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January 31, 2005

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Subject: Dry Storage Cask Annulus Air Flow Regime

Reference: USNRC Docket No. 72-1014, TAC No. L23657
SFPO Meeting with Holtec International on 19 January 2005
Holtec Letter 5014544 from E. Rosenbaum, dated 21 October 2005

Dear Sir:

On 21 October 2004, we transmitted a topical report to the NRC. This topical report (Holtec Report HI-2043258r0) evaluated the results of an EPRI/INEL test program on an actual ventilated storage cask loaded with spent fuel. The purpose of this evaluation was to determine if the airflow through the annular cooling passages of the cask was turbulent or laminar. It is our conclusion that this airflow is turbulent and that it is appropriate to model the airflow in the HI-STORM 100 System as turbulent.

This topical report was discussed in a meeting between the Spent Fuel Project Office and Holtec International on 19 January 2005. During the meeting, the SFPO Staff requested that we perform several additional analyses to confirm the results presented in our topical report. Specifically, it was requested that the sensitivity of the model to the effective thermal conductivity of the MSB, the size of the inlet vents, and the computational mesh density be examined. We agreed to perform such sensitivity studies and also committed to demonstrate turbulent flow in the annulus through an alternate method that does not rely on complicated computational models.

The alternate method calculations have been completed. These calculations use the temperature data from the EPRI report that documents the test program and analytical heat transfer correlations from respected sources to evaluate the heat transfer rates from the annulus surfaces to the air flowing through the cask. Both helium-backfilled and evacuated MSB conditions were evaluated. These calculations show that turbulent flow correlations give significantly better agreement with the measured temperatures than laminar flow correlations. *Preliminary* copies of these calculations are attached to this letter, in advance of their formal issuance in a future revision to the topical report, to allow the NRC to examine them as early as possible. These calculations will be added to the topical report in a future revision.

The sensitivity study computations have been completed and are currently undergoing technical review. The results of these calculations will be transmitted to the NRC as soon as possible, again to allow the NRC to examine them as early as possible, and will also be added to the topical report in a future revision.

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We would appreciate the SFPO's expeditious review of the attached technical material to allow us to reach a consensus on this topic as quickly as possible. Please feel free to contact me if any questions arise or if you require any additional information.

Sincerely,

Evan Rosenbaum
Project Manager, LAR 1014-3

Technical Concurrence:

Dr. Indresh Rampall
Consulting Engineer

Attachments: Preliminary Alternate Method Calculations (10 pages total)

emcc: Mr. Larry Campbell, USNRC
Mr. Wayne Hodges, USNRC
Mr. John Monninger, USNRC
Mr. Christopher Regan, USNRC

# ASCERTAINING THE ANNULUS AIR FLOW REGIME IN THE VSC-17 WITH HELIUM BACKFILL

## 1. PURPOSE

The VSC-17 cask tested at the Idaho National Engineering Laboratory (INEL) provides valuable thermal performance data to enable the flow regime (i.e., laminar or turbulent) of the air flow through the annulus between the overpack and the contained MSB canister to be determined. The temperature data from Reference 1 permits the amount of heat rejected to the ambient from the external cask surfaces (via natural convection and thermal radiation) to be quantified using classical heat transfer correlations. The balance of the decay heat energy (i.e., that portion of the total decay heat not rejected from the cask external surfaces to the ambient) must be removed by the ventilation air.

Because the temperatures of the air entering and exiting the cask cooling passages were measured quantities, the air flow rate necessary to remove the balance of the decay heat can be directly computed using an energy balance. Having determined the air flow rate corresponding flow velocity, it is then possible to compute, again using classical duct flow correlations, the quantity of heat that can be extracted by the flowing air from the annulus surfaces assuming different flow regimes (i.e., laminar and turbulent). The assumed flow regime is correct if the computed heat extracted by the flowing air is in accord with the heat energy to be removed by the air stream.

The calculation process just described has the benefit of not relying on detailed geometry of the cask cooling passages or on complex computer modeling.

Experimental data provided in Reference 1 for a canister backfilled with 0.8 atm helium (Run #1) has been used in these calculations.

## 2. REFERENCES


1. "Performance Testing and Analyses of the VSC-17 Ventilated Concrete Cask", EPRI "TR-100305, May 1992.
2. "Identifying the Appropriate Convection Correlation in FLUENT for Ventilation Air Flow in the HI-STORM System", Holtec Report HI-2043258, Rev. 0.
3. "Heat Transfer", J.P. Holman, Sixth Ed., McGraw Hill (1986).
4. "Engineering Thermodynamics", R.E. Balzhiser & M.R. Samuels, Prentice Hall, (1977).
5. "Elements of Heat Transfer", M. Jakob and G.A. Hawkins, John Wiley & Sons, (1957).


## 3. INPUT DATA

| | |
|---|---|
| $Q_{tot} := 14900watt$ | Total Heat Generation in the Cask [1] |
| $D_{cask} := 105in$ | VSC-17 Cask OD [1] |
| $D_{cav} := 58.66in$ | VSC-17 Cavity Diameter [1] |
| $gap := 2.955in$ | Radial Gap Between Canister and Cask [1] |
| $H_{cask} := 226in$ | VSC-17 Cask Height [1] |
| $H_{can} := 182.68in$ | Canister Height [1] |
| $\varepsilon_{side} := 0.63$ | Emissivity of Cask Side (Concrete) [2] |

| | |
|---|---|
| $\varepsilon_{top} := 0.66$ | Emissivity of Canister Top (Carbon Steel) [2] |
| $T_{amb} := 294K$ | Ambient Temperature [1] |
| $T_{side} := 307.6K$ | Average Cask Side Temperature [1] |
| $T_{top} := 325.7K$ | VSC-17 Top Surface Average Temperature [1] |
| $T_{in} := 308.2K$ | Annulus Air Inlet Temperature [1] |
| $T_{out} := 336.1K$ | Annulus Air Outlet Temperature [1] |
| $P := 1atm$ | Atmospheric Pressure |
| $T_{w1} := 388.7K$ | Annulus Inner Surface Mean Temperature [1] |
| $T_{w2} := 341.5K$ | Annulus Outer Surface Mean Temperature [1] |
| $\sigma := 5.670 \cdot 10^{-8} \frac{watt}{m^2 \cdot K^4}$ | Stefan Boltzman Constant [3] |
| $M := 29 \frac{gm}{mol}$ | Molecular Weight of Air [3] |
| $cp := 1008 \frac{J}{kg \cdot K}$ | Specific Heat of Air [2] |
| $RU := 82.05 \frac{cm^3 \cdot atm}{mol \cdot K}$ | Universal Gas Constant [4] |

## 4. LAMINAR FLOW CALCULATIONS

The canister in the VSC-17 test configuration is elevated in the overpack cavity. This results in a large insulating air gap (~10 inches) between the canister and overpack cavity bottoms. Thus, heat dissipation from the cask bottom is quite small and is neglected in the calculations.

### *4.1 Heat Loss from the Side of the Cask*

$A_{side} := \pi \cdot D_{cask} \cdot H_{cask}$ $\quad A_{side} = 48.097\,m^2$ Cask Side Surface Area

$A_{top} := \frac{\pi}{4} \cdot D_{cask}^2$ $\quad A_{top} = 5.586\,m^2$ Canister Top Surface

$h_{side} := 0.19 \cdot \frac{BTU}{hr \cdot ft^2 \cdot R^{\frac{4}{3}}} \cdot (T_{side} - T_{amb})^{\frac{1}{3}}$ $\quad h_{side} = 3.133 \frac{watt}{m^2 \cdot K}$ Laminar Heat Transfer Coefficient from Vertical Surfaces, Jakob and Hawkins [5]

$Q_{side} := A_{side} \cdot h_{side} \cdot (T_{side} - T_{amb}) + \sigma \cdot \varepsilon_{side} \cdot A_{side} \cdot (T_{side}^4 - T_{amb}^4)$ $\quad Q_{side} = 4594\,W$

### 4.2 *Heat Loss from the Top of the Cask*

$h_{top} := 0.18 \cdot \frac{BTU}{hr \cdot ft^2 \cdot R^{\frac{4}{3}}} \cdot (T_{top} - T_{amb})^{\frac{1}{3}}$ $\quad h_{top} = 3.935 \frac{watt}{m^2 \cdot K}$ Laminar Heat Transfer Coefficient from Horizontal Surafces, Jakob and Hawkins [5]

$Q_{top} := A_{top} \cdot h_{top} \cdot (T_{top} - T_{amb}) + \sigma \cdot \varepsilon_{top} \cdot A_{top} \cdot (T_{top}^4 - T_{amb}^4)$ $\quad Q_{top} = 1487\,W$

### 4.3 *Air Flow Calculations (Thermophysical Properties of Air from [2])*

$Q_{air} := Q_{tot} - Q_{side} - Q_{top}$ $\quad Q_{air} = 8818\,W$ Heat that must be removed by the air flowing through the annulus

$T_{avg} := \frac{(T_{in} + T_{out})}{2}$ $\quad T_{avg} = 322.15\,K$ Average Air Temperature in the Annulus

$k := 0.027 \frac{watt}{m \cdot K}$ Thermal Conductivity of Air at T-avg

$mu := 1.947 \cdot 10^{-5} \frac{kg}{m \cdot s}$ Viscosity of Air at T-avg

$mu_{w1} := 2.245 \cdot 10^{-5} \frac{kg}{m \cdot s}$ Viscosity of Air at Canister Inner Surface Average Temperature

$mu_{w2} := 2.034 \cdot 10^{-5} \frac{kg}{m \cdot s}$ Viscosity of Air at Canister Outer Surface Average Temperature

$M_{air} := \frac{Q_{air}}{cp \cdot (T_{out} - T_{in})}$ $\quad M_{air} = 0.314 \frac{kg}{s}$ Air Mass Flow Required for Heat Balance

$rho := \frac{P \cdot M}{RU \cdot T_{avg}}$ $\quad rho = 0.068 \frac{lb}{ft^3}$ Density of Air at Mean Annulus Temperature

$A_{ann} := \frac{\pi}{4}\left[D_{cav}^2 - (D_{cav} - 2 \cdot gap)^2\right]$ $\quad A_{ann} = 0.334\,m^2$ Annulus Cross-Section Area

$v_{air} := \frac{M_{air}}{(rho \cdot A_{ann})}$ $\quad v_{air} = 0.857 \frac{m}{s}$ Air Velocity Through the Annulus

$D_h := 2.gap$ $\quad D_h = 0.15\,m$ Hydraulic Diameter of Annulus

$Rey := rho \cdot D_h \cdot \frac{v_{air}}{mu}$ $\quad Rey = 7.246 \times 10^3$ Air Flow Mean Reynolds Number

$Pr := mu \cdot \frac{cp}{k}$ $\quad Pr = 0.727$ Prandtl Number for Air

From Reference 3, the Nusselt number for laminar flow through a duct is given by:

$$Nu_1 := 1.86\cdot(Rey\cdot Pr)^{0.333}\cdot\left(\frac{D_h}{H_{can}}\right)^{0.333}\cdot\left(\frac{mu}{mu_{w1}}\right)^{0.14}$$

Nusselt Number Based on Air Viscosity at Annulus Inner Surface Average Temperature

$Nu_1 = 10.091$

$$Nu_2 := 1.86\cdot(Rey\cdot Pr)^{0.333}\cdot\left(\frac{D_h}{H_{can}}\right)^{0.333}\cdot\left(\frac{mu}{mu_{w2}}\right)^{0.14}$$

Nusselt Number Based on Air Viscosity at Annulus Outer Surface Average Temperature

$Nu_2 = 10.231$

$h_{w1} := k\cdot\frac{Nu_1}{D_h}$ $\quad h_{w1} = 1.815\frac{watt}{m^2\cdot K}$ Heat Transfer Coefficient on Annulus Inner Surafce

$h_{w2} := k\cdot\frac{Nu_2}{D_h}$ $\quad h_{w2} = 1.84\frac{watt}{m^2\cdot K}$ Heat Transfer Coefficient on Annulus Outer Surafce

$Q_{d1lam} := h_{w1}\cdot\left[\pi\cdot(D_{cav} - 2\cdot gap)\cdot H_{can}\right]\cdot(T_{w1} - T_{avg})$ Heat Transfer from Annulus Inner Surface to Air

$Q_{d1lam} = 2359.15\,W$

$Q_{d2lam} := h_{w2}\cdot(\pi\cdot D_{cav}\cdot H_{can})\cdot(T_{w2} - T_{avg})$ Heat Transfer from Annulus Outer Surface to Air

$Q_{d2lam} = 773.41\,W$

$Q_{dlam} := Q_{d1lam} + Q_{d2lam}$ $\quad Q_{dlam} = 3.133\times 10^3\,W$

*4.4 Summary of Laminar Flow Calculations*

Cask Decay Heat (Qtot) = 14.90 kW
Heat Dissipation from Cask Side (Qside) = 4.59 kW
Heat Dissipation from the Cask Top (Qtop) = 1.49 kW
Heat Removed by Annulus Air Flow (Qair = Qtot - Qside -Qtop) = 8.82 kW
Heat Dissipated to Annulus Air by Laminar Flow (Qdlam) = 3.13 kW

**Observation: Heat Dissipated to Annulus Air by Laminar Flow (Qdlam) << Heat Removed by Annulus Air Flow (Qair)**

Therefore, if the flow in the annulus is assumed to be laminar, the heat that can be removed from the heated annulus surfaces by the air flowing through the annulus falls short of the amount of heat that is removed by annulus air flow by over 50%. In other words laminar flow in the VSC-17 annulus is not credible.

## 5. TURBULENT FLOW CALCULATIONS

Using the Dittus and Boelter Correlation [3], the Nusselt number for turbulent flow through a duct is calculated as:

$Nu_t := 0.023 \cdot Rey^{0.8} \cdot Pr^{0.4}$ $\quad Nu_t = 24.797$

$h_t := k \cdot \frac{Nu_t}{D_h}$ $\quad h_t = 4.46 \frac{watt}{m^2 \cdot K}$ Heat Transfer Coefficient for Turnulent Air Flow in the Annulus

$Q_{d1turb} := h_t \cdot \left[\pi \cdot (D_{cav} - 2 \cdot gap) \cdot H_{can}\right] \cdot (T_{w1} - T_{avg})$ Heat Transfer from Annulus Inner Surface to Air

$Q_{d1turb} = 5797.28\,W$

$Q_{d2turb} := h_t \cdot (\pi \cdot D_{cav} \cdot H_{can}) \cdot (T_{w2} - T_{avg})$ Heat Transfer from Annulus Outer Surface to Air

$Q_{d2turb} = 1.874 \times 10^3\,W$

$Q_{dturb} := Q_{d1turb} + Q_{d2turb}$ $\quad Q_{dturb} = 7.672 \times 10^3\,W$

### *5.1 Summary of Turbulent Flow Calculations*

Cask Decay Heat (Qtot) = 14.90 kW
Heat Dissipation from Cask Side (Qside) = 4.59 kW
Heat Dissipation from the Cask Top (Qtop) = 1.49 kW
Heat Removed by Annulus Air Flow (Qair = Qtot - Qside -Qtop) = 8.82 kW
Heat Dissipated to Annulus Air by Turbulent Flow (Qdturb) = 7.67 kW

Therefore, if the flow in the annulus is assumed to be turbulent, the heat that can be removed from the heated annulus surfaces by the air flowing through the annulus is much closer to the amount of heat removed by the annulus air flow. This corroborates that the flow of air in the annular space between the VSC-17 cask and the contained canister is turbulent.

# ASCERTAINING THE ANNULUS AIR FLOW REGIME IN THE VSC-17 UNDER VACUUM

## 1. PURPOSE

The VSC-17 cask tested at the Idaho National Engineering Laboratory (INEL) provides valuable thermal performance data to enable the flow regime (i.e., laminar or turbulent) of the air flow through the annulus between the overpack and the contained MSB canister to be determined. The temperature data from Reference 1 permits the amount of heat rejected to the ambient from the external cask surfaces (via natural convection and thermal radiation) to be quantified using classical heat transfer correlations. The balance of the decay heat energy (i.e., that portion of the total decay heat not rejected from the cask external surfaces to the ambient) must be removed by the ventilation air.

Because the temperatures of the air entering and exiting the cask cooling passages were measured quantities, the air flow rate necessary to remove the balance of the decay heat can be directly computed using an energy balance. Having determined the air flow rate corresponding flow velocity, it is then possible to compute, again using classical duct flow correlations, the quantity of heat that can be extracted by the flowing air from the annulus surfaces assuming different flow regimes (i.e., laminar and turbulent). The assumed flow regime is correct if the computed heat extracted by the flowing air is in accord with the heat energy to be removed by the air stream.

The calculation process just described has the benefit of not relying on detailed geometry of the cask cooling passages or on complex computer modeling.

Experimental data provided in Reference 1 for an evacuated canister (Run #6) has been used in these calculations.

## 2. REFERENCES


1. "Performance Testing and Analyses of the VSC-17 Ventilated Concrete Cask", EPRI "TR-100305, May 1992.
2. "Identifying the Appropriate Convection Correlation in FLUENT for Ventilation Air Flow in the HI-STORM System", Holtec Report HI-2043258, Rev. 0.
3. "Heat Transfer", J.P. Holman, Sixth Ed., McGraw Hill (1986).
4. "Engineering Thermodynamics", R.E. Balzhiser & M.R. Samuels, Prentice Hall, (1977).
5. "Elements of Heat Transfer", M. Jakob and G.A. Hawkins, John Wiley & Sons, (1957).


## 3. INPUT DATA

| | |
|---|---|
| $Q_{tot} := 14900watt$ | Total Heat Generation in the Cask [1] |
| $D_{cask} := 105in$ | VSC-17 Cask OD [1] |
| $D_{cav} := 58.66in$ | VSC-17 Cavity Diameter [1] |
| $gap := 2.955in$ | Radial Gap Between Canister and Cask [1] |
| $H_{cask} := 226in$ | VSC-17 Cask Height [1] |
| $H_{can} := 182.68in$ | Canister Height [1] |
| $\varepsilon_{side} := 0.63$ | Emissivity of Cask Side (Concrete) [2] |

| | |
|---|---|
| $\varepsilon_{top} := 0.66$ | Emissivity of Canister Top (Carbon Steel)[2] |
| $T_{amb} := 297K$ | Ambient Temperature [1] |
| $T_{side} := 311.1K$ | Average Cask Side Temperature [1] |
| $T_{top} := 325.2K$ | VSC-17 Top Surface Average Temperature [1] |
| $T_{in} := 312.1K$ | Annulus Air Inlet Temperature [1] |
| $T_{out} := 339.0K$ | Annulus Air Outlet Temperature [1] |
| $P := 1atm$ | Atmospheric Pressure |
| $T_{w1} := 391.0K$ | Annulus Inner Surface Mean Temperature [1] |
| $T_{w2} := 356.6K$ | Annulus Outer Surface Mean Temperature [1] |
| $\sigma := 5.670 \cdot 10^{-8} \frac{watt}{m^2 \cdot K^4}$ | Stefan Boltzman Constant [3] |
| $M := 29 \frac{gm}{mol}$ | Molecular Weight of Air [3] |
| $cp := 1008 \frac{J}{kg \cdot K}$ | Specific Heat of Air [2] |
| $RU := 82.05 \frac{cm^3 \cdot atm}{mol \cdot K}$ | Universal Gas Constant [4] |

## 4. LAMINAR FLOW CALCULATIONS

The canister in the VSC-17 test configuration is elevated in the overpack cavity. This results in a large insulating air gap (~10 inches) between the canister and overpack cavity bottoms. Thus, heat dissipation from the cask bottom is quite small and is neglected in the calculations.

### *4.1 Heat Loss from the Side of the Cask*

$A_{side} := \pi \cdot D_{cask} \cdot H_{cask}$ $\quad A_{side} = 48.097 m^2$ Cask Side Surface Area

$A_{top} := \frac{\pi}{4} \cdot D_{cask}^2$ $\quad A_{top} = 5.586 m^2$ Canister Top Surface

$h_{side} := 0.19 \cdot \frac{BTU}{hr \cdot ft^2 \cdot R^{\frac{4}{3}}} \cdot (T_{side} - T_{amb})^{\frac{1}{3}}$ $\quad h_{side} = 3.171 \frac{watt}{m^2 \cdot K}$ Laminar Heat Transfer Coefficient from Vertical Surfaces, Jakob and Hawkins [5]

$Q_{side} := A_{side} \cdot h_{side} \cdot (T_{side} - T_{amb}) + \sigma \cdot \varepsilon_{side} \cdot A_{side} \cdot (T_{side}^4 - T_{amb}^4)$ $\quad Q_{side} = 4875 W$

### 4.2 *Heat Loss from the Top of the Cask*

$h_{top} := 0.18 \cdot \frac{BTU}{hr \cdot ft^2 \cdot R^{\frac{4}{3}}} \cdot (T_{top} - T_{amb})^{\frac{1}{3}}$ $\quad h_{top} = 3.784 \frac{watt}{m^2 \cdot K}$ Laminar Heat Transfer Coefficient from Horizontal Surafces, Jakob and Hawkins [5]

$Q_{top} := A_{top} \cdot h_{top} \cdot (T_{top} - T_{amb}) + \sigma \cdot \varepsilon_{top} \cdot A_{top} \cdot (T_{top}^4 - T_{amb}^4)$ $\quad Q_{top} = 1308\,W$

### 4.3 *Air Flow Calculations (Thermophysical Properties of Air from [2])*

$Q_{air} := Q_{tot} - Q_{side} - Q_{top}$ $\quad Q_{air} = 8717\,W$ Heat that must be removed by the air flowing through the annulus

$T_{avg} := \frac{(T_{in} + T_{out})}{2}$ $\quad T_{avg} = 325.55\,K$ Average Air Temperature in the Annulus

$k := 0.027 \frac{watt}{m \cdot K}$ Thermal Conductivity of Air at T-avg

$mu := 1.963 \cdot 10^{-5} \frac{kg}{m \cdot s}$ Viscosity of Air at T-avg

$mu_{w1} := 2.255 \cdot 10^{-5} \frac{kg}{m \cdot s}$ Viscosity of Air at Canister Inner Surface Average Temperature

$mu_{w2} := 2.101 \cdot 10^{-5} \frac{kg}{m \cdot s}$ Viscosity of Air at Canister Outer Surface Average Temperature

$M_{air} := \frac{Q_{air}}{cp \cdot (T_{out} - T_{in})}$ $\quad M_{air} = 0.321 \frac{kg}{s}$ Air Mass Flow Required for Heat Balance

$rho := \frac{P \cdot M}{RU \cdot T_{avg}}$ $\quad rho = 0.068 \frac{lb}{ft^3}$ Density of Air at Mean Annulus Temperature

$A_{ann} := \frac{\pi}{4}\left[D_{cav}^2 - (D_{cav} - 2 \cdot gap)^2\right]$ $\quad A_{ann} = 0.334\,m^2$ Annulus Cross-Section Area

$v_{air} := \frac{M_{air}}{(rho \cdot A_{ann})}$ $\quad v_{air} = 0.888 \frac{m}{s}$ Air Velocity Through the Annulus

$D_h := 2.gap$ $\quad D_h = 0.15\,m$ Hydraulic Diameter of Annulus

$Rey := rho \cdot D_h \cdot \frac{v_{air}}{mu}$ $\quad Rey = 7.369 \times 10^3$ Air Flow Mean Reynolds Number

$Pr := mu \cdot \frac{cp}{k}$ $\quad Pr = 0.733$ Prandtl Number for Air

From Reference 3, the Nusselt number for laminar flow through a duct is given by:

$$Nu_1 := 1.86\cdot(Rey\cdot Pr)^{0.333}\cdot\left(\frac{D_h}{H_{can}}\right)^{0.333}\cdot\left(\frac{mu}{mu_{w1}}\right)^{0.14}$$

Nusselt Number Based on Air Viscosity at Annulus Inner Surface Average Temperature

$Nu_1 = 10.18$

$$Nu_2 := 1.86\cdot(Rey\cdot Pr)^{0.333}\cdot\left(\frac{D_h}{H_{can}}\right)^{0.333}\cdot\left(\frac{mu}{mu_{w2}}\right)^{0.14}$$

Nusselt Number Based on Air Viscosity at Annulus Outer Surface Average Temperature

$Nu_2 = 10.282$

$h_{w1} := k\cdot\frac{Nu_1}{D_h}$ $\quad h_{w1} = 1.831\frac{watt}{m^2\cdot K}$ Heat Transfer Coefficient on Annulus Inner Surafce

$h_{w2} := k\cdot\frac{Nu_2}{D_h}$ $\quad h_{w2} = 1.849\frac{watt}{m^2\cdot K}$ Heat Transfer Coefficient on Annulus Outer Surafce

$Q_{d1lam} := h_{w1}\cdot\left[\pi\cdot(D_{cav} - 2\cdot gap)\cdot H_{can}\right]\cdot(T_{w1} - T_{avg})$ Heat Transfer from Annulus Inner Surface to Air

$Q_{d1lam} = 2340.73\,W$

$Q_{d2lam} := h_{w2}\cdot(\pi\cdot D_{cav}\cdot H_{can})\cdot(T_{w2} - T_{avg})$ Heat Transfer from Annulus Outer Surface to Air

$Q_{d2lam} = 1247.16\,W$

$Q_{dlam} := Q_{d1lam} + Q_{d2lam}$ $\quad Q_{dlam} = 3.588\times 10^3\,W$

*4.4 Summary of Laminar Flow Calculations*

Cask Decay Heat (Qtot) = 14.90 kW
Heat Dissipation from Cask Side (Qside) = 4.88 kW
Heat Dissipation from the Cask Top (Qtop) = 1.31 kW
Heat Removed by Annulus Air Flow (Qair = Qtot - Qside -Qtop) = 8.72 kW
Heat Dissipated to Annulus Air by Laminar Flow (Qdlam) = 3.59 kW

**Observation: Heat Dissipated to Annulus Air by Laminar Flow (Qdlam) << Heat Removed by Annulus Air Flow (Qair)**

Therefore, if the flow in the annulus is assumed to be laminar, the heat that can be removed from the heated annulus surfaces by the air flowing through the annulus falls short of the amount of heat that is removed by annulus air flow by over 50%. In other words laminar flow in the VSC-17 annulus is not credible.

## 5. TURBULENT FLOW CALCULATIONS

Using the Dittus and Boelter Correlation [3], the Nusselt number for turbulent flow through a duct is calculated as:

$Nu_t := 0.023 \cdot Rey^{0.8} \cdot Pr^{0.4}$ $\quad Nu_t = 25.214$

$h_t := k \cdot \frac{Nu_t}{D_h}$ $\quad h_t = 4.535 \frac{watt}{m^2 \cdot K}$ Heat Transfer Coefficient for Turnulent Air Flow in the Annulus

$Q_{d1turb} := h_t \cdot \left[\pi \cdot (D_{cav} - 2 \cdot gap) \cdot H_{can}\right] \cdot (T_{w1} - T_{avg})$ Heat Transfer from Annulus Inner Surface to Air

$Q_{d1turb} = 5797.35\,W$

$Q_{d2turb} := h_t \cdot (\pi \cdot D_{cav} \cdot H_{can}) \cdot (T_{w2} - T_{avg})$ Heat Transfer from Annulus Outer Surface to Air

$Q_{d2turb} = 3.058 \times 10^3\,W$

$Q_{dturb} := Q_{d1turb} + Q_{d2turb}$ $\quad Q_{dturb} = 8.856 \times 10^3\,W$

### *5.1 Summary of Turbulent Flow Calculations*

Cask Decay Heat (Qtot) = 14.90 kW
Heat Dissipation from Cask Side (Qside) = 4.88 kW
Heat Dissipation from the Cask Top (Qtop) = 1.31 kW
Heat Removed by Annulus Air Flow (Qair = Qtot - Qside -Qtop) = 8.72 kW
Heat Dissipated to Annulus Air by Turbulent Flow (Qdturb) = 8.86 kW

Therefore, if the flow in the annulus is assumed to be turbulent, the heat that can be removed from the heated annulus surfaces by the air flowing through the annulus is much closer to the amount of heat removed by the annulus air flow. This corroborates that the flow of air in the annular space between the VSC-17 cask and the contained canister is turbulent.