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# HYDRODYNAMIC MEASUREMENTS IN IRRADIATION POSITION FOR MO-99 PRODUCTION LEU TARGET

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## ABSTRACT

Neutron irradiation of a low-enriched uranium (LEU) target for production of Molybdimun-99 generates heat that must be dissipated. Safety guidelines in place at the University of Missouri Research Reactor (MURR) dictate that the temperature of any surface in contact with the water coolant must remain at a temperature below the saturation temperature of the coolant. To ensure that the LEU target surface temperatures do not exceed the water saturation temperature, a thermal and hydraulic analysis of the proposed irradiation channel is being completed. Initial hydraulic measurements taken using a hot wire anemometer indicate that the coolant velocity is 3.4 ± 0.8 m/s. The measured velocity was used to calibrate a numeric simulation completed using the software FLUENT. A corresponding thermal performance map was then generated. Additional hydrodynamic measurements are planned using a dummy wedge in order to obtain flow measurements with a smaller uncertainty.

## 1.0 INTRODUCTION

Neutron irradiation of low-enriched uranium (LEU) for production of Molybdimun-99 generates heat that must be dissipated. Safety guidelines in place at the University of Missouri Research Reactor (MURR) dictate that the temperature of any surface in the pool must remain at a temperature below the saturation temperature for water. To ensure that the LEU target surface temperatures do not exceed the water saturation temperature, a thermal and hydraulic analysis of the N-1 channel is being completed. The MURR N-1 channel is the proposed irradiation position for preliminary irradiation studies.

Thermal-hydraulic modeling of the LEU target in the LEU channel can be easily completed using a commercial software package, such as FLUENT or CFX. Unfortunately, the exact boundary conditions in the MURR reactor are not known so the cooling capacity of the water flowing through the N-1 channel cannot be readily determined. Therefore a series of experiments have been planned in order to obtain a reasonable estimate of the water velocity through the N-1 channel. With the water velocity thus measured, it will be possible to more accurately estimate the heat transfer capacity of the LEU target. The purpose of the study described in this report is to measure the water velocity in the N-1 channel using a hot wire anemometer. A future study is planned to take more accurate velocity measurements in addition to taking direct thermal measurements on a heated sample.

## 2.0 MODELING

A simplified analytical model for convective heat transfer from a cylindrical target is developed here to motivate the need for measuring the coolant velocity, and to provide the basis for a more rigorous analytic model. A side view sketch of the cylindrical target in the N-1 channel is shown in Figure 1. Ignoring temperature gradients perpendicular to the flow velocity and treating convection from the target walls as an internal heat generation term, the energy balance for the control volume is [1]:

$$\frac{d(\rho V C_p T)}{dx} = \frac{\bar{h} P (T_w - T_i)}{A_{flow}} \qquad (1)$$

where $\rho$ is the water density, $V$ is the water velocity, $C_p$ is the water heat capacity, $T$ is the temperature of the water, $\bar{h}$ is the average heat transfer coefficient over the target surface, $P$ is the wetted perimeter of the target ($P = \pi D$), $A_{flow}$ is the flow cross-sectional area, $T_w$ is the target surface temperature, and $T_i$ is the water inlet temperature.

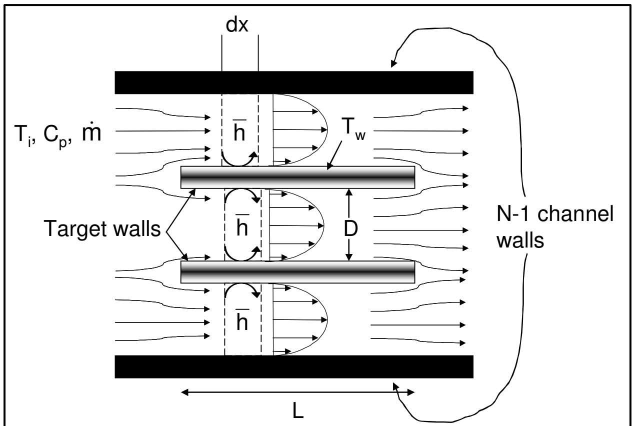

Figure 1. Geometry Definition for Simplified Model

Assuming that the local heat transfer coefficient, the density, and the specific heat can be described by average values, the energy balance over the differential area shown can be integrated over the entire length of the channel to find the exit temperature. The resulting expression for the total heat dissipation from the target is:

$$q = \dot{m} C_p (T_w - T_e) = \dot{m} C_p (T_w - T_i)\left[1 - e^{-\frac{\bar{h} P L}{\dot{m} C_p}}\right] \qquad (2)$$

where $q$ is the total heat transfer, $\dot{m}$ is the water mass flow rate ($\dot{m} = \rho V A_{flow}$), $T_e$ is the water exit temperature, and $L$ is the target length. It should be noted that Equate (2) can be interpreted using heat exchanger formalism, where the term in the square brackets is the heat exchanger effectiveness and the term in the exponent is the number of transfer units (NTU's). Hence the target can be envisioned to be a heat exchanger.

The heat transfer coefficient, strictly speaking, is a complex parameter to obtain. For purposes of this study, a simplified approach is used to determine the parametric dependence of the heat transfer coefficient. More accurate calculations for developing turbulent flow through the annular cylinder and in the annulus region will be taken up in a later publication. Further, it should be pointed out that the target holder has been ignored in this analysis as its presence un-necessarily complicates the analysis at this point.

It is assumed at this time that the average heat transfer coefficient can be calculated from a Nusselt number correlation with the form:

$$Nu = C\,\mathrm{Re}^{n}\,\mathrm{Pr}^{m} = \frac{hD}{k} \tag{3}$$

where *Nu* is the Nusselt number, *C* is a constant, Re is the Reynolds number, Pr is the Prandtl number for water, *k* is the water thermal conductivity, and n and m are constants. For turbulent flow, n is typically about 0.8 and m is about $\frac{1}{3}$. By substituting eqn. (3) into eqn. (2), and expressing the exponential function as a Taylor's series, and assuming that n ≅ 1, an expression for the heat flux can be obtained:

$$q'' = KV^{n}\left(T_w - T_i\right)\left[1 - 2\frac{K\frac{L}{D}}{\rho C_p} + \left(\frac{1}{9}\frac{K\left(\frac{L}{D}\right)}{\rho C_p}\right)^{2} - \left(\frac{1}{3456}\frac{K\left(\frac{L}{D}\right)}{\rho C_p}\right)^{3}\right] \tag{4}$$

where *K* is the property grouping $C\frac{k}{\upsilon^{n}}\mathrm{Pr}^{m}$, $\nu$ is the water viscosity and *q"* is the heat flux. The approximation in eqn. (4), keeping only 4 terms in the Taylor's series, will provide results within 1% of eqn. (2) as long as the exponential argument is 1 or less, quite common for this particular application.

Equation (4) clearly illustrates the dependence of the target heat flux on the flow velocity and the L/D ratio of the target. Therefore, it is necessary to obtain an estimate of the flow velocity in the N-1 channel to determine what the maximum allowable heat transfer will be for a given target geometry. The rest of this paper will be devoted to obtaining an initial measurement of the flow velocity.

## 3.0 EXPERIMENTAL SET-UP

The top of the N-1 irradiation channel is located about 7m below the surface of the MURR cooling water pool in a graphite wedge as shown in Figure 2. The diameter of the channel is 41.53mm and the channel is 0.89m long. A photograph of the reactor wedge that contains the N-1 channel is shown in Figure 3. Note that there is a neighboring channel, N-6, which shares a common drain with N-1 in the same wedge.

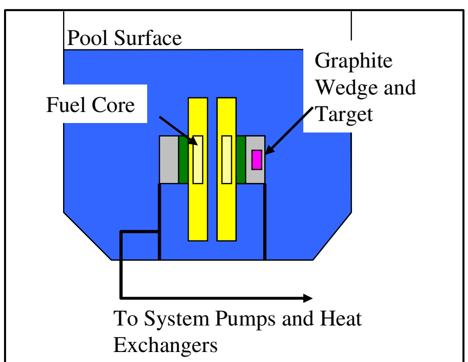


Figure 2. MURR Pool Configuration

### 3.1 Hardware

The challenges involved with measuring the water velocity include identifying a sensor that will minimize flow blockage in the channel and positioning the sensor in the N-1 channel from above the pool surface. A Dantec Dynamics fiber-film hot wire anemometer (model no. 55R11) was selected. A fixture was designed to hold the probe while providing protection to the fragile sensing element. The fixture, shown in Figure 4, was fabricated from stainless steel and had adjustable nylon screws placed in tapped holes around the periphery to allow the fixture to fit in channels other than the N-1. A close-up photograph of the hot wire probe is shown in Figure 5.

The fixture with the hot wire probe was lowered by hand into the N-1 channel using a steel cable. The length of the cable was measured as the probe was lowered to determine the probe depth in the N-1 channel during each of the tests. The hot wire probe signal and power co-axial cable was tied to the steel cable, along with a type J thermocouple probe and lead wire (see Fig. 6). All connections submerged in the water were coated with water sealant to prevent water leakage and shorting of the electric signals.

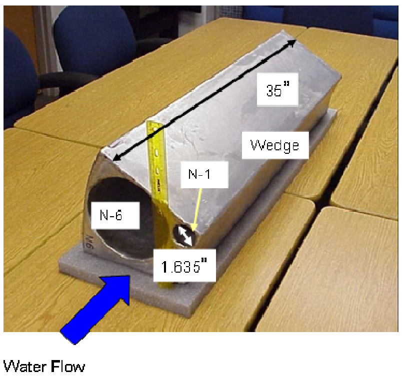


Figure 3. Photograph of Graphite Wedge That Contains N-1 Irradiation Channel

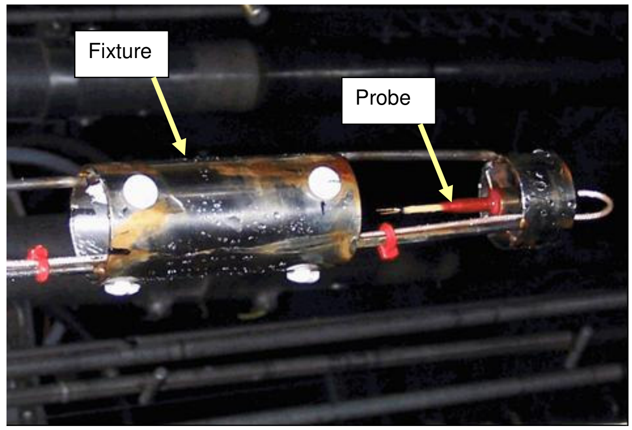


Figure 4. Photograph of Fixture and Hot-Wire Probe.

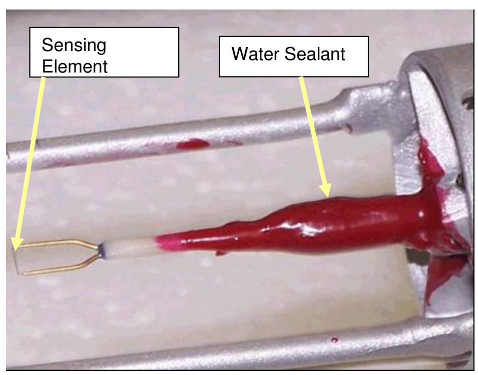


Figure 5. Close-up Photo of Hot Wire Probe in Fixture

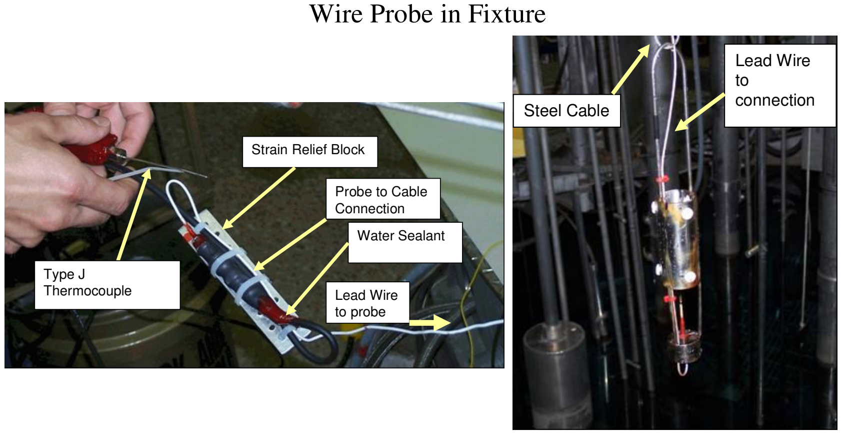


Figure 6. Hot Wire Connections and Fixture Getting Lowered into the Reactor Pool

The signal and power cable for the hot wire probe was connected to a control and signal conditioning module provided by Dantec Dynamics, Inc (see Fig. 7). The output voltage from the module, as well as the thermocouple voltage, was measured with a Keithly 2701 Digital Multi-Meter connected by an Ethernet cable to a laptop computer. The measurements were automatically recorded using Excelinx, a data logging software application.

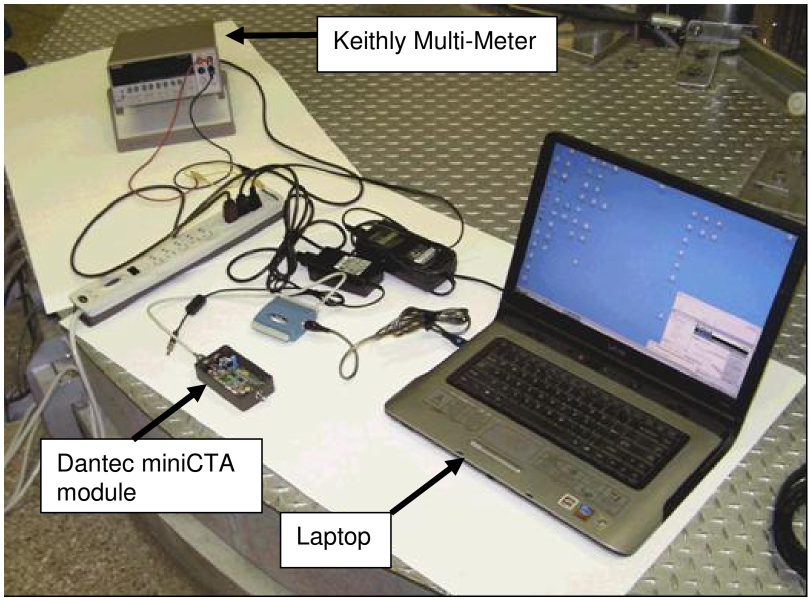


Figure 7. Photograph of Equipment used to Take Hot Wire Measurements in MURR Pool.

## 3.2 Hot Wire Calibration

The voltage output from the Dantec bridge circuitry is related to the flow velocity. Theory suggests that for constant temperature operation, the hot wire voltage is related to the flow velocity through King's Law [2].

$$Emf^2 = A + BV^n \tag{5}$$

where *Emf* is the measured voltage, *V* is the flow velocity, and A, B, and n are empirical coefficients. Unfortunately, the coefficients A and B, and the exponent n, need to be obtained from a calibration. A calibration facility based on a weight tank method was constructed to obtain those constants.

The calibration of a hot wire anemometer in water is very sensitive to temperature. Consequently a significant amount of care was taken to ensure that the water temperature used for the calibration was kept at nearly the same value as what would be encountered in the MURR pool. Previous measurements in the MURR pool indicated that the water temperature is around 37 $^oC$ when the reactor is shut down, the conditions in which the measurements are taken. Using nearly 37 $^oC$ water, the velocity/EMF data shown in Figure 8 was collected in the calibration facility. The error bars indicate the ± 1 standard deviation range due to measurement fluctuation.

The calibration curve plotted in the form of Kings' Law is shown in Figure 9. The exponent on the velocity term was found to be 1.0. This relation is used to calculate the flow velocity in the MURR pool when the hot wire EMF is measured.

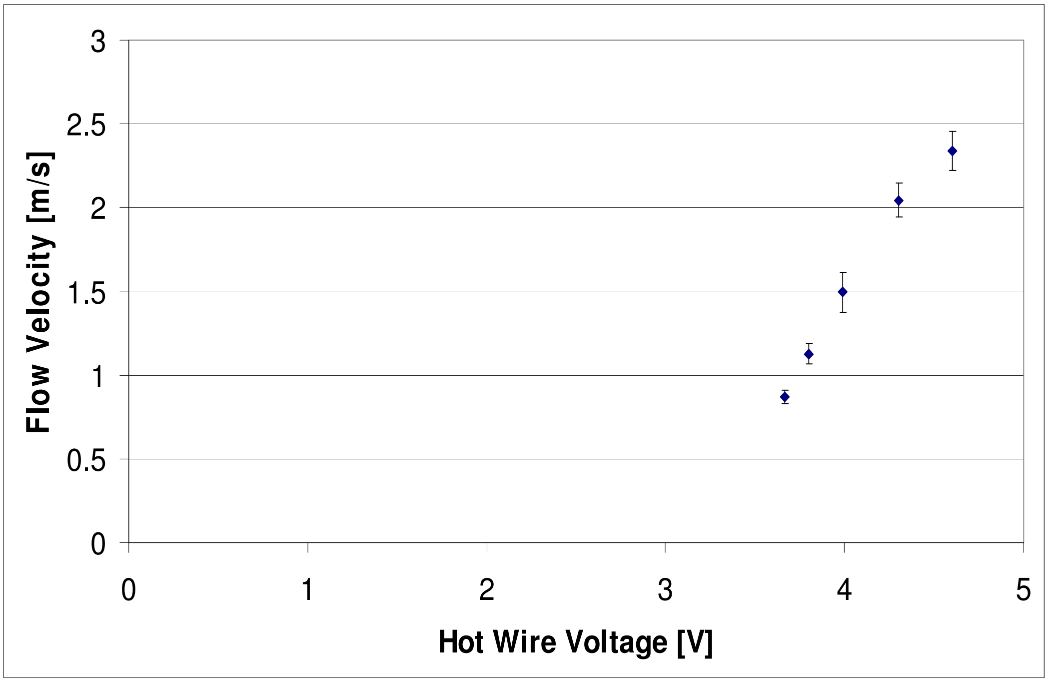

Figure 8.  Hot Wire Velocity/EMF Response (37 ºC water).

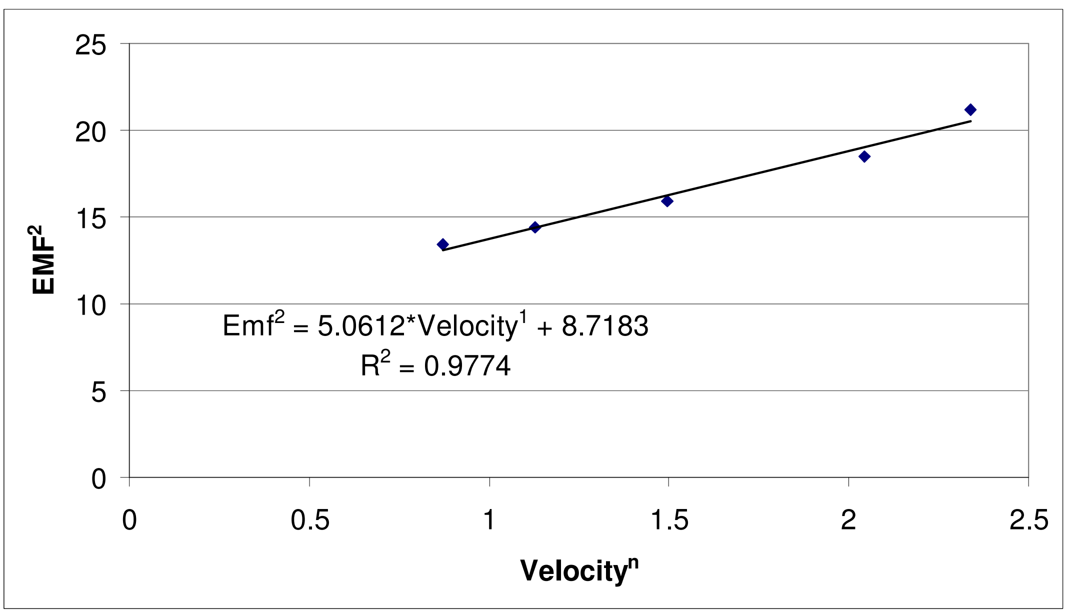

Figure 9. Hot Wire Calibration Curve (37 ºC water).

**3.3 Experimental Plan**

Hot wire measurements were taken in the MURR reactor during a routine weekly shutdown. The pool circulation pumps remained on while the hot wire probe fixture was placed at three locations within the N-1 channel – 60.96cm, 25.4cm, and 5.08cm from the inlet of the N-1 channel.  The influence of the N-6 channel was evaluated by taking measurements with and without a cover placed over that channel.

## 4.0 RESULTS

The measured flow velocity for each of the tested conditions is shown in Table 1. It should be noted that the measured data was adjusted to account for the variation in the flow temperature during the course of the experiments. The experiment that most closely represents the flow configuration when a target is being irradiated is when the N-6 channel is blocked (see Fig. 3) and the probe is at a depth of 60.96cm in the N-1 channel. For this case the measured velocity is $3.4 \pm 0.8$ m/s at a 95% confidence interval.

Table 1. Summary of Measurements Taken in N-1 Channel of MURR Pool.

| N-6 Channel | Probe Depth [cm] | Water Temperature [C] | Velocity [m/s] | Uncertainty @ 95% [m/s] |
|---|---|---|---|---|
| closed | 60.96 | 36.4 | 3.4 | 0.8 |
| closed | 25.4 | 37.4 | 3.5 | 0.8 |
| closed | 5.08 | 37.6 | 2.2 | 0.9 |
| open | 60.96 | 37.6 | 2.9 | 0.8 |
| open | 25.4 | 37.4 | 2.8 | 0.8 |
| open | 5.08 | 37.9 | 1.3 | 1.0 |

Figure 10 shows that removing the plug from the N-6 channel results in a velocity reduction of about 0.5 m/s in the N-1 channel. This can be explained primarily by the fact that the N-6 and the N-1 channels share a common flow exit at the bottom of the wedge shown in Fig. 3. There is also a flow interaction at the inlet of the N-1 and N-6 channels caused by their close proximity. The conclusion from this observation is that closing off the flow to the N-6 channel will allow more coolant flow through the N-1 channel. Since it is expected that the N-6 channel will be filled with items to be irradiated, the N-6 closed configuration should most closely represent the configuration during MURR operation. However, in high volume production, multiple irradiation channels are likely. Thus there will likely be a flow cannibalization problem between each of the channels.

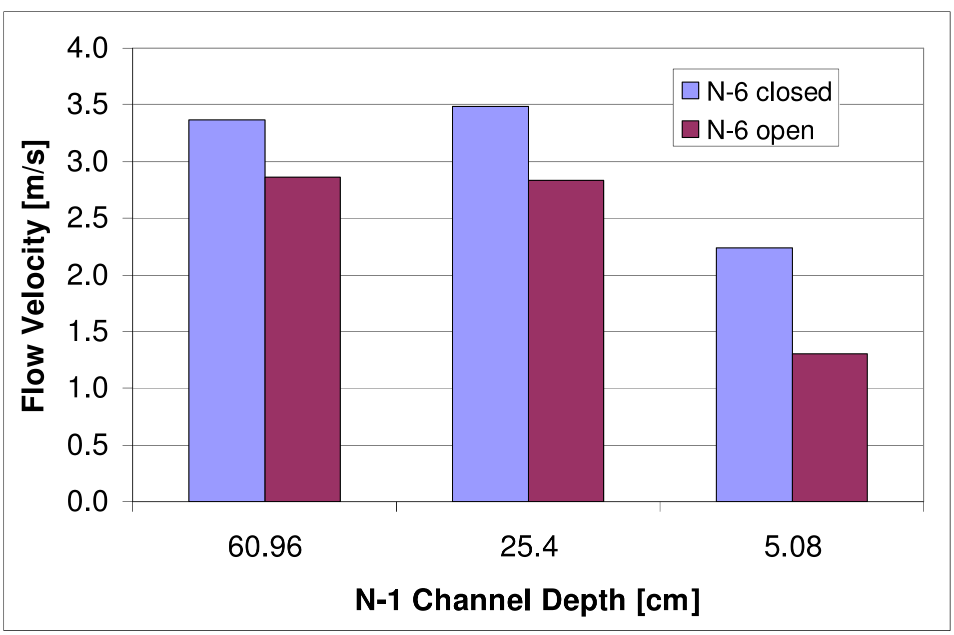


Figure 10. Flow Velocity in the N-1 Channel

Figure 10 also suggests that as the probe is moved vertically within the N-1 channel, there is no impact to the flow velocity until the probe is near the top of the channel where the flow velocity drops off. Thus, placing the irradiated target deeper in the channel will provide the maximum centerline flow velocity (note that the water mass flow rate is the same at all depths, however). The lower velocity can be explained by the developing velocity profile in the channel near the inlet.

## 5.0 CONCLUSIONS

Preliminary flow measurements in the MURR reactor have been taken with a hot wire anemometer to allow accurate convective heat transfer modeling activities to be completed. The flow velocity under expected flow conditions is 3.4 ± 0.8 m/s at a 95% confidence interval. The rather large confidence interval is an artifact of the extreme temperature and turbulence sensitivity inherent in using a hot wire probe. Further experimental measurements are planned using a dummy wedge that utilizes a variety of flow sensing strategies to validate the measurements taken. The dummy wedge structure will also allow the impact of multiple channels with a common drain to be studied.

## 6.0 ACKNOWLEDGEMENTS

We acknowledge the extensive help of Ron Govoro in calibrating the hot wire anemometer and taking the measurements in MURR. We would also like to thank the MURR manager Les Foyto, John Fruits, and Carl Herbold.

## 7.0 REFERENCES

[1] VanEngelenhoven, J., G. L. Solbrekken, and K. Geisler, "Air Cooling Limit Thermal Analysis for Ruggedized Electronics Enclosures," InterPack'07, Vancouver, BC, CA, July 8-12, 2007, Paper IPACK2007-33641.

[2] Doebelin, E. O., Measurement Systems: Application and Design, 5th ed., McGraw Hill, NY, NY, 2004.