Some target and beam window challenges and limits

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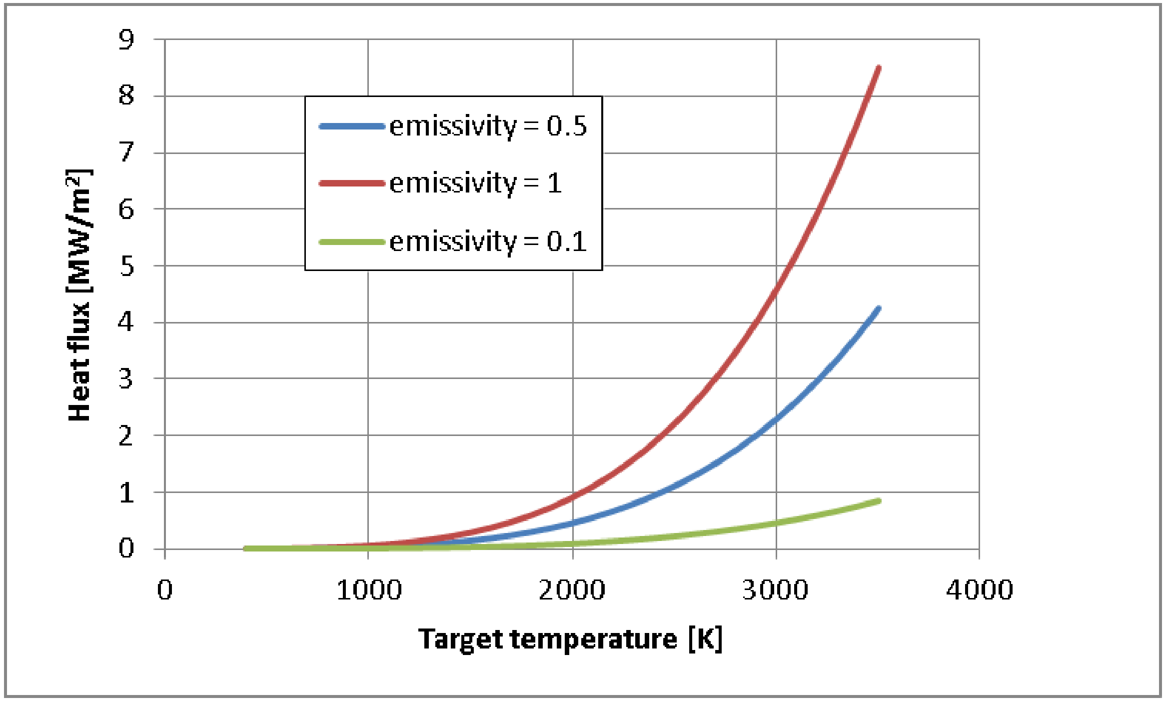
Conclusions

Radiation cooling

$$Q\left[\frac{W}{m^2}\right] = \sigma\varepsilon(T_H^4 - T_C^4)$$



High temperatures require refractory metals and also good vacuum quality to avoid target loss through oxidation and evaporation cycles

Forced Convection

Consider turbulent heat transfer in a 1.5mm diameter pipe – Dittus Boelter correlation

$$\mathrm{Nu}_D = 0.023\mathrm{Re}_D^{4/5}\mathrm{Pr}^n$$

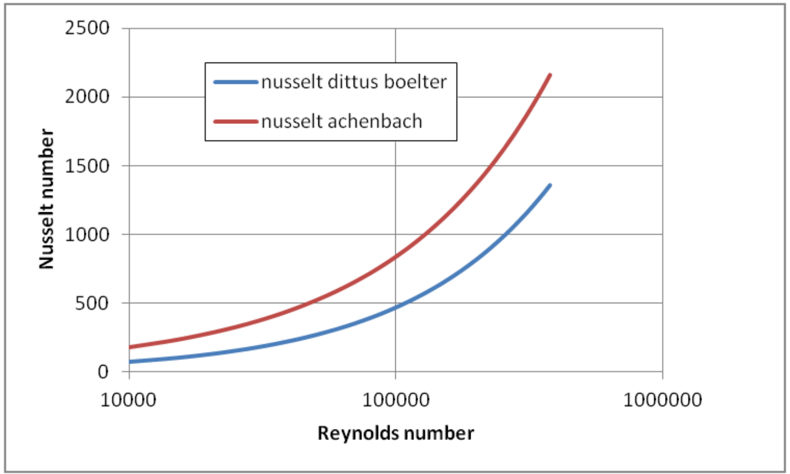
n=0.4 for fluid being heated

Valid for: $\mathrm{Re}_D \gtrsim 10\,000$ $\quad 0.6 \leq \mathrm{Pr} \leq 160$

	velocity [m/s] (Mach=0.3 for gases)	Pr	Re	Nu	heat transfer coefficient [W/m^{2}K]	allowable temp rise [K]	heat flux [MW/m^2]
air at 300K 1bar	100	0.72	11114	35	557	500	0.22
air at 300K at 10bar	100	0.73	111958	222	3558	500	1.4
helium at 300K at 1bar	300	0.67	4235	15	1516	500	0.6
helium at 300K at 10bar	300	0.67	42112	98	9520	500	3.74
helium at 1023K at 10 bar	560	0.68	8400	27	6514	500	2.56
water at 300K and 5bar	5	6.13	8823	68	26344	100	2.6
water at 300K and 5bar	10	6.13	17647	119	45868	100	4.6
water at 300K and 5bar	15 (erosion limited?)	6.13	26470	164	63444	100	6.3

Achenbach correlation for heat transfer in a packed bed of spheres

$$\mathrm{Nu} = \frac{\mathrm{hd}}{\mathrm{k_g}} = [(1.18\mathrm{Re}^{0.58})^4 + (0.23\mathrm{Re}^{0.75})^4]^{0.25}$$



Max power density for a sphere

$$\frac{Q}{V} = \frac{hA\Delta T}{V}$$

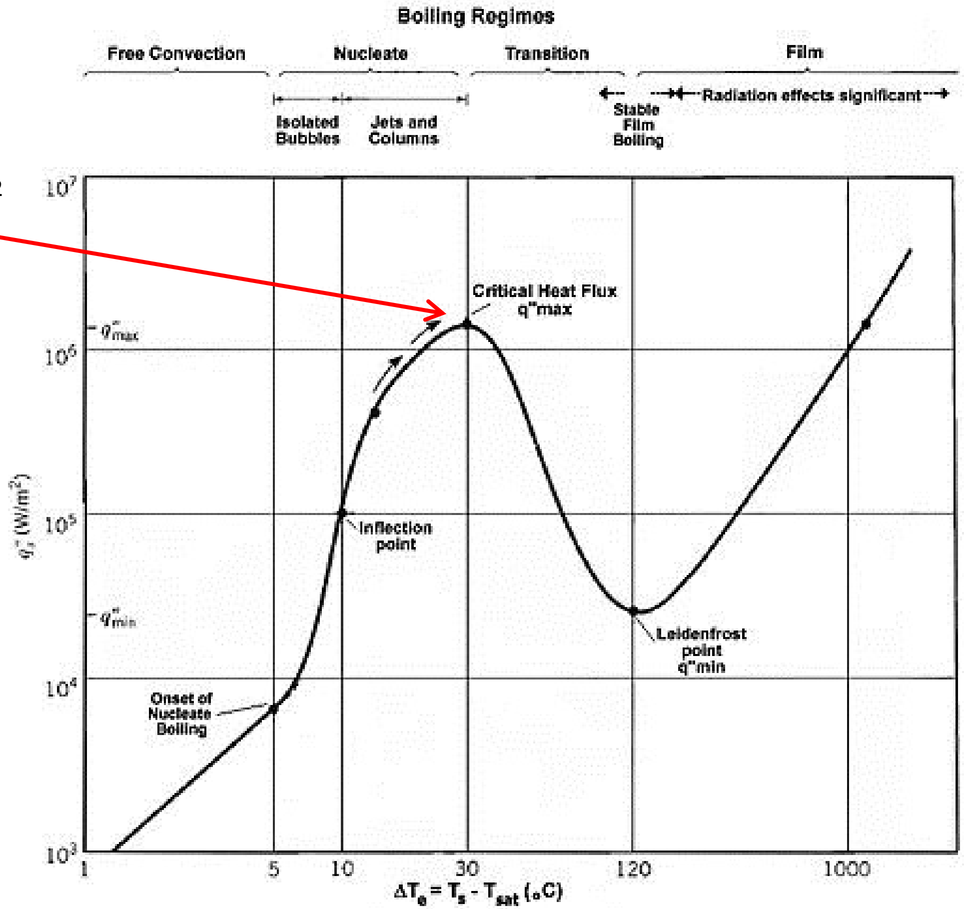
$$for\ a\ sphere\ A = 4\pi r^2\ and\ V = \frac{4}{3\pi r^3}\ \ so$$

$$\frac{Q}{V} = \frac{3h\Delta T}{r} = \frac{3 * 5000[\frac{W}{m^2K}] * 500[K]}{0.003[m]} = 2.5[\frac{GW}{m^3}] = 2.5[\frac{MW}{l}]$$

Nucleate Boiling

Vapour bubbles forming at nucleation sites and separating from the heated surface thus enhances mixing and heat transfer

Critical heat flux >1MW/m^2

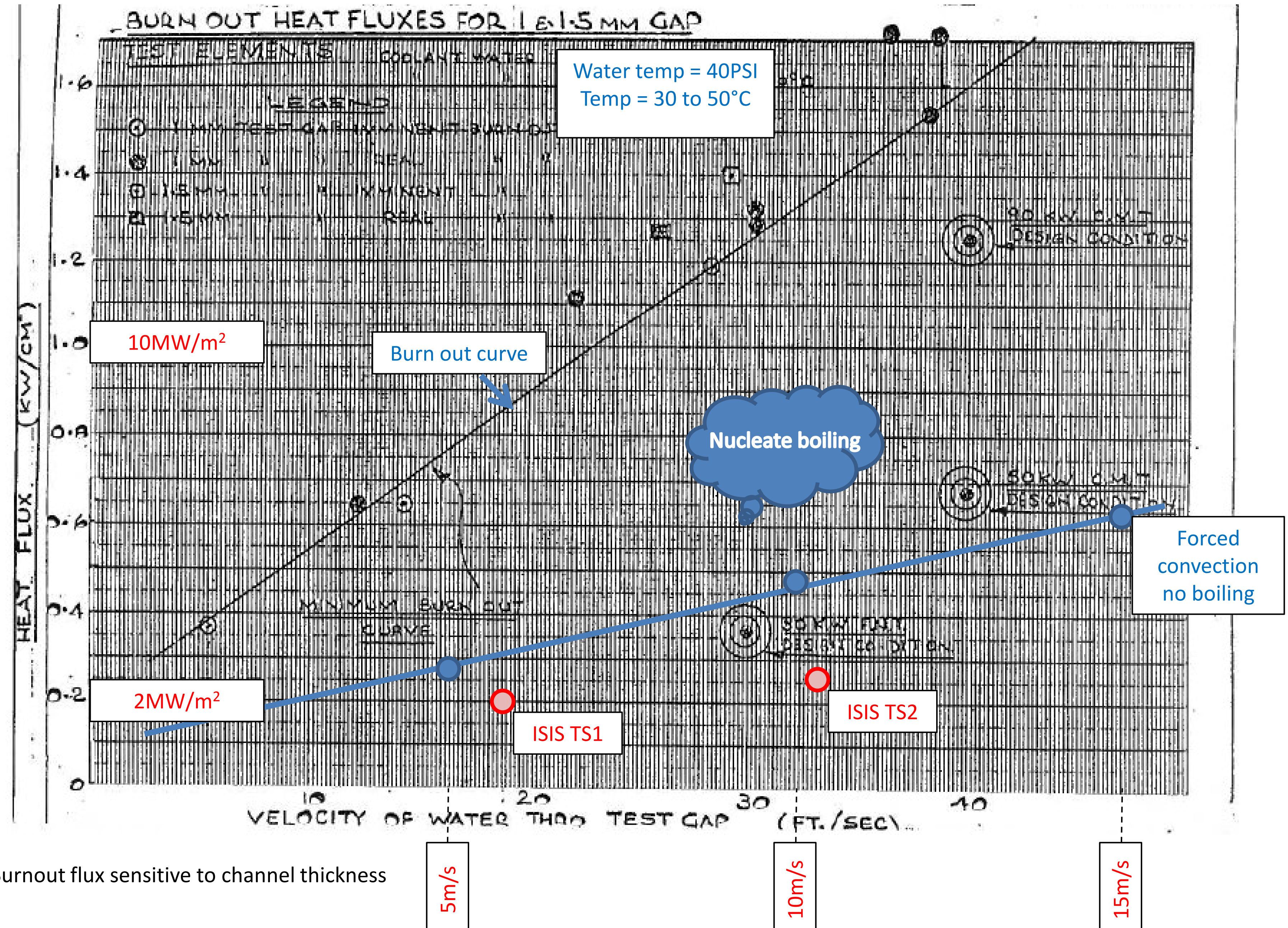


Boiling Curve for water at 1 atm.
Surface heat flux q" as a function of excess temperature $\Delta T_e = T_s - T_{sat}$

Heat transfer driven by temperature difference alone, i.e. Plate above boiling temperature of water and no forced convection

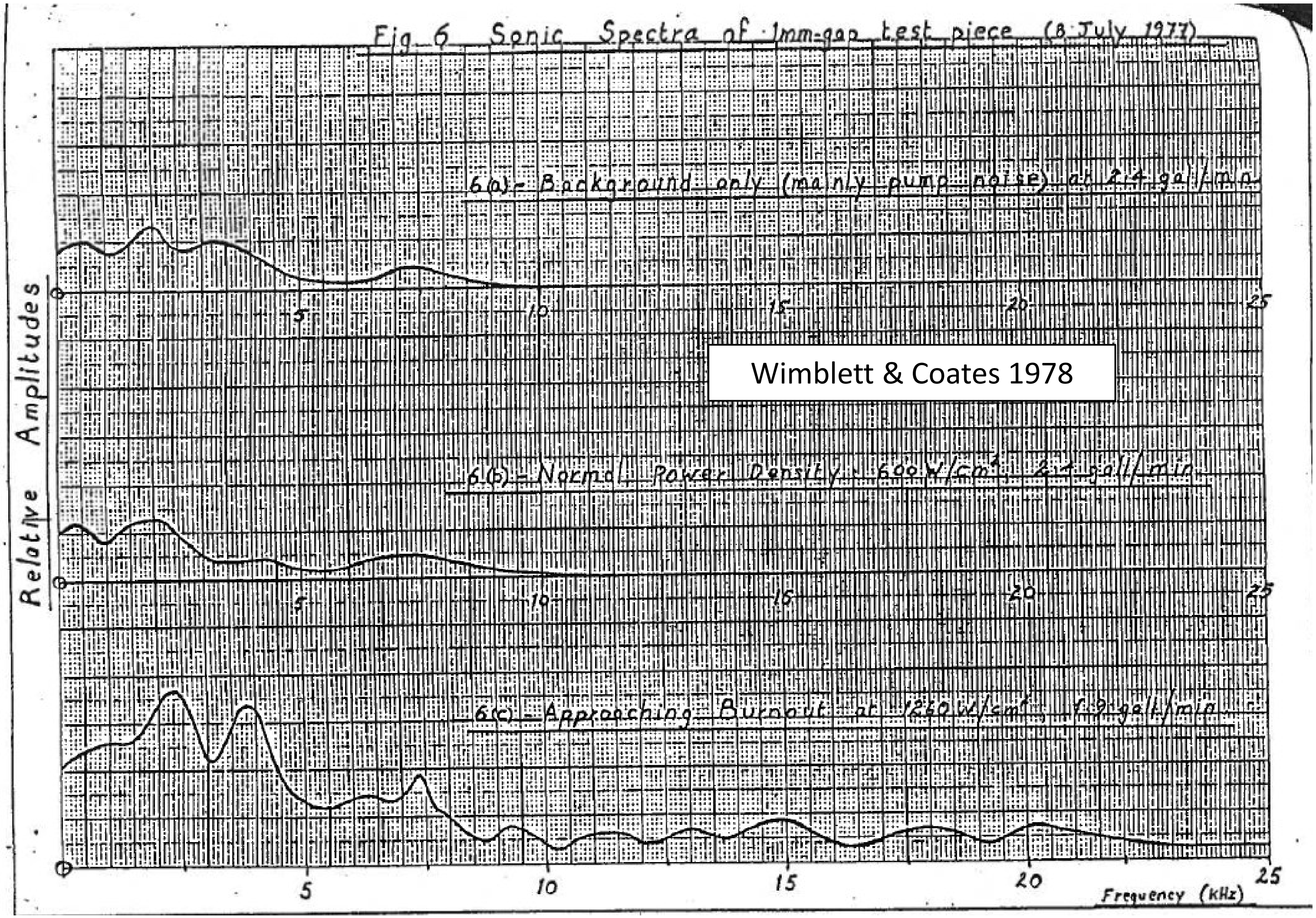
Critical heat flux

forced convection water flow (original graph Wimblett)



Burnout flux sensitive to channel thickness

Acoustic transducer used to detect burnout



Maximum heat flux could be achieved by monitoring for burnout

Heat flux may be limited by erosion due to high water velocities

Other ideas

Hypervapotrons designed to cope with high heat fluxes present in fusion devices

•Water flow, heat load and channel width tuned to generate a repetitive cycle that moves steam out into the sub cooled bulk flow.
•Typically, these can sustain power densities of up to 20-30 megawatts/m^2 in steady-state, using water at flow velocities < 10 m/s and operating pressures < 10 bar.

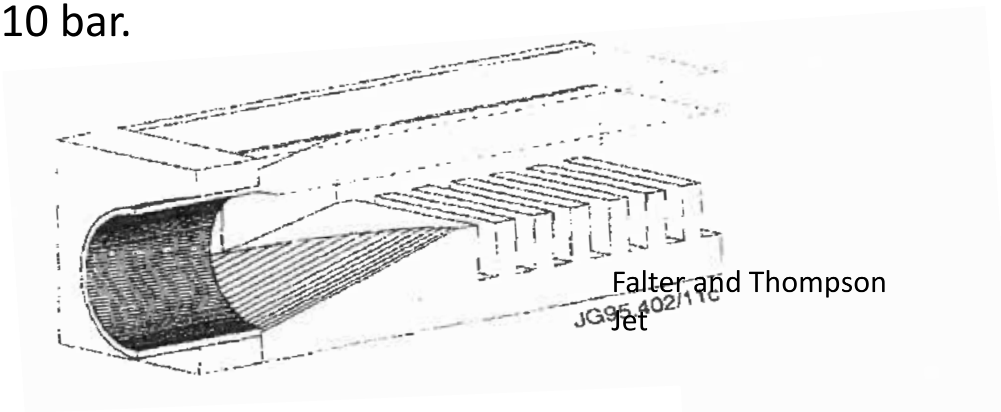
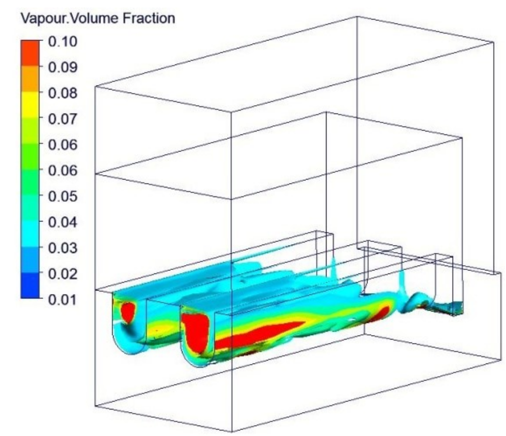


Fig.2a: Hypervapotron beam stopping elements as used in the JET Test Bed beam bump. the Test Bed box scraper (TBBS)

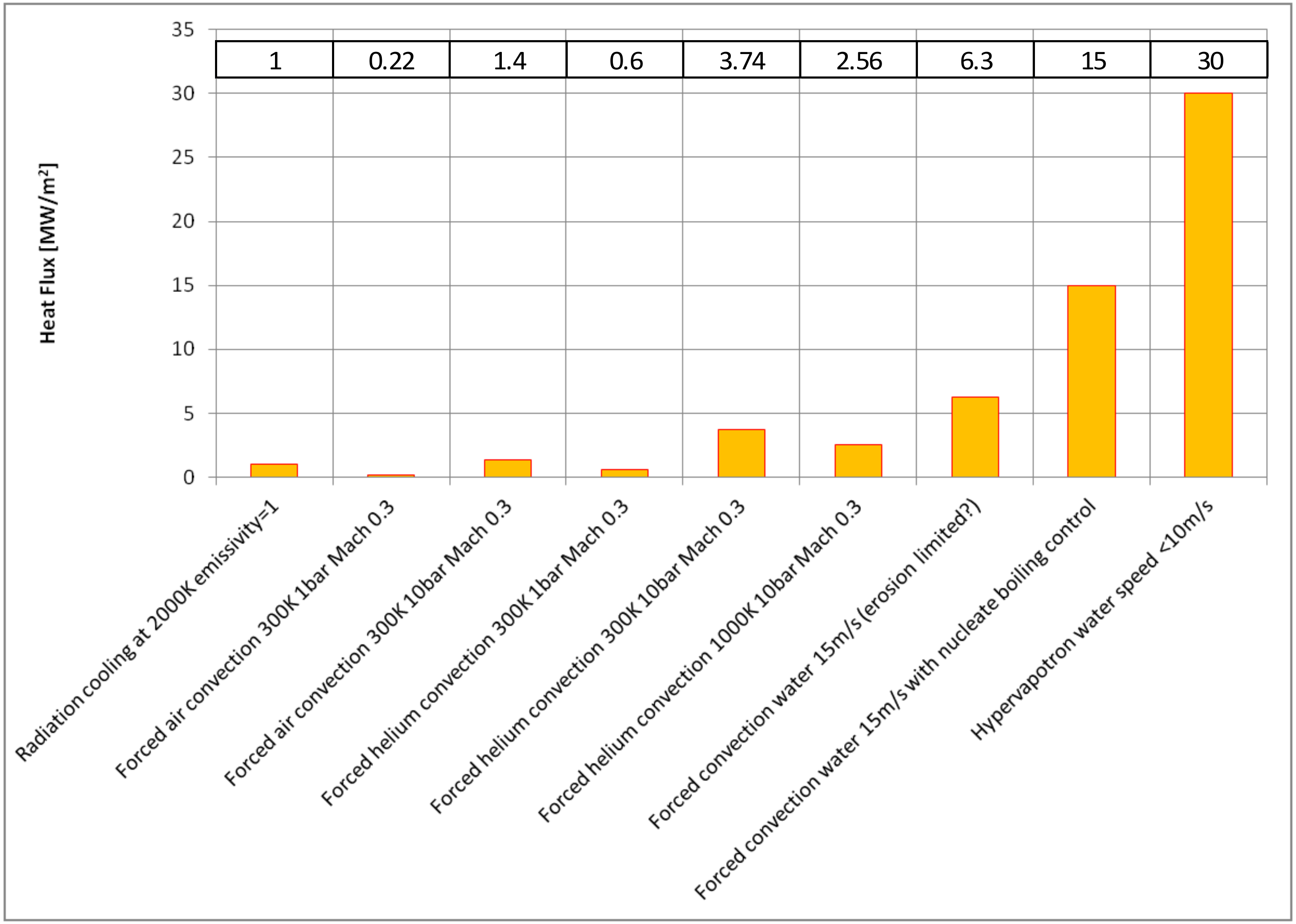
Falter and Thompson
Jet



Nanofluids
•Water-based nanofluids (suspensions of 0.001-10% nanoparticles, <100nm) have the potential to deliver much improved cooling while retaining the advantages of water.
•10-14% increase in convective/conductive heat transfer and 100-200% increase in critical heat flux have been reported.

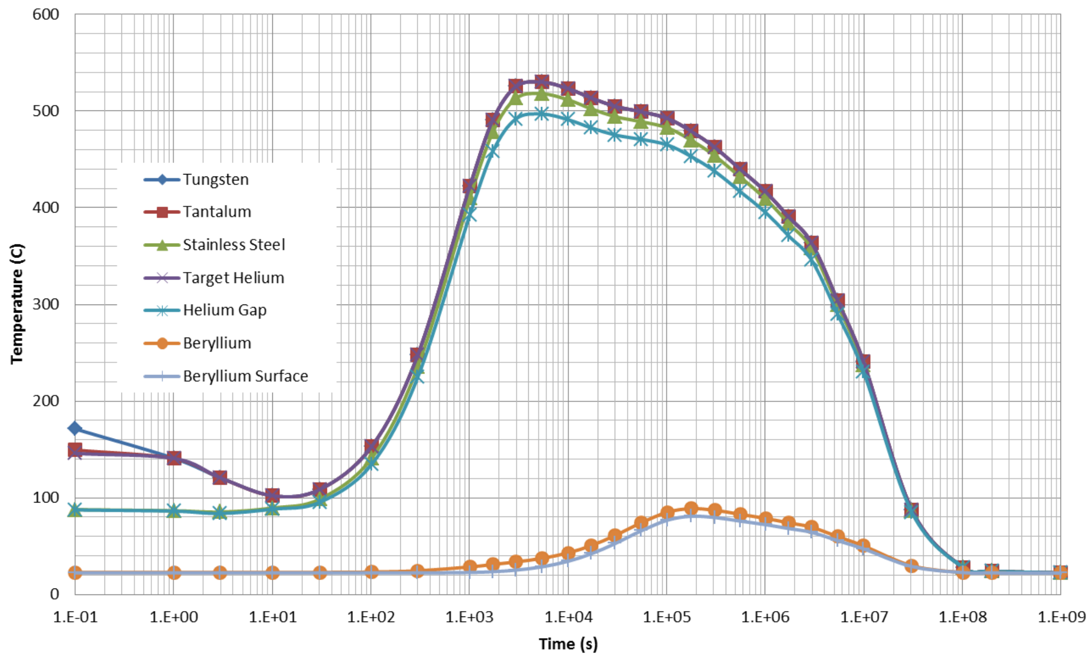
S. K. Das et al., Nanofluids, First ed., John Wiley & Sons, 2007

Max heat flux summary

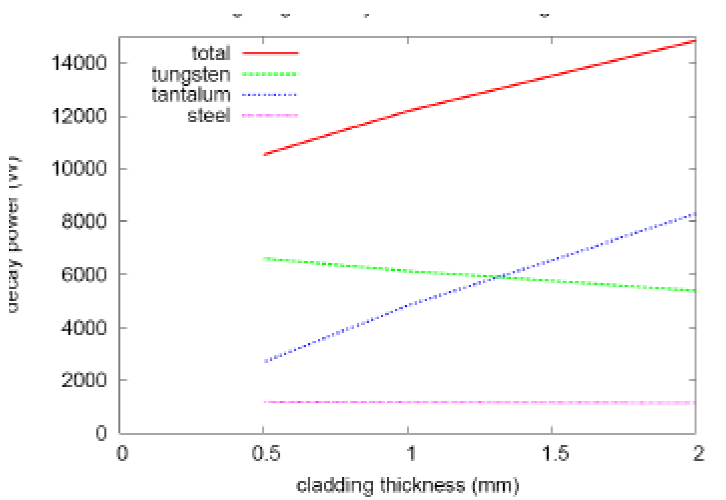


Decay heat important for neutron spallation targets

ISIS TS1 - target temperature prediction following shut down and coolant failure



SNS TS2 - decay heat as a function of cladding thickness



Must be able to dissipate decay heat via passive cooling.

SNS 2nd target design is a target wheel instead of a stationary target to accommodate decay heat

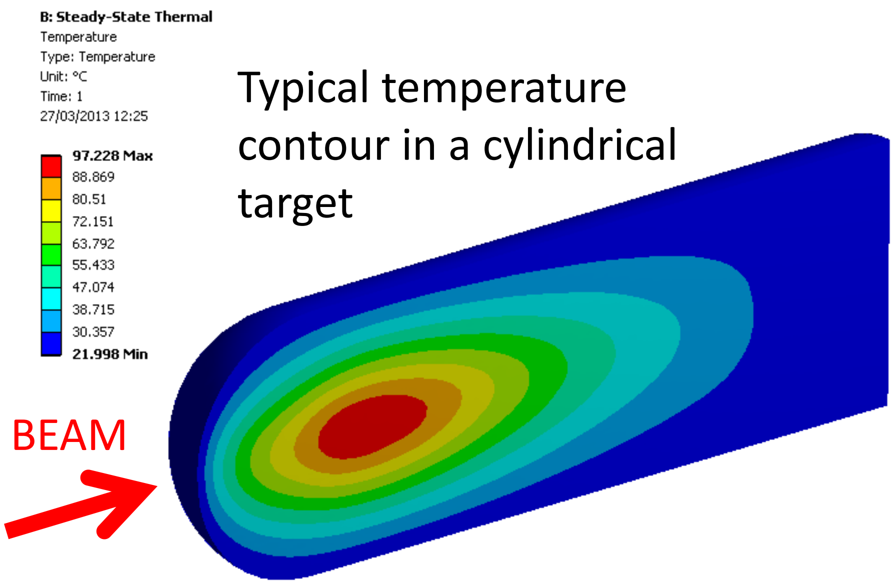
Tantalum cladding thickness important

Target design can be constrained by decay heat

Elastic stress (non inertial)

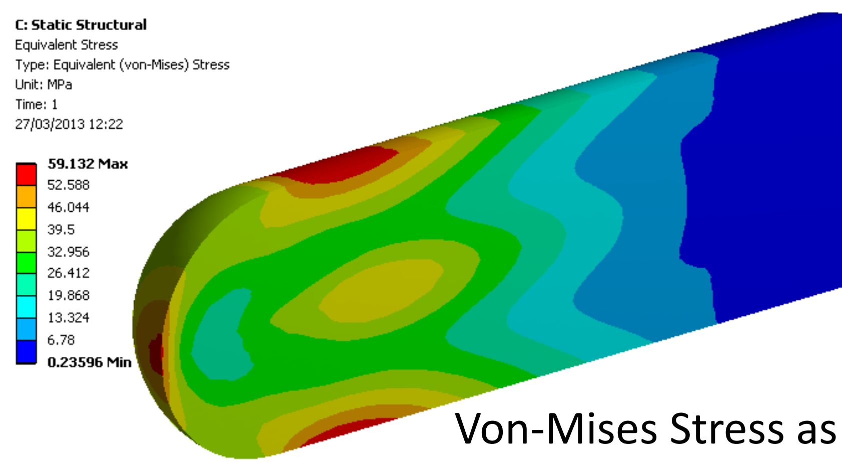
(reversible, small strain deformations)

Typical temperature contour in a cylindrical target



A 'continuous' beam results in constant heat power deposited within a target
The target is cooled resulting in a temperature gradient (which primarily depends on power deposition, thermal conductivity and geometry)

As a result of thermal expansion and the temperature gradient a stress field is setup within the target



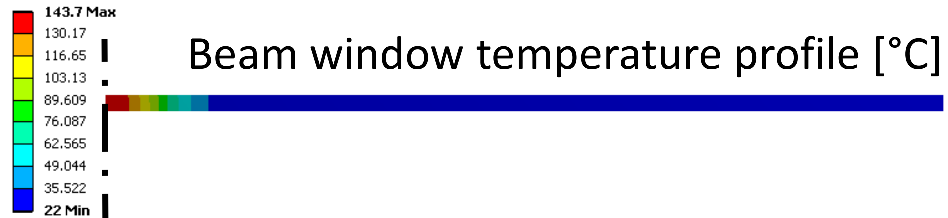
Von-Mises Stress as a result of temperature contour

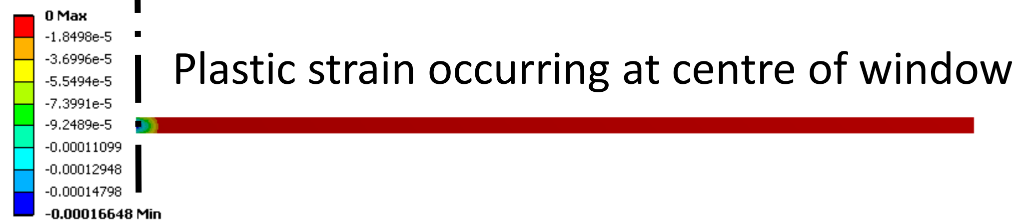
Plastic stress (non inertial)

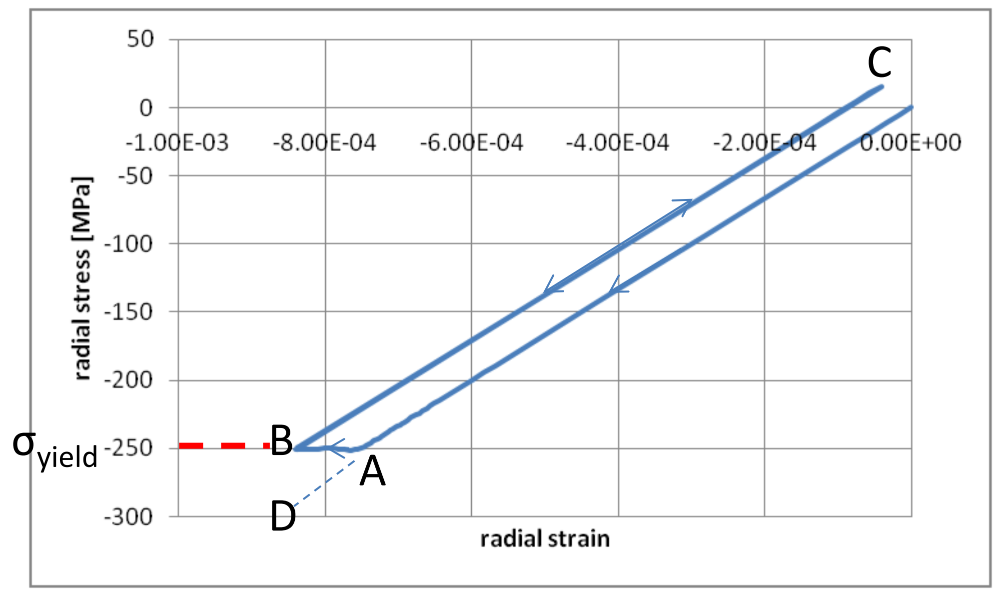
stress exceeds yield point and plastic deformation occurs

Consider the stress and strain near the centre of a window heated by a 'large' beam pulse

Plastic deformation starts to occur at point A until the point of maximum compressive stress occurs at point B.
If the window is then cooled back to ambient temperature the stress unloads along the line B-C.
Point C has a small amount of tension resulting from the plastic deformation.
If the window is heated again by the same amount the stress will reach point B without any further plastic deformation.







Point D represents stress prediction with a simple linear model

EXPERIMENTAL RESULTS OF BERYLLIUM EXPOSED TO INTENSE HIGH ENERGY PROTON BEAM PULSES*

K. Ammigan[†], B. Hartsell, P. Hurh, R. Zwaska, FNAL, Batavia, IL 60510, USA
M. Butcher, M. Guinchard, M. Calviani, R. Losito, CERN, Geneva, Switzerland
S. Roberts[1], V. Kuksenko, Oxford University, Oxford, UK
A. Atherton, O. Caretta, T. Davenne, C. Densham, M. Fitton, P. Loveridge, J. O'Dell, RAL, Didcot, UK

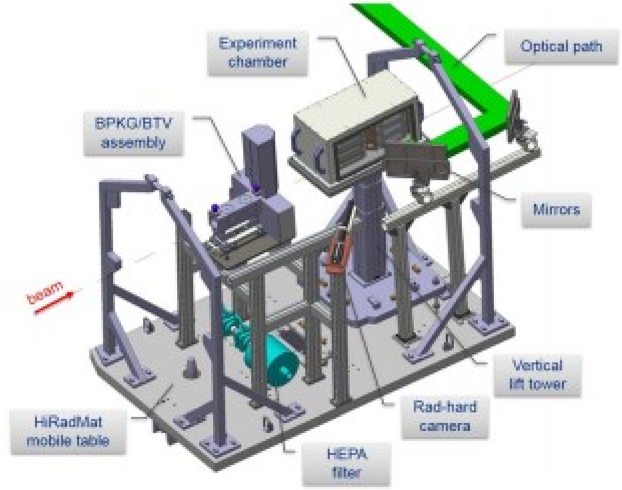


Figure 1: Experimental chamber assembled on mobile table.

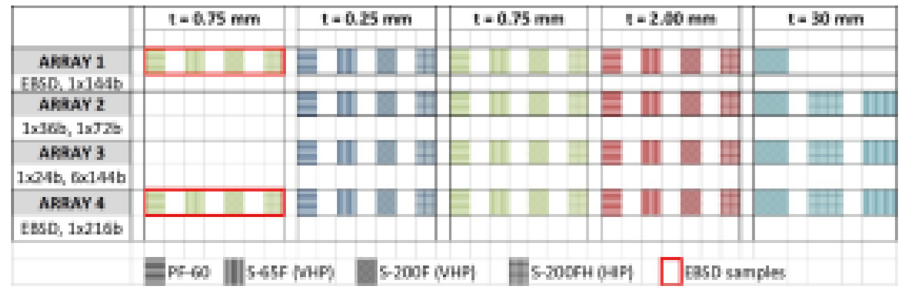


Figure 3: Test matrix showing specimen type, size, grade and number of bunches.

First experiment achieved plastic deformation but no failure

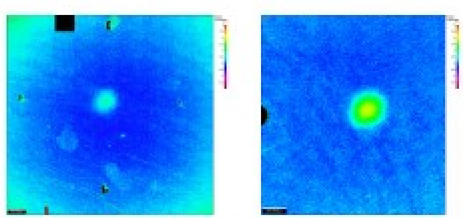


Figure 7: Profilometry maps of S-65F grade thin discs from Array 1 (left) and Array 4 (right).

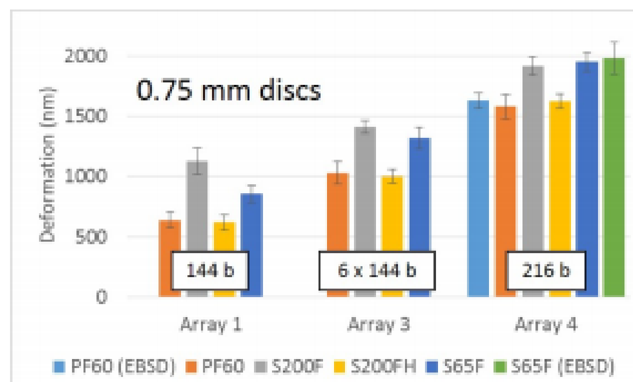


Figure 8: Out-of-plane deformations of 0.75 mm thick discs.

Second experiment aims to test irradiated beryllium (less ductile)

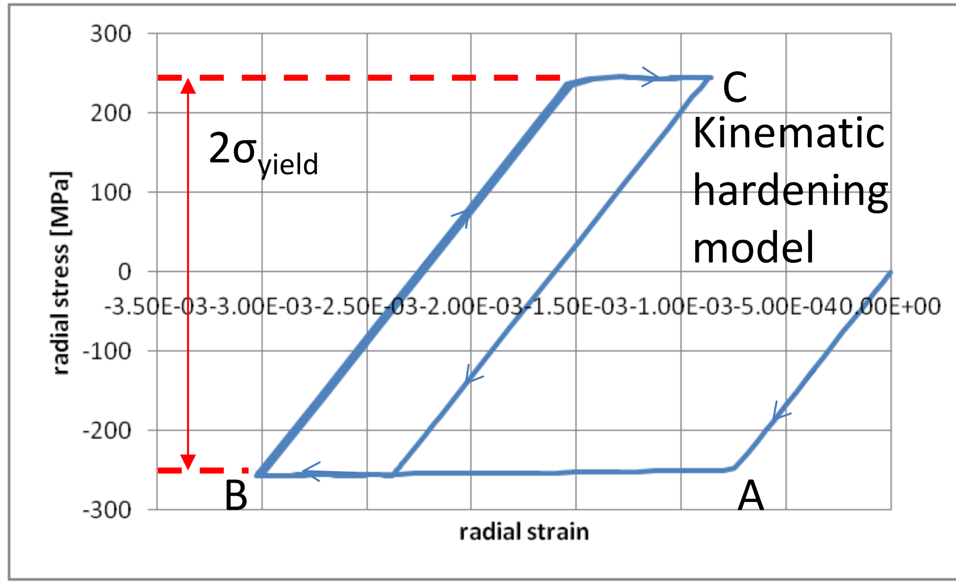
Plastic stress – shake down

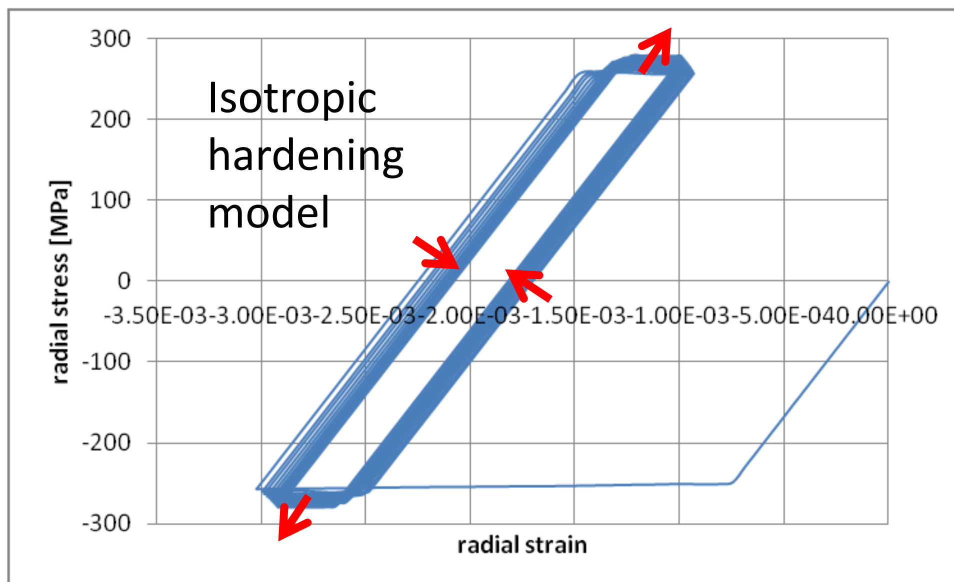
Plastic shakedown behavior is one in which the steady state is a closed elastic-plastic loop, with no net accumulation of plastic deformation

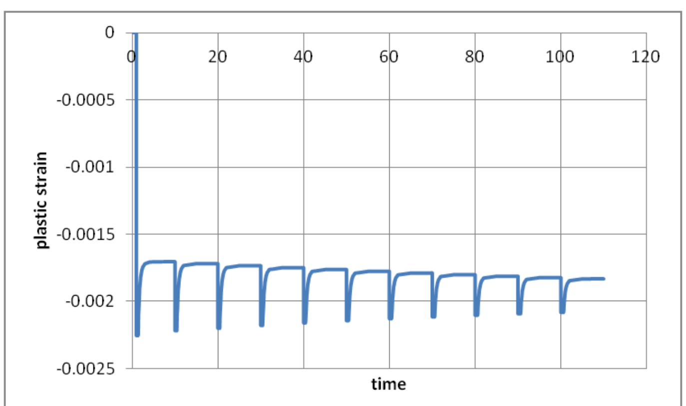
Consider more significant heating to the window resulting in significantly more plastic deformation between A and B.

Unloading now follows line B-C thus setting up a loop of repetitive cycles of plastic deformation

If the yield stress increases following plastic work then the magnitude of the cyclic plastic deformation reduces until return to the elastic regime.



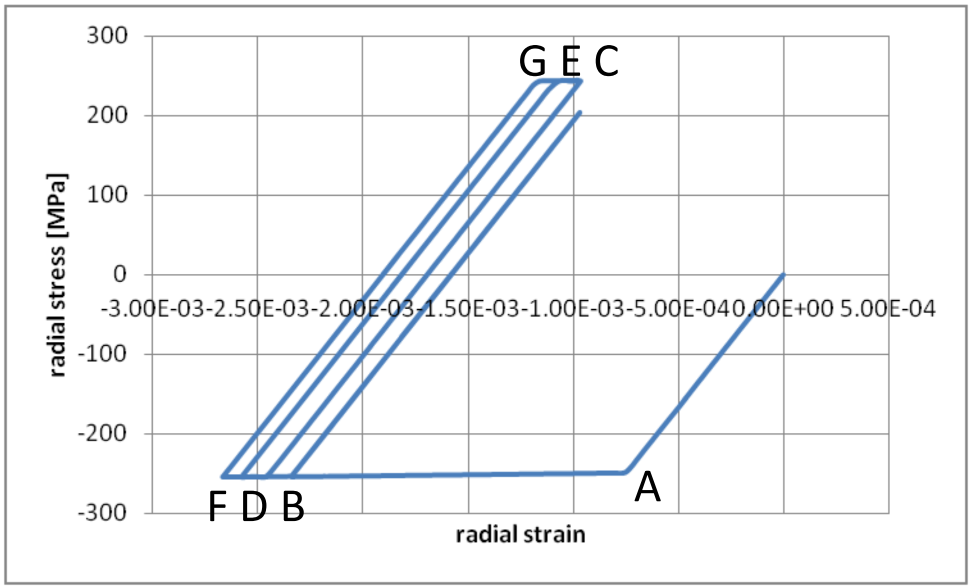


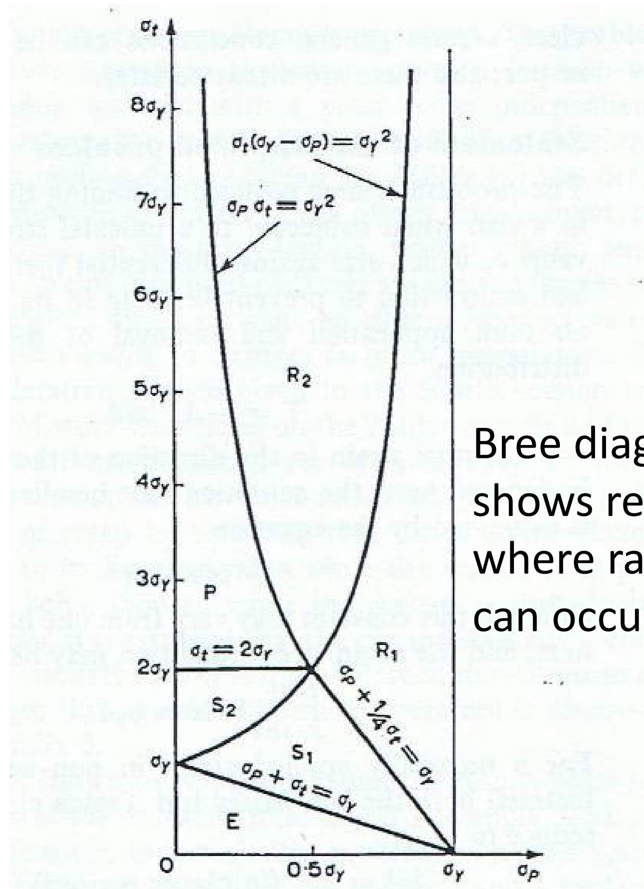


Plastic stress – ratcheting

Ratcheting behavior is one in which the steady state is an open elastic-plastic loop, with the material accumulating a net strain during each cycle

UNSTABLE Ratcheting behaviour observed by increasing window thickness



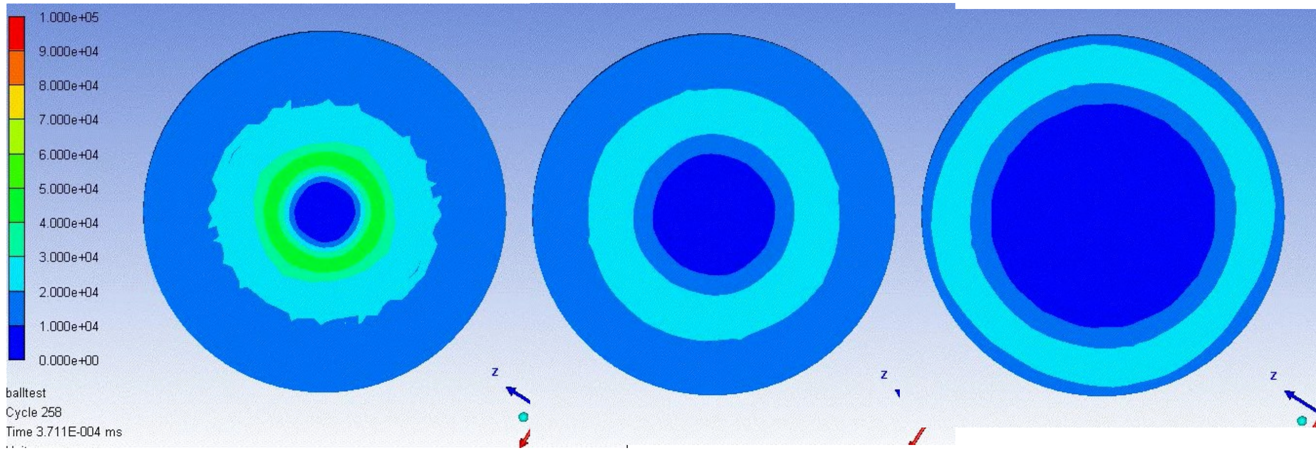


Stress régime	Can behaviour
R_1 and R_2	Ratchetting
S_1 and S_2	Shakedown after first half-cycle
P	Plastic cycling
E	Elastic

Bree diagram shows regions where ratcheting can occur

Inertial Stress - Elastic Waves

Stress waves with a magnitude below the yield stress propagating with small reversible deflections

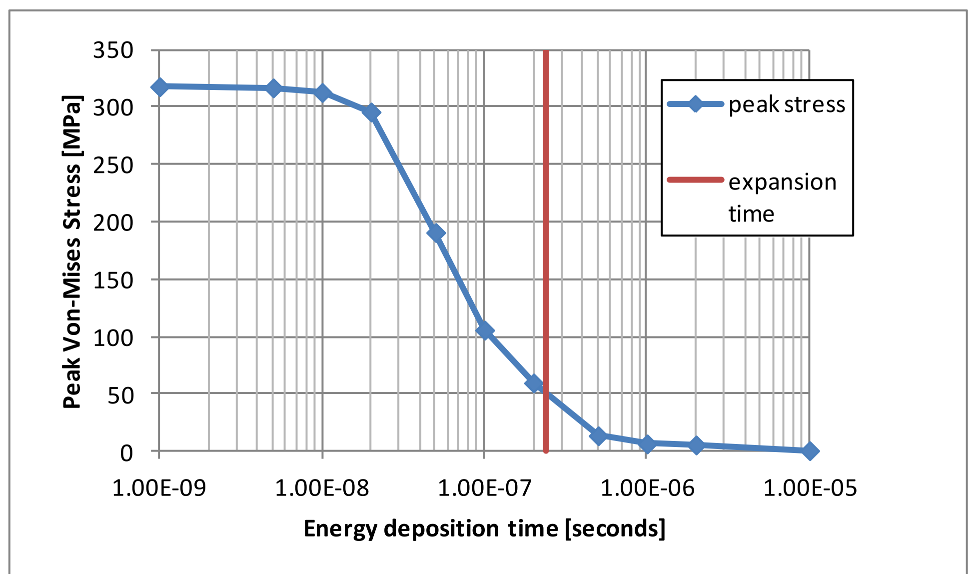


Consider a spherical target being rapidly and uniformly heated by a beam pulse.

If it is heated before it has had time to expand a pressure/stress occurs. This results in oscillating stress waves propagating through the target as it expands, overshoots and contracts again.

The waves travel at the speed of sound in the material. (longitudinal or shear sound speeds)

Stress depends on heating time



Analytical solution for radial stress waves in a beam window

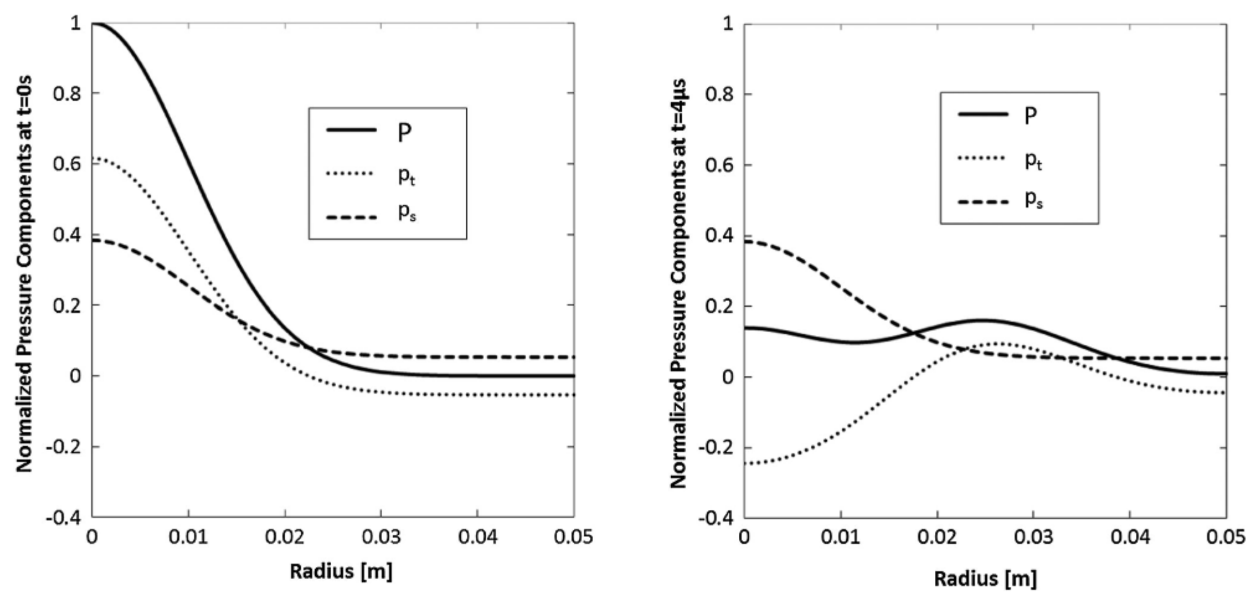
$$P(r,t) = p_s(r) + p_t(r,t)$$

$$p_s(r) = E\alpha T_0 \left[\frac{(1+\nu)}{(1-\nu)} \frac{\sigma^2}{R^2} \{1 - e^{(-R^2/2\sigma^2)}\} + \frac{1}{2} e^{(-r^2/2\sigma^2)} \right]$$

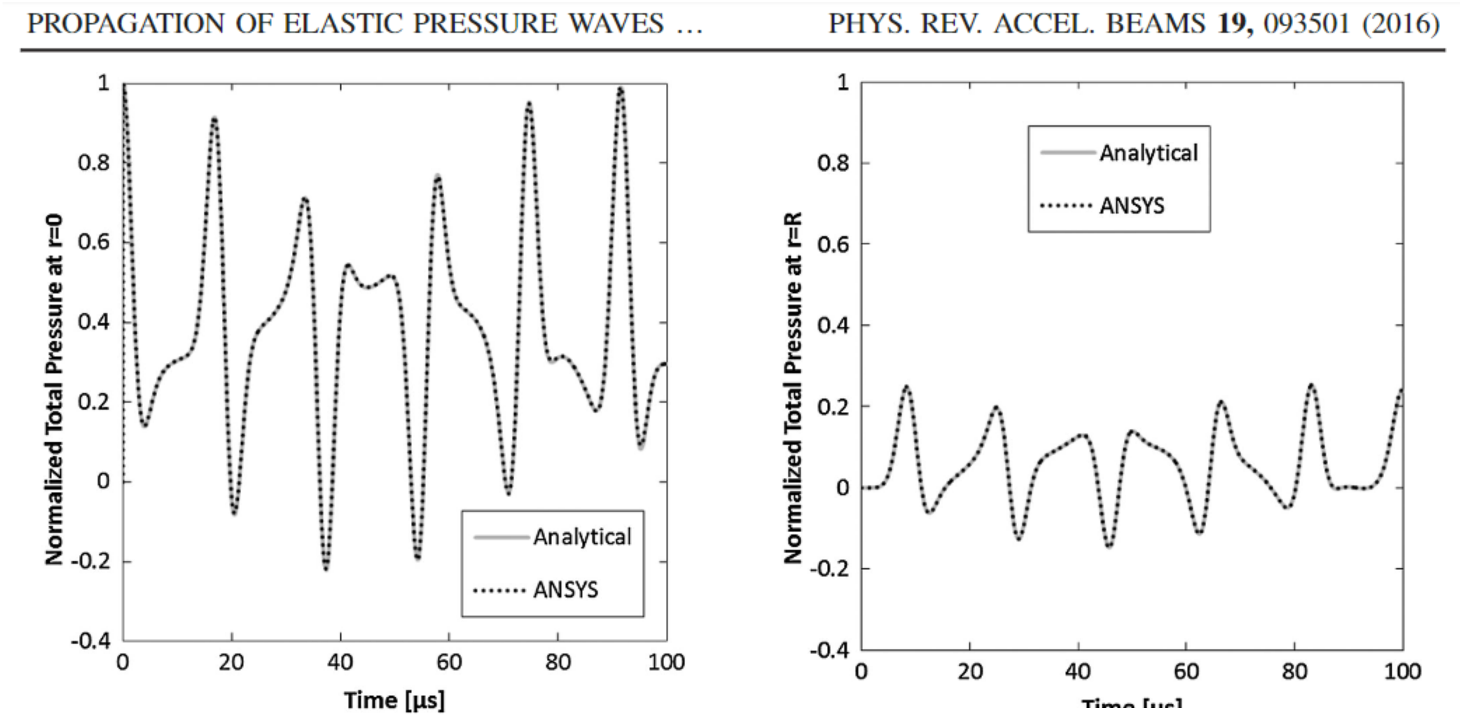
$$p_t(r,t) = \frac{2r}{R^2} + \frac{2}{R^2} \sum_{n=1}^{\infty} \frac{1}{J_0^2(\lambda_n)} J_0\left(\lambda_n \frac{r}{R}\right) \cos\left(\lambda_n \frac{ct}{R}\right) \times \int_0^R r p_t(r,0) J_0\left(\lambda_n \frac{r}{R}\right) \mathrm{dr} \qquad (20)$$

Solution proves that total stress at any point is composed of a static and transient component

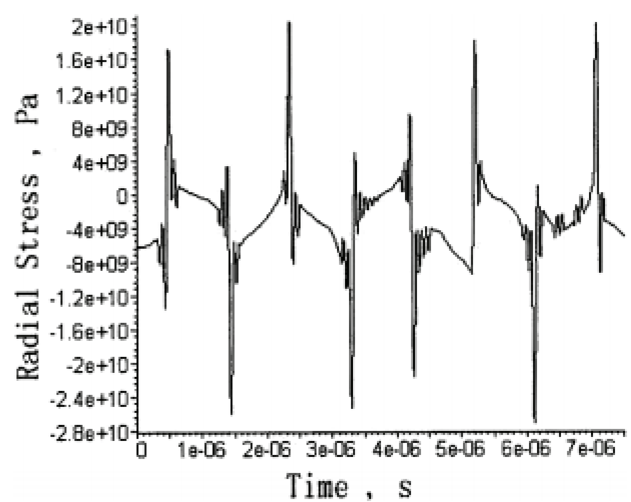
T. R. DAVENNE and P. LOVERIDGE PHYS. REV. ACCEL. BEAMS **19,** 093501 (2016)



Solution achieves stable bounded results with perfect agreement to linear elastic FEA – also paper presents guidelines for doing inertial stress FEA



Previous analytical solutions by others including Zheng and Taleyarkhan showed instability at stress peaks



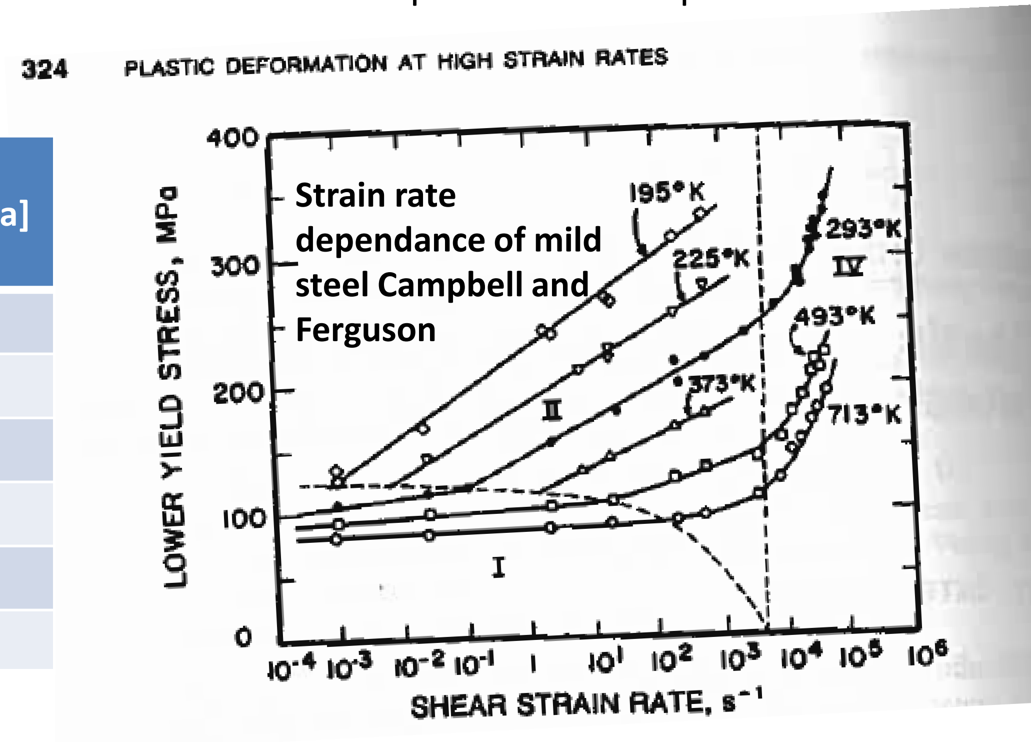
Inertial Stress - Plastic Waves

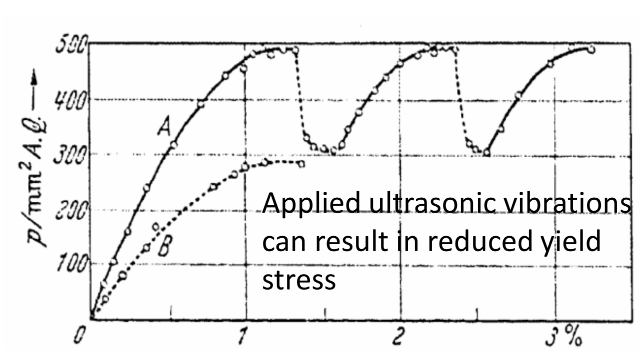
If a pulse is transmitted to a material that has an amplitude exceeding the elastic limit the pulse will decompose into an elastic and a plastic wave

Plastic waves travel slower than acoustic elastic waves due to the dissipative effect of plastic work

But what is the dynamic yield point?

Material	Hugoniot Elastic Limit [GPa] Meyers	Typical static yield point [Gpa]
2024 Al	0.6	0.25
Ti	1.9	0.225
Ni	1	0.035
Fe	1-1.5	0.1
Sapphire	12-21	
Fused Quartz	9.8	





Acousto-plastic-effect

Figure 1.1: Blaha and Langenecker [1] reported the first APE by a compression experiment.

Do we induce vibratory stress relief by bouncing inertial waves through a target?

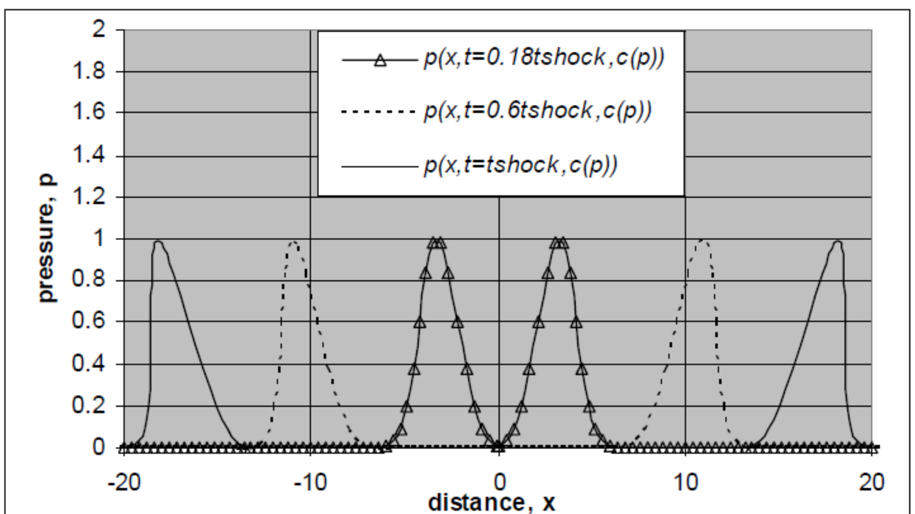
Shock Waves – Inertial

A discontinuity in pressure, temperature and density

Shock waves in solids normally studied using impacts and involve multiple GPa pressures

Requirement for formation of a shock wave (in a target or window)
Higher amplitude regions of a disturbance front travel faster than lower amplitude regions

Solution of wave equation with c(p) non linear steepening



Isothermal compression

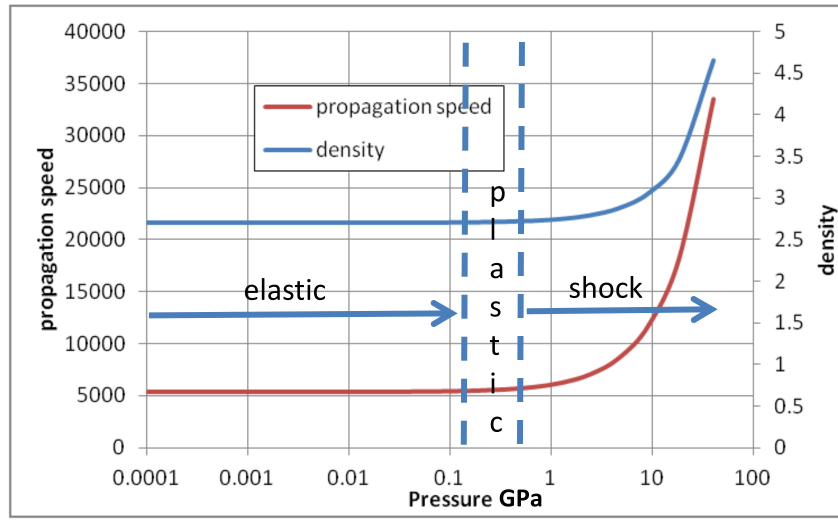
$$\beta_T = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T$$

$$P = \frac{-ln(v) + \beta_T P_0 + ln(v_0)}{\beta_T}$$

shock compression

$$p = p_r + \frac{\gamma}{v}(e - e_r)$$

$$P = \frac{c_0^2(v_r - v)}{\left(v_r - s(v_r - v)\right)^2}$$



High pressures required for non-linear wave steepening
Geometric spreading of waves in targets results in a reduction in wave amplitude
Acoustic attenuation of wave energy opposes Non-linear steepening (ref Goldberg number)
Formation of a shock wave from a beam induced pressure wave is unlikely

Conclusions

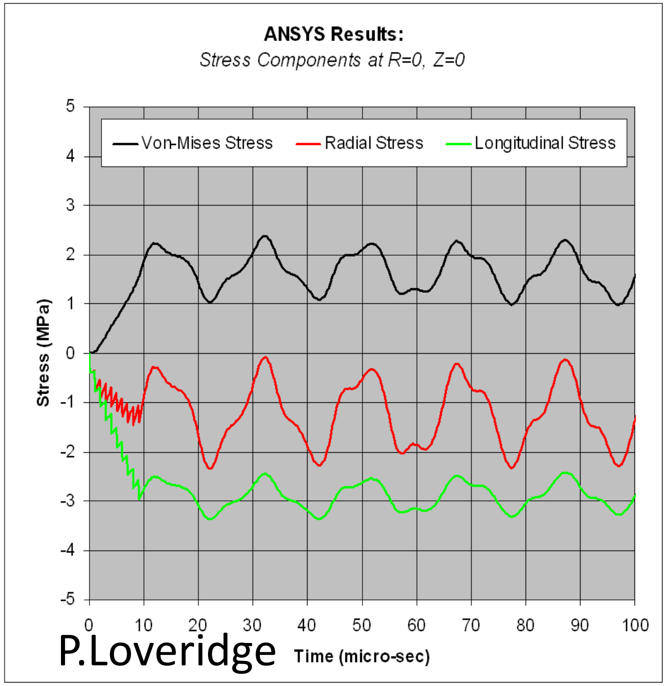
- Surface heat flux of the order of a few MW/m^2 is possible with forced convection gas cooling
- Tens of MW/m^2 is possible with water cooling and controlled boiling
- A few kW/cc are removable with packed beds or highly segmented targets
- Decay heat must be considered and removable with passive cooling

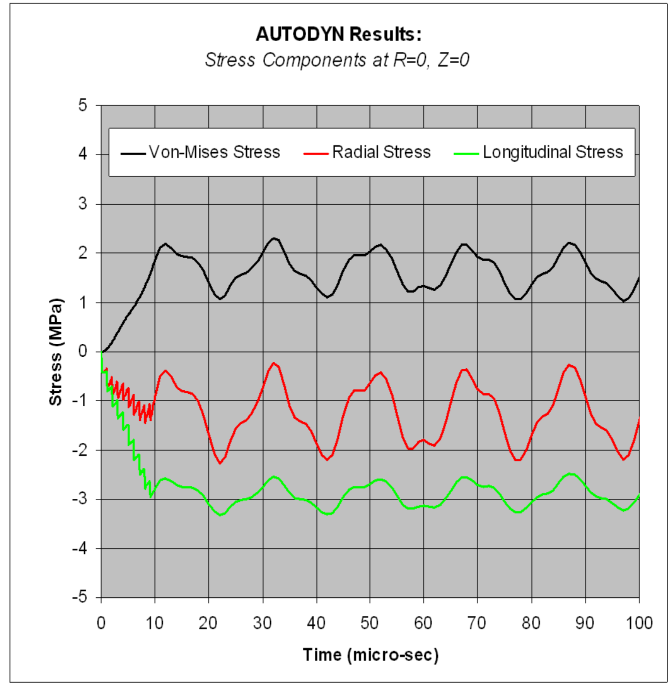
- Targets and windows experience static and often transient inertial stress.
- Usually design to remain in the elastic regime for long life
- Dynamic yield point maybe higher than static yield point
- Plastic shakedown scenario maybe acceptable, need to avoid ratcheting
- Shock waves not likely to occur in a target or beam window due to beam heating.

Back UP

ANSYS Classic vs AUTODYN for inertial stress modelling

Comparison of implicit and explicit finite element codes in the elastic regime





•Autodyn time step limited by Courant number stability criteria, sometimes may be able to get away with slightly longer timesteps using implicit method, still needs to be short enough to capture physics

•ANSYS classic has advantages for temperature dependant material modelling in the elastic and plastic regions

•Autodyn shock equations of state are for high compressions – shock EOS data not employed in this calculation as compression is small

•Explicit method does offer stability for highly non linear phenomena if you have them

•Before employing Autodyn or LS-dyna be certain you are in a regime where you need it, are the equations of state and material strength models relevant to your problem?

The Calculation of Critical Heat Flux in Forced Convection Boiling

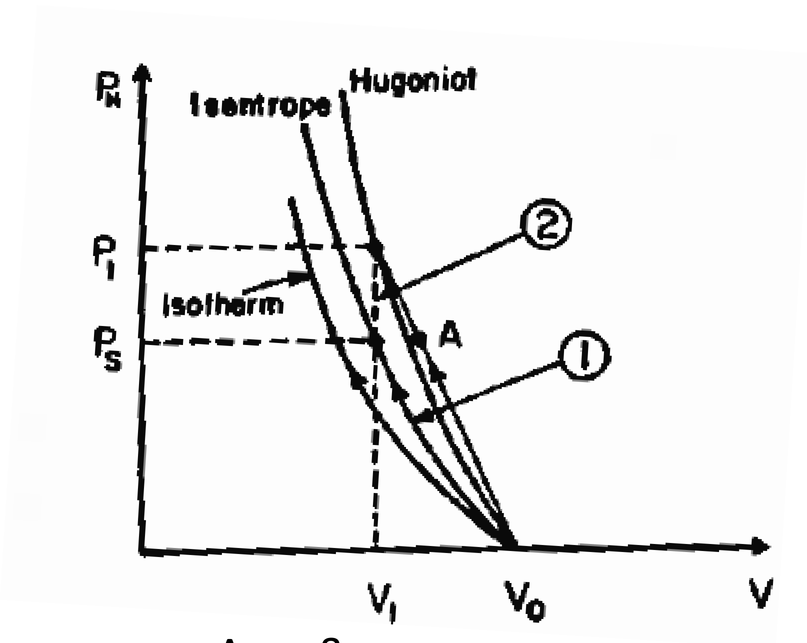
P. B. Whalley, G. F. Hewitt, P. Hutchinson

Atomic Energy Research Establishment, 1973 - 17 pages

International Journal of Heat and Mass Transfer
Volume 30, Issue 11, November 1987, Pages 2261–2269

Critical heat flux of forced convective boiling in uniformly heated vertical tubes with special reference to very large length-to-diameter ratios

Journals > Heat Transfer Research > Volume 33, 2002 Issue 5&6 > **Calculation of Critical Heat Flux in Natural and Forced Convection Boiling**



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