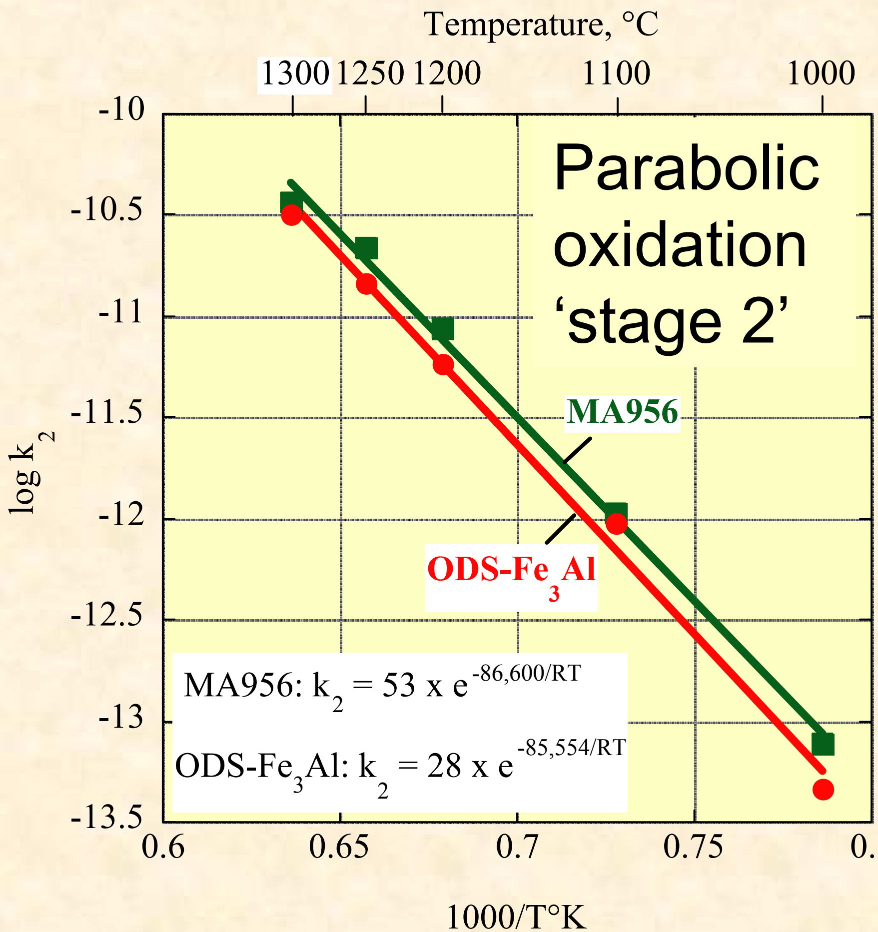
The current expression of the model is:

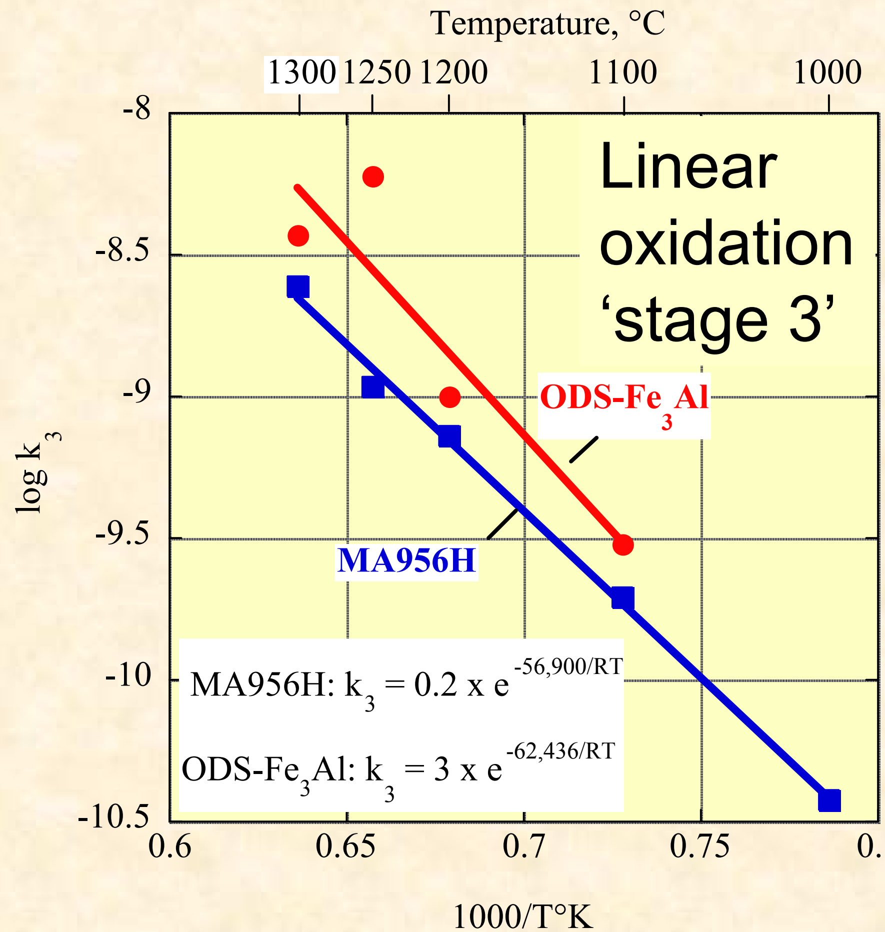
$$t_b = \{[S*10^{-4}*\rho_A*A_\tau*e^{-Q\tau/(1.987*T)}]^2/(3600*A_2*e^{-Q2/(1.987*T)})\} + \{[1/(3600*M)*(V/A)*(\rho_M/(A_3*e^{-Q3/(1.987*T)}))* [(C_{Bo}-C_{Bb}) - M*S*10^{-4}*(A/V)*(\rho_A/\rho_M)*A_\tau*e^{-Q\tau/(1.987*T)}]\} \text{ hours}$$

Input required is:

1. Alloy data: ρ_M; C_{Bo}; C_{Bb} (need to measure C_{Bb})
2. Oxide data: ρ_A; M; S; (constants based on oxide/alloy stoichiometry)
3. Alloy oxidation descriptors: Arrhenius data A_2, Q_2; A_3, Q_3, and A_τ, Q_τ
4. The metal temperature (T), and the component size (V/A)

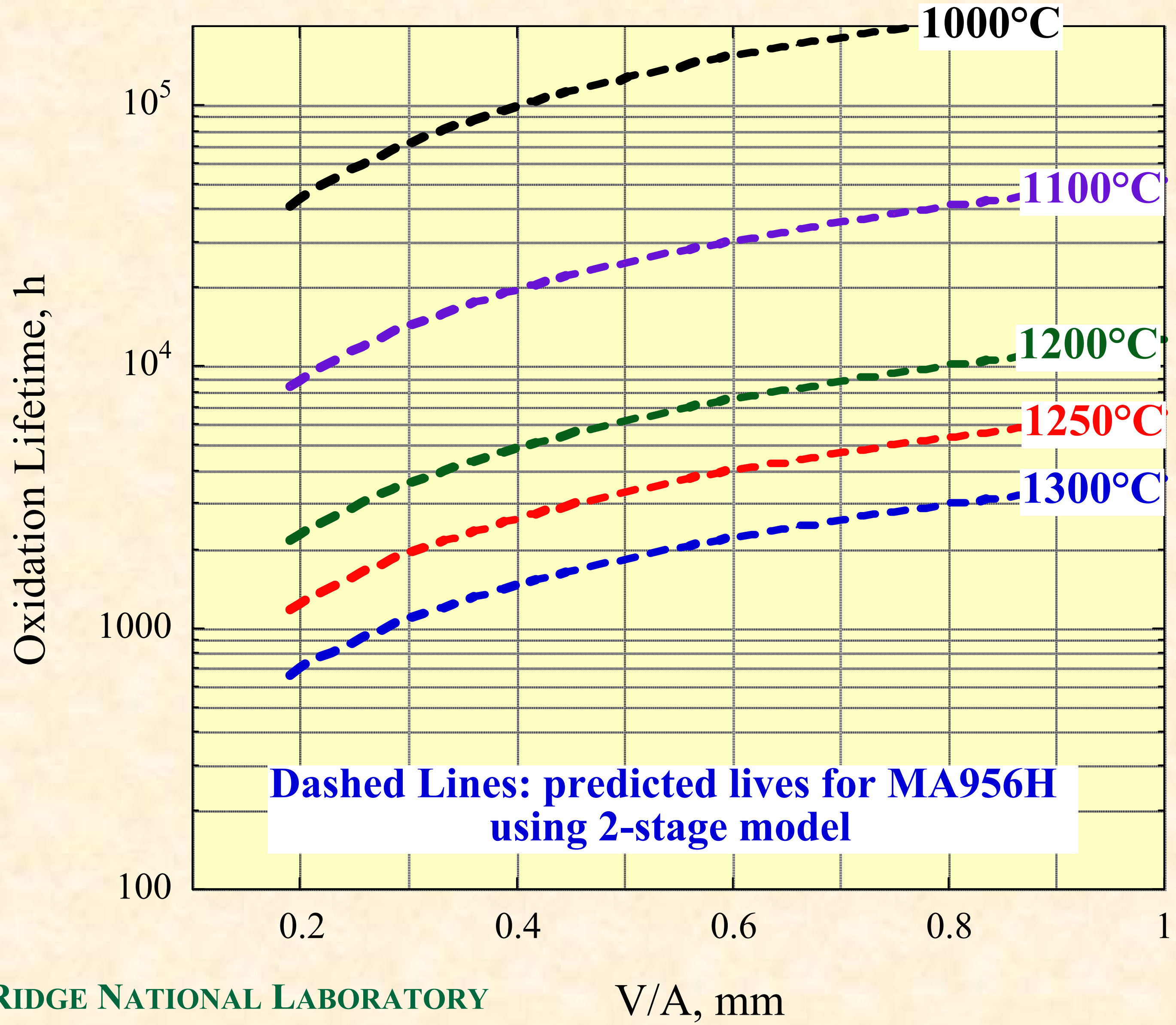
Summary of Oxidation Kinetics



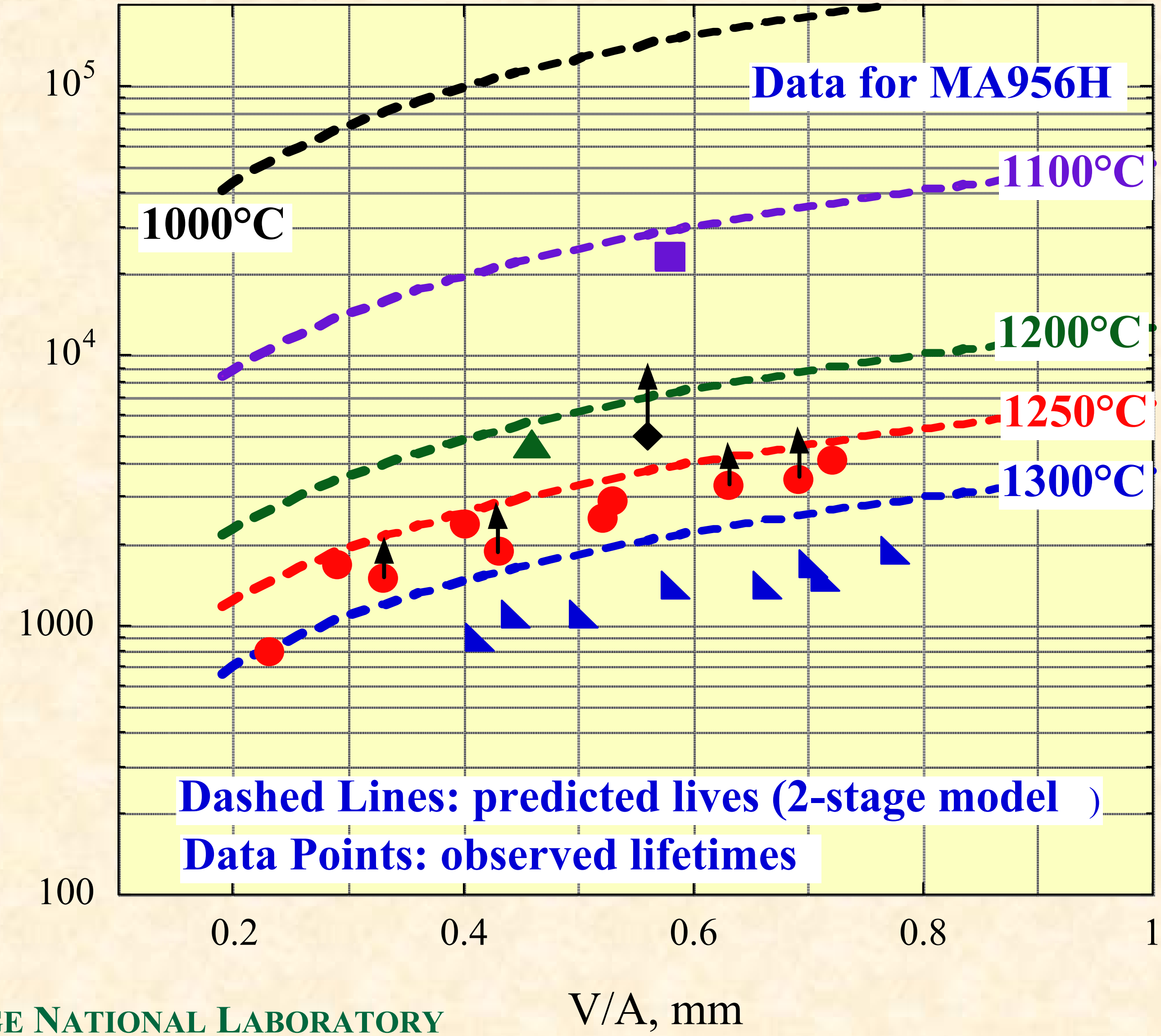


Some alloys haven't run long enough to establish the Stage 3 oxidation rate

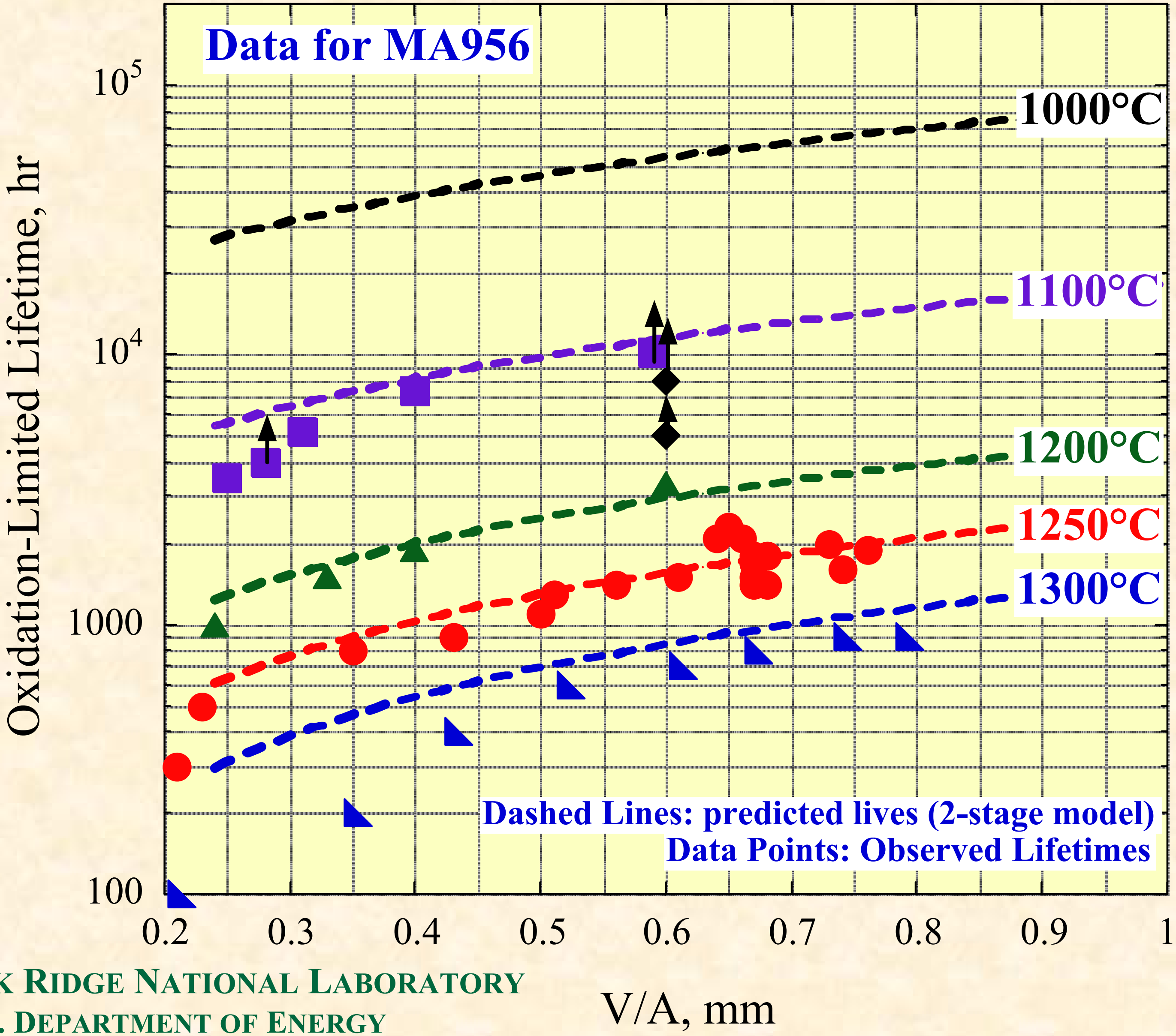
Calculated Lifetimes



Calculated vs Observed Lifetimes

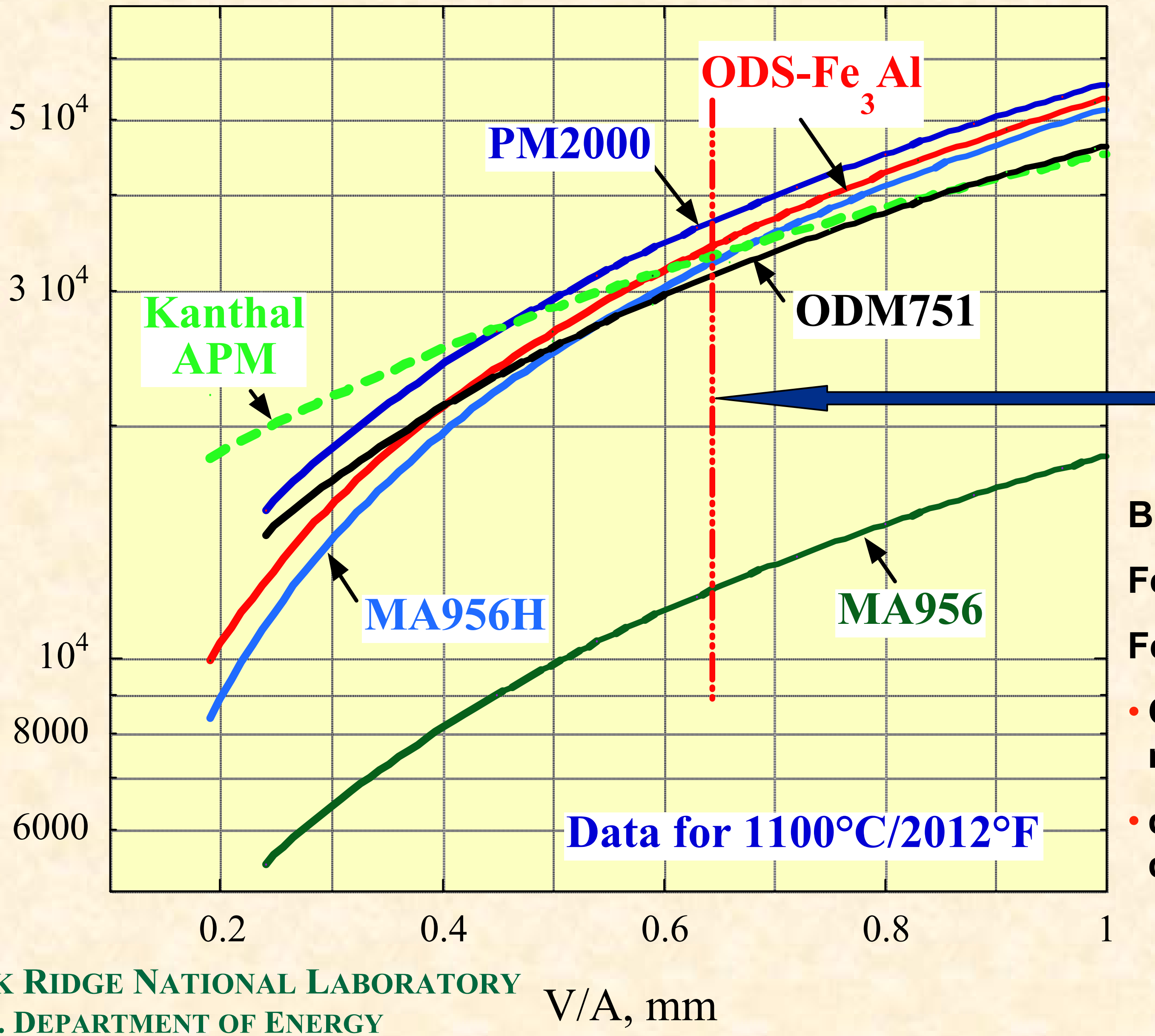


Calculated vs Observed Lifetimes



Reasonable predictions for 1100-1300°C

Calculated Lifetimes at 1100°C



TUBE
1in OD x 0.1in
(25.4 x 2.54 mm),
V/A = 0.64 mm

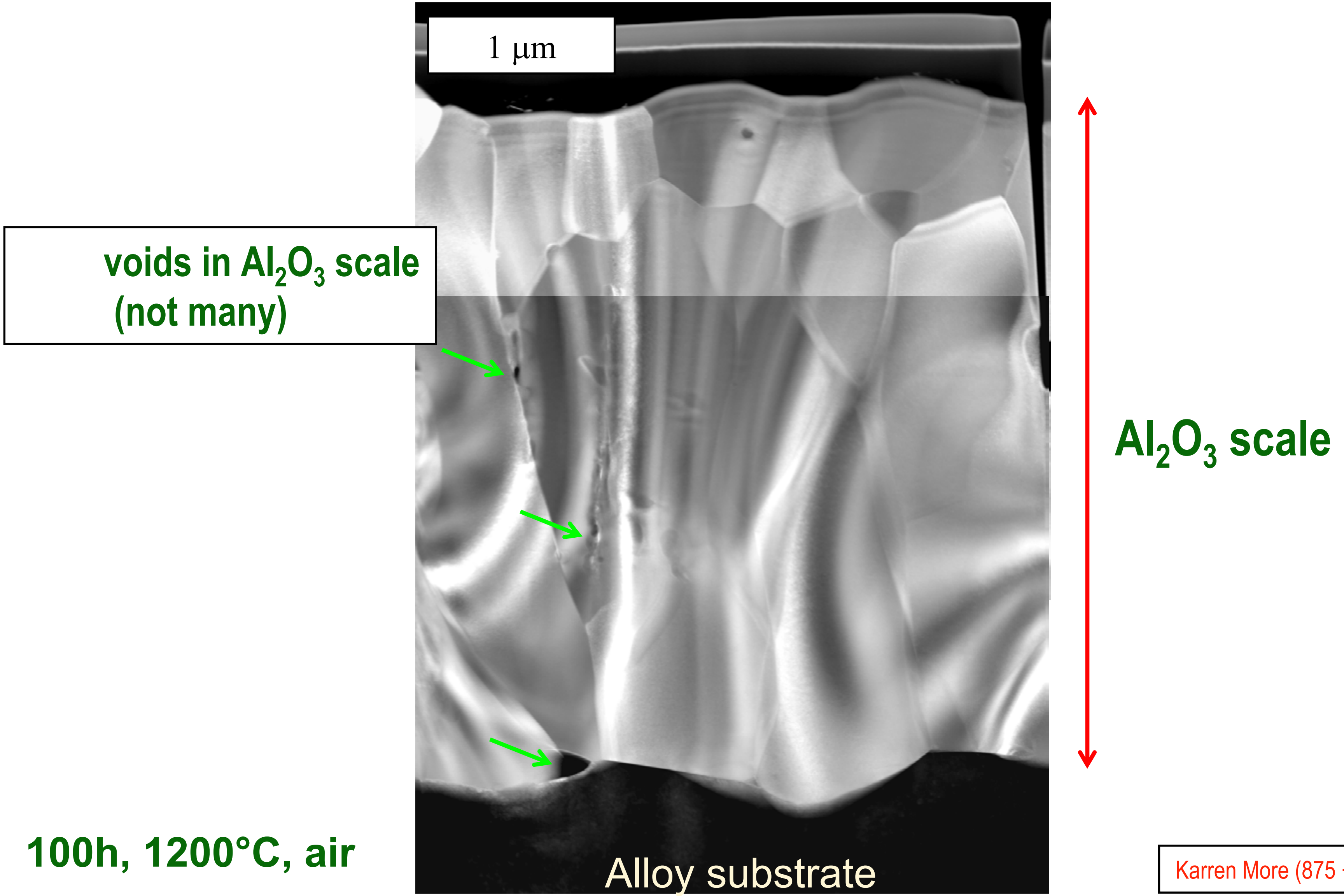
Based on C_{Bb} values:

FeCrAls--0.001

Fe_3Al--0.056

- C_{Bb} is difficult to measure
- don't know if it is T-dependent

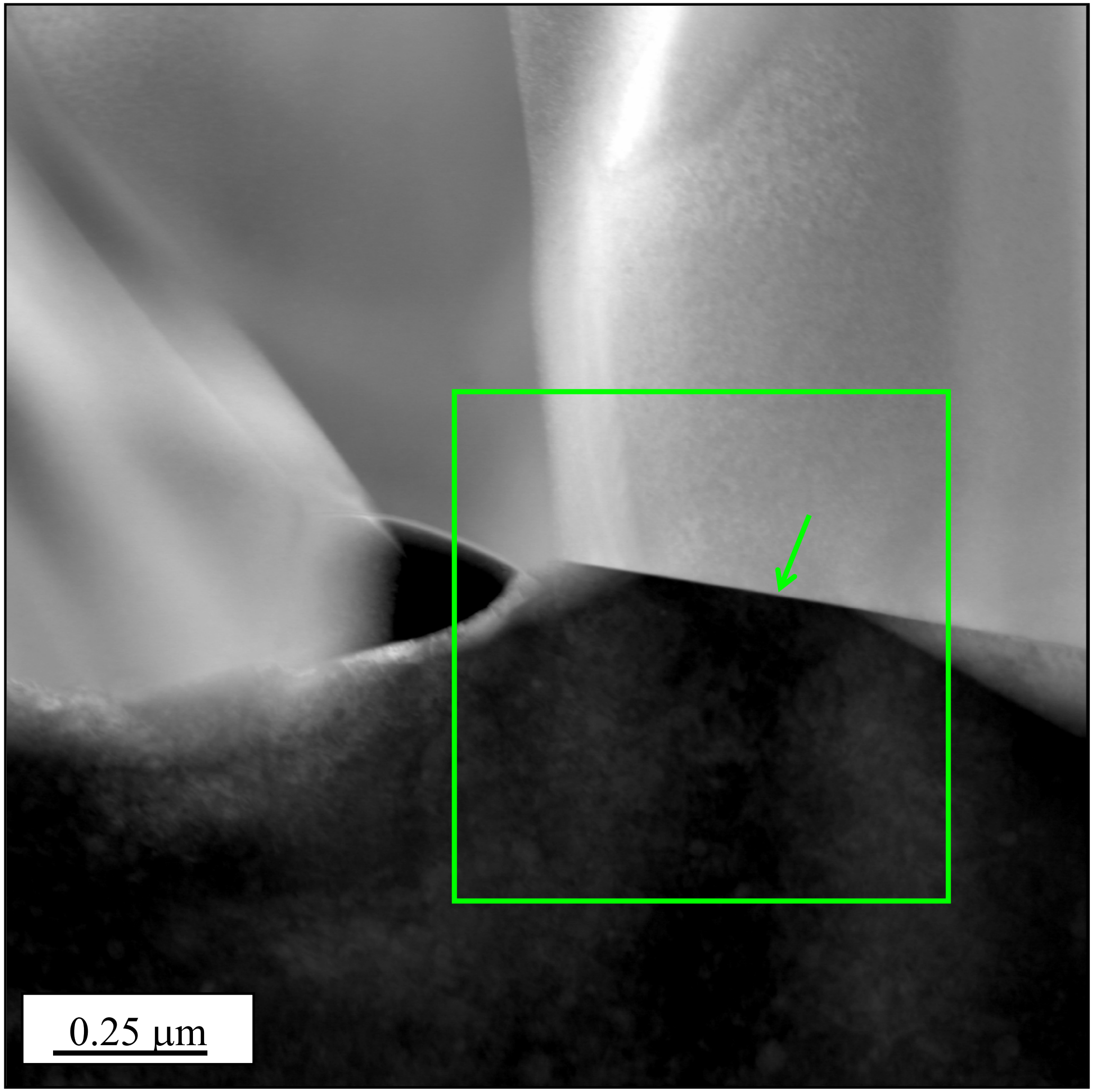
Cross section of scale on MA956H



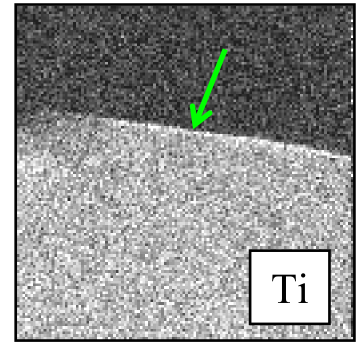
100h, 1200°C, air

Karren More (875 + 876)

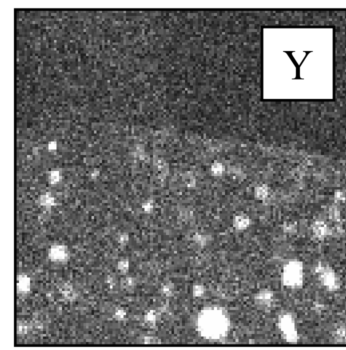
Alloy-oxide interface on MA956H



Karren More (879 + maps 880…)

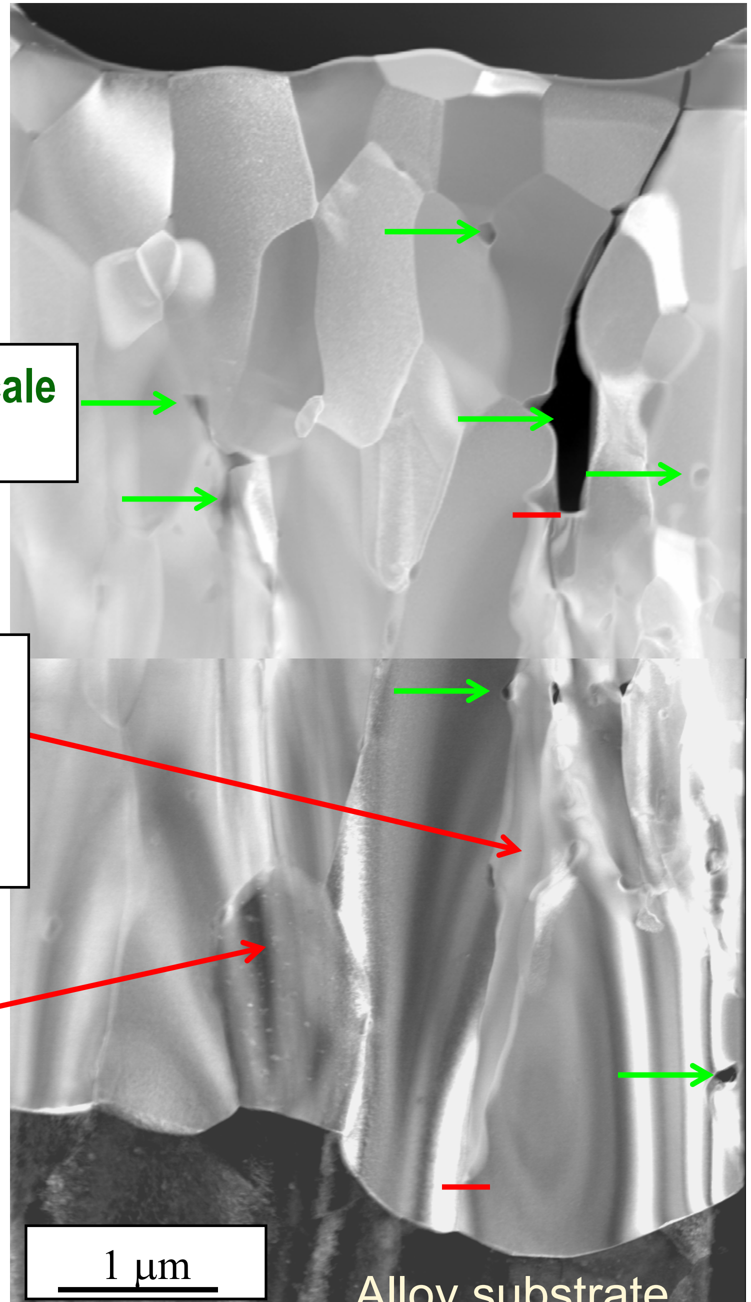


Ti-enriched at interface



Y-containing particles in alloy
There is also Y-enrichment at Al_2O_3 grain boundaries (not shown)

Scale cross section on MA956



voids in Al_2O_3 scale (many more)

elongated Y-Ti-Si-C grain (no oxygen!) ~4 mm long between Al_2O_3 grains (red bars show ends of grain)

TiC particle at interface

thicker Al_2O_3 scale than on 956H

100h, 1200°C, air

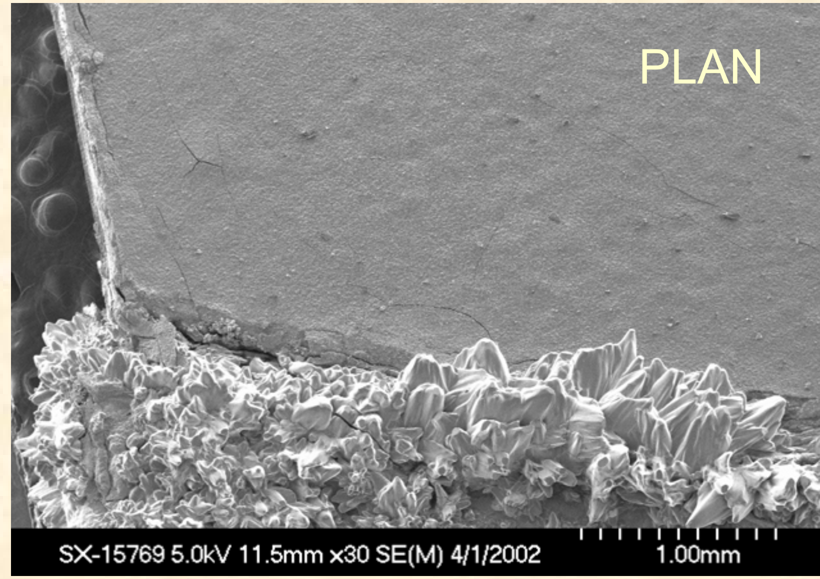
Karren More (881 + 882)

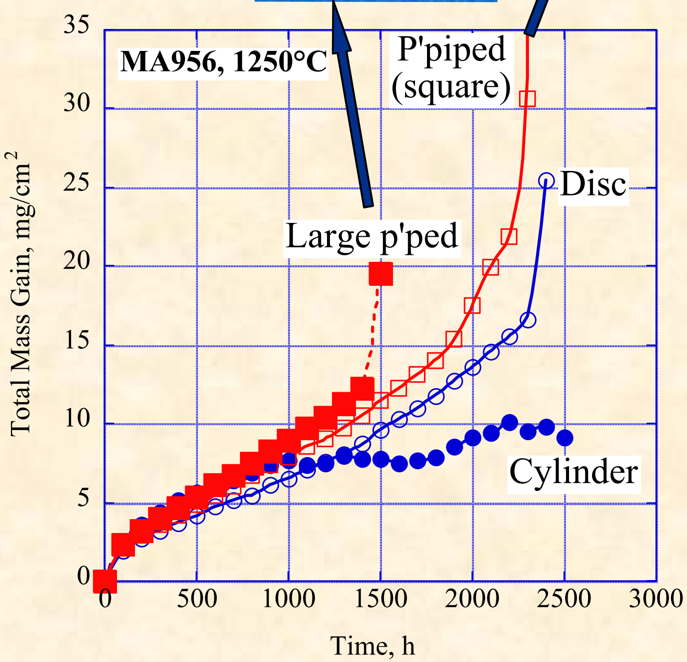
Current approach under-predicts oxidation lifetime

- Predictions should be conservative!
- Are lab results overly affected by specimen shape?
- V/A is a 'shape factor,' but doesn't discriminate among parallelepipeds
- Other shapes:

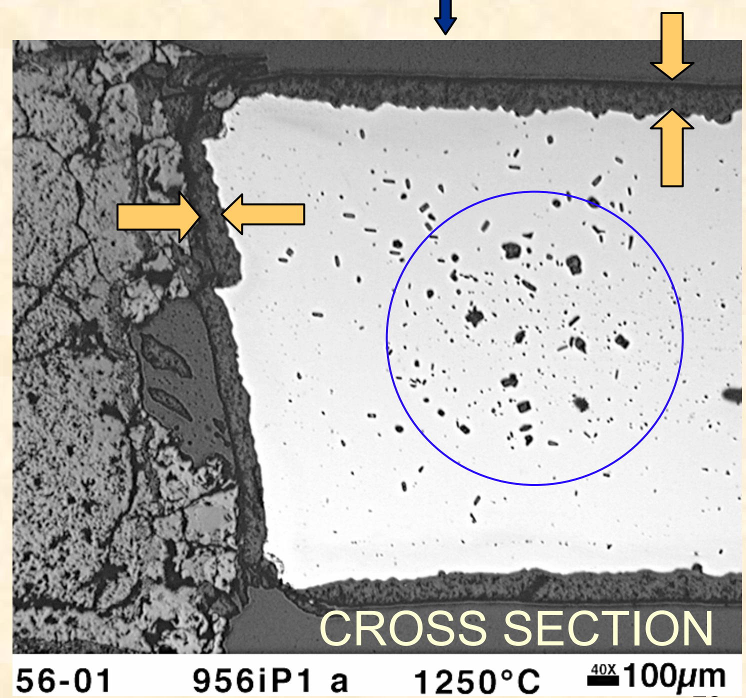
Shape	Thickness mm	Length mm	Width mm	Surface area mm^2	Volume mm^3	V/A mm
Standard parallelepiped	1.6	23	12.5	686	460	0.67
Cylinder		23	5	400	452	1.13
Parallelepiped-2	1.6	14	12.5	435	280	0.64
Disc	1.6		15	353	283	0.80

Effect of Specimen Shape

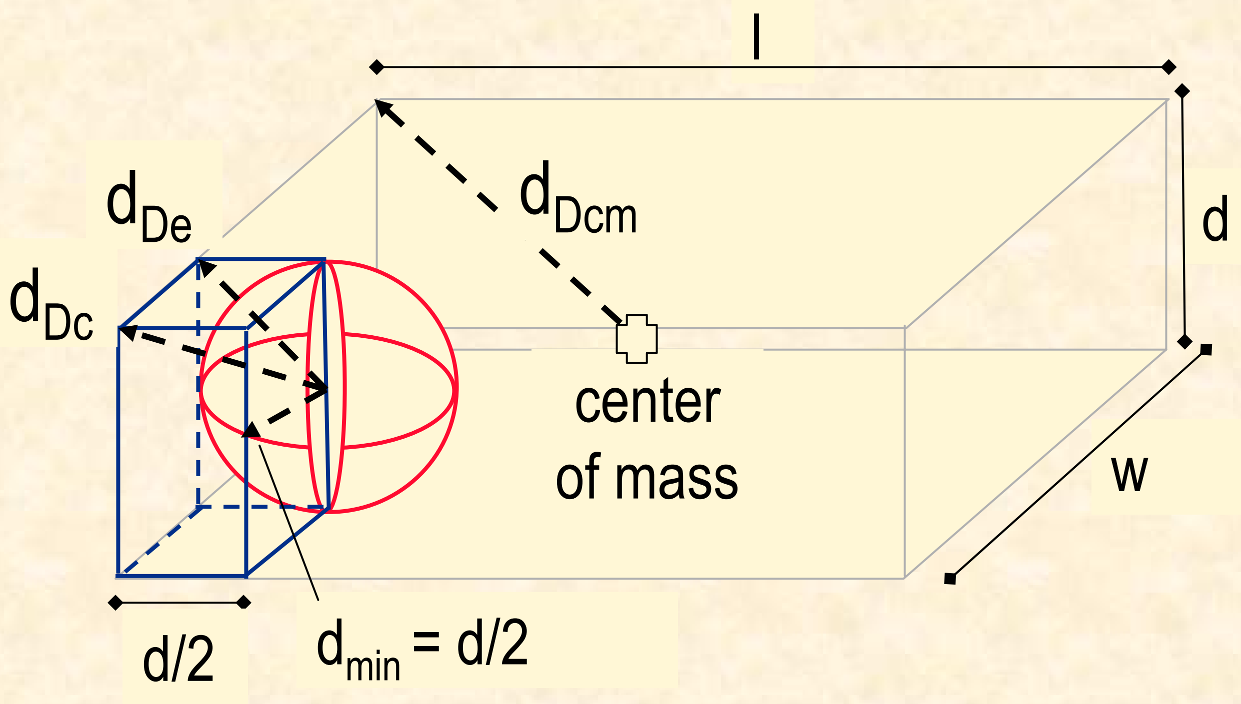




some shapes make less efficient use of the Al reservoir?



Possible Shape Factors



Shortest diffusion path from center of specimen thickness to outer surface (d_{min}) is given by locus of surface of a sphere of radius = d/2

d_{De} = diffusion length to an <u>edge</u>

d_{Dc} = diffusion length into a <u>corner</u>

Longest diffusion path is from the <u>center of mass</u> (= d_{Dcm})

Shape Factors: Diffusion Lengths

Shape	Edge d_{De}	Corner d_{Dc}	Center of Mass d_{Dcm}
P'piped	0.707 x d	0.866 x d	0.5 x sqrt($l^2 + w^2 + d^2$)
Cylinder	—	0.707 x diam	0.5 x sqrt(l^2 + diam^2)
Disc	0.707 x d	0.707 x d	0.5 x sqrt(d^2 + diam^2)

d = specimen thickness

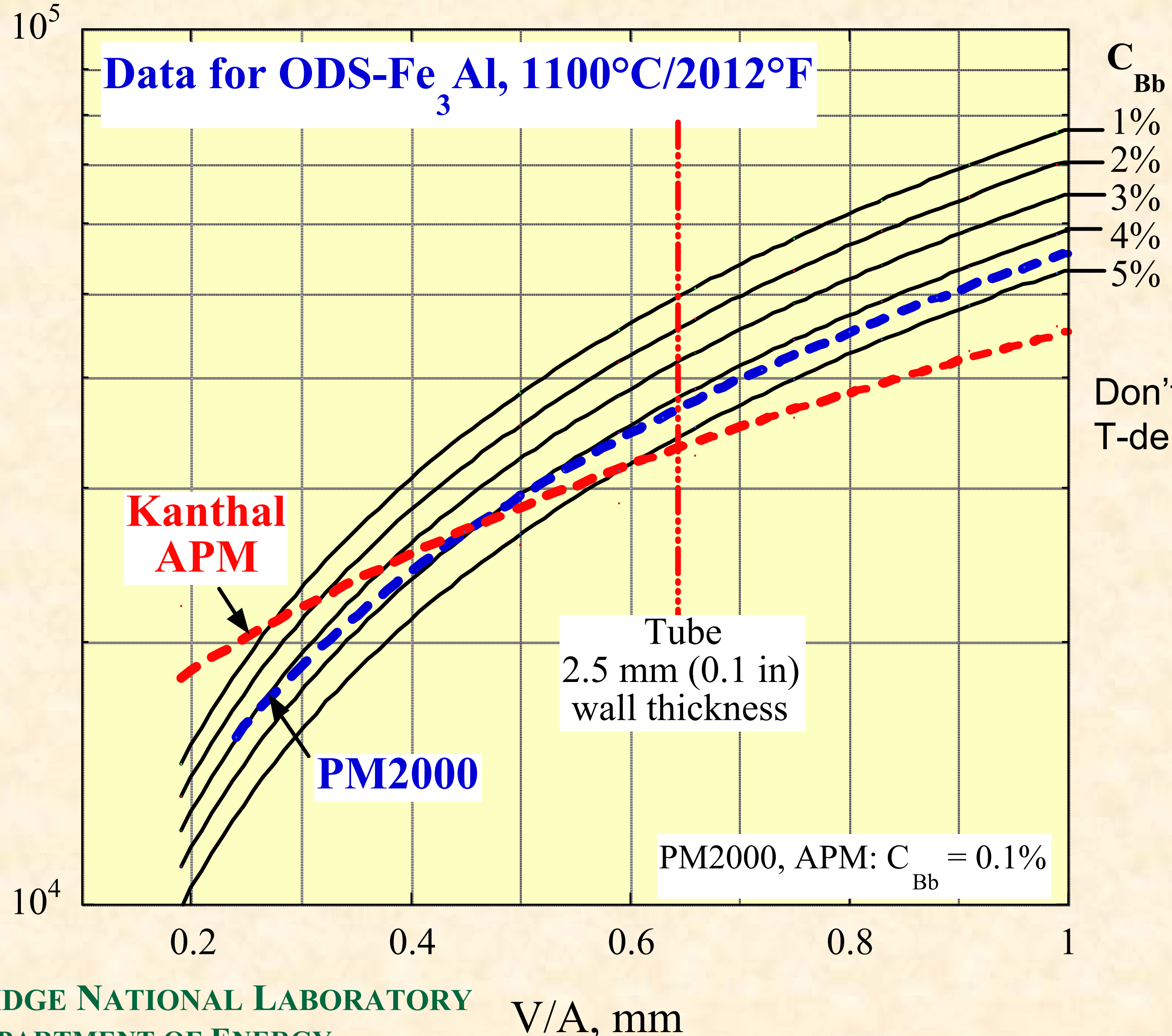
l = specimen length

w = specimen width

Summary

- Joining
  - 3 routes are being evaluated
    - inertia welding--controlled microstructural distortion
    - plasma-assisted diffusion--clean joints (?); examining reinforced design
    - TLP bonding--questions about amount of residual elements and their effects
  - significant effort on other techniques in the Vision 21-SM project
- Temperature limits
  - generating data for all available ODS-FeCrAls
  - have an initial working model for life prediction
    - continuing long-term exposures to validate and improve the model
    - issues of over-prediction, and the influence of shape
  - lifetimes of 30-70kh at 1100°C in air for typical tube sizes
  - continuing to generate data in steam, other environments

Sensitivity to C_{Bb}



Don't know if C_{Bb} is T-dependent