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Thermo-Mechanics of Foam/Liquid Structures

UCLA

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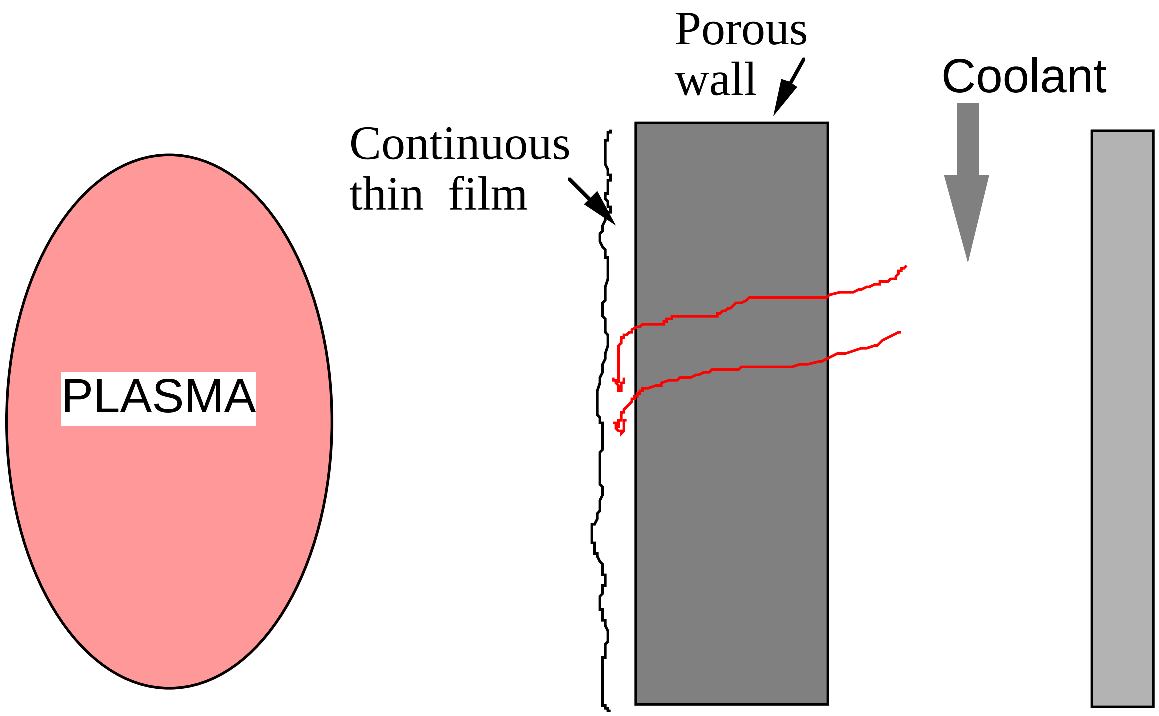
BACKGROUND

Thin film/Porous Wall Concept

(Liquid-infiltrated wall + thin film)



POTENTIAL ADVANTAGES

- Eliminate film drop. Turbulence on inner wall side.
- Reduce wall stiffness.
- Increase conductivity (if liquid has higher k than solid).
- Provide protection.
- Transport a fraction of surface heat load (?).

ISSUES AND ANALYSES

- WALL PROPERTIES:
  - -- Effective elastic moduli, conductivity
  - -- Strength, failure mechanisms, design criteria

- VOLUMETRIC HEAT GENERATION
  - -- Nuclear heat
  - -- Bremsstrahlung deposition

- HEAT TRANSFER/FLUID FLOW
  - -- Film convection + convection in wall
  - -- Temperature profile
  - -- Liquid permeation and film creation

- STRESS ANALYSIS/MECHANICAL DESIGN
  - -- Thermal stresses
  - -- Primary stresses
  - -- Stress <=> Materials Limits

- POWER HANDLING CAPABILITY

WALL PROPERTIES

- Theoretical techniques (Effective medium theory)
- Experimental Results (Data......)

MECHANICAL:

We wish to determine the relationship:

$$\bar{\boldsymbol{\sigma}} = <\boldsymbol{\sigma}> = \bar{\mathbf{c}}:\bar{\boldsymbol{\varepsilon}} \qquad \text{or} \qquad \bar{\boldsymbol{\varepsilon}} = <\boldsymbol{\varepsilon}> = \bar{\mathbf{s}}:\bar{\boldsymbol{\sigma}}$$

$\bar{\boldsymbol{\sigma}}$: mean stress $\qquad$ $\bar{\boldsymbol{\varepsilon}}$: mean strain

$\bar{\mathbf{c}}$: effective stiffness tensor $\qquad$ $\bar{\mathbf{s}}$: effective compliance tensor

For isotropic materials, $\bar{\mathbf{c}}$ and $\bar{\mathbf{s}}$ are described in terms of two engineering constants E and $\boldsymbol{\nu}$.

THERMAL:

We wish to determine the relationship:

$$\bar{\mathbf{q}} = <\mathbf{q}> = -\bar{\mathbf{K}}\cdot\overline{\nabla T} = -\bar{\mathbf{K}}\cdot <\nabla T>$$

$\bar{\mathbf{q}}$: heat flux $\quad$ $\overline{\nabla T}$: macro. temp. gradient $\quad$ $\bar{\mathbf{K}}$:effective cond.

WALL PROPERTIES

FLUID PERMEATION:

We wish to determine the relationship:

$$\bar{\mathbf{u}} = <\mathbf{u}> = -\frac{1}{\boldsymbol{\mu}}\bar{\mathbf{k}} \cdot \overline{\nabla \mathrm{p}} = -\frac{1}{\boldsymbol{\mu}}\bar{\mathbf{k}} \cdot <\nabla \mathrm{p}>$$

$\bar{\mathbf{u}}$: permeation speed

$\bar{\mathbf{k}}$: permeability tensor

$\boldsymbol{\mu}$: viscosity

$\overline{\nabla \mathrm{p}}$: pressure gradient

MEAN FIELDS:

$\bar{\boldsymbol{\psi}} = \frac{1}{\boldsymbol{\Omega}_{\mathrm{RVE}}}\int_{\boldsymbol{\Omega}} \boldsymbol{\psi}(\mathbf{r})\mathrm{d}\boldsymbol{\Omega}$; $\boldsymbol{\Omega}_{\mathrm{RVE}}$ volume of a representative volume element

- $\boldsymbol{\psi}(\mathbf{r})$: any scalar, vector or tensor field quantity.
- **An effective property** appears in the constitutive laws relating mean field variables.

WALL PROPERTIES

METHODS OF ANALYSIS:

- Dilute distributions (DD) of inhomogeneities:
  -- small volume fractions.

- Differential schemes (DS):
  -- applies to arbitrary volume fractions; numerically extensive.

- Self-consistent methods(SC):
  -- small volume fractions; involves n-point correlation integrals.

- Bounds: upper and lower:
  -- arbitrary volume fractions; relatively simpler.

- Simple Scaling laws

- Computer simulations.

IN ALL CASES, Microstructural (geometrical) features go into the analysis.

WALL PROPERTIES

EXAMPLE 2-D RESULTS:

Dilute Pore Distribution:

$$\frac{\bar{\mu}}{\mu} = \begin{cases} [1+f(\boldsymbol{\kappa}+1)]^{-1} \\ 1-f(k+1) \end{cases} \qquad \frac{\bar{\boldsymbol{\kappa}}}{\boldsymbol{\kappa}} = \begin{cases} \left\{1+f\,\dfrac{2(\boldsymbol{\kappa}+1)}{\boldsymbol{\kappa}}\right\}\{1+f(\boldsymbol{\kappa}+1)\}^{-1} & \text{(traction B.C.)} \\ \left\{1-f\,\dfrac{(\boldsymbol{\kappa}+1)(\boldsymbol{\kappa}^2-2\boldsymbol{\kappa}+2)}{\boldsymbol{\kappa}(\boldsymbol{\kappa}-1)}\right\} & \text{(displ. B.C.)} \end{cases}$$

where $\quad \boldsymbol{\kappa} = \begin{cases} 3-4\boldsymbol{\nu} & \text{plane strain} \\ (3-\boldsymbol{\nu})/(1+\boldsymbol{\nu}) & \text{plane stress} \end{cases}$

Self-Consistent Method:

$$\frac{\bar{\mu}}{\mu} = (1-3f)\{1+f(\boldsymbol{\kappa}-2)\}^{-1} \qquad \frac{\bar{\boldsymbol{\kappa}}}{\boldsymbol{\kappa}} = \left\{1-f\,\frac{(\boldsymbol{\kappa}-2)}{\boldsymbol{\kappa}}\right\}\{1+f(\boldsymbol{\kappa}-2)\}^{-1}$$

WALL PROPERTIES

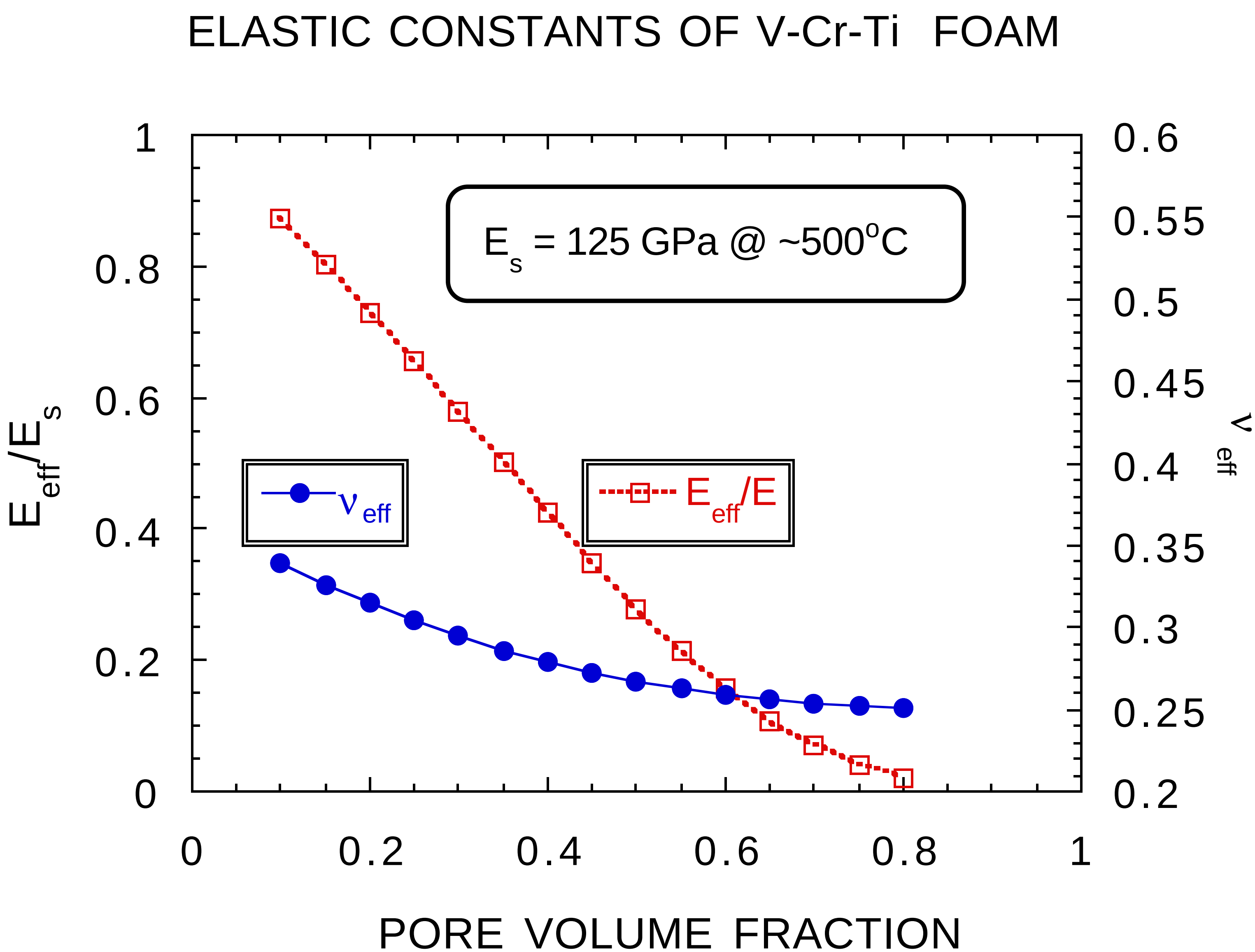
EXAMPLE 2-D RESULTS:

Differential Scheme:

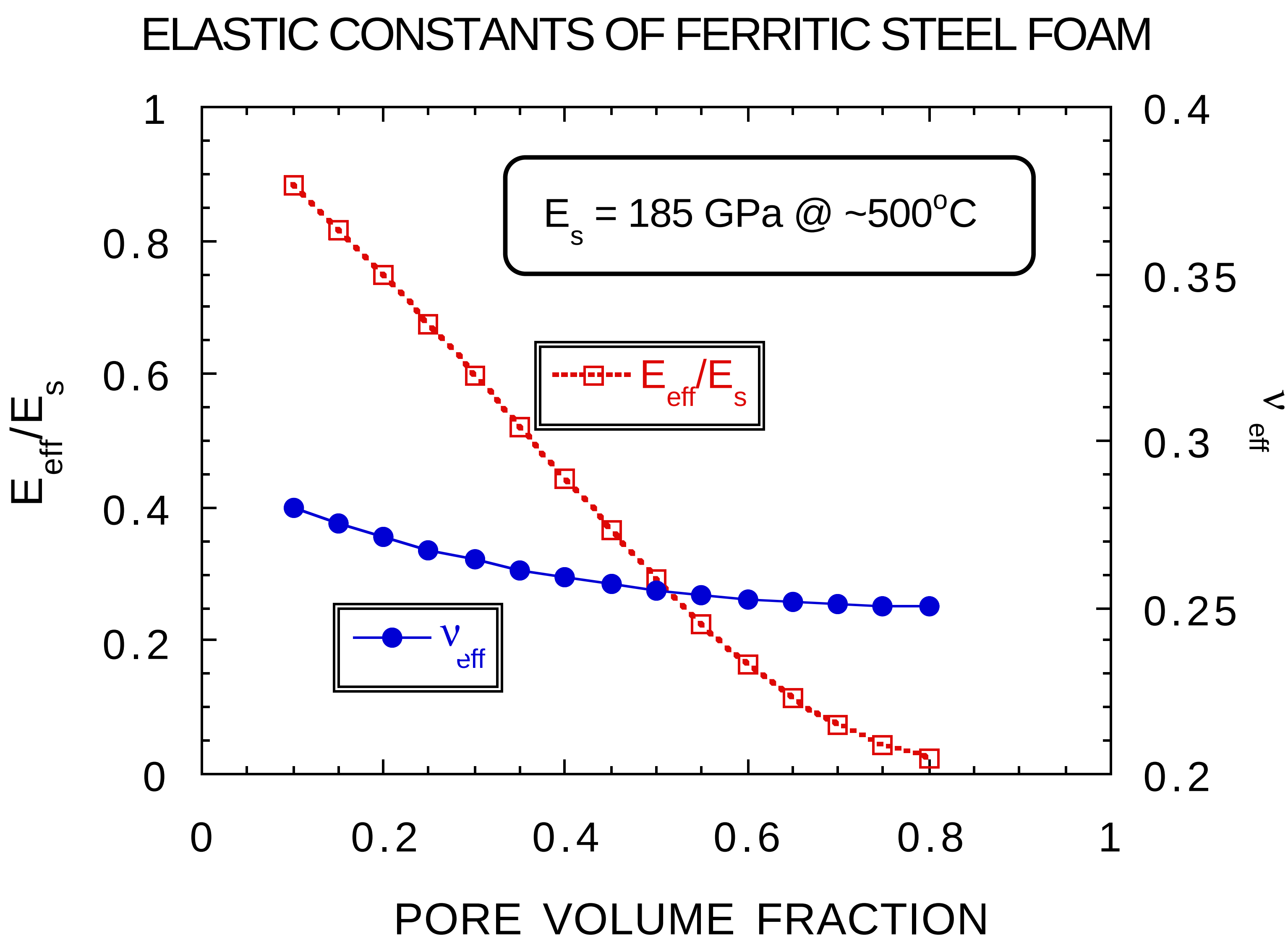
$$\frac{\bar{\boldsymbol{\mu}}}{\boldsymbol{\mu}} = \left\{1 + \frac{(\boldsymbol{\kappa}+1)}{3}\left[1-(1-f)^{-3}\right]\right\}^{-1}$$

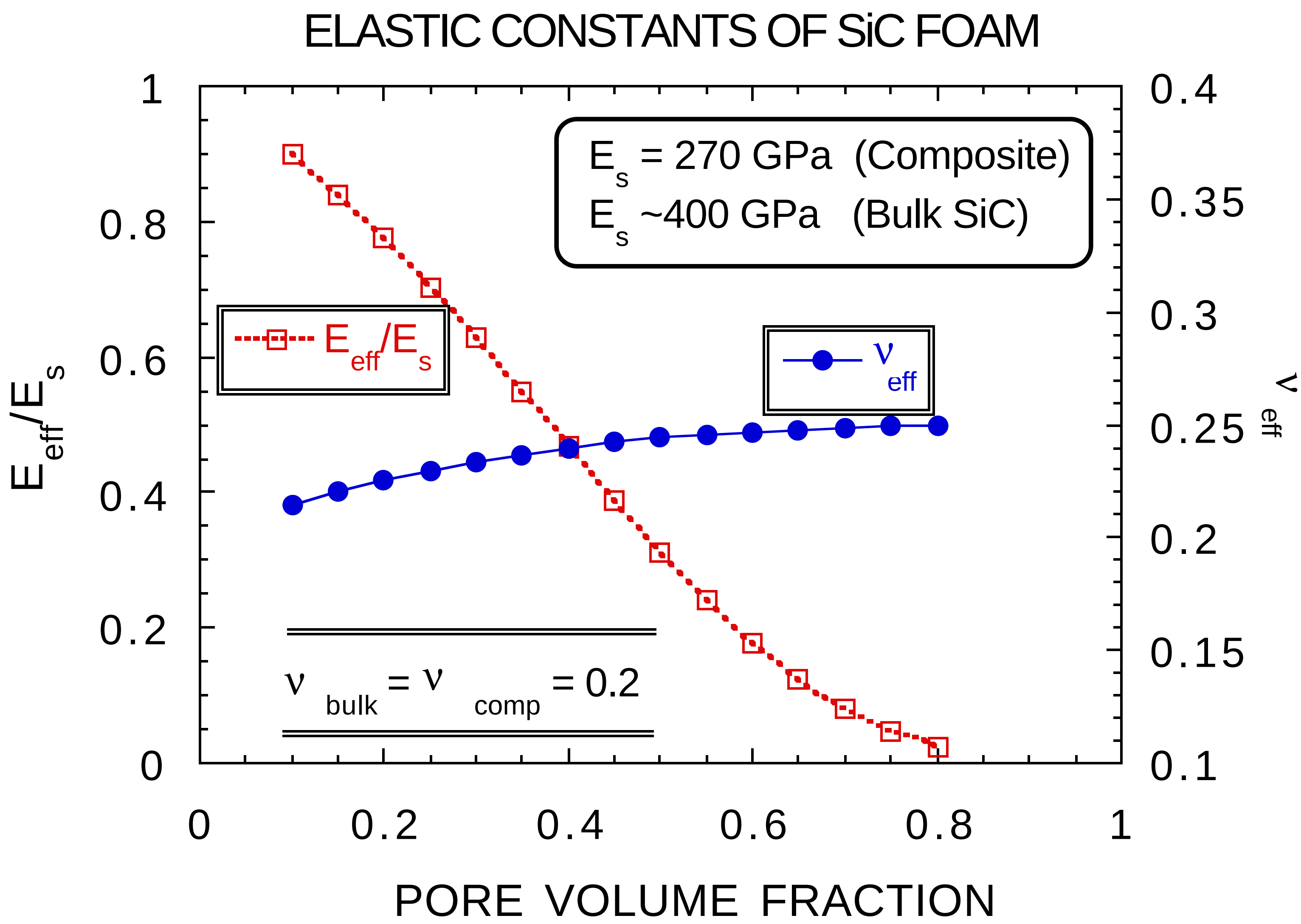
$$\frac{\bar{\boldsymbol{\kappa}}}{\boldsymbol{\kappa}} = \frac{(\boldsymbol{\kappa}+1)}{\boldsymbol{\kappa}}\left\{1 + \frac{(\boldsymbol{\kappa}+1)}{3}\left[1-(1-f)^{-3}\right]\right\}^{-1}(1-f)^{-3} - \frac{1}{\boldsymbol{\kappa}}$$

Here we report results for V-Cr-Ti, Ferritic steel and SiC (bulk and composite) mechanical properties using the **differential scheme**.



ELASTIC CONSTANTS OF V-Cr-Ti FOAM
E_s = 125 GPa @ ~500°C
ν_{eff}
E_{eff}/E
E_{eff}/E_s
ν_{eff}
PORE VOLUME FRACTION
0
0.2
0.4
0.6
0.8
1
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6


ELASTIC CONSTANTS OF FERRITIC STEEL FOAM
E_s = 185 GPa @ ~500°C
E_{eff}/E_s
ν_{eff}
PORE VOLUME FRACTION
0
0.2
0.4
0.6
0.8
1
0.25
0.3
0.35



ELASTIC CONSTANTS OF SiC FOAM
E_s = 270 GPa (Composite)
E_s ~400 GPa (Bulk SiC)
E_eff/E_s
ν_eff
ν_bulk = ν_comp = 0.2
E_eff/E_s
ν_eff
PORE VOLUME FRACTION
0
0.2
0.4
0.6
0.8
1
0.1
0.15
0.2
0.25
0.3
0.35
0.4

COMPOSITE

E for solid is based on fiber volume fraction of 40%.

If these calculations are to apply to SiC-SiC composites, then we are assuming that the solid in the foam still has the composition (40%fiber-60%matrix).

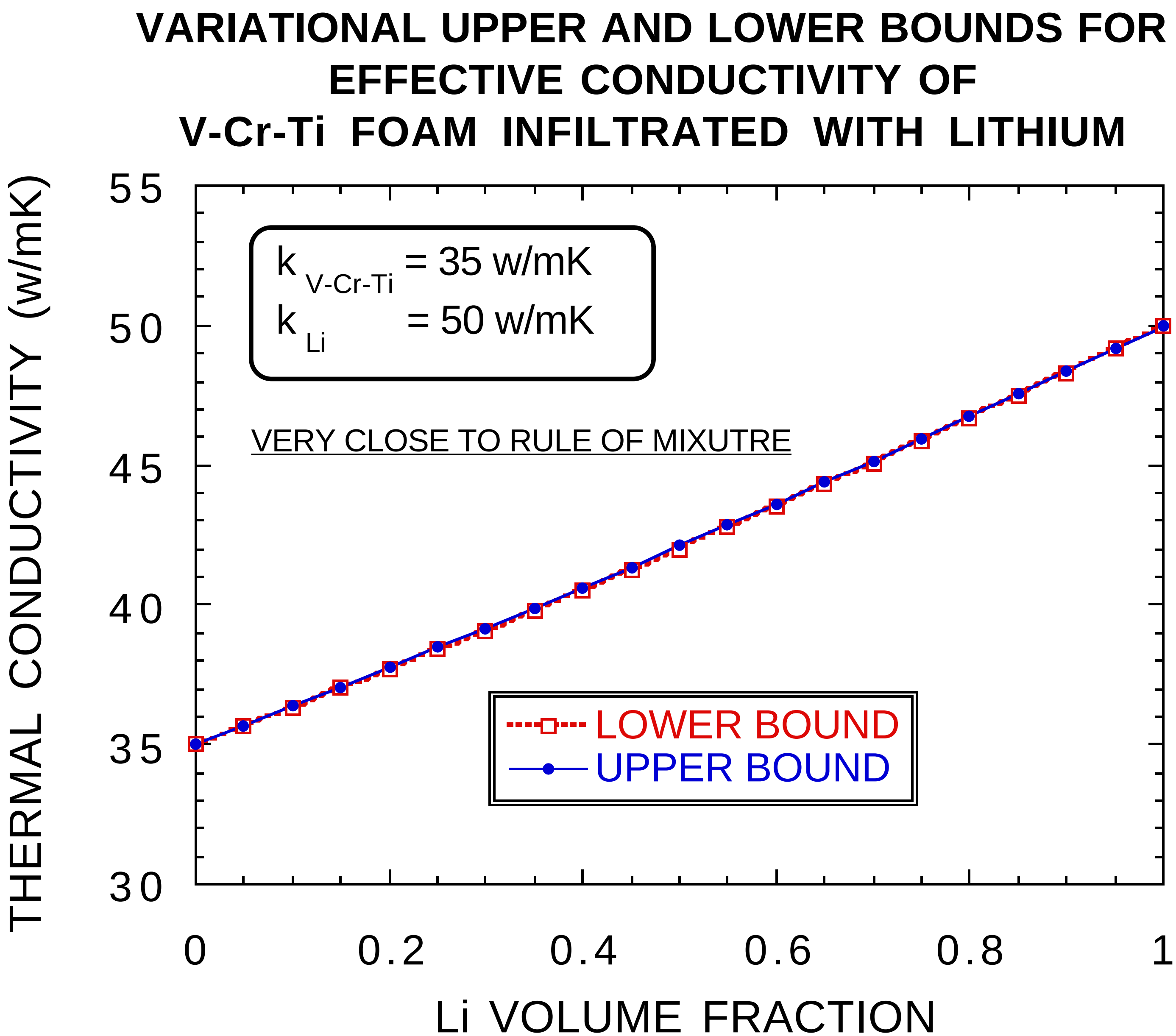
WALL PROPERTIES

EFFECTIVE CONDUCTIVITY:

VARIATIONAL BOUNDS:

$$k^L = k_1 + \frac{f_2}{\frac{1}{k_2 - k_1} + \frac{f_1}{3k_1}} \qquad\qquad k^U = k_2 + \frac{f_1}{\frac{1}{k_1 - k_2} + \frac{f_2}{3k_2}}$$

- for $k_2 > k_1$
- $k_1 = k_{V-Cr-Ti} = 35 \quad w/mK$ and $k_2 = k_{Li} = 50 \quad w/mK$



VARIATIONAL UPPER AND LOWER BOUNDS FOR
EFFECTIVE CONDUCTIVITY OF
V-Cr-Ti FOAM INFILTRATED WITH LITHIUM
k V-Cr-Ti = 35 w/mK
k Li = 50 w/mK
VERY CLOSE TO RULE OF MIXUTRE
LOWER BOUND
UPPER BOUND
THERMAL CONDUCTIVITY (w/mK)
Li VOLUME FRACTION
55
50
45
40
35
30
0
0.2
0.4
0.6
0.8
1

NEAR-FUTURE WORK

- Calculation of mechanical behavior of foams past elastic limit.
- Determination of stress limits of foams based on (available) experimental data and models.
- Radiation and nuclear heat deposition.
- Thermomechanical/Fluid flow models and calculations.
- Calculation of NWL limits for the present concept.