High flux heat transfer in a target environment

T. Davenne
High Power Targets Group
Rutherford Appleton Laboratory
Science and Technology Facilities Council

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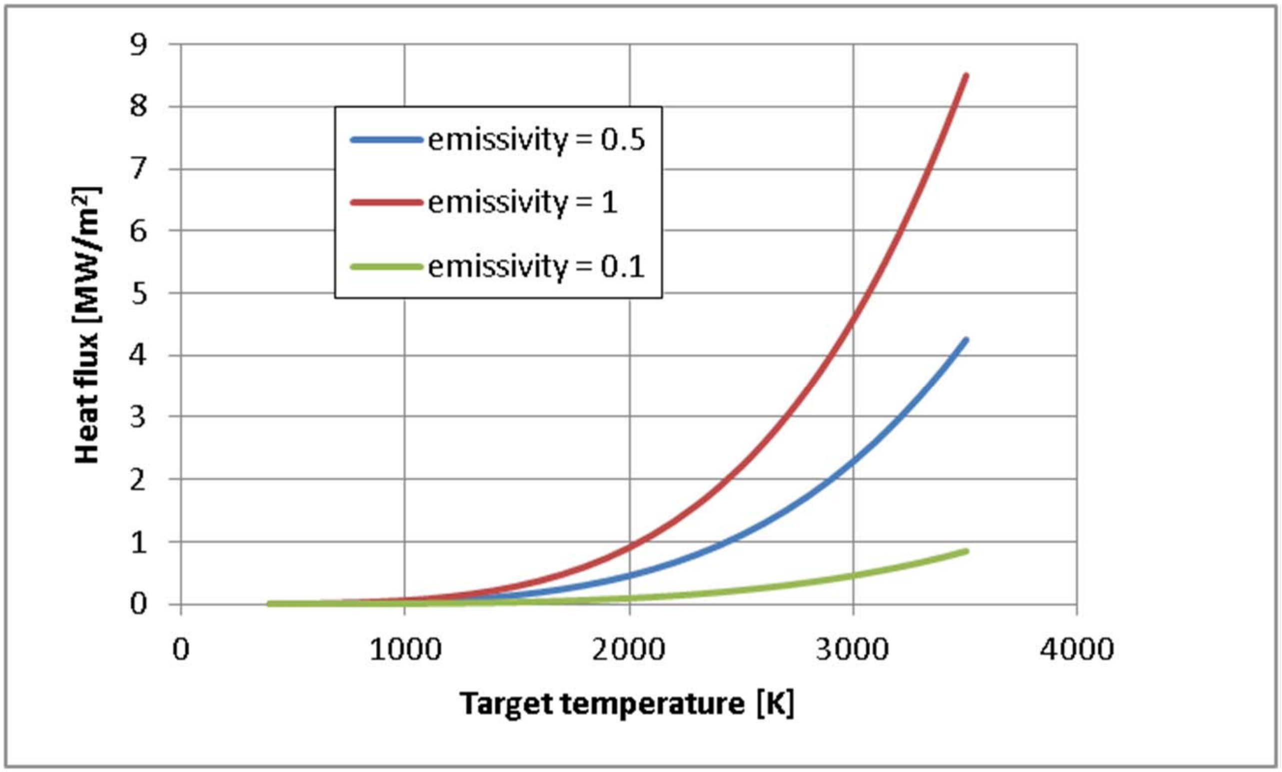
Radiation cooling

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



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:

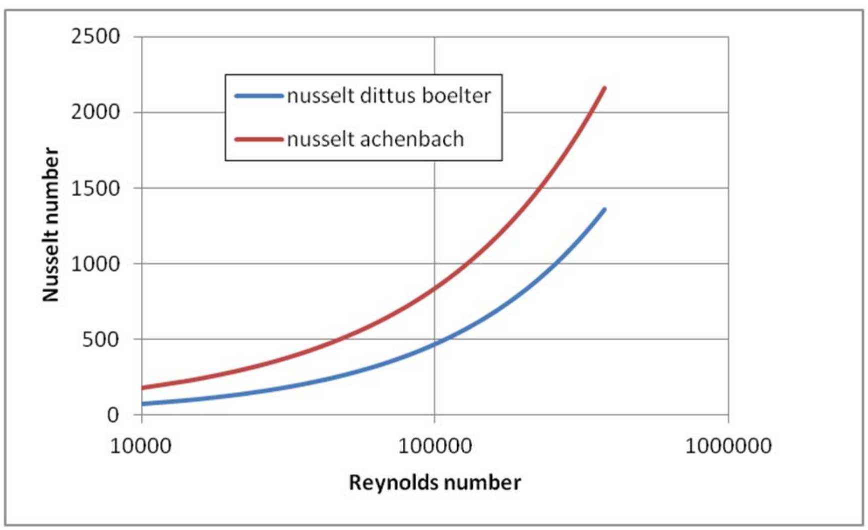
$$\mathrm{Re}_D \gtrsim 10\,000$$

$$0.6 \leq \mathrm{Pr} \leq 160$$

	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

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



Max power density for a sphere

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

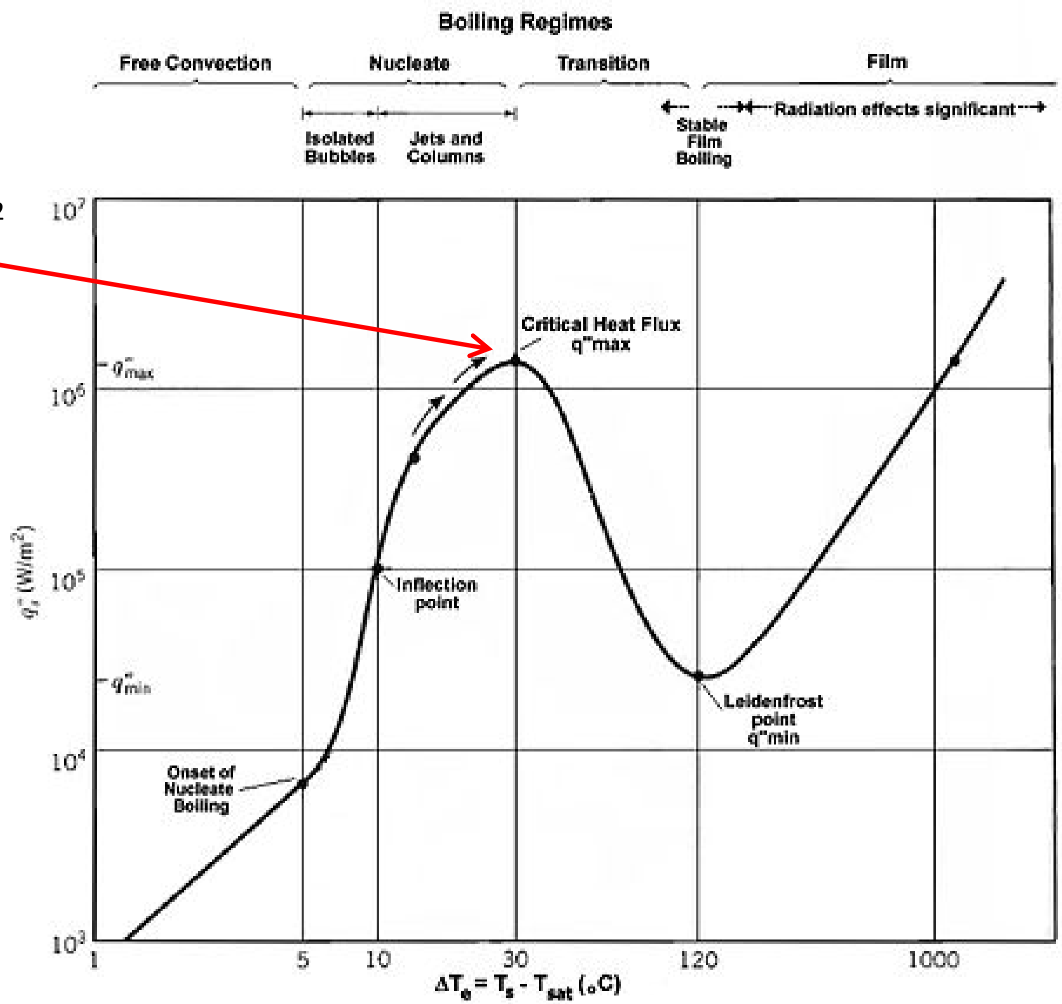
$$\textit{for a sphere } A = 4\pi r^2 \textit{ and } V = \frac{4}{3\pi r^3} \textit{ so}$$

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

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

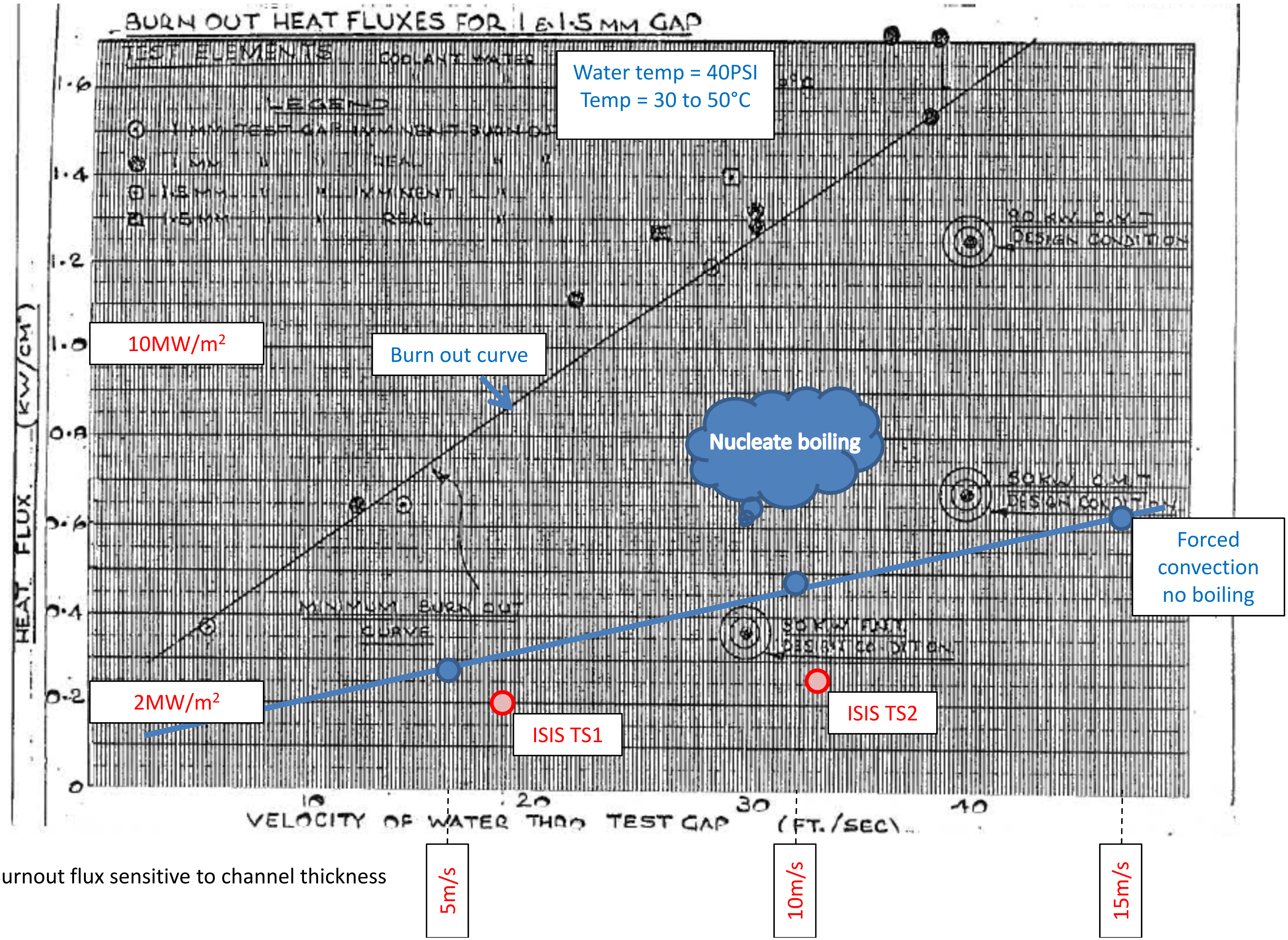


Boiling Curve for water at 1 atm.
Surface heat flux q" as a function of excess temperature $\Delta T_e = T_s - T_{sat}$

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

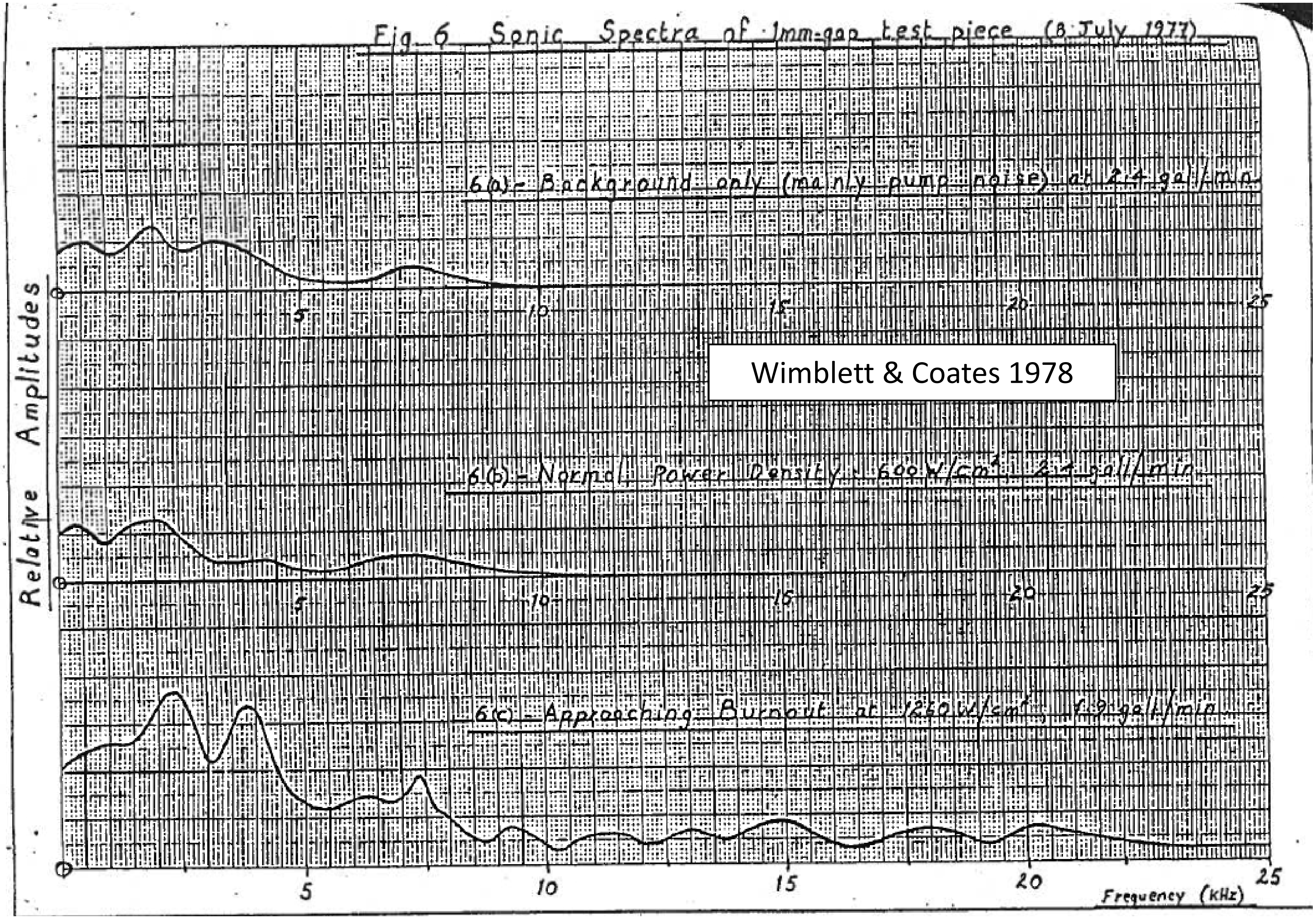
Critical heat flux

forced convection water flow (original graph Wimblett)



Burnout flux sensitive to channel thickness

Acoustic transducer used to detect burnout

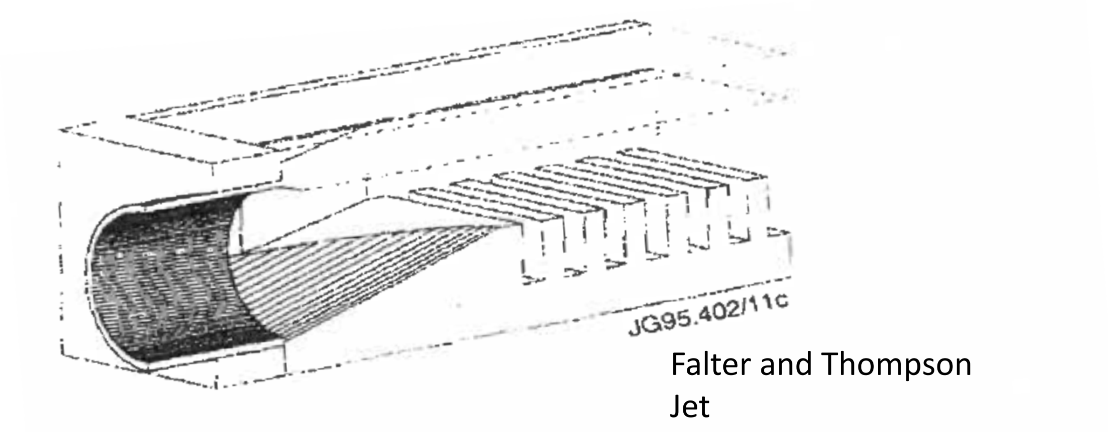


Maximum heat flux could be achieved by monitoring for burnout
Heat flux may be limited by erosion due to high water velocities

Other ideas

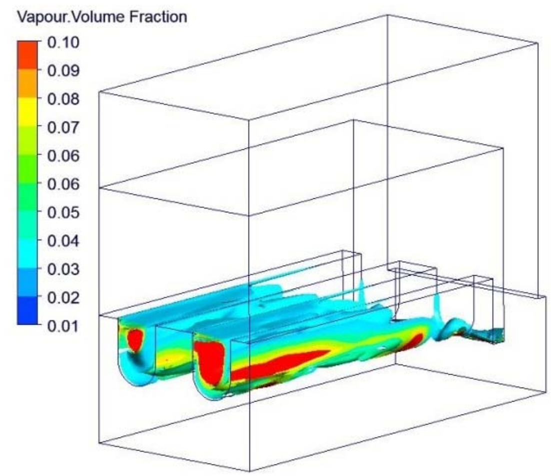
Hypervapotrons

•Water cooled finned heat exchangers developed to cope with the high heat fluxes present in experimental fusion devices and ancillary systems.
•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.



Falter and Thompson
Jet

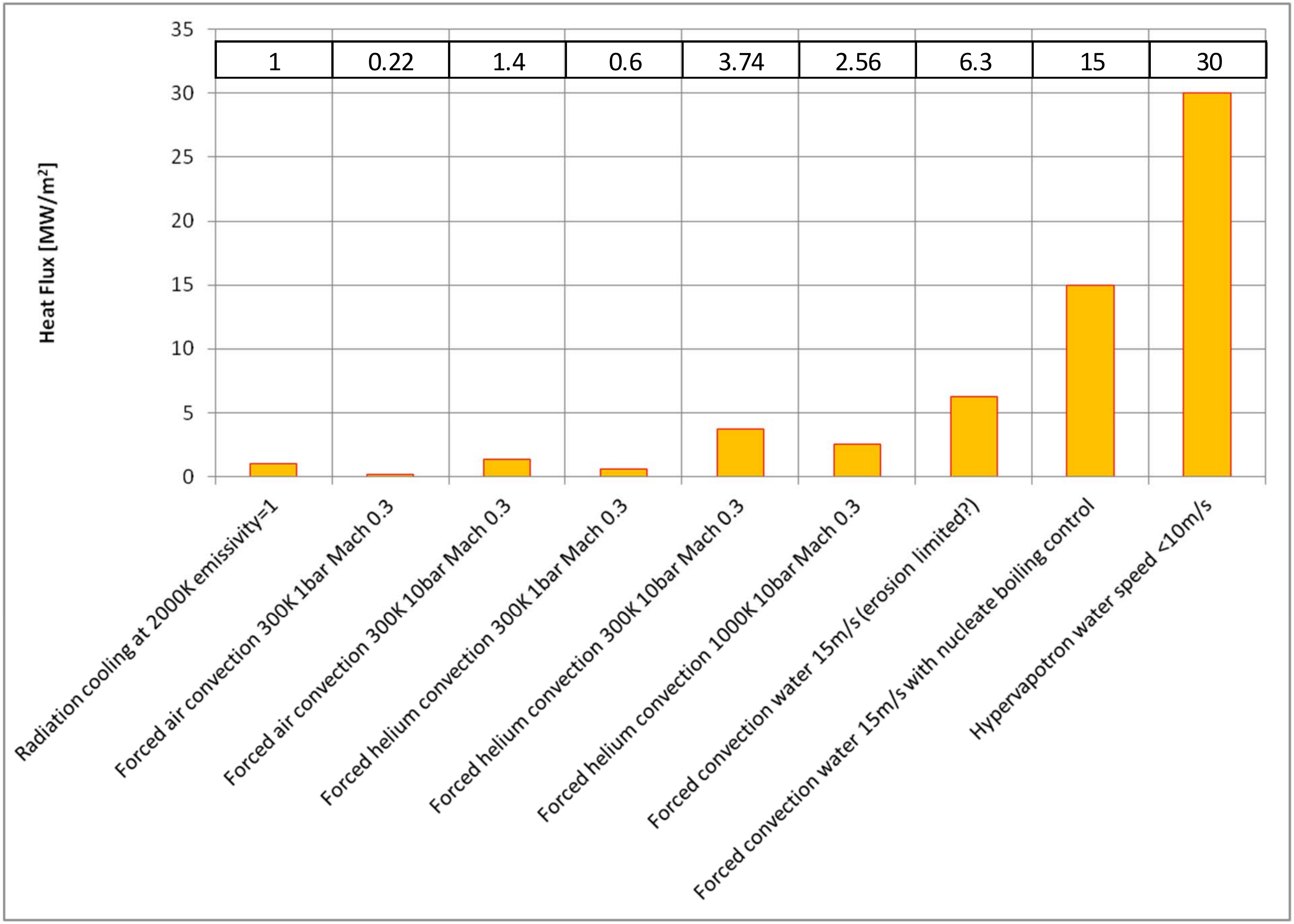
Fig.2a: Hypervapotron beam stoppimg elements as used in the JET Test Bed beam bump..



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.
•Long-term stability of nanofluids, the deposition of particles, and their effect on erosion are not well understood.

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

Summary



35
30
25
20
15
10
5
0
Heat Flux [MW/m²]
1
0.22
1.4
0.6
3.74
2.56
6.3
15
30
Radiation cooling at 2000K emissivity=1
Forced air convection 300K 1bar Mach 0.3
Forced air convection 300K 10bar Mach 0.3
Forced helium convection 300K 1bar Mach 0.3
Forced helium convection 300K 10bar Mach 0.3
Forced helium convection 1000K 10bar Mach 0.3
Forced convection water 15m/s (erosion limited?)
Forced convection water 15m/s with nucleate boiling control
Hypervapotron water speed <10m/s

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**