MHD Effects on Vapor Flow in a Conductive Fluid

(experimental work in support of the APEX - EVOLVE reactor concept)

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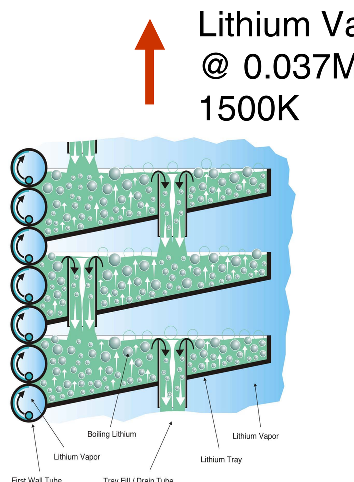
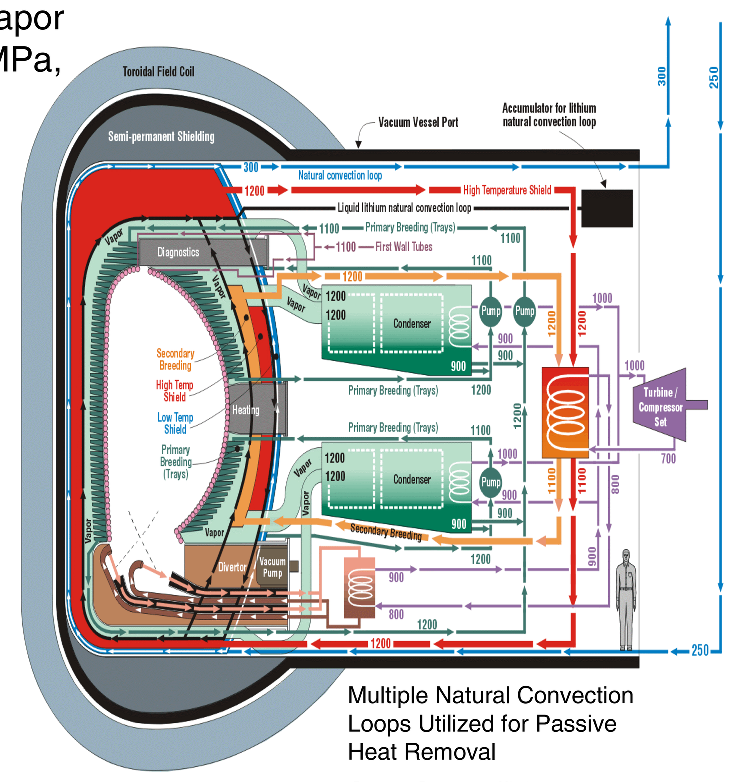
EVOLVE Reactor Concept

Efficient heat removal at high temperatures is a key issue for blankets in nuclear fusion applications. The EVOLVE (EVaporation Of Lithium and Vapor Extraction) concept was conceived of and developed within the APEX project as an advanced concept capable of handling high power densities with high power conversion efficiency (Abdou et al. 2001, Wang et al. 2001). It utilizes the extremely high heat of vaporization of lithium (about 10 times higher than water) to remove the entire heat deposited in the first wall (FW) and blanket. Tungsten trays filled with lithium located behind the first wall volumetrically absorb neutron energy, which causes boiling of the lithium and generation of the high temperature (1200 C) lithium vapor. The lithium vapor then leaves the trays as a result of buoyancy forces and is passed though a heat exchanger to heat helium gas for power conversion in high temperature turbines (Mattis et al. 1999). This concept of liquid metal evaporative heat transfer has been shown to be able to remove up to 200MW/m^2 in heat pipe applications and seems to be a viable option for a highly efficient fusion reactor heat extraction mechanism.



Conceptual Design of Lithium Boiling Trays



Multiple Natural Convection Loops Utilized for Passive Heat Removal

Cycle Gross efficiency 57.5%

	98.0	84.2	72.9	64.1	56.8	
104.4						
104.5	13.5	11.9	10.4	9.3	8.4	56.7
105.5	13.7	12.1	10.6	9.5	8.5	55.8
106.4	14.1	12.3	10.9	9.8	8.8	54.8
107.2	14.6	12.6	11.5	10.3	9.3	53.8
109.0	27.0	23.1	20.0	17.7	16.0	52.7

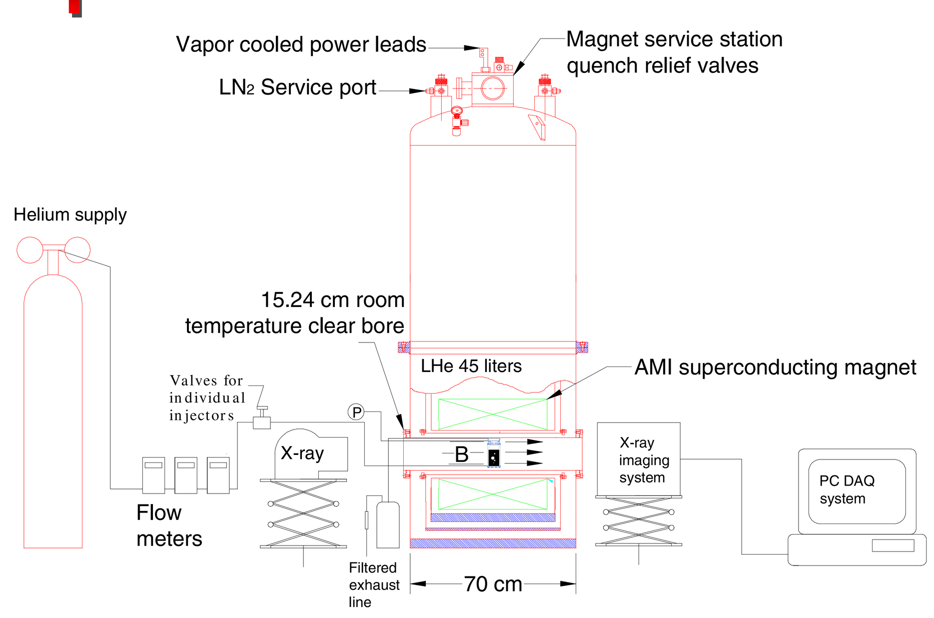
0.6 cm; 50 cm; 0.5 cm; 15 cm; 0.5 cm

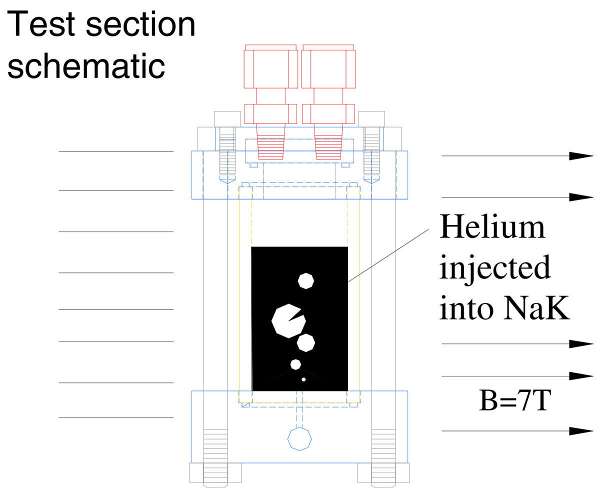
Nuclear heating in lithium and tungsten tray assuming an average void fraction of 55%.

Reproduced from: Sawan, M. "Neutronics Performance Characteristics of the High Power Density EVOLVE First Wall/Blanket System", Fusion Technology, Vol. 39 pp793 - 797

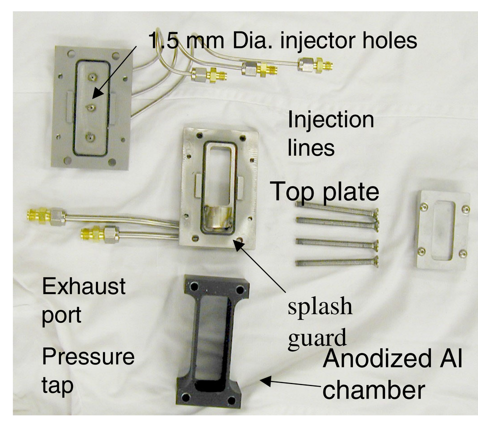
- The analysis of the void distribution in the lithium was initially assumed to be independent of the MHD forces.
- Experiments need to be conducted to examine the effects of MHD forces on the vapor distribution.

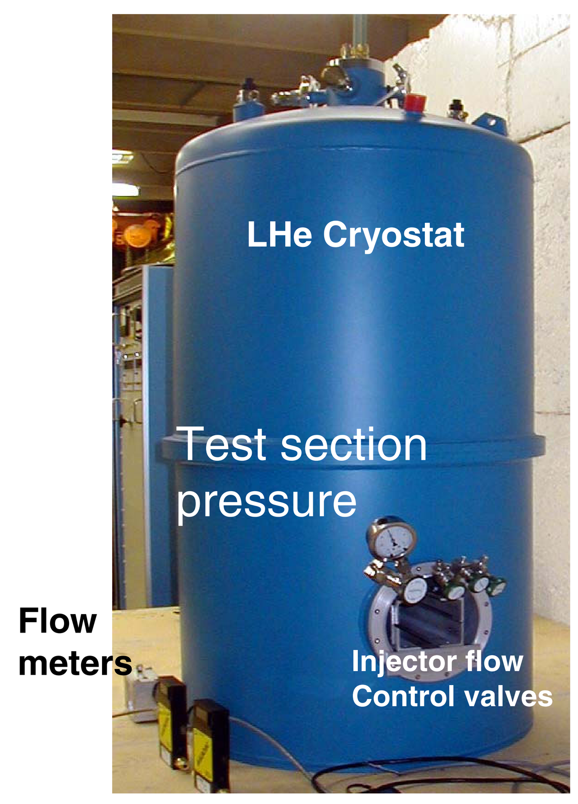
Experimental Test Section

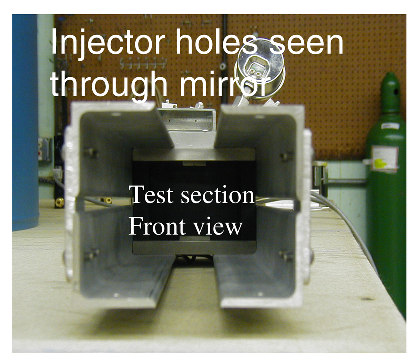




Test section schematic

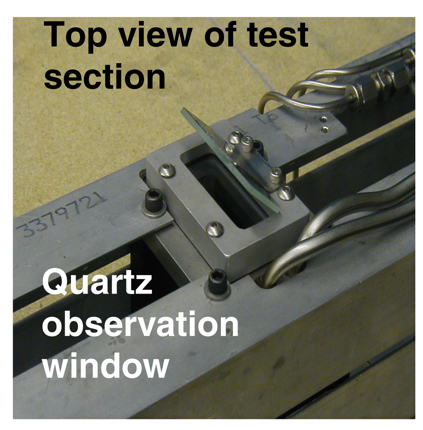




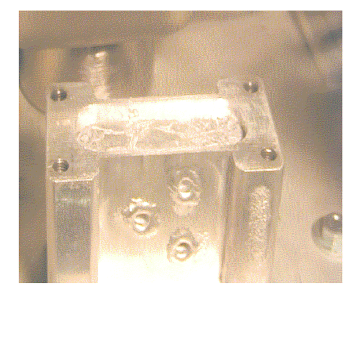


Quartz window

Support rails for magnet bore

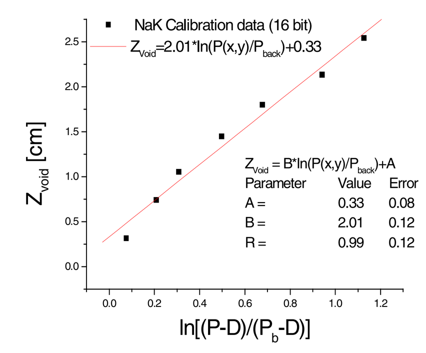


X-ray Absorption Calibration to Determine Void



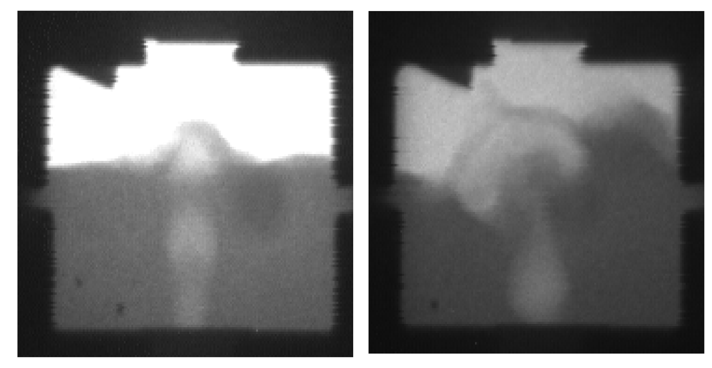
NaK filled calibration block

X-ray image of calibration block used to generate the curve below



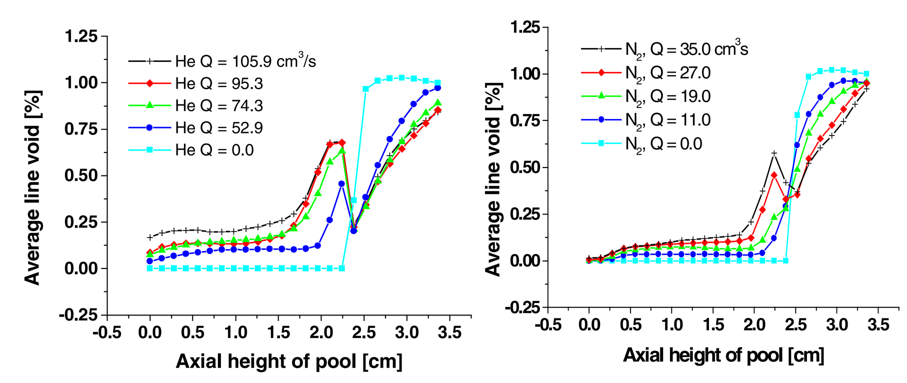
Calibration curve relating pixel value with void into the pool

Instantaneous Void Distribution in NaK Pool Without MHD



19 cm^3/s N_2 106 cm^3/s He

Images taken at a frame rate of 136 frames/s with a Dalsa 256x256 – 12 bit CCD camera. The X-ray source is a GE fluoroscope unit set to 90 keV for a two second exposure. Two second dynamic images of the injection are recorded on a PC.



From the images above the line average void distribution in the pool can be calculated using the calibration curve relating the pixel value with void.

Plots show the average void produced for different volumetric flow rates. As the flow increases the amount of liquid metal lifted by the jet increases.

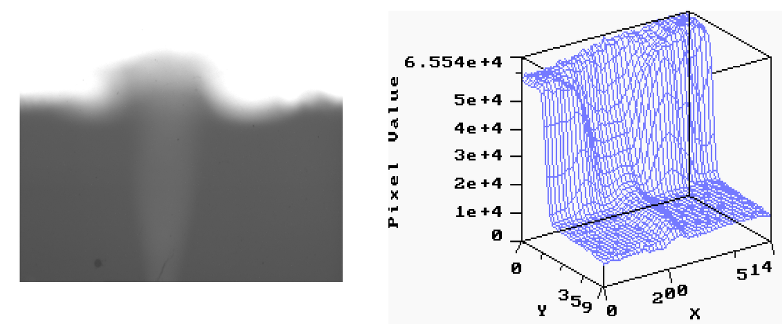
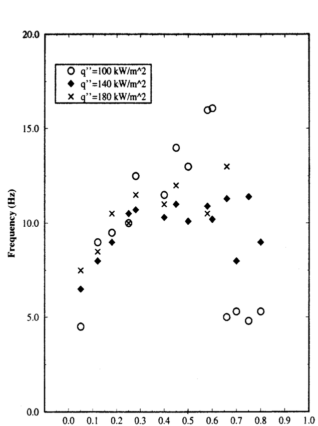


Image from a 1024 x 1024 –16 bit CCD camera. This image is the average over the two second period of the void distribution within the pool.

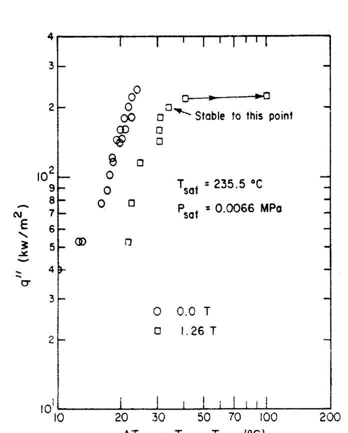
Average void distribution of helium injected into NaK at 85 cm^3/s. The pixel value is proportional to the void.

Background Research on Boiling Conductive Metals

The most relevant previous experiments where conducted by Lykoudis (1975, 1981, 1998) and Takahashi (1994). The Takahashi experiments were conducted at ~6T but in a vertical field. He saw only a slight shift in the nucleate boiling curve. Lykoudis' experiments were in a horizontal field with a ~1.26T field. He also saw a slight shift in the nucleate boiling curve. He also saw an initial increase in bubble frequency at ~0.4T (due to the suppression of convection) and then a sharp decrease possibly due to film boiling brought about from the Lorentz forces on the liquid metal.



Reproduced from: Int. J. of Heat Mass Transfer Vol. 41, pp. 3491-3500, 1998



Reproduced from: Int. J. of Heat Mass Transfer Vol. 24, No. 4, pp. 635- 643, 1981

Scaling Considerations

Properties of Li @ T=1500 K, P= 0.033 MPa	Properties of NaK @ T=293 K, P=0.023 MPa
μ = 0.0001785 [Ns/m^2]	μ=0.000522 [Ns/m^2]
ρ = 420.1 [kg/m^3]	ρ=860 [kg/m^3]
K = 69.31 [W/m/K]	k=99.2 [W/mK]
σ = 0.1775 [N/m]	σ=0.122 [N/m]
ρv = 0.01871 [kg/m^3]	ρHe=0.03829 [kg/m^3]
ρe=35.7 μΩ cm	ρe=33.5 μΩ cm

From the previous data only a slight shift in the nucleate boiling curve is expected with the addition of the magnetic field. This suggests that we can simulate the vapor produced during boiling with injection of gas from a nozzle of diameter of the Laplace constant:

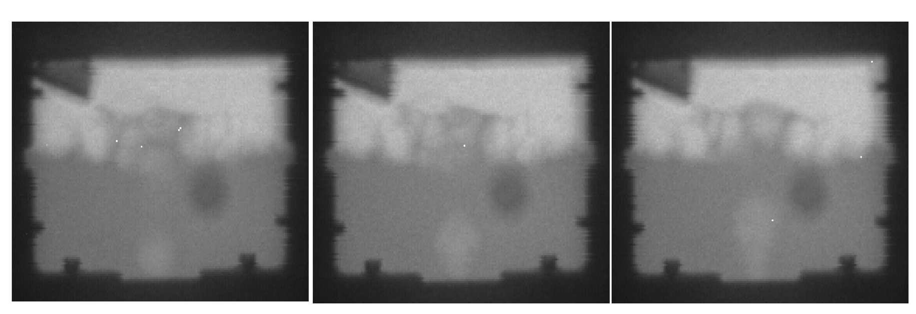
$$A = \sqrt{\frac{\sigma}{\Delta \rho \, g}}$$

$$J_g^* = \frac{J_g}{\left(\frac{\sigma g(\rho_l - \rho_g)}{\rho_l^2}\right)^{0.25}} \sim 5$$

and inject gas such that the dimensionless superficial velocity is consistent with that anticipated in the EVOLVE boiling situation.

Initial MHD Experiments

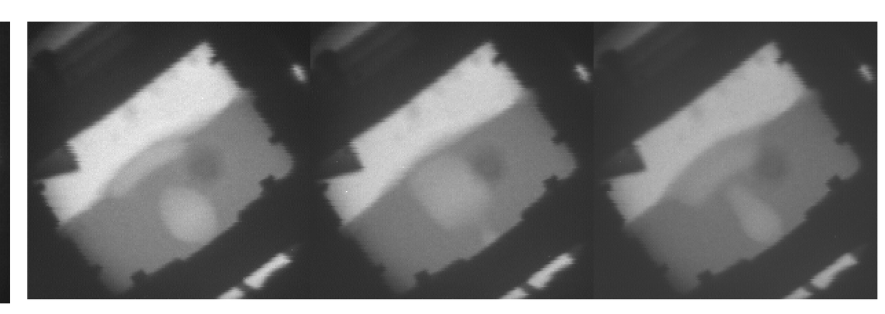
Progression of bubble with 0kG field



t = 0 t = 15ms t = 30ms

Helium injection at 23 cm^3/s into NaK with no magnetic field. There is significant surface agitation and bubbling.

Progression of bubble with 10kG field



t = 0 t = 74ms t = 148ms

Injection of helium at 23 cm^3/s with a 10kG magnetic field. The pool becomes very calm and the bubbles become larger and wider with a lower frequency of departure. The bubbles are elongated when they leave the pool surface (the image was rotated due to effects of B field on CCD array).

Effects of High Horizontal Magnetic Fields

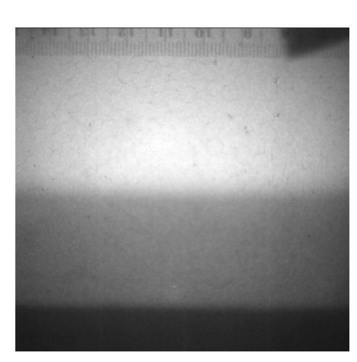
Movies taken with a frame rate of 120 f/s

CCD camera 512 x 512-8bit Dalsa camera

GE medical X-ray - 90keV, 2 s. exposure

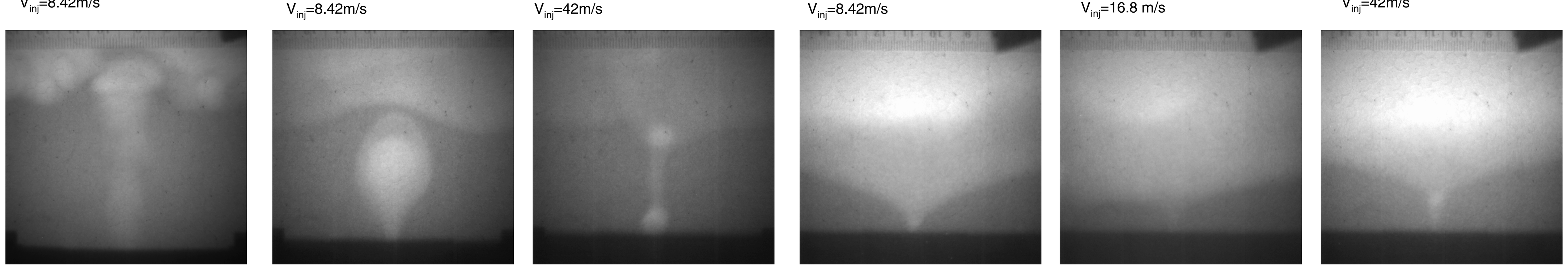
Flow rate 0-5 lpm (23cm^3/s) at magnetic field of 0 and 4T

Static/no flow X-ray image of the NaK



At higher magnetic fields > 5T there is a funnel shape gas area formed above the injector and the NaK is held in position

Gas flow =1 lpm/16.7cm^3/s, B=0 T, V_{inj}=8.42m/s	Gas flow =1 lpm/16.7cm^3/s, B=3 T, V_{inj}=8.42m/s	Gas flow =5 lpm/ 83.3cm^3/s, B=3 T, V_{inj}=42m/s	Gas flow =1 lpm/16.7cm^3/s, B=6 T, V_{inj}=8.42m/s	Gas flow =2 lpm/ 33.4 cm^3/s through injectors 1 and 2, B=6 T, V_{inj}=16.8 m/s	Gas flow =5 lpm/ 83.3cm^3/s, B=6 T, V_{inj}=42m/s



Observations from Experiments

- As the magnetic field increases the bubbles become more defined and the agitation of the pool is decreased dramatically.
- Liquid metal carryover is decreased as the magnetic field is increased.
- Pressure of injection increases slightly (a few psi) as the magnetic field is increased to 4T.
- Some fluid is held up at the edges of the vessel as the field is increased causing a decrease in apparent pool level.
- The bubbles from the injection become significantly larger at modest magnetic fields and move much slower.
- At lower magnetic fields the bubbles flatten out as they leave the surface of the NaK pool (become elongated).
- A more defined channel starts to form at higher magnetic fields; however, the channel becomes narrower and there are periodic bursts of vapor emanating from the bottom of the pool. A funnel shape is evident at fields > 5 T.
- As the flow rate is increased at the higher magnetic fields > 3 T the channel is narrowed further and the periodicity of the bursts of vapor becomes more regular.
- It appears that some of the gas entering the pool builds up on the bottom until a burst of vapor emanates from the injection site.