Design of the Universal Neutron Irradiator

Experimental Operations and Facilities Division

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Design of the Universal Neutron Irradiator

by

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1 Introduction

SHINE medical isotopes is developing a novel method to produce the medical isotope Mo-99, which is the parent of Tc-99m, the most widely used diagnostic compound in nuclear medicine. This method utilizes U-235 fission in a subcritical liquid target solution, driven by an accelerator-based neutron source that is based on a deuterium-tritium reaction in a gaseous target. In this approach, the neutron-generating target is surrounded by uranyl sulfate (low-enriched uranium); fission in the uranium salt solution efficiently produces the desired Mo-99, as well as other fission products. After irradiation, Mo-99 is separated and the uranyl sulfate solution can be irradiated again to produce Mo-99. This allows the solution to be recycled for a very long time and significantly reduces the amount of associated nuclear waste.

SHINE has received U.S. Nuclear Regulatory Commission (NRC) approval to construct an Mo-99 production facility based on this method. In order to produce Mo-99 efficiently, the solution should be as close as possible to criticality. Because the solution is over moderated, any precipitation could push the solution to become critical and thereby hard to control. One of the possible precipitation scenarios is the formation of uranyl peroxide. Under irradiation, water decomposes into the products of radiolysis, some of which will form peroxide. To prevent precipitation, one has to develop a way to decompose the peroxide before it can react with uranium and form hard-to-dissolve precipitates.

To study peroxide formation and develop methods to prevent precipitation, we are developing an experiment capable of mimicking radiation conditions in the SHINE system. This report describes the irradiation setup we designed to irradiate a small volume of uranyl sulfate solution for the duration of one SHINE irradiation (~6 days) at the relevant fission power (~0.5 W/cc).

2 Overall Design Description

The Universal Neutron Irradiator (UNI) Station layout is shown in Figure 1. The target assembly is at the electron beam center line and is located in the beryllium reflector. Target cooling is provided by deionized (DI) water flowing through tubes connected to the existing Cu-67 cooling system. The capsule assembly is located in the beryllium reflector just behind the target assembly. The bottom of the capsule assembly contains the process solution that is to be irradiated. The upper portion of the capsule contains a hydrogen recombiner and required heating elements, as well as cooling and heating coils. Thermocouples located in the capsule provide temperature readouts and control. These coils are connected to new heater/chiller units located next to the station. Penetrations through the top flange of the capsule provide for heating/cooling lines, thermocouple leads, gas sampling lines, and an access port. A glove box surrounding these connections provides secondary containment.

Figure 1 Overall View of UNI Station

3 Target Design Description

The target assembly is shown in Figure 2. The tantalum converter plate holder is installed in the housing and sealed with mating flanges. Cooling water enters the housing through a 0.75-inch outer diameter (OD) tube and is directed across the 19 plates through 20 parallel channels. The water then exits through the 0.75-inch OD tube opposite the inlet. The plates are held in place at the top and bottom by slots in the holder mount. The beam window is integral with the housing as shown.

Figure 2 Target Assembly

4 Thermal Hydraulic Analysis of Target Assembly

Beam parameters for analyzing the cooling of the window and converter plates are as follows:

- Beam power: 20 kW
- Beam energy: 40 MeV
- Beam spot on the target: 20 mm full width at half maximum (FWHM)

The thermal hydraulic (and window stress) design and requirements of the window and the plates are the same as previously analyzed for the successfully operated tantalum target assembly.

Therefore, the analysis details will not be repeated here. MathCad calculations are shown in the appendix 1.

5 Effect of DU Converter

Neutron yield is a strong function of the photoneutron target composition. In reference [1] the neutron flux is studied as a function of beam energy for tungsten and uranium target. It was shown that the uranium target produces roughly two times higher neutron flux than any other high-Z material. Figure 3 shows results of Monte Carlo simulations for the photoneutron target combining the tantalum x-ray converter and secondary depleted uranium (DU) target. As shown in Figure 3, the addition of a secondary DU target increases the fission power density in the uranyl sulfate solution by 30%. Although the DU target significantly increased the neutron flux, it also significantly increased the radioactive materials inventory in the experiment. Because it is difficult to obtain safety approval for high-radioactive-inventory experiments, we decided not to use the DU secondary target in our final design.

Figure 3 Fission Power Density in 50-mL Solution Centered in the Middle of Be Reflector as a Function of Secondary Depleted Uranium Target Size and Dimensions

6 Use of Smaller Be Reflector

Although a large Be reflector provides the best neutron flux and fission rate in the solution volume, after negotiations with the vendor we realized that a full-scale 50-cm $\times$ 50-cm $\times$ 50-cm reflector is too expensive to manufacture, and that the time to delivery is too long. In order to get a more reasonable price and delivery dates, we had to decrease the volume of the Be reflector to 20-cm $\times$ 20-cm $\times$ 20-cm. The remaining volume of the reflector will be occupied by water. The studied geometries and corresponding fission rates in the solution are presented in Figure 4.

option	Be ref. volume(cc)	U volume(cc)	fission/source	fission/20kW	fission/cc/20kW	current(pnA)	fission power(W/cc)
①	50X50X50	50	3.89E-04	1.22E+12	2.43E+10	3.90	0.789
②	20X20X20	50	2.44E-04	7.62E+11	1.52E+10	2.44	0.494
③	20X20X20	50	1.87E-04	5.84E+11	1.17E+10	1.87	0.379
④	20X20X20	50	2.72E-04	8.49E+11	1.70E+10	2.72	0.551

Figure 4 Different Geometries for Reflector and Corresponding Fission Rates in 50-mL Uranyl Sulfate Solution

Case 4, depicted in Figure 4, provides a reasonable compromise between the size of the Be reflector and fission rate in the solution. We also found that fission rates in the solution benefit from the addition of a small volume of water surrounding the uranyl sulfate solution itself.

7 Effect of Internal Water Volume

We conducted a systematic study to discover how the water volume inside the Be reflector affects the fission rate in 50 mL of uranyl sulfate solution. The results of the simulations are shown in Figures 5 and 6. We also varied the distance between the tantalum x-ray converter and the solution. We found that the distance has a significant effect on the fission rate.

- fission power for each options

option	Be ref. volume(cc)	U volume(cc)	fission/source	fission/20kW	fission/cc/20kW	current(pnA)	fission power(W/cc)
①	20X20X20	50	1.50E-04	4.67E+11	9.35E+09	1.50	0.303
②	20X20X20	50	1.55E-04	4.83E+11	9.66E+09	1.55	0.314
③	20X20X20	50	1.98E-04	6.18E+11	1.24E+10	1.98	0.401
④	20X20X20	50	1.48E-04	4.62E+11	9.23E+09	1.48	0.299

Figure 5 Simulations for Four Different Geometries

- fission power for each options

option	distance(cm)	fission/source	fission/20kW	fission/cc/20kW	current(pnA)	fission power(W/cc)
①	6.5	1.71E-04	5.36E+11	1.07E+10	1.72	0.348
②	6.5	2.14E-04	6.70E+11	1.34E+10	2.15	0.435

Figure 6 Fission Rates for Be Converter Completely behind Tantalum X-ray Converter vs. Configuration where Be Converter Surrounds X-ray Converter

8 Distance between Converter and Sample

For the next study, we fixed the overall shape and configurations of the reflector and only varied the distance between the x-ray converter and the 50-mL uranyl sulfate solution. Results of the simulations are presented in Figure 7. The optimal distance was found to be ~7 cm.

option	distance(cm)	fission /source	fission/20kW	fission/cc/20kW	current(pnA)	fission power(W/cc)
①	4.5	2.51E-04	7.84E+11	1.57E+10	2.51	0.509
②	5.5	2.58E-04	8.08E+11	1.62E+10	2.59	0.524
③	6.5	2.59E-04	8.10E+11	1.62E+10	2.60	0.526
④	7.5	2.82E-04	8.82E+11	1.76E+10	2.83	0.572

Figure 7 Optimization of Distance between X-ray Converter and Solution Volume

9 Capsule Assembly Design

The capsule assembly is shown in Figure 8. The process solution to be irradiated is contained at the bottom of the 347SS primary. Installed around the outside bottom of the primary is a coil for heating or cooling the solution. A thermocouple located in the solution monitors and controls the solution temperature. The gas sample return is located just above the solution surface, and purges the gas generated from the solution upward toward the recombiner. Cooling coils are installed around the outside of the primary just above the solution in order to condense water vapor as it evaporates from the solution. The access port tube opening is located just above the solution surface. The port is used to insert a borescope to examine precipitates that may form at the bottom of the solution and to fill and extract samples from the bottom.

The recombiner matrix is located at the inside lower end of the recirculation separator cylinder. Gas is drawn upward through the matrix by natural convection due to the heating and cooling of the gas. As free hydrogen recombines oxygen, water vapor forms and is carried upward. Resistance element heaters are installed in and around the matrix to encourage recombining. Thermocouples located in the matrix control the heaters. The recirculation separator cylinder acts as a chimney to force gas upward, where it is cooled. The cylinder is double walled to insulate the hot gas on the inside from the cooler gas outside of the cylinder in the annular space. Hot gas with water vapor from the recombiner discharges at the top of the recirculation separator cylinder and is directed toward the side wall, which is cooled by coils located around the upper part of the primary. There the gas is cooled by the wall and the water vapor condenses and flows down the wall back to the liquid solution.

The top flange has penetrations for all the required tubes and wire leads. Compression fittings seal all of these penetrations. The primary container is welded stainless steel. A secondary that surrounds the primary is welded aluminum. An aluminum glove box located above the capsule provides secondary containment around the penetration through the top flange.

Figure 8 Capsule Assembly

10 Thermal Hydraulic Analysis of Capsule Assembly

Gas flow through the recombiner is caused by natural convection, as shown in Figure 9. Gas is heated in the recombiner by resistance heaters and by the exothermic chemical reaction of the hydrogen and oxygen. Buoyancy of the heated gas in the recombiner causes an upward flow through the recirculation separator. Gas is discharged at the top of the separator and directed against the cool primary wall. The cooled gas flows down through the annular space due to its increased density. At the bottom of the separator, the gas is forced back into the recombiner and then is reheated. Recirculation of the gas through the recombiner continually removes the free hydrogen. In addition, water vapor from the recombining condenses on the cold walls and flows back to the solution.

Figure 9 Capsule Assembly Thermal Hydraulic Concept

ANSYS CFX [2] was used to simulate the thermal hydraulic behavior in the UNI capsule during operation. The CFX model is shown in Figure 10. The inputs to the model are as follows:

- All cooled walls: 60°F
- Heated/cooled wall: 176°F maximum, 60°F minimum
- All other walls are insulated
- Process volume: 50 mL
- Heat generation in process solution: 20 W
- Solution temperature: 176°F maximum
- Recombiner heater power: 10 W
- Recombiner flow resistance is assumed to be negligible
- Gas is assumed to be helium at a pressure of 950 mbar
- Hydrogen gas is assumed negligible for the T-H modelling (<2%)
- Helium flow rate to and from gas sampling: 2 L/min

Figure 10 Capsule Assembly CFX Thermal Hydraulic Model

The CFX thermal hydraulic results are shown in Figure 11. The temperature profile in the capsule is shown in the left image. The temperature of gas leaving the recombiner is 309°F; due to heat loss to the outer annular channel, it cools to approximately 284°F as it flows upward in the separator. Gas discharge at the top of the separator rapidly cools to 85°F, and is further cooled to near 60°F as the gas flows down through the annular space to the bottom of the separator. The gas near the surface of the process solution remains near 60°F.

The velocity profile result is shown in the right-hand image of Figure 11. The maximum flow velocity in the separator is 0.7 ft/sec. The approximate average flow velocity downward in the annulus is 0.21 ft/s. The flow velocities are strong functions of the local temperature of the gas. However, the mass flow remains constant and is calculated to be 5 L/minute (at standard temperature and pressure) in the annulus and 7 L/minute up through the recombiner that flow value includes the 2 L/minute from the gas handling system. Note that the 2 L/minute is exhausted to the gas handling system at the top of the capsule.

Figure 11 Capsule Assembly CFX Thermal Hydraulic Model

A summary of the CFX results and comments are below:

- Of primary importance is control of the hydrogen concentration within the process assembly.
- A maximum concentration of 2% must be maintained.
- The maximum hydrogen generation that is expected from the 50 mL process solution is 20 mL/minute.
- As determined from the CFX thermal hydraulic analysis, the minimum recirculation flow through the recombiner is 7L/minute at standard temperature and pressure (STP)
- Assuming a 95% recombining efficiency, this results in a maximum of <0.3% hydrogen concentration within the assembly.
- A prototype process assembly with appropriate instrumentation will be tested to verify the thermal hydraulic calculation and the recombining efficiency of the hydrogen.

11 Reflector Assembly Design

The beryllium reflector assembly is shown in Figure 12. The assembly is located behind the target and surrounds the process capsule. The assembly consists of bare, solid, nuclear-grade beryllium blocks installed in a rectangular aluminum container. The container structure holds the blocks in place and provides flow channels for coolant flow over the surfaces of the blocks.

Figure 12 Beryllium Reflector Assembly

12 Thermal Hydraulic Analysis of Beryllium Reflector Assembly

Significant heat is generated in the beryllium due to irradiation from the electron beam. The internal heat generation is determined from a transport computer program and the data is used for the heat transfer calculations. The worst-case heat transfer condition is the front beryllium block at the center line of the beam. Calculations using MathCad are performed on this block. A classical correlation is used to determine the convective coefficient in the cooling channel at the faces of the front block. Internal heat generation at the beam centerline is used to determine the maximum beryllium temperature and the channel surface temperature, assuming a conservative one-dimensional heat transfer model. The limiting temperature criterion for the design is to avoid boiling at the surface of the channel. This, in turn, limits the thickness of the front block to 0.75 inches. The MathCad calculation is shown in the appendix 2.

13 New Chiller/Heater Unit Requirements

Based on the thermal hydraulic analyses for the capsule assembly, the following are requirements for the new chiller/heater units that are needed to support the UNI experiments:

Recombiner chiller requirements at 7 L/minute recirculation

- Condensing heat load: 60 W
- Sensible heat load: 10 W
- Heat load from moderator: 20 W
- Minimum capacity of chiller: 100 W at 1 L/minute water flow and 15°C
- Pump head at 1 L/minute: 8 psi

Process chiller/heater:

- Process heat load: 5 W, due to evaporation
- Heat load from moderator: 5:W
- Minimum chiller capacity: 15 W at 0.2 L/minute water flow and 15°C
- Minimum heating capacity: 25 W at 0.2 L/minute water flow and 85°C
- Pump head at 0.2 L/minute: 4 psi

14 UNI Capsule Prototype Test Description

The purpose of these tests is to validate the ANSYS CFX computer modeling of the thermal hydraulic behavior and associated recombiner calculations of the UNI capsule during operation. Tests are performed “on bench” and do not include irradiation of the capsule. The overall test arrangement is shown in Figure 8. The tests are performed in two phases. The first phase is intended to validate the modelling of helium flows and heat transfer in the absence of hydrogen (i.e., no recombining reactions). The second phase is to validate the calculations related to the recombining efficiency of the hydrogen and oxygen.

In phase 1, the resistance heaters are used to raise the helium gas to operating temperatures. The temperature of the gas will be measured by thermocouples at the location shown in Figure 13. The gas flow velocity will be measured at the discharge from the recirculation separator using a hot wire anemometer. Gas flow to and from the gas sampling system will be established and gas temperatures and flow rate will be measured again. This data will be compared to the analyses results.

Figure 13 UNI Capsule Prototype Design and Instrumentation

Phase 2 will be similar to phase 1, except that a small measured amount of free hydrogen will be introduced into the gas sampling return to the capsule. The gas sampling system will then be used to determine the effectiveness of the recombiner to remove the hydrogen.

15 Conclusion

The UNI irradiation setup was designed to study peroxide formation and develop methods to prevent precipitation in uranyl sulfate solution at the radiation conditions similar to the SHINE system. This experimental setup allows irradiation of a small volume of uranyl sulfate solution for the duration of one SHINE irradiation (~6 days) at the relevant fission power (~0.5 W/cc).

16 References

1. Makarashvili V., Chemerisov S., Micklich B., "Simulations of a LINAC-based photoneutron source," *NIM A*, 696, p. 136–140 (2012).
2. ANSYS CFX, Release 19.2, 2018. Ansys, Inc., Canonsburg, PA.

Appendix 1

MathCad Thermal Hydraulic and Stress Calculations for the Converter

(Same as previous calculations for the Ta Target Assembly)

Hydraulic Calculations for the Converter Cooling

Water properties at STP

$$\rho_{\text{h2o}} := 62.3 \frac{\text{lbm}}{\text{ft}^3} \quad \text{Density}$$

$$C_{\text{Ph2o}} := 1 \frac{\text{Btu}}{\text{lbm} \cdot \Delta^\circ\text{F}} \quad \text{Heat capacity}$$

$$\nu_{\text{h2o}} := 1 \cdot 10^{-5} \frac{\text{ft}^2}{\text{s}} \quad \text{Dynamic viscosity}$$

$$k_{\text{h2o}} := .347 \frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot \Delta^\circ\text{F}} \quad \text{Thermal conductivity}$$

$$\text{Pr}_{\text{h2o}} := 6.8 \quad \text{Prandtl number}$$

Channel geometry

$$w_{\text{chn}} := 1\text{mm} \quad \text{Channel width}$$

$$D_{\text{chn}} := 2 \cdot w_{\text{chn}} \quad \text{Hydraulic diameter}$$

Channel flow conditions

$$v_{\text{chn}} := 13 \frac{\text{ft}}{\text{s}} \quad \text{Average water flow velocity in channel}$$

$$\text{Re}_{\text{chn}} := \frac{v_{\text{chn}} \cdot D_{\text{chn}}}{\nu_{\text{h2o}}} = 8.53 \times 10^3 \quad \text{Reynolds number} > 10,000, \text{ turbulent flow}$$

$$Nu_{chn} := 0.023 \cdot Re_{chn}^{.8} \cdot Pr_{h2o}^{.33} = 60.426 \quad \text{Nusselt number for turbulent flow}$$

$$h_{chn} := \frac{Nu_{chn} \cdot k_{h2o}}{D_{chn}} = 3.195 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \Delta^\circ\text{F}} \quad \text{Thermal convective coefficient}$$

$$h_{chn} = 1.814 \times 10^{-3} \cdot \frac{\text{kW}}{\text{cm}^2 \cdot \Delta^\circ\text{C}} \quad h_{chn} = 18.145 \cdot \frac{\text{kW}}{\text{m}^2 \cdot \Delta^\circ\text{C}}$$

$$\Delta P_e := 1.5 \cdot \frac{\rho_{h2o}}{2 \cdot g} \cdot v_{chn}^2 = 1.704 \cdot \frac{\text{lb}}{\text{in}^2} \quad \text{Pressure differential across disk face}$$

$$N_{chn} := 19 \quad \text{Need total 6mm Ta at 0.667mm each} = 10$$

$$L_{chn} := 1 \text{ in}$$

$$F_{total} := N_{chn} \cdot L_{chn} \cdot w_{chn} \cdot v_{chn} = 30.31 \text{ gpm}$$

Thermal Hydraulic Calculations for the Converter Disks

$$P_{\text{beam}} := 10 \text{ kW}$$

$$q_{\text{Ubeam}} := 0.15 \frac{\text{kW}}{\text{cm}^3 \cdot \text{K}} \quad \text{From DU Target Report at FWHM} = 9.2 \text{ mm}$$

$$\rho_{\text{U}} := 19.1 \frac{\text{gm}}{\text{cm}^3}$$

$$\rho_{\text{Ta}} := 16.7 \frac{\text{gm}}{\text{cm}^3}$$

$$A_{\text{ratio}} := 4 \quad \text{Assumes half the beam diameter from DU Target}$$

$$q_{\text{Tabeam}} := \frac{\rho_{\text{Ta}}}{\rho_{\text{U}}} \cdot A_{\text{ratio}} \cdot q_{\text{Ubeam}} = 0.525 \frac{\text{kW}}{\text{cm}^3 \cdot \text{K}}$$

$$q_{\text{Taden}} := P_{\text{beam}} \cdot q_{\text{Tabeam}} = 5.246 \frac{\text{kW}}{\text{cm}^3}$$

$$t_{\text{plate}} := 0.167 \text{ mm} \quad 1/2 \text{ total thickness of plate}$$

$$T_{\text{he}} := 70^\circ \text{F} \quad \text{Water temperature}$$

$$k_{\text{plate}} := 57.5 \frac{\text{W}}{\text{m} \cdot \text{K}} \quad \text{Thermal conductivity of disk material}$$

$$h_{\text{he}} := 18 \frac{\text{kW}}{\text{m}^2 \cdot \text{K}} \quad \text{Typical thermal convective coefficient for high velocity water flow}$$

$$T_{\text{max}} := q_{\text{Taden}} t_{\text{plate}} \left(\frac{t_{\text{plate}}}{2 \cdot k_{\text{plate}}} + \frac{1}{h_{\text{he}}} \right) + T_{\text{he}} = 159.899^\circ \text{F}$$

Maximum temperature in disk assuming a 1-D heat transfer model with internal resistance and one convective and one insulated boundary and no radiant heat transfer

$$T_{\text{max}} = 71.055^\circ \text{C}$$

$$T_{\text{surf}} := \frac{q_{\text{Taden}} t_{\text{plate}}}{h_{\text{he}}} + T_{\text{he}} = 157.609^\circ \text{F}$$

Maximum wall surface temperature in coolant channel

$$T_{\text{surf}} = 69.783^\circ \text{C}$$

Thermal Hydraulic and Stress Calculations for Window for Cu-67 Project

$$p_{he} := 75 \frac{\text{lbf}}{\text{in}^2} \quad \text{Water pressure}$$

$$\nu_{pos} := 0.285 \quad \text{Poisson's ratio for window material}$$

$$a_{rad} := 15\text{mm} \quad \text{Window radius}$$

$$\sigma_{max} := 10000 \frac{\text{lbf}}{\text{in}^2} \quad \text{ASME Code Allowable at operating temperature 6061-T6 aluminum}$$

$$q_{Tabeam} := 0.742 \frac{\text{kW}}{\text{cm}^3} \quad \text{From Density Al / Density U}$$

$$t_{plate} := a_{rad} \left[\frac{3}{8} \cdot \frac{p_{he} \cdot (3 + \nu_{pos})}{\sigma_{max}} \right]^{\frac{1}{2}} = 0.057 \cdot \text{in} \quad \text{From stress equation for a uniform thick round disk free edges}$$

$$t_{plate} = 1.442 \cdot \text{mm}$$

$$T_{he} := 70 \text{ } ^\circ\text{F} \quad \text{Water temperature}$$

$$k_{plate} := 237 \frac{\text{W}}{\text{m} \cdot \Delta^\circ\text{C}} \quad \text{Thermal conductivity of window material}$$

$$h_{he} := 18 \frac{\text{kW}}{\text{m}^2 \cdot \Delta^\circ\text{C}} \quad \text{Typical thermal convective coefficient for water}$$

$$T_{max} := q_{Tabeam} \cdot t_{plate} \cdot \left(\frac{t_{plate}}{2 \cdot k_{plate}} + \frac{1}{h_{he}} \right) + T_{he} = 182.839 \cdot ^\circ\text{F} \quad \text{Maximum temperature in window assuming a 1-D heat transfer model with internal resistance and one convective and one insulated boundary and no radiant heat transfer}$$

$$T_{max} = 83.799 \cdot ^\circ\text{C}$$

Appendix 2

Thermal Hydraulic “MathCad+ hand calculations for the Be Reflector

Thermal Hydraulic Calculations for the Be Plates

$$q_{Ta} := 162 \frac{W}{cm^3}$$

$$t_{plate} := \frac{19}{2} mm = 9.5 \cdot mm \quad \text{1/2 total thickness of plate}$$

$$t_{chn} := 3 mm$$

Be plate size

$$H_{chn} := 3 in$$

Number of flow channels

$$N_{chn} := 1$$

$$Ax_{chn} := N_{chn} \cdot t_{chn} \cdot H_{chn} = 0.354 \cdot in^2 \quad \text{Xsect area of flow channel}$$

$$F_{h2o} := 30 gpm \quad \text{Total flow through assembly}$$

$$v_{chn} := \frac{F_{h2o}}{Ax_{chn}} = 27.164 \cdot \frac{ft}{s} \quad \text{Average flow velocity in channel}$$

$$T_{h2o} := 70 \text{ } ^\circ F \quad \text{Water temperature}$$

Water properties at STP

$$\rho_{h2o} := 62.3 \frac{lbm}{ft^3} \quad \text{Density}$$

$$Cp_{h2o} := 1 \frac{Btu}{lbm \cdot \Delta ^\circ F} \quad \text{Heat capacity}$$

$$\nu_{h2o} := 1 \cdot 10^{-5} \frac{ft^2}{s} \quad \text{Dynamic viscosity}$$

$$k_{h2o} := .347 \frac{Btu}{hr \cdot ft \cdot \Delta ^\circ F} \quad \text{Thermal conductivity}$$

$$Pr_{h2o} := 6.8 \quad \text{Prandtl number}$$

Channel geometry

$$D_{\text{chn}} := 2 \cdot t_{\text{chn}} = 6 \cdot \text{mm} \quad \text{Hydraulic diameter of channel}$$

Channel flow conditions

$$Re_{\text{chn}} := \frac{v_{\text{chn}} \cdot D_{\text{chn}}}{v_{\text{h2o}}} = 5.347 \times 10^4 \quad \text{Reynolds number} > 10,000 \text{ turbulent flow}$$

$$Nu_{\text{chn}} := 0.023 \cdot Re_{\text{chn}}^{.8} \cdot Pr_{\text{h2o}}^{.33} = 262.397 \quad \text{Nusselt number for turbulent flow}$$

$$h_{\text{chn}} := \frac{Nu_{\text{chn}} \cdot k_{\text{h2o}}}{D_{\text{chn}}} = 4.625 \times 10^3 \cdot \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \Delta^\circ\text{F}} \quad \text{Thermal convective coefficient}$$

$$h_{\text{chn}} = 2.626 \cdot \frac{\text{W}}{\text{cm}^2 \cdot \Delta^\circ\text{C}} \quad h_{\text{chn}} = 26.264 \cdot \frac{\text{kW}}{\text{m}^2 \cdot \Delta^\circ\text{C}}$$

Thermal Analysis

$$k_{\text{plate}} := 200 \frac{\text{W}}{\text{m} \cdot \Delta^\circ\text{C}} \quad \text{Thermal conductivity of window material}$$

$$T_{\text{max}} := q_{\text{Ta}} \cdot t_{\text{plate}} \cdot \left(\frac{t_{\text{plate}}}{2 \cdot k_{\text{plate}}} + \frac{1}{h_{\text{chn}}} \right) + T_{\text{h2o}} = 241.266 \cdot ^\circ\text{F} \quad \text{Maximum temperature in plate assuming a 1-D heat transfer model with internal resistance and one convective and one insulated boundary and no radiant heat transfer}$$

$$T_{\text{max}} = 116.259 \cdot ^\circ\text{C}$$

$$T_{\text{surf}} := \frac{q_{\text{Ta}} \cdot t_{\text{plate}}}{h_{\text{chn}}} + T_{\text{h2o}} = 175.474 \cdot ^\circ\text{F} \quad \text{Maximum wall surface temperature in coolant channel}$$

$$T_{\text{surf}} = 79.708 \cdot ^\circ\text{C}$$

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