PRINTED SENSORS FOR MONITORING REACTOR HEALTH AWARD DE-SC0022749E

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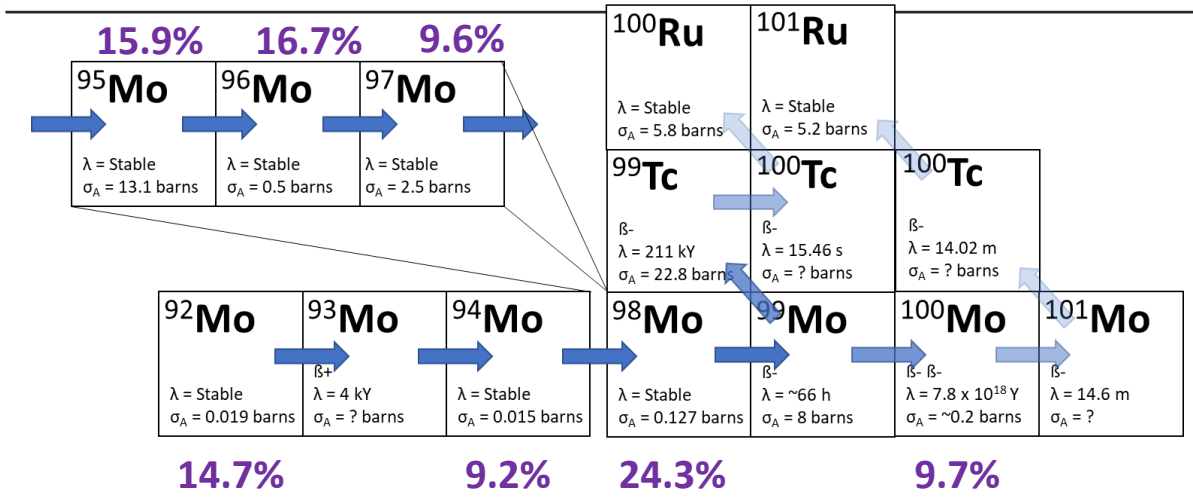
MOTIVATION SLIDE

- In-core reactor measurements using thermocouples require temperatures as high as 1600 °C, under high neutron flux.
- Many high-temperature TCs lose calibration in high neutron flux due to transmutation.
- INL pioneered HTIR (high temperature, irradiation resistant) thermocouples using Mo and Nb alloy wires.
- HTIR-TCs require heat treatments, prone to breaking and restrict geometry.
- Printing HTIR TCs may provide higher resilience, flexibility in alloy concentration, geometry, and ability to manufacture other sensors such as heat flux sensors.

STABILITY OF HTIR IN NEUTRON FLUX



Skifton et al., 2018, INL Data

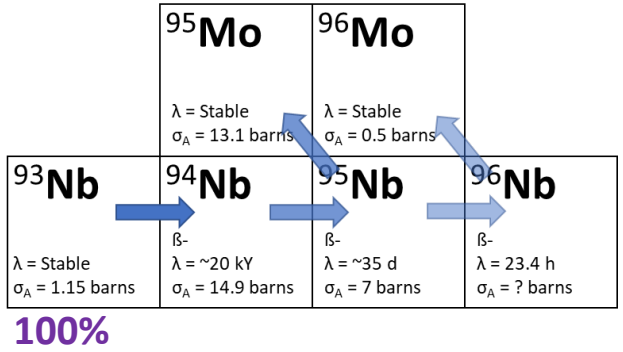
Neutron Cross Sections

Mo – 2.48 Barns

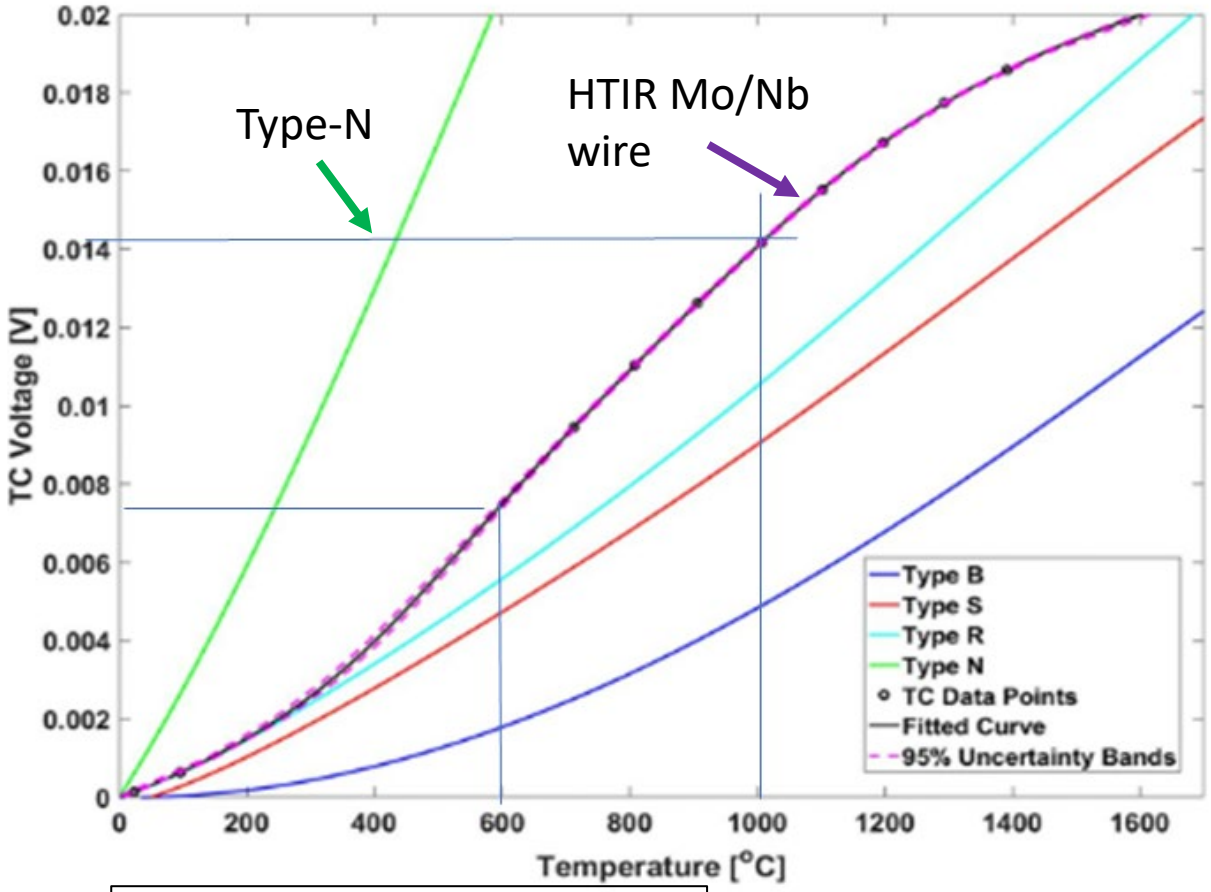
Nb – 1.15 Barns

Zr – 0.185 Barns

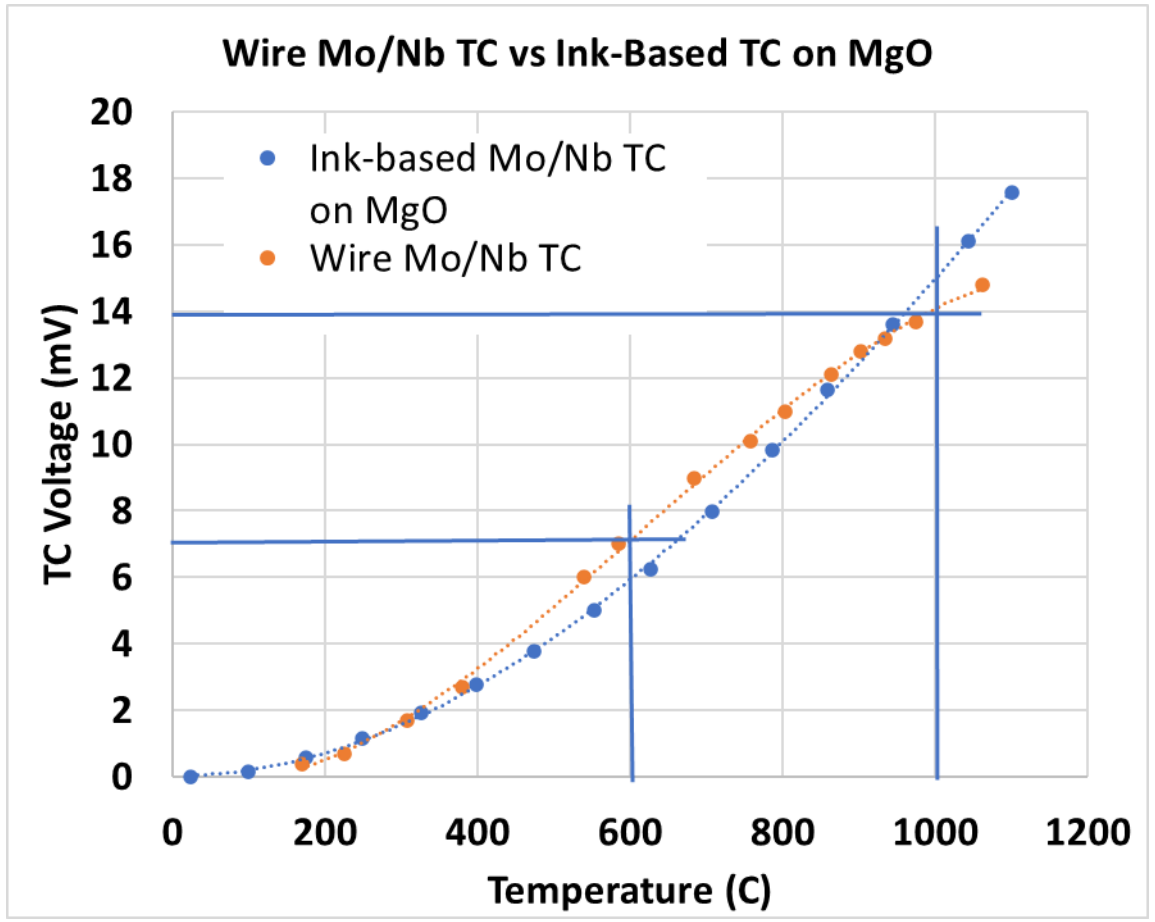
This program also explored if using Zr vs either Nb or Mo will have an advantage



THERMOCOUPLES



Skifton et al., 2018, INL Data

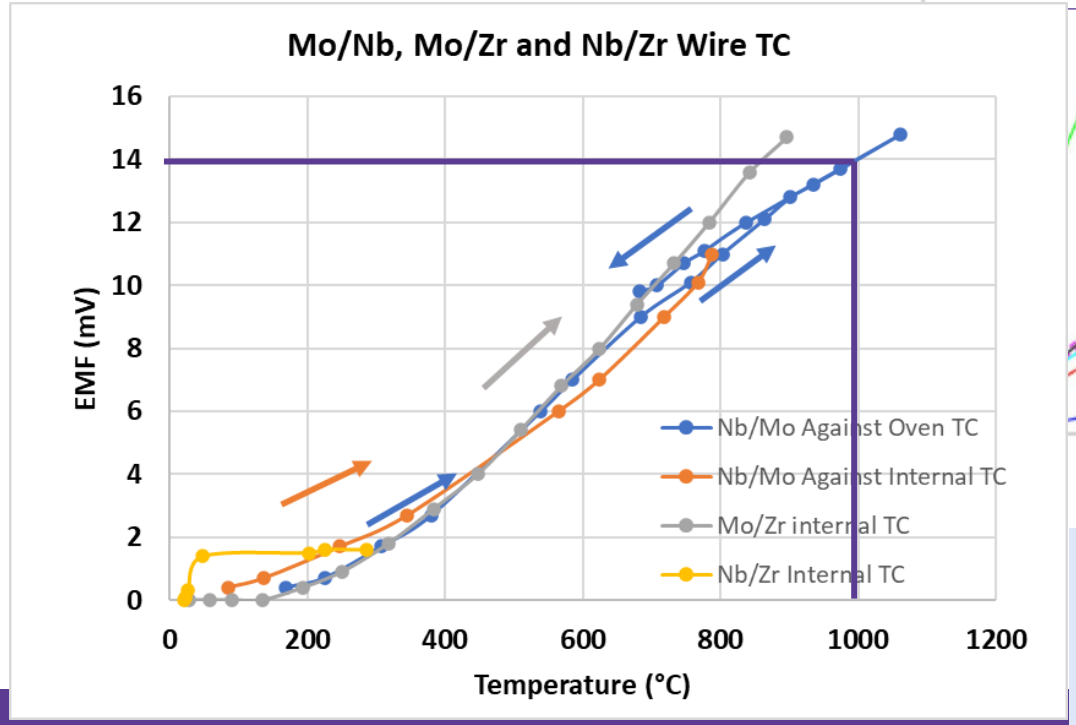


Ink-based and wire Mo/Nb thermocouple, ANI Data, 2023

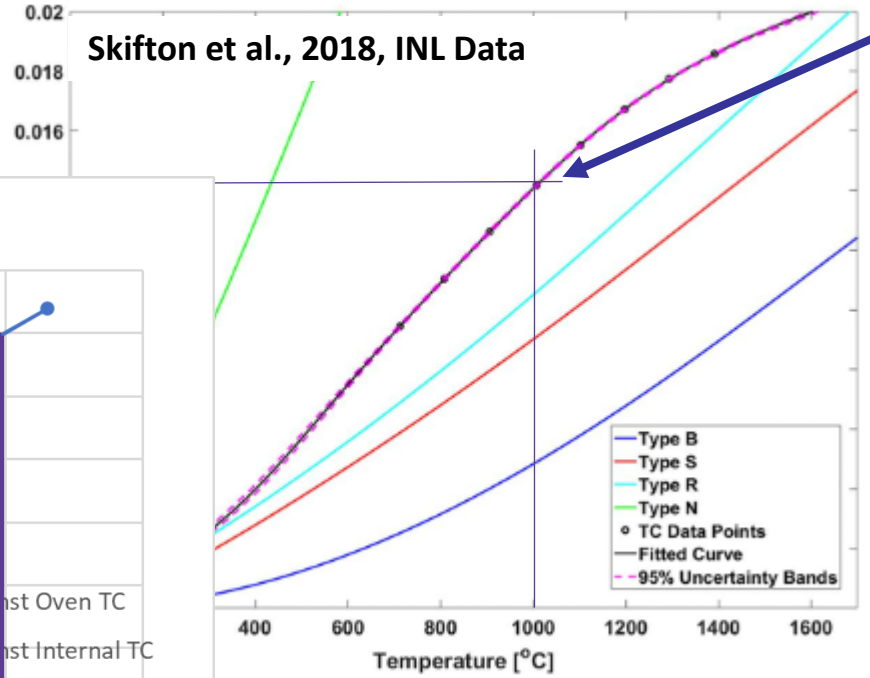
COMPARE THERMOCOUPLES

Compare response of thermocouples made from Mo/Zr, Nb/Zr and Mo/Nb.

This effort, ANI Data



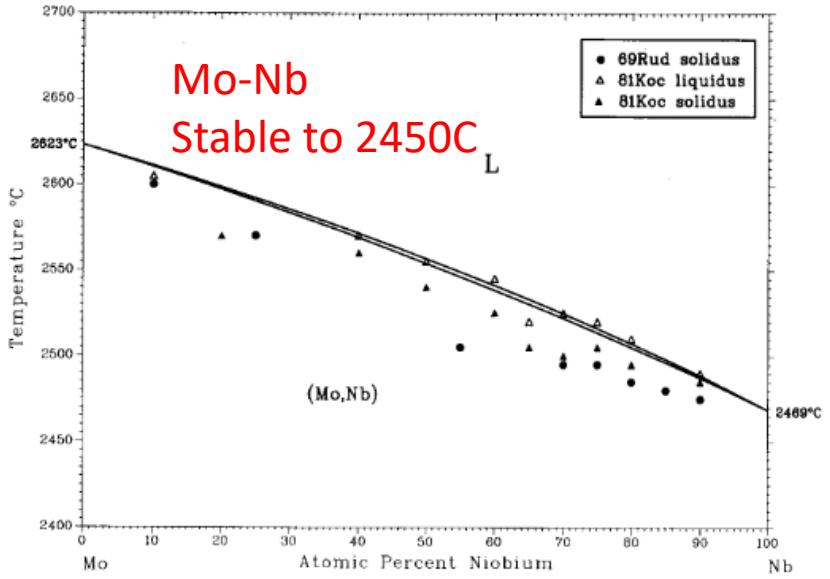
Skifton et al., 2018, INL Data

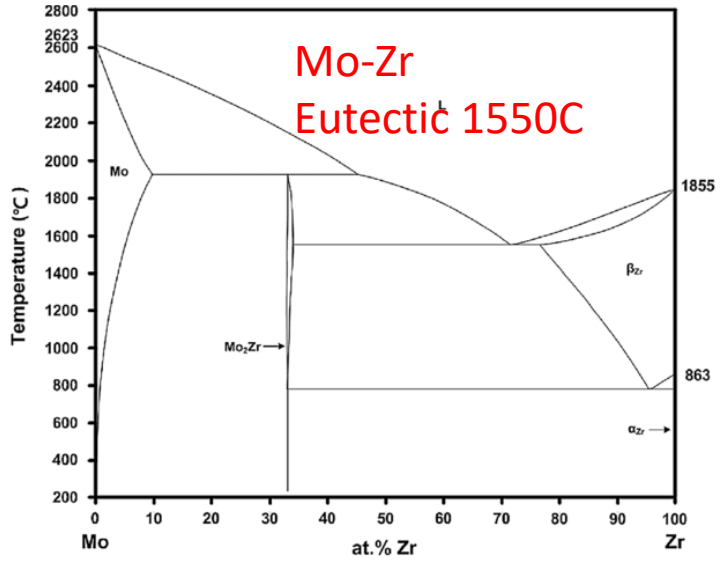


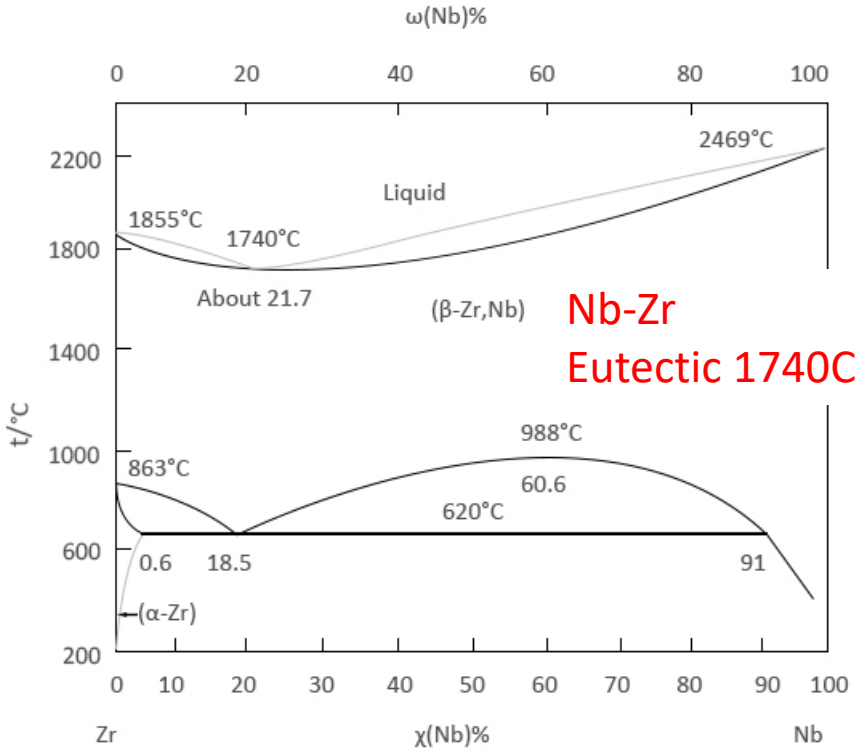
- ANI Mo/Nb wire data compares to INL data
- Mo/Zr performance as good or better than Mo/Nb

ANI applied NANOTECH INC.

PHASE DIAGRAMS







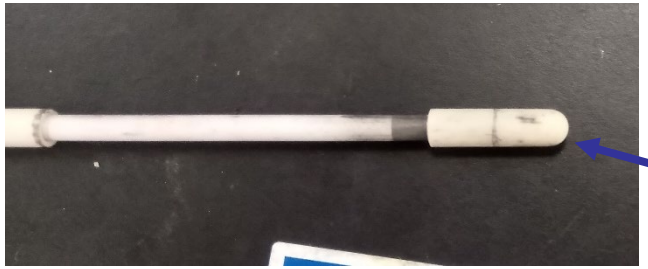
Nb-Zr system phase diagram

INK-BASED HTIR TC

Concept = Force Nb and Mo ink down channels of extruded ceramic TC tubing, dry and sinter in Ar gas to > 1100C, ink overlap is junction at one end.

Mo jumper wire between Nb and Mo channels

Type-K reference TC

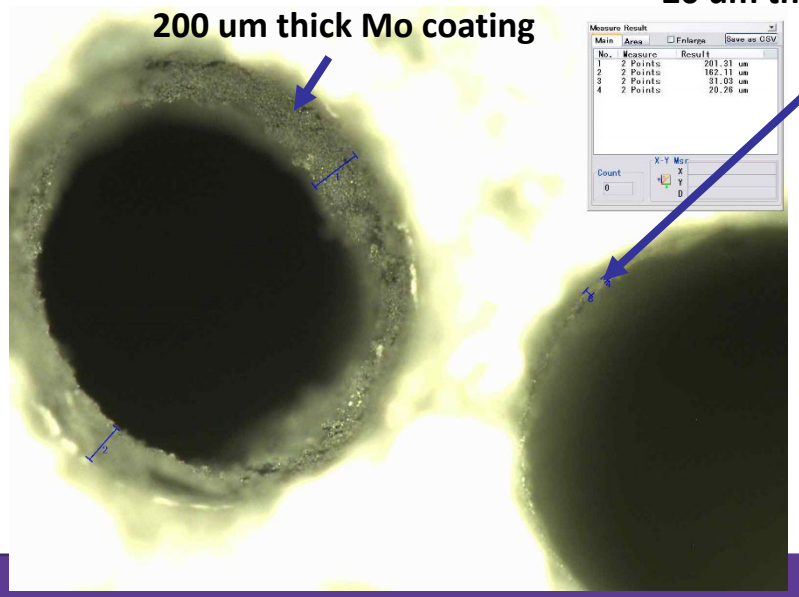


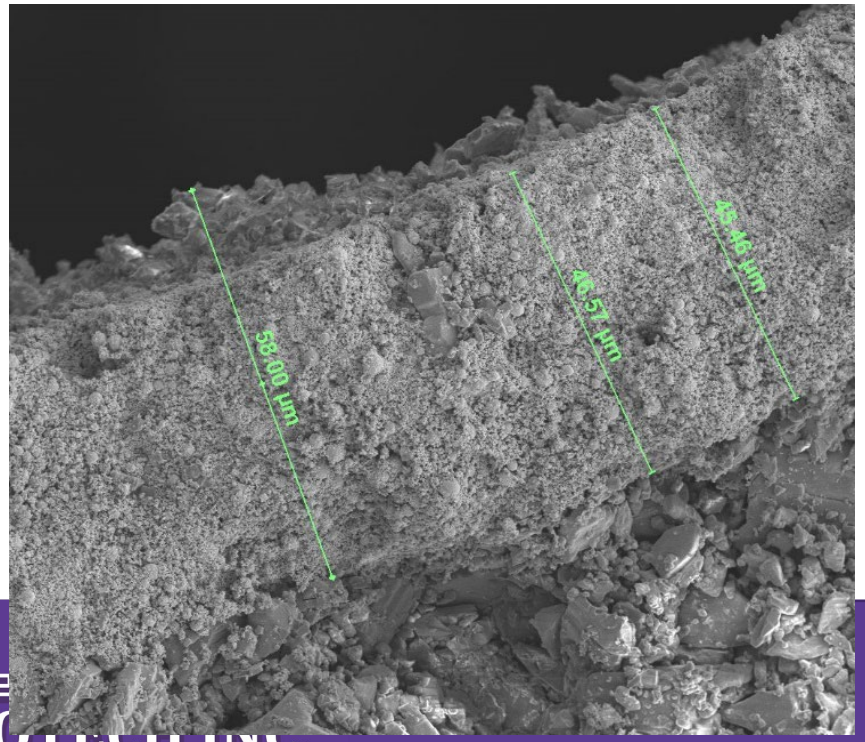
Ceramic cap
Could be Nb tubing

INK-BASED HTIR TC

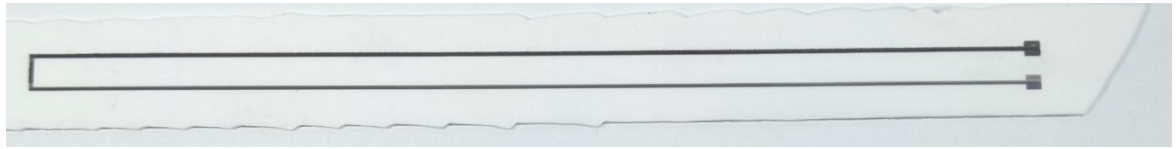
Concept = Force Nb and Mo ink down channels of extruded ceramic TC tubing, dry and sinter in Ar gas to > 1100C, ink overlap is junction at one end.

45 um Mo coating on MgO ceramic TC tubing

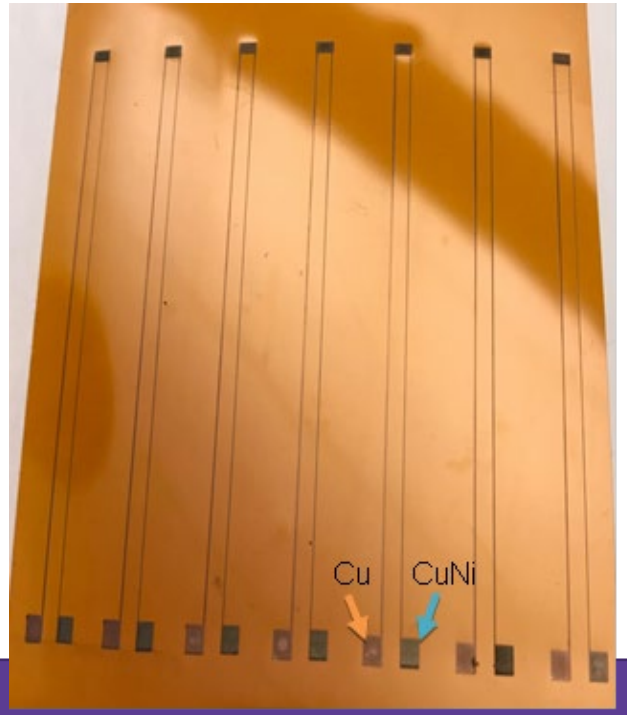




INKS FOR PRINTING THERMOCOUPLES



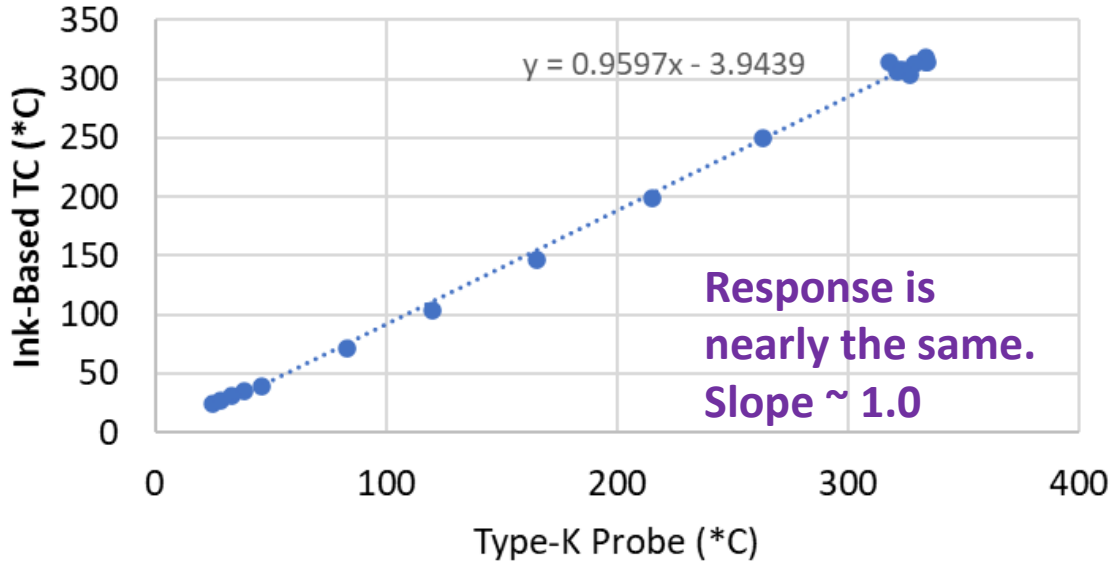
Aerosol Jet printed HTIR Mo/Nb thermocouple on Al2O3, Data BSU Feb2023



Aerosol Jet printed Type-T thermocouple (Cu:CuNi-alloy) on Kapton

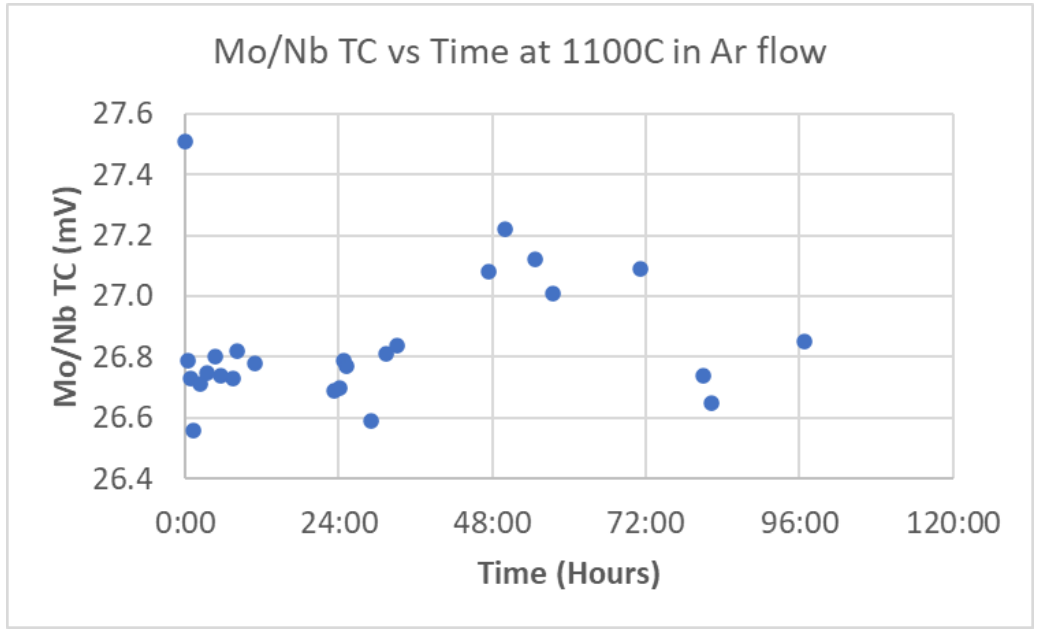
Data Optomec Inc.

Response of ink-based Type-K (chromel:alumel) thermocouple vs wires-based TC probe, Data ANI

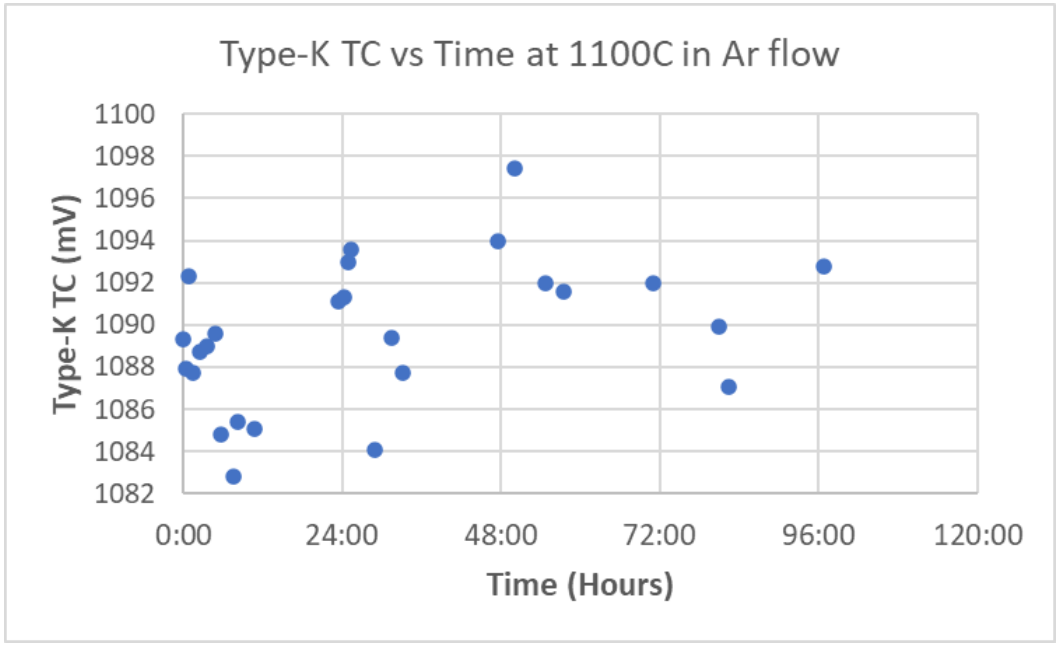


STABILITY OF INK-BASED HTIR TC

2.2% variation



1.5% variation



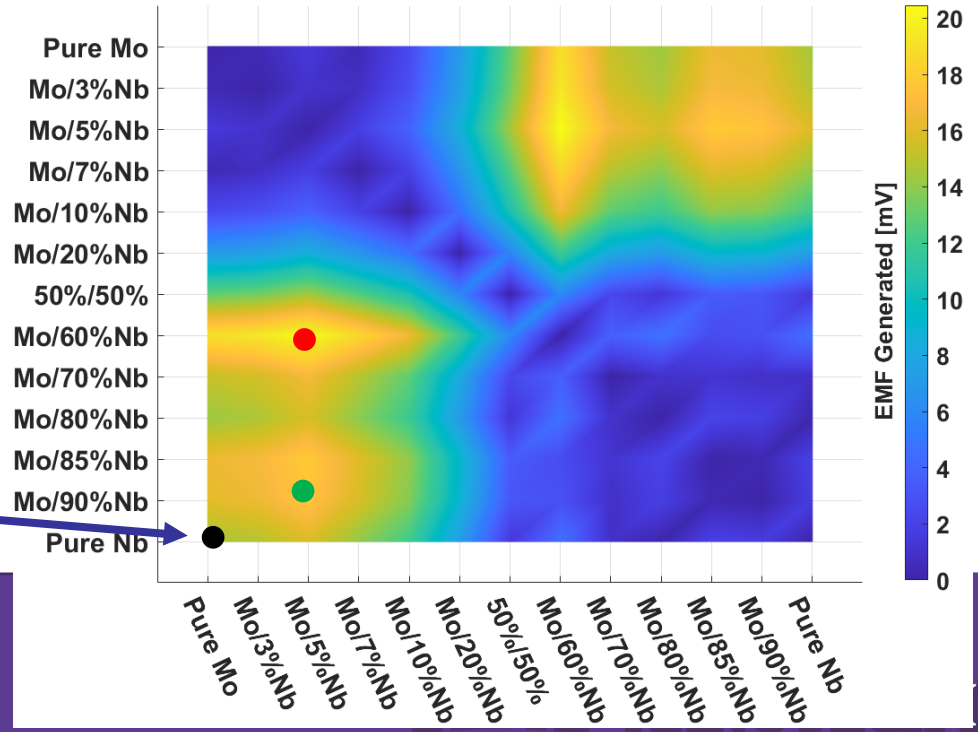
ALLOYS OF MO AND NB EXPECTED TO PROVIDE LARGER SIGNAL

Schley and Metauer showed that

- Mo-5%Nb : Nb-40%Mo (red dot)
- Mo-5%Nb : Nb-10%Mo (green dot)

may be better thermocouples (higher EMF output and less saturation in the range of interest (1500–2000C))

EMF for various alloys HTIR for response from 0°C to 1600°C



Current HTIR

Skifton et al., "A First Principle Look…"

Result: TC made of MIXTURES of Mo and Nb particles does NOT give desired response as would be expected from alloys.

CONCLUSIONS

- Stability at 1100C achieved if oxygen is kept out of the system. Flowing Ar works if testing in gas phase!
- Stability demonstrated within about 2% over 100 Hrs at 1100C, most of which appears to be system noise and oven stability, not sensor drift.
- Mo/Nb HTIR much better than Zr/Mo and Zr/Nb. Zr-based TC not stable, possible reactions at higher temperature.
- Demonstrated a printed Type-K (chromel – alumel) TC to 1100C.
- Tuning response of Mo/Nb using different mixtures of Mo and Nb particles does not work

ACKNOWLEDGMENT AND DISCLAIMER

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