NEW CONCEPTS FOR HIGH-POWER-DENSITY ENERGY EXTRACTION SYSTEMS

Nasr M. Ghoniem

Mechanical and Aerospace Engineering Department
University of California, Los Angeles (UCLA)
Los Angeles, CA. 90095-1600

APEX Meeting
UCLA

January 12, 1998

COOLING CAPABILITIES FOR V/Li & SiC/LiPb

Reactor Surface Area $= 1000\ m^2$
Neutron Wall Load $= 5\ MW/m^2$

Calculations:

Porosity: $\eta = (\rho/\rho_s)$
Permeability: $K = A\, d^2\, (1-\eta)^{3/2}$
Evaporation Rate

$$q'' = \dot{m}\, h_{fg}$$

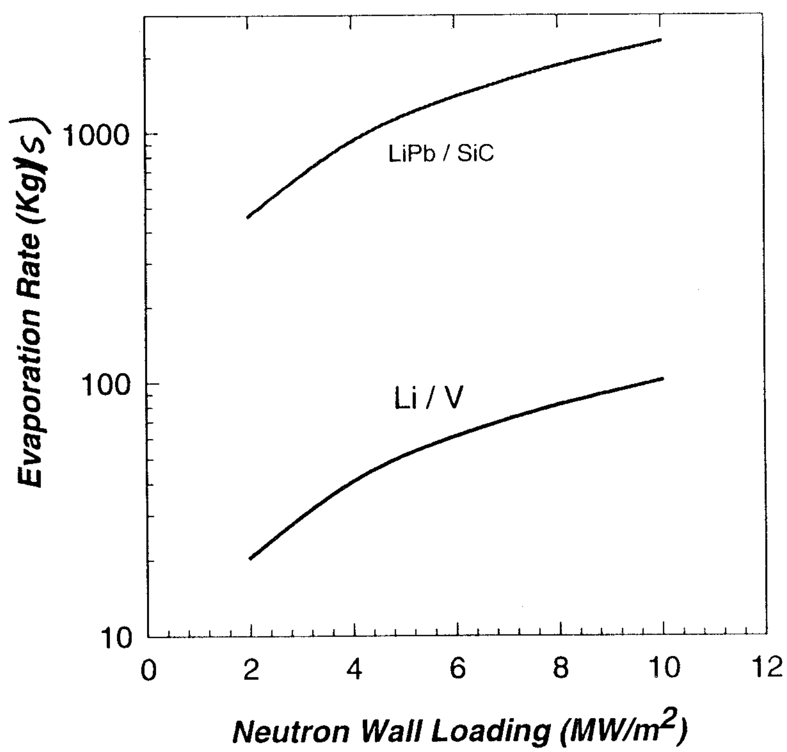
Exit Fluid Velocity: $u = (dm/dt)/\rho$

Darcy's Law: $$u = -\frac{K}{\mu}\frac{dP}{dx}$$

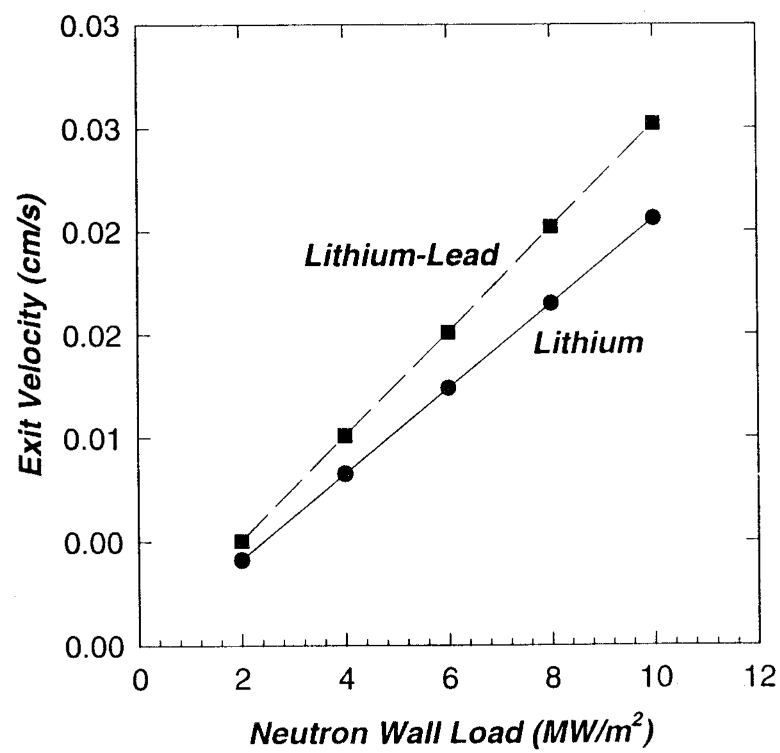
Property	V/ Li System	SiC/LiPb System
Hfg (MJ/Kg)	19.6	0.862
Viscosity (Ns/m2)	0.003675	0.0147
ΔX (m)	0.003	0.003
Density (Kg/m^3)	495	9200
PPI	120	120
Permeability (m^2)	1.16E-08	1.16E-08

Fractional Density	0.25	0.25
Diameter (m)	0.000212	0.000212
Evaporation Rate (Kg/s)	51	1160
Pressure Drop (Pa)	0.11	1.05
Exit Velocity (cm/s)	1.03E-02	1.26E-02

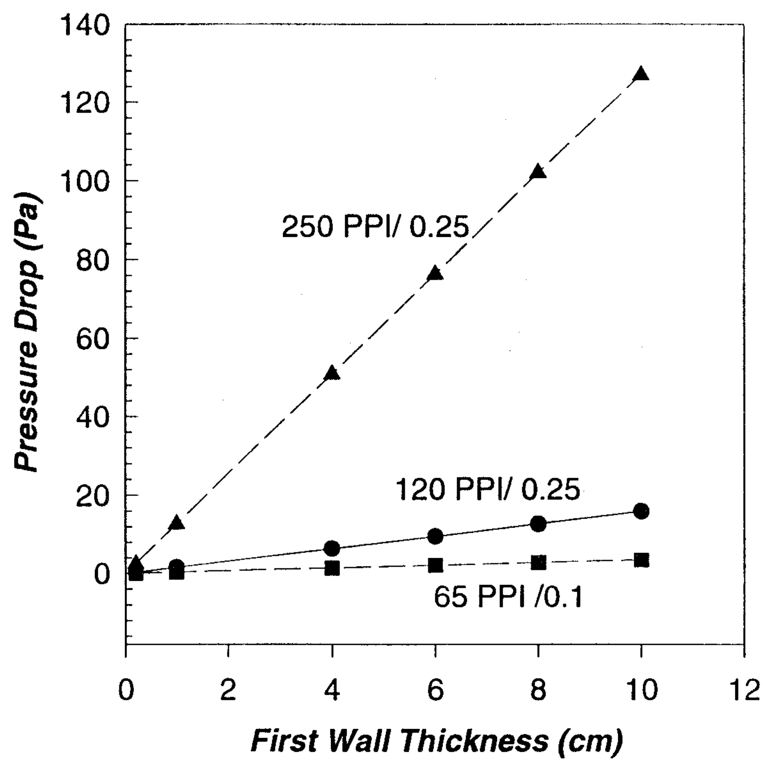
Estimated Evaporation Rates for Li/V and LiPb/SiC Systems (1000 m^2)



Fluid Exit Velocity (cm/s)
for Li and LiPb



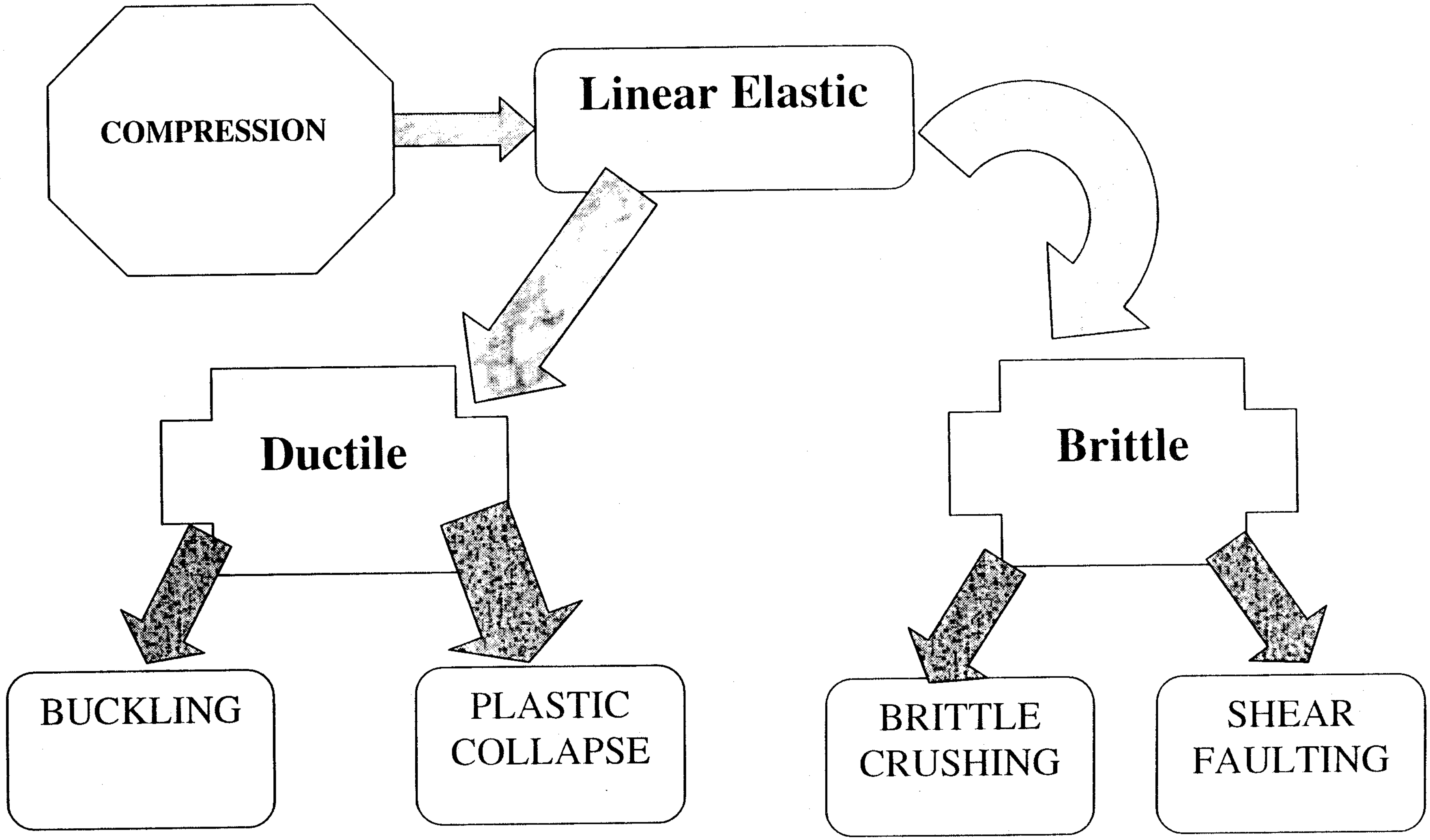
Pressure Drop on the First Wall
as Function of Wall Thickness

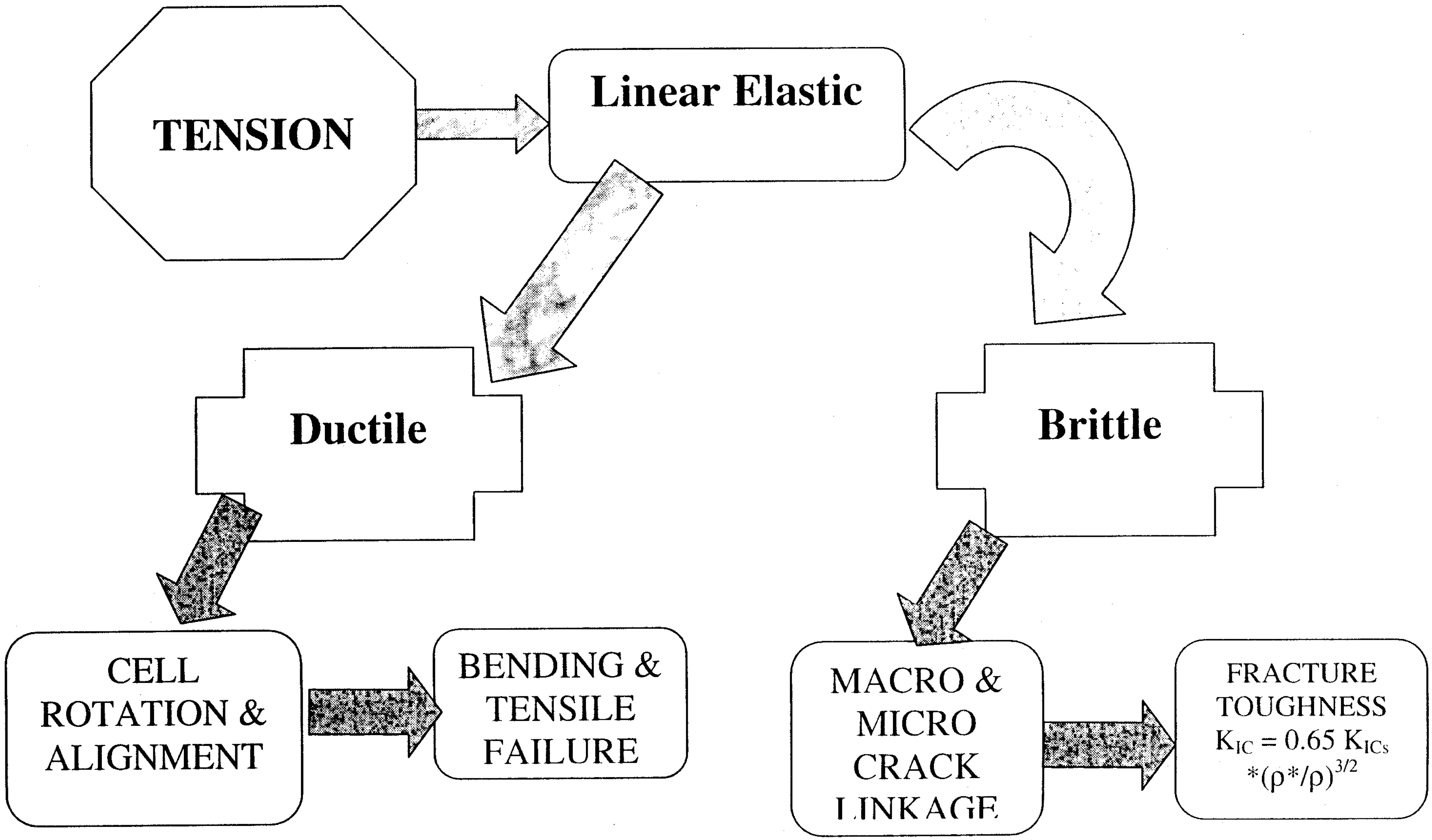


4. MANUFACTURING OF STRUCTURAL FOAMS

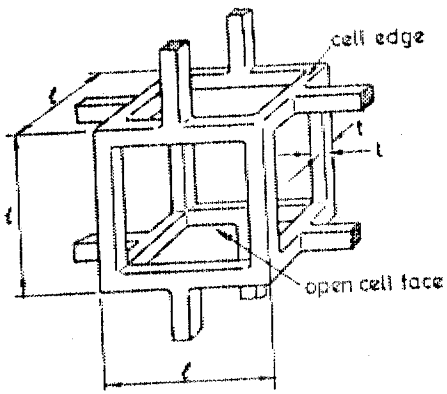
- Form Vapor Pre-cursors
- Transport to Polyurethane Substrate
- Pyrolize Polyurethane and form a thin graphitic skeleton structure
- Cause Reaction/ Deposition of desired elements on the graphitic skeleton
- Exhaust Reaction Products
- Vanadium is deposited from the thermal decomposition of its iodide
- The iodide is vaporized in vacuum at 700 – 1000 °C
- Vanadium diiodide can be prepared from either vanadium carbide or a vanadium metal sponge, prepared by reducing VCl_4 or VCl_2 with magnesium.

5. FOAM MECHANICAL BEHAVIOR

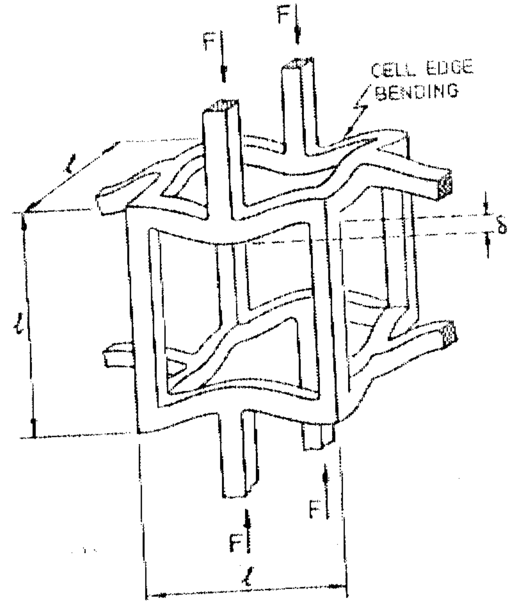



TENSION
Linear Elastic
Ductile
Brittle
CELL ROTATION & ALIGNMENT
BENDING & TENSILE FAILURE
MACRO & MICRO CRACK LINKAGE
FRACTURE TOUGHNESS $K_{IC} = 0.65\ K_{ICs} *(\rho^*/\rho)^{3/2}$

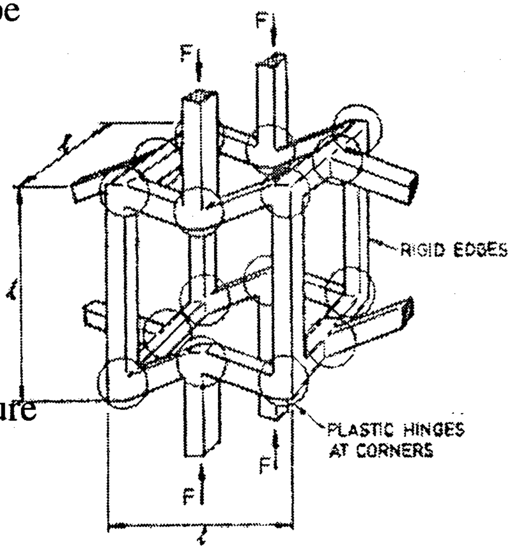
POSSIBLE FAILURE MODES IN CELLULAR FOAM STRUCTURES



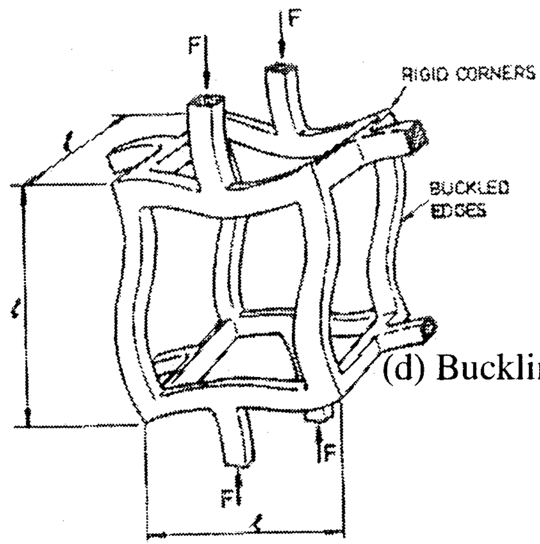
(a) Un-deformed Shape



(b) Bending-Type Deformation

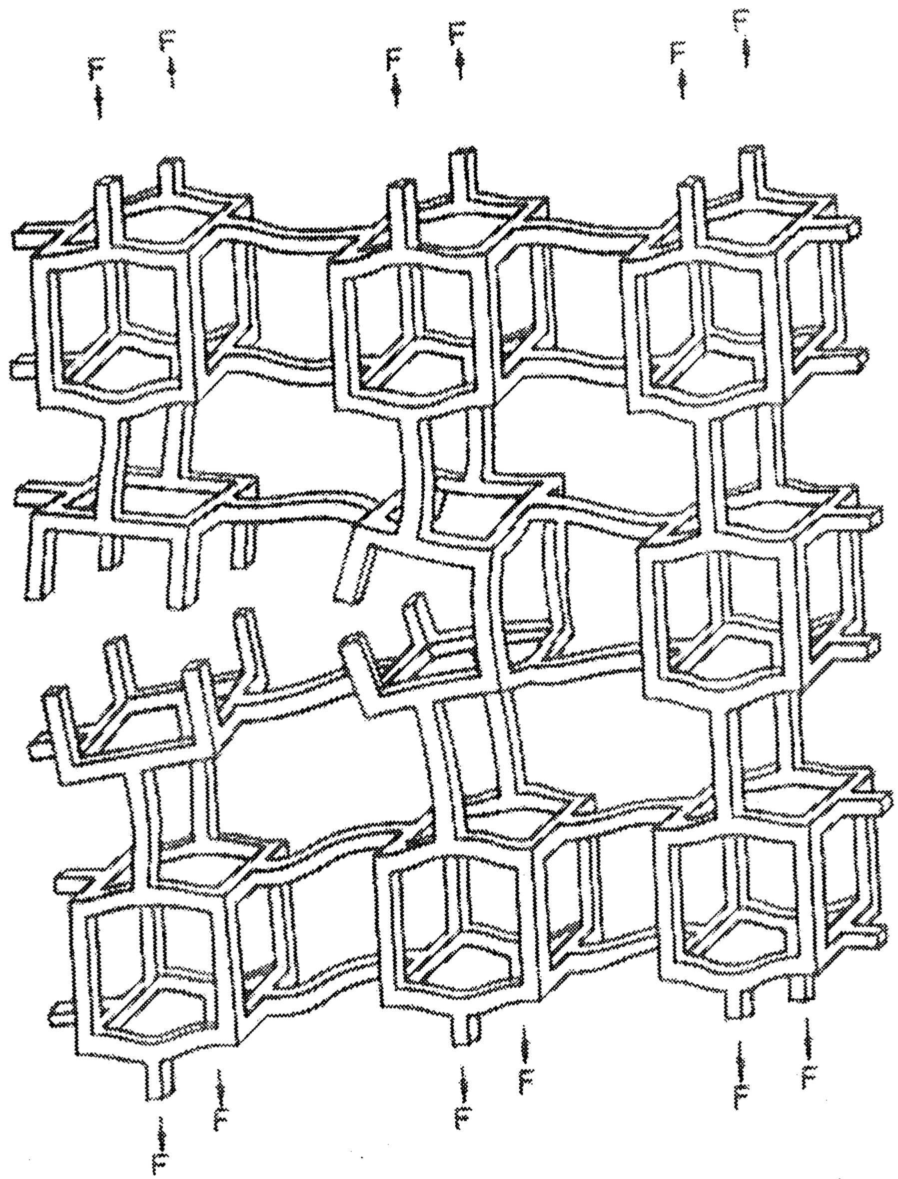


(c) Plastic Hinge Failure

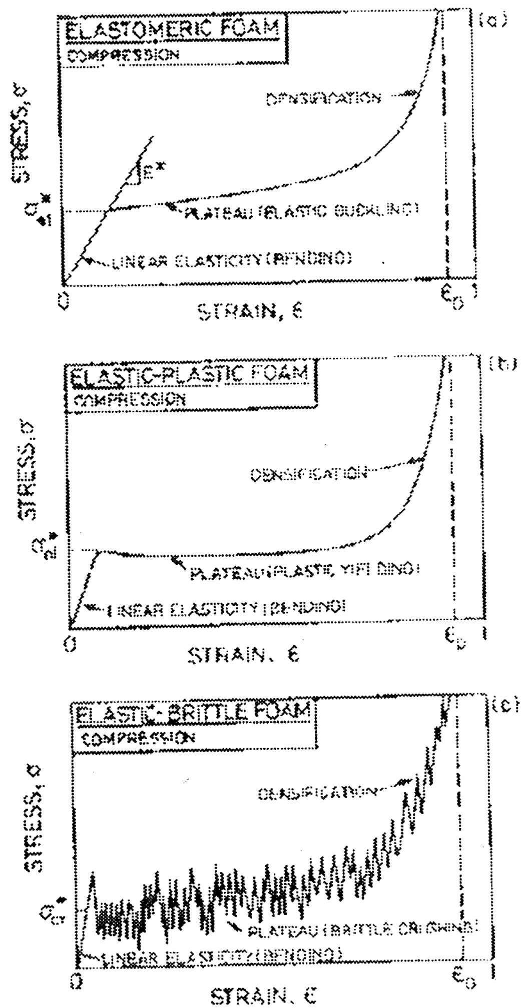


(d) Buckling-type Failure

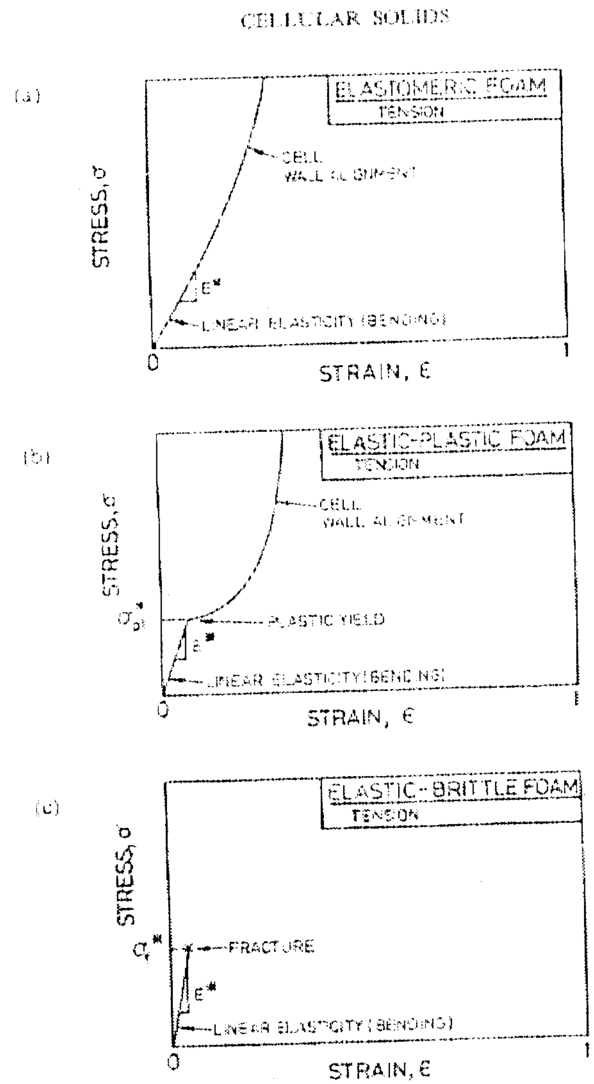
OUTLINE



Crack Propagation in Brittle Cellular Solids



Stress-Strain Behavior in Compression



Stress-Strain Behavior in Tension

SCALING RELATIONSHIPS FOR MECHANICAL PROPERTIES

I. Elastic Constants: Let the fractional density be $\eta = \dfrac{\rho}{\rho_s}$

$$\boxed{E = C_1 E_s \eta^2 \qquad G = C_2 G_s \eta^2, \; C_1 \cong 1, \; C2 \cong 3/8, \; \nu = \left(\frac{C_1}{2C_2} - 1\right)}$$

II. Densification Strain:

$$\varepsilon_D = 1 - 1.4\,\eta$$

III. Plastic Collapse Strength (Metals):

$$\sigma_{pl} = C_3 \sigma_{ys} \eta^{3/2} (1 + \sqrt{\eta})$$

IV. Brittle Crushing Strength (Ceramics):

$$\boxed{\sigma_{cr} = C_4 \sigma_{fs} \eta^{3/2}}, \; C_4 \cong 0.65$$

$$\boxed{\sigma_{fs} = \frac{Y K_{ICs}}{\sqrt{\pi a}}}$$, Y = Geometry factor, K_{ICs}= solid fracture strength, a= flaw size

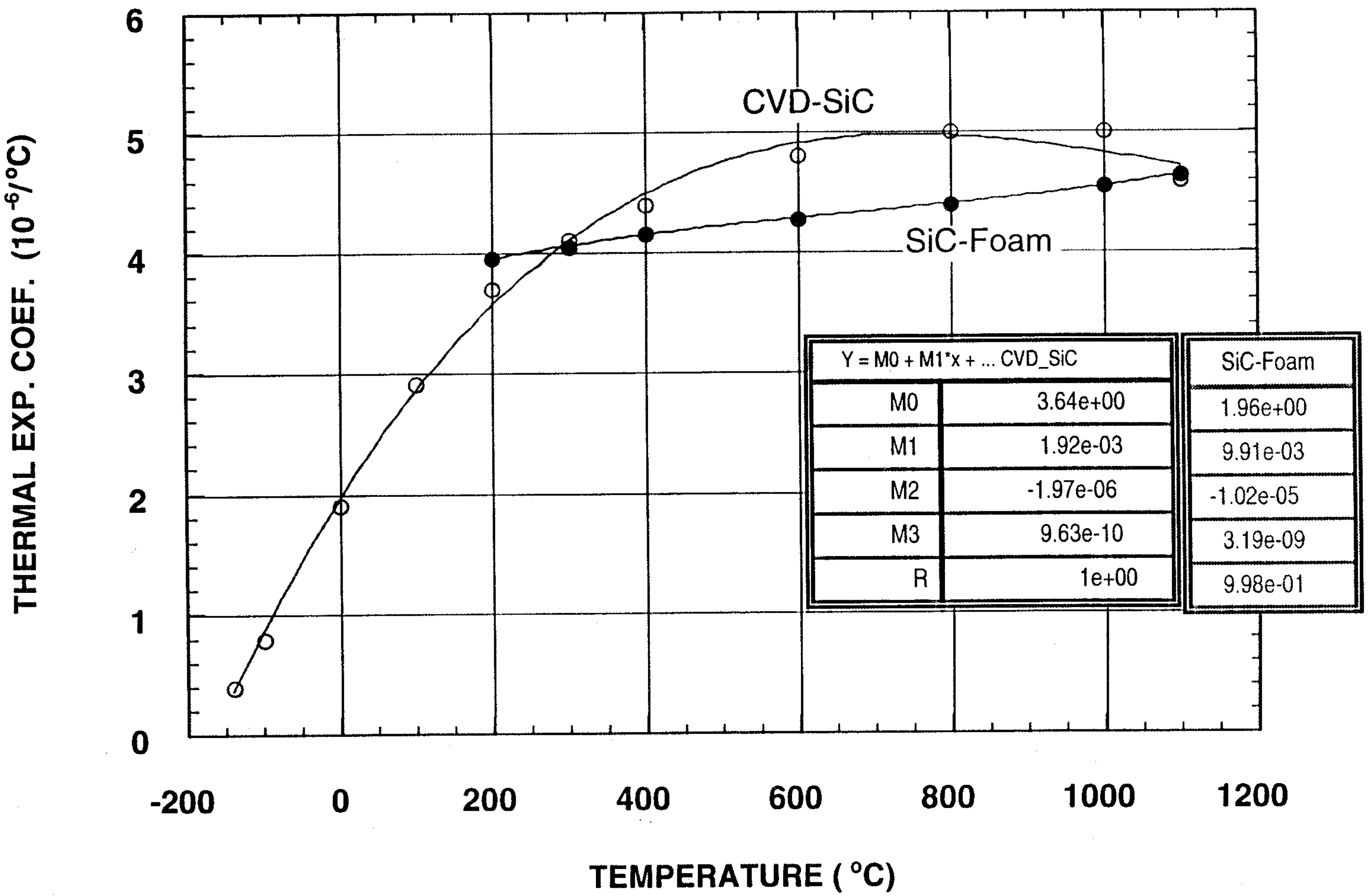
V. Fluid Effects:

Internal Fluids will add another contribution to the strength due to " side-squeezing" effects.

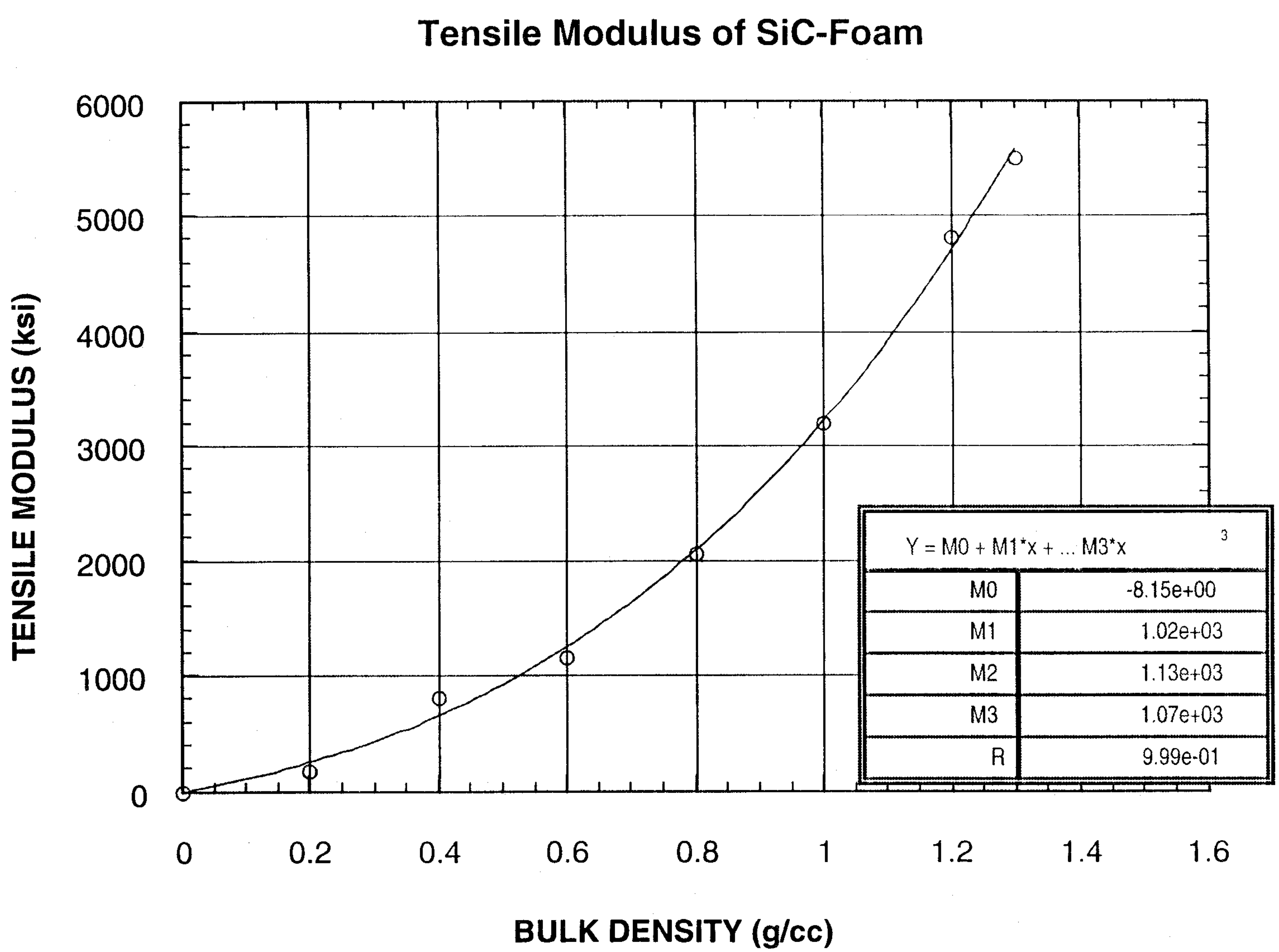
$$\boxed{\sigma_f = \frac{C \mu \dot{\varepsilon}}{1-\varepsilon} \left(\frac{L}{l}\right)^2}$$

C = Constant, μ= viscosity, ε = strain, $\dot{\varepsilon}$ = strain rate, L = FW thickness, l = pore size.

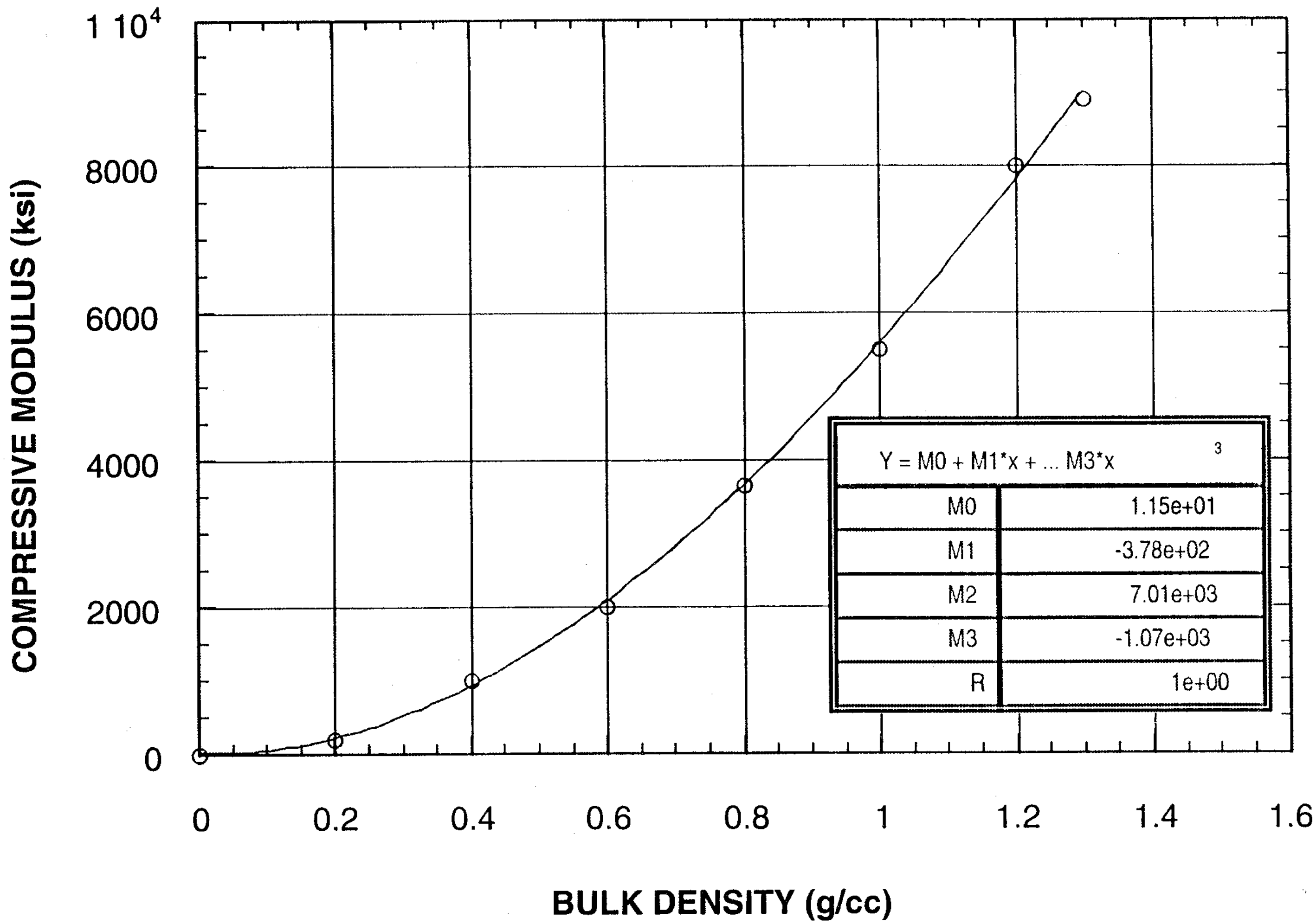
COEFFICIENT OF THERMAL EXPANSION OF CVD-SiC AND SiC-FOAM



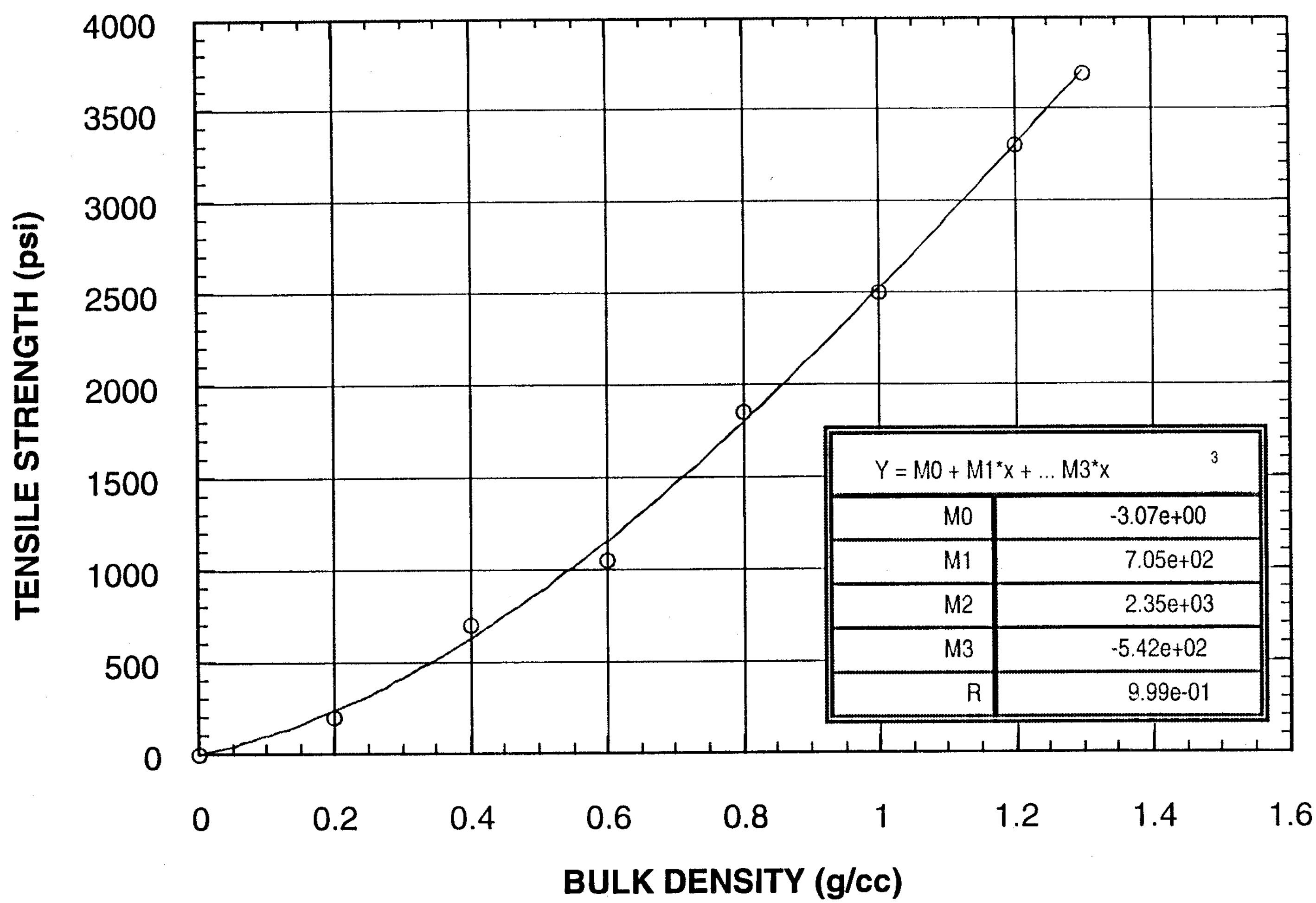
Y = M0 + M1*x + ...	CVD_SiC	SiC-Foam
M0	3.64e+00	1.96e+00
M1	1.92e-03	9.91e-03
M2	-1.97e-06	-1.02e-05
M3	9.63e-10	3.19e-09
R	1e+00	9.98e-01


Tensile Modulus of SiC-Foam
TENSILE MODULUS (ksi)
6000
5000
4000
3000
2000
1000
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
BULK DENSITY (g/cc)
Y = M0 + M1*x + ... M3*x 3
M0 -8.15e+00
M1 1.02e+03
M2 1.13e+03
M3 1.07e+03
R 9.99e-01

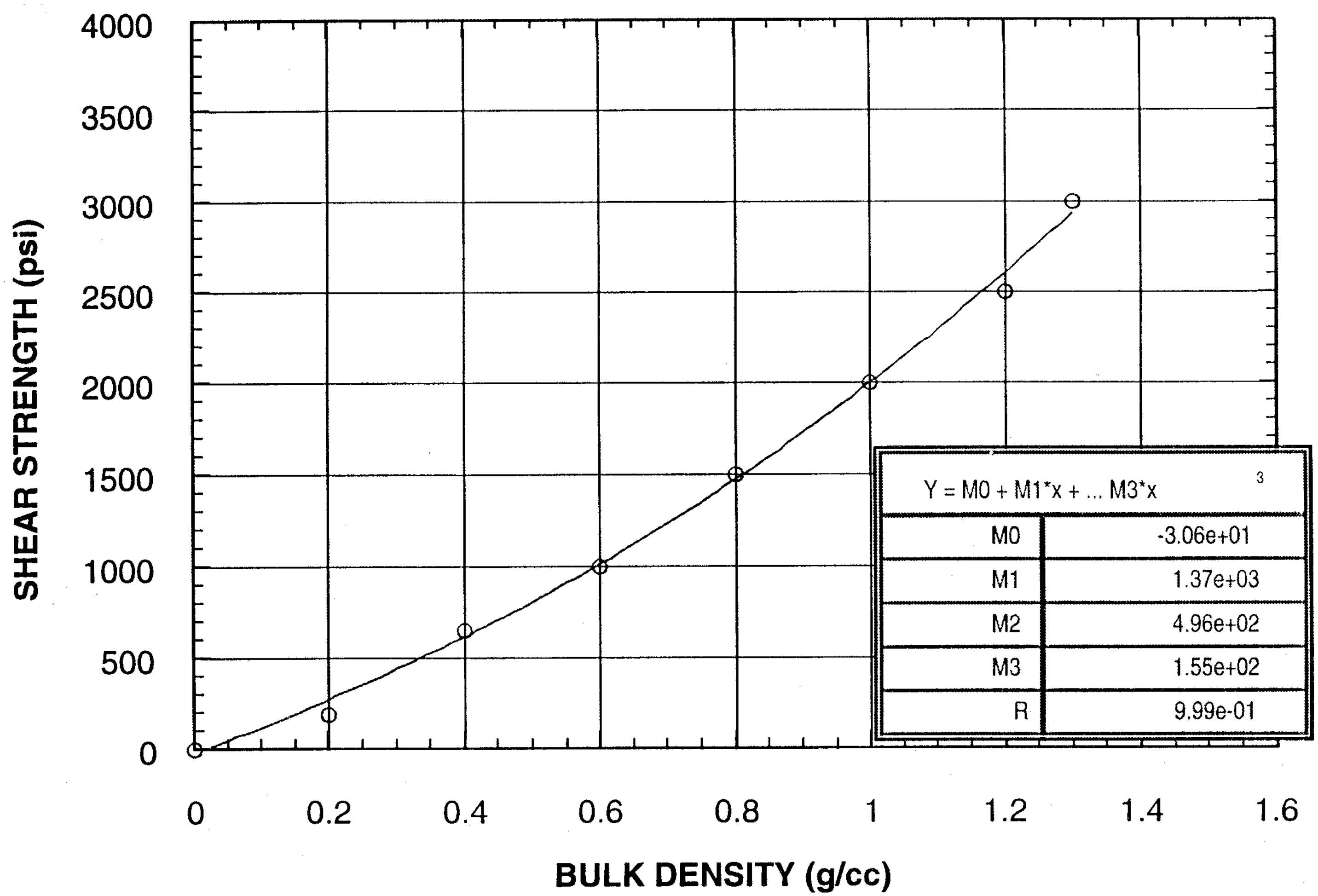
Compressive Modulus of SiC-Foam



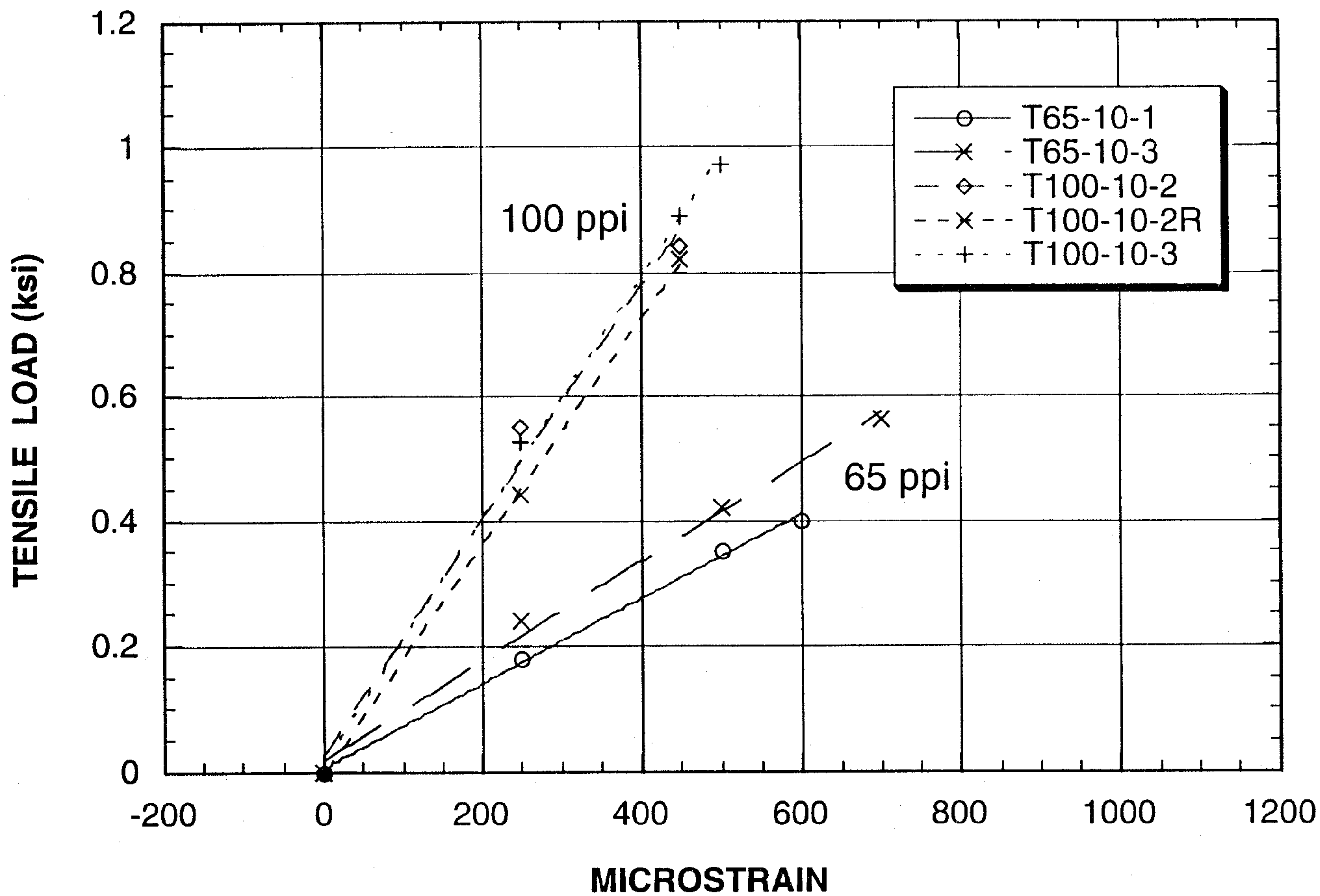
Tensile Strength of SiC-Foam



Shear Strength of SiC-Foam



Tension Data for 10% dense SiC-Foam with 65 and 100 ppi



1. LIMITATIONS OF PRESENT CONCEPTS

$\Gamma_n \cong 5\, q''$ MW/m^2 , $q'' \cong k\, \Delta T / \Delta x$, $\sigma \cong 1.5\, \alpha\, E\, \Delta T$

Solve for $\sigma \cong S_{mt} \Rightarrow\Rightarrow\Rightarrow \Gamma_n = (3.3\, k\, S_{mt})/(\alpha\, E\, \Delta x)$, $\Delta x = 3$ mm

	k (W/mK)	α	E (Gpa)	S_{mt} (Mpa)	T_{max} (°C)	Γ_n (MW/m^2)
Ferritics	26	1.18x10^{-5}	190	140	≈ 550	1.79
Vanadium	28	1.03x10^{-5}	118	120	≈ 700	3.04
SiC	6	0.30x10^{-5}	220	97.15	≈ 1000	0.97

2. STRUCTURAL FOAM / EVAPORATIVE LIQUID SYSTEMS

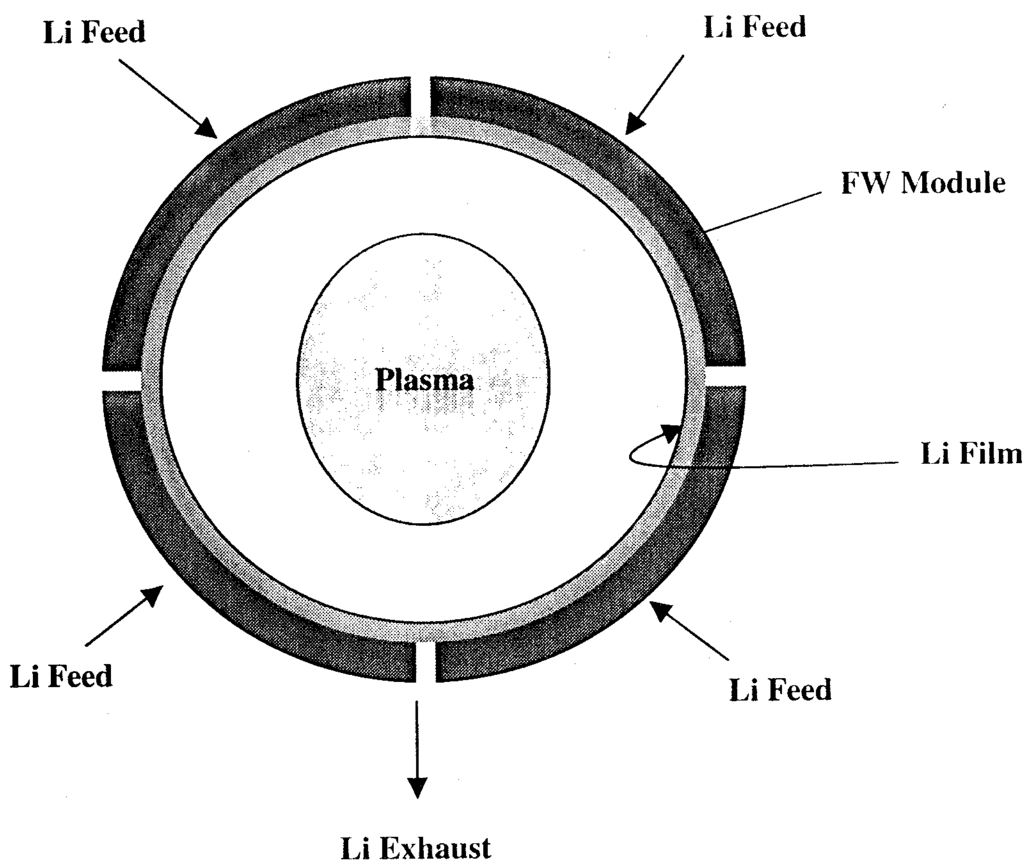
Possible Advantages:

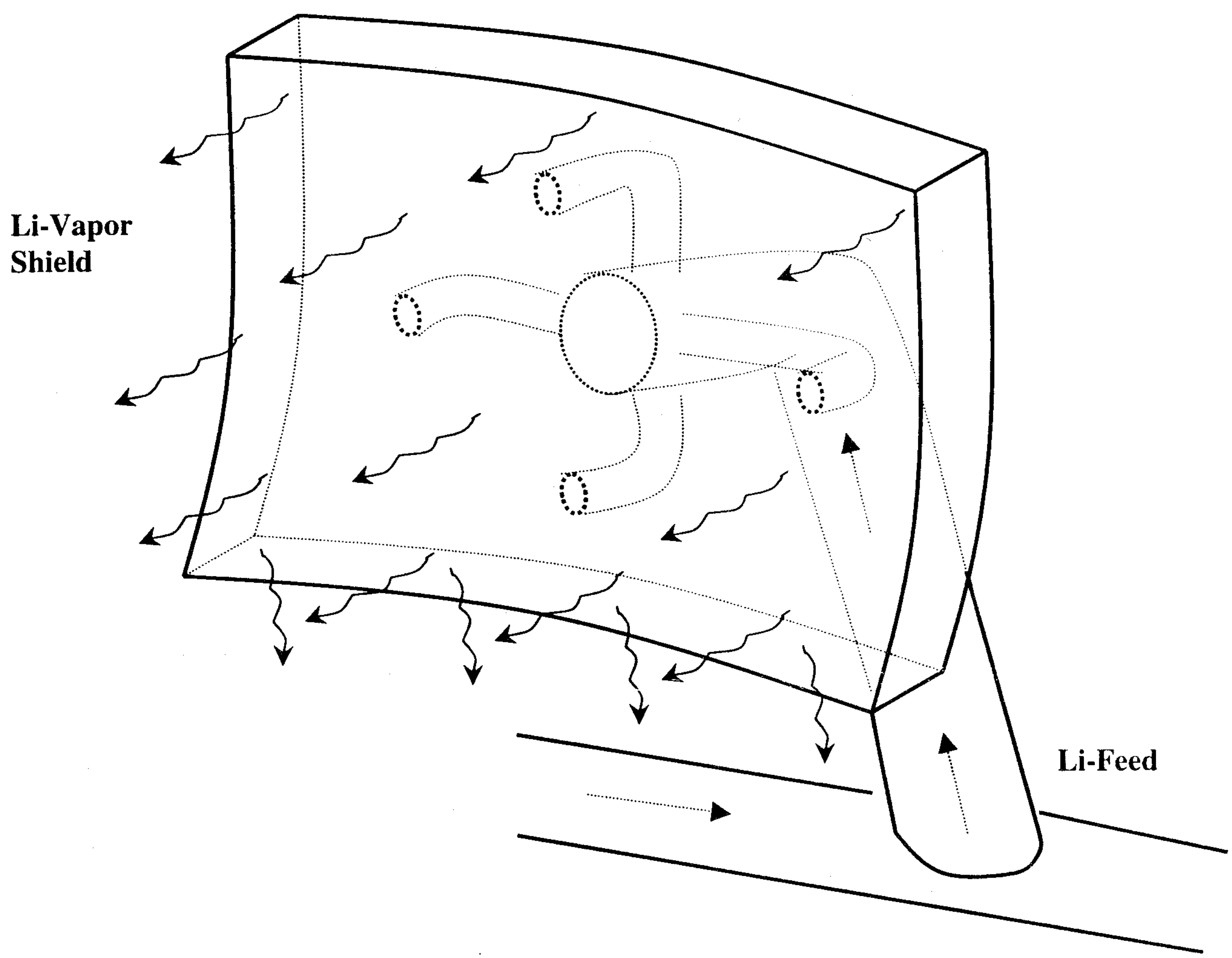
- Reduction of Thermal Stress Limitations.
- Increase in Maximum Operational Temperature.
- Minimal MHD effects.
- Accommodation of Inelastic Deformation (e.g. swelling & creep).
- Higher Reliability.
- High Power Density.
- Stable Thin Liquid Film.

Uncertainties:

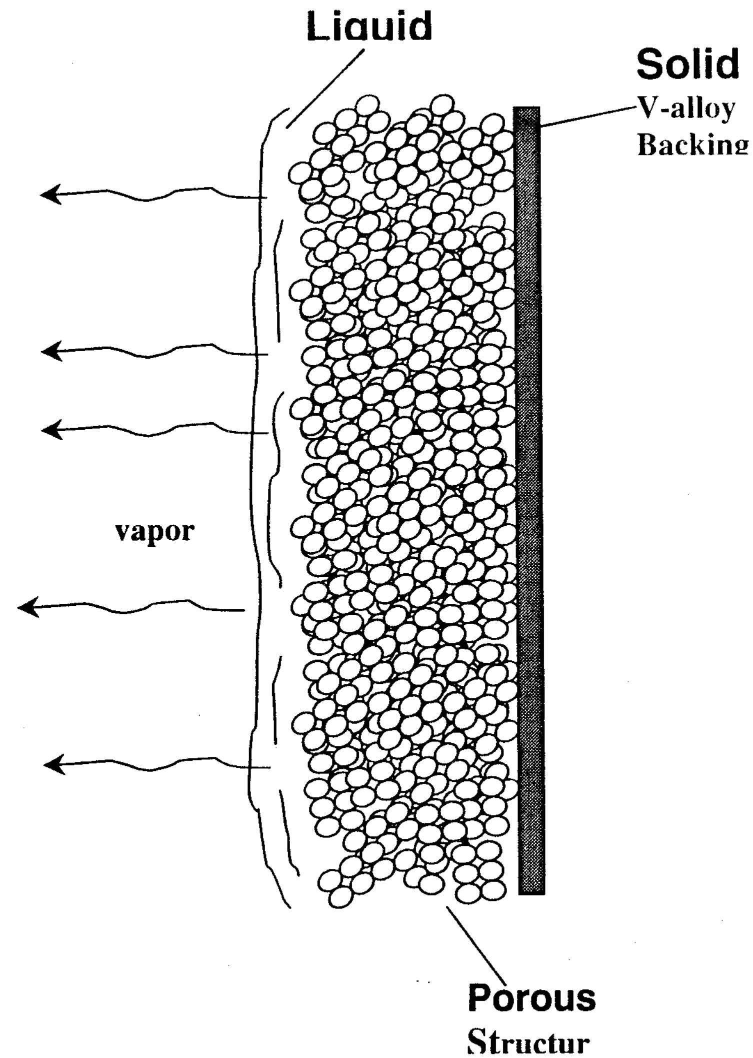
- Failure Modes under Irradiation.
- Pumping Power Requirements.
- Vacuum Requirements.
- Plasma Stability.

3. CONCEPT SCHEMATICS
First Wall Transpiration Cooling

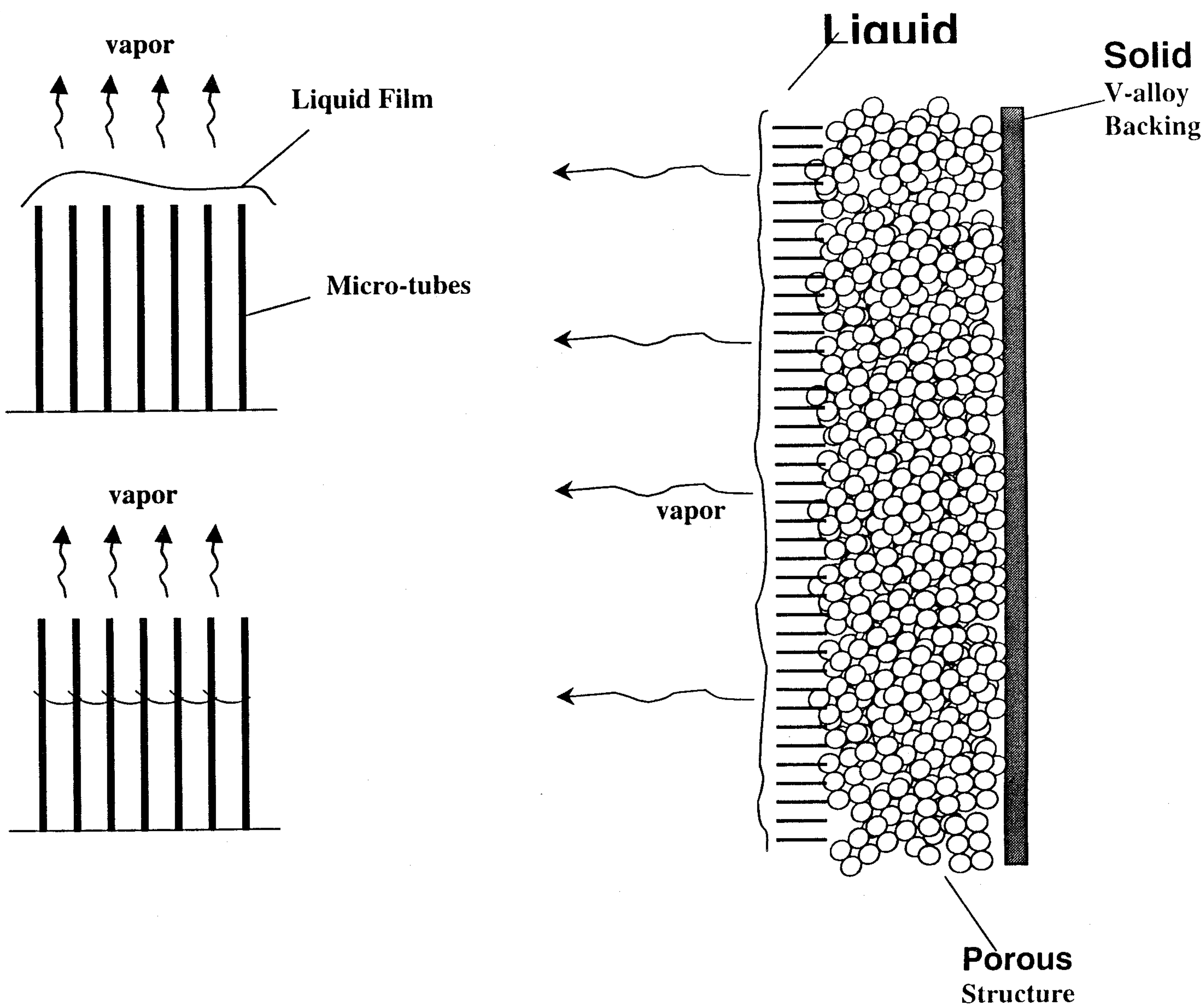



Li-Vapor
Shield
Li-Feed

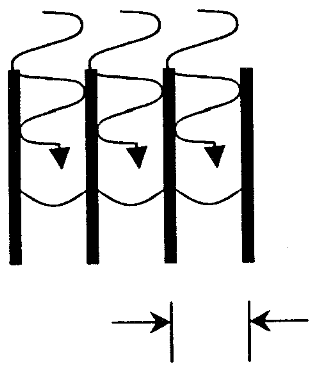
First Concept: Baseline Porous WetWall™



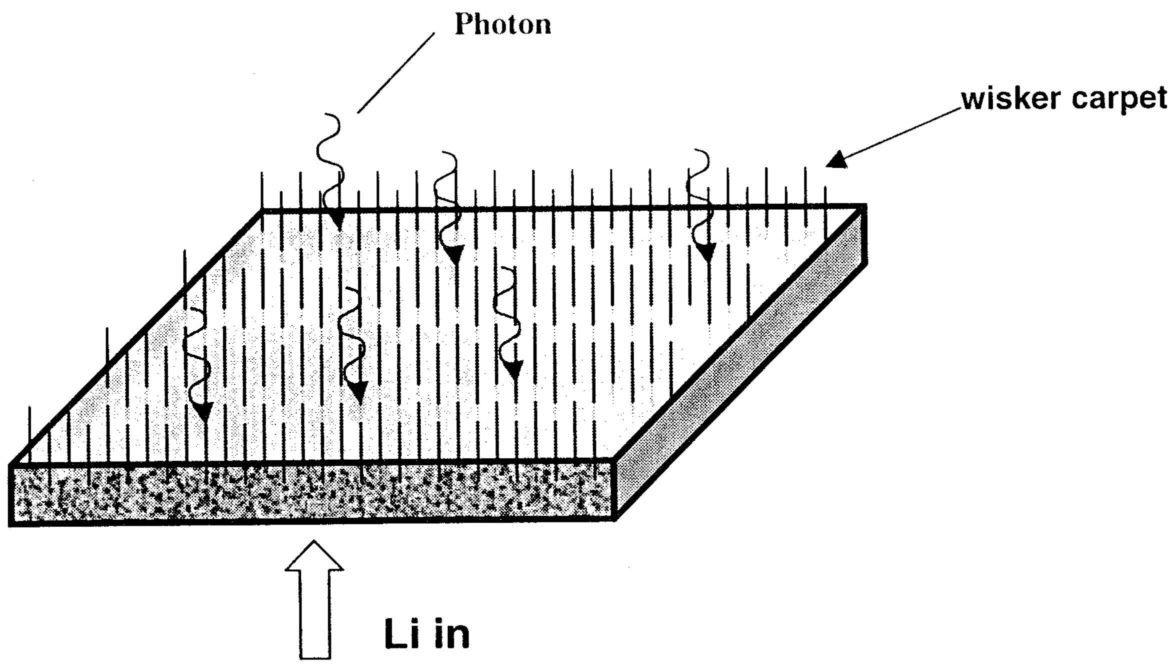
Second Concept: Micro-Tube Cooling (MicroCool™



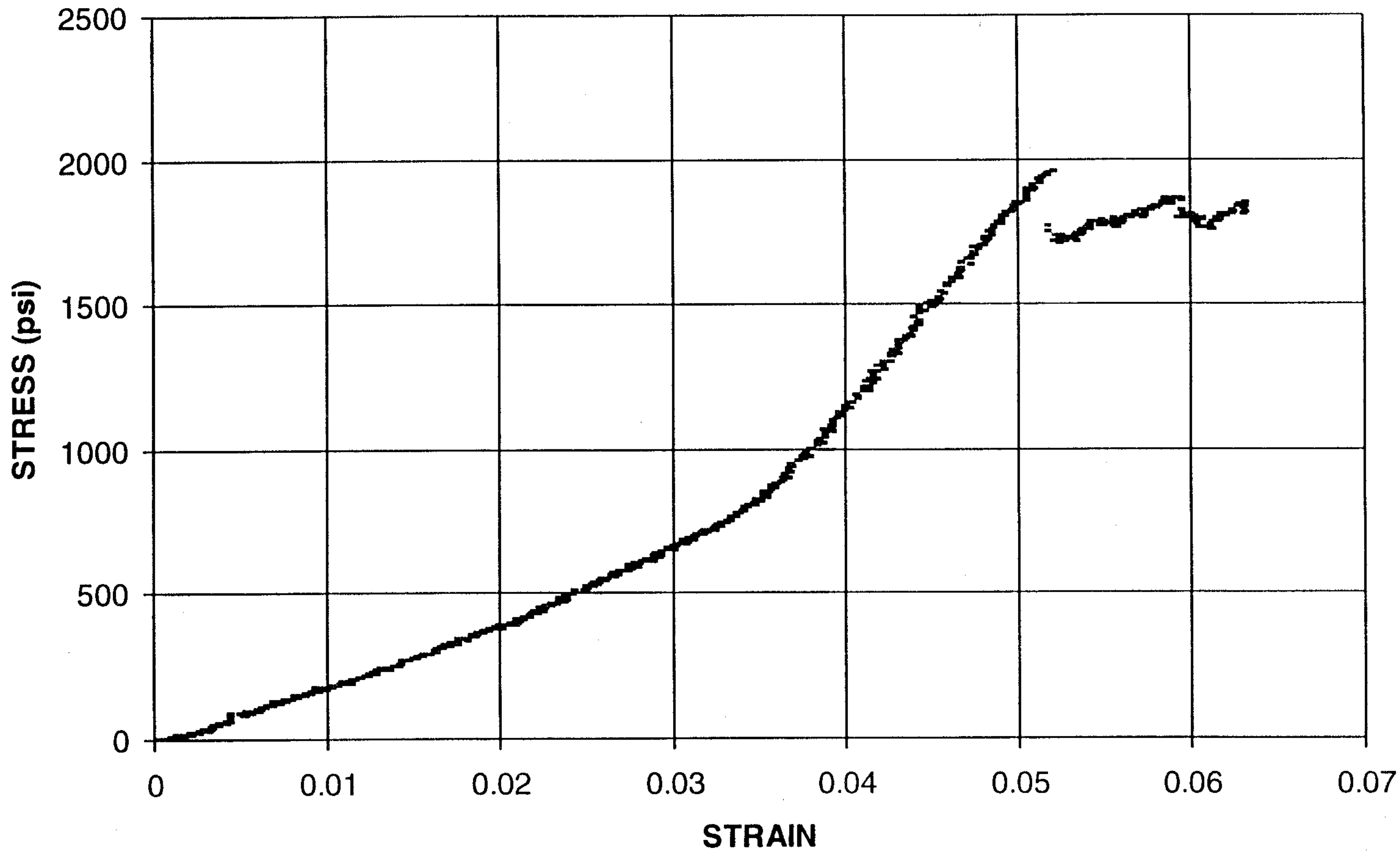
Third Concept: Thermal Waveguide (ThermoWave^{TM})



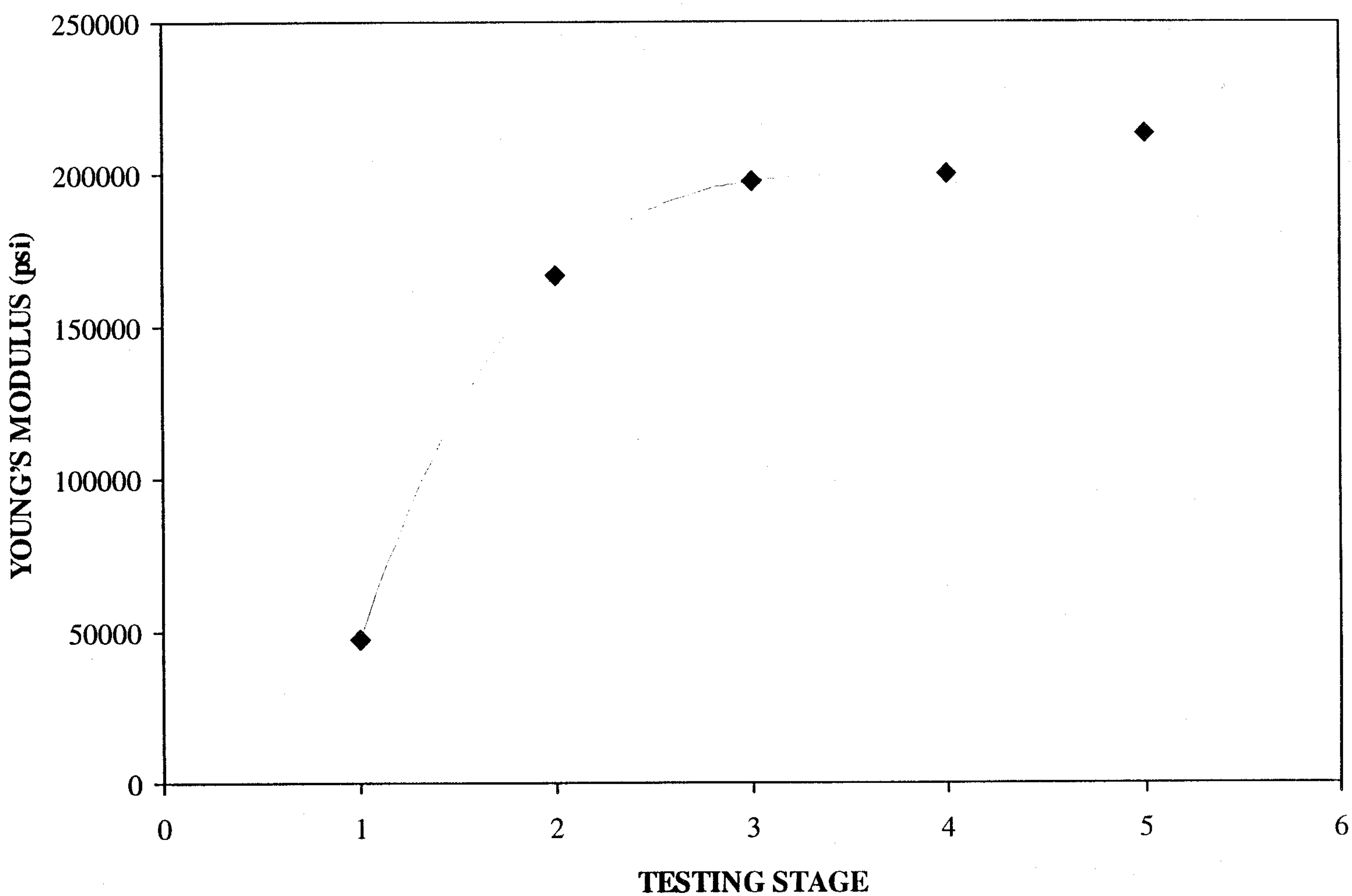
$D \approx \lambda = 10 - 100$ nm



Compression Stress-Strain Behavior of SiC Foam



AVERAGE YOUNG'S MODULUS



6. CONCLUSIONS

- **Utilization of a Foam/ liquid/ vapor system in first wall cooling seems to be feasible for high power density operation.**
- **The large energy stored in h_{fg} can be used in an evaporation/ condensation cycle.**
- **Condensation on a liquid metal divertor requires recycling of about 50 Kg/s for the entire reactor.**

- **Numerous advantages may be possible with our system: low-pressure drops (including MHD), high temperature limits for first wall operation, high power density.**
- **Limitations on power density will be determined by plasma physics and Li vapor pumping requirements.**