THERMACORE

INC

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Contract Number DE-FG05-91ER81233

High Efficiency Vapor-Fed AMTEC System for Direct Conversion

Appendices
for Final Report

Appendix A: 700°C Vapor-Fed AMTEC Cell Calculations

Appendix B: 700°C Vapor-Fed AMTEC Cell Parts Drawings

Appendix C: 800°C Vapor-Fed AMTEC Cell Calculations

Appendix D: 800°C Wick-Pumped AMTEC Cell System Design

May 23, 1997

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Prepared For:

U.S. Department of Energy
Washington, D.C. 20585

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APPENDIX A

700°C VAPOR-FED AMTEC CELL CALCULATIONS

Wick Pumped AMTEC Cell Design Calculations

9/4/92

Objective: Develop a wick design for a vapor-fed AMTEC cell that will operate near 700 C, for both the evaporator and condenser wicks.

Design Requirements	
Operating Temperature, C	700-800
Condenser Temperature, C	250-400
Working Fluid	Sodium
Design Power into AMTEC cell, W	60.000
Assumed cell efficiency:	0.200
Electrical Output, W	12.000
BASE Power out/area, W/cm ²	0.200
BASE current flux, A/cm ²	0.500
Sodium flow rate, g/hr/Amp	1.000

The Amtec cell has two main regions: (1) a high pressure, high temperature region with the evaporator connected to the BASE tube, and a low temperature, low pressure condenser region. Heat supplied to the evaporator vaporizes sodium, which travels to the BASE region and condenses. There are two sodium circulation patterns that must be accounted for when designing the AMTEC wick. First, roughly 80 percent of the sodium supplies heat to the BASE tube, then is wicked back to the evaporator in the high pressure region.

The remaining sodium (20%, based on the assumed 20% efficiency), passes through the BASE, generating electricity. This sodium then vaporizes and travels to the condenser, which has a temperature of typically 400 C, and a vapor pressure near zero (50 Pa or less). This sodium must be wicked back to the evaporator, which has a vapor pressure above 12,000 Pa. This is accomplished with a relatively coarse cable artery in the condenser, which is embedded in the fine sintered powder of the evaporator wick.

The current conceptual design uses four different wicks:

1. A relatively coarse wick in the condenser, to collect the sodium.
2. A cable artery to return sodium from the condenser to the evaporator.
3. A fine wick in the evaporator, that can supply the pumping capability to return the liquid
4. A relatively coarse wick in the BASE.

The current conceptual design has a free-standing wick in the BASE, with a gap between the wick and the BASE. This is done for several reasons: First, this removes problems with differential thermal expansion between the wick and the BASE tube, which is relatively brittle. Second, separating the wick from the BASE should help to minimize the thermal stress on the BASE during start-up, when the thermal front moves down the wick.

Sodium Properties	Evaporator	Condenser
Condenser Temperature, C	700.000	400.000
Condenser Na Latent Heat, J/kg	4.063E+06	4.374E+06
Condenser Na Liquid Density, kg/m ³	784.048	856.221
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Condenser Na Liquid Thermal Conductivity, W/m C	60.012	70.379
Condenser Na Liquid Viscosity, kg/m s	1.814E-04	2.846E-04
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Condenser Na Vapor Pressure, Pa	13940.790	47.195
Condenser Na Surface Tension, N/m	0.137	0.167

Title: AMTEC Vapor-Fed Cell
Conceptual Design

Calculated by: W. Anderson Date: 9/14/92
 Checked by: J. Zanderath Date: 9/14/92
 Reviewed by: _____ Date: _____

Project: 11-1140

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Wick-Pumped, Vapor-Fed Amtec Cell

Title: AMTEC Vapor-Fed Cell
BASE Dimensions

Calculated by: W. Anderson Date: 9/14/92
 Checked by: J. L. Lankford Date: 9/14/92
 Reviewed by: _____ Date: _____

Project: _____

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The design requirements can be used to estimate the BASE length

BASE area to generate 12 W

$$A = \frac{12 \text{ W}}{0.2 \text{ W/cm}^2} = 60 \text{ cm}^2$$

$$A = \pi D L, \quad L = \frac{A}{\pi D} = \frac{60}{(\pi)(1.5)} = 12.73 \text{ cm}$$

Current Flow

$$I = (A) \left(\frac{I}{A} \right) = (60) \left(0.5 \frac{\text{A}}{\text{cm}^2} \right) = 30 \text{ Amps}$$

Sodium Flow rate through BASE

$$\dot{m}_{\text{Base}} = (30 \text{ A}) \left(1 \frac{\text{gram}}{\text{hour amp}} \right) = \frac{30 \text{ g}}{\text{hr}} \left| \frac{\text{Kg}}{1000 \text{ g}} \right| \left| \frac{1 \text{ hr}}{3600 \text{ s}} \right|$$

$$= 8.33 \times 10^{-6} \text{ Kg/s}$$

Since the efficiency is 20%, the sodium flow through the BASE is 20% of the total flow.

$$\dot{m}_{\text{Total}} = \frac{\dot{m}_{\text{Base}}}{0.2} = \frac{150 \text{ g/hr}}{0.2} = 4.17 \times 10^{-5} \text{ Kg/hr}$$

recirculating flow.

$$\dot{m}_{\text{recirculate}} = (0.8) \dot{m}_{\text{Total}} = 120 \text{ g/hr} = 3.33 \times 10^{-5} \text{ Kg/s}$$

Active Base Length = 12.7 cm

Total Base length = 12.7 + 2(0.5) $\approx$ 14 cm,

allow 0.5 cm Bare tube on either side of electrodes

Title: AMTEC Vapor-Fed Cell

Calculated by: W. Anderson

Date: 9/4/92

System Dimensions

Checked by: J. L. Lunden

Date: 9/14/92

Reviewed by: _____

Date: _____

Project: 11-1140

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System Dimensions

Base O.D. 1.5 cm

Base length 14 cm

Evaporator I.D. 2 cm

Evaporator length: 8 cm

BASE wick O.D.: 1.3 cm

Base wick thickness 0.254 cm = 0.100"

Base wick I.D. = 0.792 cm

Evaporator Wick thickness = 0.127 cm = 0.050"

Evaporator Wick I.D. 1.746 cm

Recirculating Flow Pressure drops

$$L_{Base} + L_{evap} = 8 + 14 = 22 \text{ cm} = 0.22 \text{ m}$$

gravity

$$\Delta P_{grav} = \rho_{lg} g h = (784)(9.8)(0.22) = 1690 \text{ Pa}$$

Title: AMTEC Vapor Feed Cell
Recirculating Pressure Drops
 Project: 11-1140

Calculated by: J. J. Anderson Date: 9/14/92
 Checked by: He Zunden H Date: 9/14/92
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Recirculating Loop - Vapor Pressure Drops

all of the mass flow is used for the vapor.

$$\dot{m}_{\text{vapor}} = \dot{m}_{\text{total}} = 4.17 \times 10^{-5} \text{ kg/s}$$

$$\text{Evaporator vapor area } A_{\text{evap}} = \frac{\pi}{4} D^2 = \left(\frac{\pi}{4}\right) (1.746)^2 \left(\frac{\text{m}^2}{10^4 \text{ cm}^2}\right) = 2.39 \times 10^{-4} \text{ m}^2$$

$$\text{Vapor Velocity} = \dot{m} / A = \frac{4.17 \times 10^{-5}}{(0.0404)(2.39 \times 10^{-4})} = 4.3 \text{ m/s in the evaporator}$$

$$\text{Reynolds number } Re = \frac{\rho V D}{\mu} = \frac{(0.0404)(4.3)\left(\frac{1.746}{100}\right)}{2.041 \times 10^{-5}} = 149 \text{ laminar}$$

Effective length

$$L_{\text{eff}} = L_{\text{evap}} / 2 = \frac{8}{2} = 4 \text{ cm} = 0.04 \text{ m}$$

Evaporator vapor pressure drop

$$\Delta P_{\text{Evap-vapor}} = \frac{32 L_{\text{eff}} \mu_v V}{D_{\text{vapor}}^2} = \frac{(32)(0.04)(2.041 \times 10^{-5})(4.3)}{(0.01746)^2}$$

$$\Delta P_{\text{Evap-vapor}} = 0.37 P_g$$

Vapor Flow in BASE

$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4} \left(\frac{0.712}{100}\right)^2 = 4.92 \times 10^{-5} \text{ m}^2$$

$$\text{Velocity } V_{\text{Base}} = \frac{\dot{m}}{A} = \frac{4.17 \times 10^{-5}}{(0.0404)(4.92 \times 10^{-5})} = 20.9 \text{ m/s}$$

Title: AMTEC Vapor-Fed Cell
Recirculating Pressure Drops

Calculated by: W. Anderson Date: 9/4/92
 Checked by: J. E. Lundquist Date: 9/14/92
 Reviewed by: _____ Date: _____

Project: 11-1140

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Recirculating loop - vapor pressure drops

$$Re_{Base} = \frac{\rho V D}{\mu} = \frac{(0.0404)(20.9)(0.00792)}{2.041 \times 10^{-5}} = 328 \quad \text{Laminar}$$

$$\Delta P = \frac{(32)(L_{eff})\mu V}{D^3}$$

$$L_{eff} = \frac{14}{2} = 7 \text{ cm} = 0.07 \text{ m}$$

$$\Delta P_{Base-vapor} = \frac{(32)(0.07)(2.041 \times 10^{-5})(20.9)}{(0.00792)^2} = 15.2 \text{ Pa}$$

There will also be a pressure drop due to the contraction between the evaporator and BASE cell. This is neglected, since the vapor pressure drops are so small.

Liquid Pressure Drops: Recirculating flow

$$BASE \text{ Effective Length} = \frac{14 \text{ cm}}{(2)(100 \frac{\text{cm}}{\text{m}})} = 0.07 \text{ m}$$

Liquid Flow Cross-Sectional Area

$$A = \frac{\pi (D_{out}^2 - D_{in}^2)}{4} = \frac{\pi (1.3^2 - 0.792^2)}{4} \frac{\text{cm}^2}{10^4 \text{ cm}^2} = 8.347 \times 10^{-5} \text{ m}^2$$

Assume E-1 nickel wick

$$K = 2 \times 10^{-11} \text{ m}^2, \quad r_c = 2.5 \times 10^{-5} \text{ m}$$

$$\dot{m} = \frac{K \rho A}{\mu} \frac{dP}{dx}$$

$$\Delta P_{Base} = \frac{\dot{m} \mu L_{eff}}{K \rho A} = \frac{(3.33 \times 10^{-5})(1.814 \times 10^{-4})(0.07)}{(2 \times 10^{-11})(784)(8.347 \times 10^{-5})} = \underline{\underline{323 \text{ Pa}}}$$

Title: Amtec Vapor Fed Cell
Recirculating Pressure Drop.
 Project: 11-1140

Calculated by: R. Anderson Date: 9/8/92
 Checked by: J. J. Anderson Date: 9/14/92
 Reviewed by: _____ Date: _____

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$$(\Delta P_{gr})_{B,sc} = \rho g h = (784)(9.8)(0.14) = 1076 \text{ Pa}$$

BASE to Evaporator Transition:

wick thickness

$$0.050" = 0.127 \text{ cm}$$

$$L = (1.746 - 0.792) / 2 = 0.477 \text{ cm} = 4.77 \times 10^{-3} \text{ m}$$

Flow Area - use smallest area - conservative answer

$$A = \pi D t = (\pi)(0.792)(0.127)(10^{-4} \frac{\text{m}^2}{\text{cm}^2}) = 3.16 \times 10^{-5} \text{ m}^2$$

Wick: Assume a hypothetical wick, extrapolating from measured wick properties to smaller sizes.

$$K = 1 \times 10^{-12} \text{ m}^2, \quad r_c = 1 \times 10^{-5} \text{ m}$$

$$\Delta P = \frac{\mu L \dot{m}}{K_f A} = \frac{(3.33 \times 10^{-5})(1.814 \times 10^{-4})(4.77 \times 10^{-3})}{(10^{-12})(784)(3.16 \times 10^{-5})}$$

$$\frac{\text{Kg Kg m s}^2}{\text{s m}^2 \text{ or Kg m}^2} = \frac{\text{Kg m}}{\text{m}^2 \text{ s}^2} = \text{Pa}$$

$$\Delta P_{\text{Transition}} = \underline{\underline{1164 \text{ Pa}}}$$

Title: AMTEC Vapor Fed Cell
Recirculating Pressure Drops

Calculated by: W. Anderson Date: 9/8/92
 Checked by: J. L. Lander Date: 9/14/92
 Reviewed by: _____ Date: _____

Project: 11-1140

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Evaporator Wick Pressure Drop

$$L_{eff} = L_{evap}/2 = \frac{8}{(2)(100 \frac{cm}{m})} = 0.04 \text{ m}$$

$$A = \frac{\pi}{4} (D_o^2 - D_i^2) = \frac{\pi}{4} (2^2 - 1.746^2) (10^{-4} \frac{m^2}{cm^2}) = 7.47 \times 10^{-5} \text{ m}^2$$

hypothetical wick properties: $K = 1 \times 10^{-12} \text{ m}^2$, $r_c = 1 \times 10^{-5} \text{ m}$.

$$\Delta P_{Evap} = \frac{\mu L_{eff}}{K \rho A} = \frac{(3.33 \times 10^{-5})(1.814 \times 10^{-4})(0.040)}{(10^{-12})(784)(7.47 \times 10^{-5})} = \underline{\underline{4128 \text{ Pa}}}$$

For The recirculating System, there are two wicks That must be checked,

First, the BASE wick must be able to overcome gravity as well as liquid flow

$$(\Delta P_{Total})_{Base} = \Delta P_{grav} + \Delta P_{Liq} = 1076 + 323 = 1399 \text{ Pa}$$

$$BASE \text{ Wick Pumping Capability} = \frac{2\sigma}{r_c} = \frac{(2)(0.137)}{2.5 \times 10^{-5}} = 10,936 \text{ Pa} \quad O.K.$$

The liquid pressure drop in the recirculating loop = $\Delta P_{Base} + \Delta P_{Transition} + \Delta P_{Evap}$

$$\Delta P_{Liq} = 323 + 1164 + 4128 = 5616 \text{ Pa}$$

$$\Delta P_{Total} = \Delta P_{grav} + \Delta P_{vap} + \Delta P_{Liq} = 1690 + 15.6 + 5616 = 7322 \text{ Pa}$$

$$Wick \text{ Capability} = \frac{2\sigma}{r_c} = (2)(0.137) / 1 \times 10^{-5} = 27,340 \text{ Pa}$$

$$Excess \text{ Capability} = 27,340 - 7322 = 20,000 \text{ Pa} \quad O.K.$$

Title: AMTEC Vapor-Fed Cell - Condenser
Loop Pressure Drop

Calculated by: V. Anderson Date: 9/8/92
 Checked by: J. Zander Date: 9/14/92
 Reviewed by: _____ Date: _____

Project: 11-1140

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Condenser Loop Pressure Drops

Gravitational Pressure drop: The condenser and evaporator operate at different temperatures, so the gravitational pressure drop must be calculated separately for the evaporator and condenser.

Condenser Length $L = 0.2 \text{ m}$, $T = 400^\circ\text{C}$, $\rho = 856 \text{ kg/m}^3$

$$(\Delta P_{\text{grav}})_{\text{condense}} = \rho g h = (856)(9.8)(0.2) = 1678 \text{ Pa}$$

$$(\Delta P_{\text{grav}})_{\text{evap}} = \rho g h = (784)(9.8)(0.08) = 615 \text{ Pa}$$

$$(\Delta P_{\text{grav}})_{\text{Total}} = 1678 + 615 = 2293 \text{ Pa}$$

There are three different wicks to be considered in the condenser loop:

1. Condenser wick
2. Cable Artery
3. Evaporator wick.

Condenser Wick

N = number of Arteries

Length between Arteries = $\frac{\pi D}{2N}$, Effective Length = $\frac{\pi D}{4N}$

$$D_{\text{condense}} = 2.5 \text{ cm}, \text{ 1 cable artery } L_{\text{eff}} = \frac{\pi D}{(4)(1)} = \frac{(\pi)(2.5)}{(4)(100 \frac{\text{cm}}{\text{m}})} = 0.0196 \text{ m}$$

$$t_{\text{wick}} = 0.050" = 0.127 \text{ cm}$$

$$D_i = D_o - 2 t_{\text{wick}} = 2.5 - (2)(0.127) = 2.25 \text{ cm}$$

Title: Amtec Vapor-Feed Cell-Condenser
Loop Pressure Drop

Calculated by: William B. Anderson Date: 9/8/92
 Checked by: J. L. Anderson Date: 9/14/92
 Reviewed by: _____ Date: _____

Project: 11-1140

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Condenser

$$A_{Flow} = L_{Active} \cdot t_{active} = (6)(.127) / 10^4 \text{ cm}^2 = 7.62 \times 10^{-5} \text{ m}^2$$

The condenser wick must have sufficient pumping capability to withstand

1. Liquid Flow Pressure drop in the condenser wick
2. Gravitational wicking for the entire condenser.

$$\Delta P_{grav} = 1678 \text{ Pa}$$

Assume a -50+100 wick $K = 3.8 \times 10^{-11} \text{ m}^2$, $r_c = 5.5 \times 10^{-5}$

$$\text{wick capability } P_c = \frac{2\sigma}{r_c} = \frac{(2)(0.167)}{5.5 \times 10^{-5}} = 6061 \text{ Pa}$$

$$\dot{m}_{condenser} = 8.33 \times 10^{-6} \text{ kg/s}$$

$$\Delta P_{condense wick} = \frac{\dot{m} \mu L_{eff}}{K P_{400} A} = \frac{(8.33 \times 10^{-6})(2.85 \times 10^{-4})(0.0196)}{(3.8 \times 10^{-11})(856)(7.62 \times 10^{-5})} = 19 \text{ Pa}$$

$$\Delta P_{condenser} = \Delta P_{grav} + \Delta P_{wick} = 1678 + 19 = 1697 \text{ Pa}$$

$$\text{Excess wick capability} = 4364 \text{ Pa}$$

Title: AMTEC Vapor Fed Cell - Cable ArteryCalculated by: William B. Anderson Date: 7/8/92Checked by: JF. Lander Date: 9/19/92

Reviewed by: _____ Date: _____

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Cable Artery

The cable artery must sustain the following pressure drops.

1. Liquid flow in the condenser wick
2. Liquid flow in the cable artery
3. Gravity over the condenser length

Assume we use the cable that was used in Phase 1, $d_o = 0.25" = 0.635 \text{ cm}$

$$K = 6.86 \times 10^{-10} \text{ m}^2, \quad r_c = 1.2 \times 10^{-4} \text{ m}$$

$$\text{Pumping Capability} \quad P_c = \frac{2\sigma}{r_c} = \frac{(2)(.137)}{1.2 \times 10^{-4}} = 2283 \text{ Pa} @ 700^\circ\text{C}$$

$$L_{eff} = L_{evap} + L_{condense} = 0.28 \text{ m.}$$

$$\Delta P = \frac{m \mu_{400^\circ\text{C}} L_{eff}}{K \rho_{400^\circ\text{C}}} = \frac{(8.33 \times 10^{-6})(2.846 \times 10^{-4})(0.28)}{(6.86 \times 10^{-10})(1856.2)(3.167 \times 10^{-5})} = 35.7 \text{ Pa}$$

Cable Pressure Drop

$$\left(\Delta P_{Total} \right)_{Cable} = 19 + 1678 + 35.7 = 1733 \text{ Pa.}$$

$$\text{Excess Capability} = 2283 - 1733 = 551 \text{ Pa} \quad \text{O.K.}$$

Title: AMTEC Vapor-Feed Cell - Evaporator WickCalculated by: William J. Anderson Date: 9/8/92Checked by: J. E. Anderson Date: 9/14/92

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Evaporator Wick - Condenser flow

The evaporator wick must sustain the following pressure drops

1. Gravity in the evaporator and condenser = 2293 Pa
2. Vapor pressure differential
3. Liquid flow in the condenser wick = 19 Pa
4. Liquid flow in the cable artery = 35.7 Pa
5. Liquid flow in the evaporator wick

Difference in vapor pressure

$$\Delta P_{\text{vapor}} = P_{700^{\circ}\text{C}} - P_{400^{\circ}\text{C}} = 13941 - 47 = 13893 \text{ Pa}$$

Evaporator wick pressure drop

There are two options for the cable artery location in the evaporator

Along the side

Coiled Around the Top

easier to fabricate

Potential problem with
boiling

Assume that the coiled cable artery is used. - Calculate the evaporator pressure drop for the entire flow, since the recirculating fluid is traveling in the same path.

Title: AMTEC Vapor-Fed Cell-Evaporator
Wick Pressure dropCalculated by: William A. Anderson Date: 9/8/92Checked by: St. Zander Date: 9/14/92

Reviewed by: _____ Date: _____

Project: _____

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Coiled Cable Artery - Flow travels down the evaporator

$$\Delta P = \frac{m \mu L_{eff}}{k \rho A} = \frac{(4.167 \times 10^{-5})(1.814 \times 10^{-4})(0.04)}{(1 \times 10^{-12})(784)(7.47 \times 10^{-5})}$$

$$= 5160 \text{ Pa}$$

$$\Delta P_{Total} = \Delta P_{grav} + \Delta P_{evapor} + \Delta P_{condense \text{ wick}} + \Delta P_{cable} + \Delta P_{Evap. \text{ wick}}$$

$$\Delta P_{Total} = 2293 + 13,893 + 19 + 36 + 5160 = 21,400 \text{ Pa}$$

$$\Delta P_{wick \text{ capability}} = 27,340$$

$$\text{Excess capability} = 27,340 - 21,400 = 5,936 \text{ Pa}$$

Wick-Pumped, Vapor-Fed AMTEC Cell Design
 Prototype Design: Revised for shorter BASE tube
 10/7/92

NEWAMTEC.XLS

Design Calculations for a Wick Pumped AMTEC cell design

Assume:

Remote Condenser
 Cable Artery Liquid Return
 Porous wick

Wick Pumped AMTEC Cell Design Calculations

9/4/92

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Condenser Na Vapor Density, kg/m ³	0.0404	2.203E-04
Condenser Na Liquid Thermal Conductivity, W/	60.012	70.379
Condenser Na Liquid Viscosity, kg/m s	1.814E-04	2.846E-04
Condenser Na Vapor Viscosity, kg/m s	2.041E-05	1.638E-05
Condenser Na Vapor Pressure, Pa	13940.790	47.195
Condenser Na Surface Tension, N/m	0.137	0.167

Wick-Pumped, Vapor-Fed AMTEC Cell Design
 Prototype Design
 September 8, 1992

Design Requirements

Operating Temperature, C	700-800
Working Fluid	Sodium
Design Power into AMTEC cell, W	35.000
Assumed cell efficiency:	0.200
Electrical Output, W	7.000
BASE Power out/area, W/cm ²	0.200
BASE current flux, A/cm ²	0.500
Sodium flow rate, g/hr/Amp	1.000

BASE DIMENSIONS AND Na FLOW RATES

BASE diameter, cm	1.500
Required BASE area, cm ²	35.000
Required BASE length, cm	7.427
Required BASE length, in	2.924
Current, A	17.500
Sodium flow rate through BASE, g/hr	17.500
Sodium flow rate through BASE, kg/s	4.8611E-06
Total sodium flow rate, g/hr	87.500
Total sodium flow rate, kg/s	2.4306E-05
Recirculating sodium flow rate, g/hr	70.000
Recirculating sodium flow rate, kg/s	1.9444E-05

CONSTANTS

Stefan-Boltzman const., W/cm ² K ⁴	5.67E-12
Sodium Gas Constant, R, N-m/kg K	361.639
Na Ratio of Specific Heats, gamma	1.667
Gravitational Acceleration, m/s ²	9.800

OPERATING CONDITIONS

Ambient Temperature, C	20.000
Condenser Temperature, C	400.000

Condenser Sodium Properties

Liquid Density: Foust, pg 13, Stone's equation

Vapor Pressure: Foust, pg 56

Surface Tension: Foust, pg 36

Liquid Viscosity: Foust, pg 23: for T < 500 C

Condenser Temperature, C	400.000	400.000	400.000	400.000
Condenser Temperature, K	673.000	673.000	673.000	673.000
Condenser Na Latent Heat, J/kg	4.374E+06	4.374E+06	4.374E+06	4.374E+06
Condenser Na Liquid Density, kg/m ³	856.221	856.221	856.221	856.221
Condenser Na Vapor Density, kg/m ³	2.203E-04	2.203E-04	2.203E-04	2.203E-04

Condenser Na Liquid Thermal Conductivity, W/	70.379	70.379	70.379	70.379
Condenser Na Liquid Viscosity, cP (T < 500C)	0.285	0.285	0.285	0.285
Condenser Na Liquid Viscosity, kg/m s	2.846E-04	2.846E-04	2.846E-04	2.846E-04
Condenser Na Vapor Viscosity, cP	0.016	0.016	0.016	0.016
Condenser Na Vapor Viscosity, kg/m s	1.638E-05	1.638E-05	1.638E-05	1.638E-05
Condenser Na Vapor Pressure, Pa	47.195	47.195	47.195	47.195
Condenser Na Surface Tension, N/m	0.167	0.167	0.167	0.167

Evaporator Sodium Properties

Based on Fluprop

Liquid Density: Foust, pg 13, Stone's equation

Vapor Pressure: Foust, pg 56

Surface Tension: Foust, pg 36

Liquid Viscosity: Foust, pg 23: for T > 500 C

Range: 450-1100 C

Evap. Operating Temperature, C	700.000	750.000	700.000	750.000
Evap. Operating Temperature, K	973.000	1023.000	973.000	1023.000
Evap. Na Latent Heat, J/kg	4.063E+06	4.012E+06	4.063E+06	4.012E+06
Evap. Na Liquid Density, kg/m ³	784.048	771.946	784.048	771.946
Evap. Na Vapor Density, kg/m ³	0.0404	0.0740	0.0404	0.0740
Evap. Na Liquid Thermal Conductivity, W/m C	60.012	58.667	60.012	58.667
Evap. Na Liquid Viscosity, cP	0.181	0.171	0.181	0.171
Evap. Na Liquid Viscosity, kg/m s	1.814E-04	1.711E-04	1.814E-04	1.711E-04
Evap. Na Vapor Viscosity, cP	0.020	0.021	0.020	0.021
Evap. Na Vapor Viscosity, kg/m s	2.041E-05	2.104E-05	2.041E-05	2.104E-05
Evap. Na Vapor Pressure, Pa	13940.790	25885.002	13940.790	25885.002
Evap. Na Surface Tension, N/m	0.137	0.132	0.137	0.132

System Dimensions

BASE O.D., cm	1.500	
BASE Active Length, cm	7.493	
BASE Active Length, in	2.950	
BASE Length, cm (need 0.5 cm on either side of	10.160	
BASE + Sleeve Length, in	4.000	Note: Includes moly sleeve and flange
Sleeve Length, cm	2.667	
Effective BASE length, cm	6.414	

Condenser I.D., cm	2.500
Condenser Temperature, C	400.000
Condenser Temperature, K	673.000
Emissivity	0.900
Radiation, W/cm ²	1.009
Waste Thermal Energy	28.000
Area required to radiate input power	27.744
Required condenser length, cm	3.532
Active condenser length, cm	6.000
Condenser length, cm (BASE length + active le	16.160
Condenser Length, in	6.362

BASE Wick

BASE Wick O.D, cm must be less than BASE I. 0.991

BASE Wick O.D, in 0.390

BASE Wick Thickness, cm	0.178
BASE Wick Thickness, in	0.070
BASE Wick I.D., cm	0.635
BASE Wick I.D., in	0.250
Cross-Sectional Area for Liquid Flow, m ²	4.540E-05
Cross-Sectional Area for Vapor Flow, m ²	3.167E-05

Evaporator Wick	
Evaporator I.D., cm	2.000
Evaporator I.D., in	0.787
Evaporator Wick Thickness, in	0.050
Evaporator Wick Thickness, cm	0.127
Evaporator Vapor Diameter, cm	1.746
Evaporator Vapor Diameter, in	0.687
Evaporator Vapor Flow Area, m ²	2.394E-04
Heat Flux, W/cm ²	1.500
Required Area, cm ²	23.333
Required Evaporator Length, cm	3.714
Required Evaporator Length, in	1.462
Evaporator Length, in	2.000
Evaporator Length, cm	5.080

BASE-to-Evaporator Transition Wick

Transition wick thickness, cm	0.127
Transition wick thickness, in	0.050
Evaporator vapor diameter, cm	1.746
BASE wick I.D., cm	0.635
Transition wick length, cm	0.556

Condenser Wick

Number of Cable Arteries	1	1	1	1
Condenser Wall I.D., cm	2.500	2.500	2.500	2.500
Condenser Wall I.D., in	0.984	0.984	0.984	0.984
Active condenser length, cm	6.000	6.000	6.000	6.000
Condenser wick thickness, in	0.050	0.050	0.050	0.050
Condenser wick thickness, cm	0.127	0.127	0.127	0.127
Condenser wall vapor I.D., cm	2.246	2.246	2.246	2.246
Effective liquid flow length, m	0.0196	0.0196	0.0196	0.0196
Liquid flow area, m ²	7.620E-05	7.620E-05	7.620E-05	7.620E-05

Wick Properties**Candidate Evaporator Wicks: Sintered Nickel**

Sieve Size	-200+325	-100+150	-50+100	E-1 Nickel
Permeability, m ²	5.000E-12	1.500E-11	3.800E-11	2.000E-11
Pore Size, m	2.000E-05	3.900E-05	5.500E-05	2.500E-05
Wick pumping capability at 700C, Pa	13700.00	7025.64	4981.82	10960.00

Candidate Cable Properties

Cable type	Phase 1 Cable	1/8" cable
Permeability, m ²	6.860E-10	7.308E-11
Pore Size, m	1.200E-04	4.834E-05
Wick pumping capability at 700C, Pa	2283.33	5668.77

Diameter, in	0.25	0.08
Diameter, m	0.0064	0.0020
Area, m ²	3.167E-05	3.243E-06

Cable Properties

Cable type	0.080" braid	0.080" braid	Phase 1 Cable	Phase 1 Cable
Permeability, m ²	7.308E-11	7.308E-11	6.860E-10	6.860E-10
Pore Size, m	4.834E-05	4.834E-05	1.200E-04	1.200E-04
Wick pumping capability at 700C, Pa	5668.77	5668.77	2283.33	2283.33
Diameter, in	0.0800	0.0800	0.25	0.25
Diameter, m	0.00203	0.00203	0.0064	0.0064
Area, m ²	3.243E-06	3.243E-06	3.167E-05	3.167E-05
Number of cables	1	1	1	1
Total flow area, m ²	3.243E-06	3.243E-06	3.167E-05	3.167E-05

Recirculating Loop

BASE+Evaporator Length, m	0.152	0.152	0.152	0.152
BASE+Evaporator Length, in	6.000	6.000	6.000	6.000
Gravitational Pressure Drop, Pa	1170.991	1152.917	1170.991	1152.917

Vapor Pressure Drop

Vapor mass flow rate, kg/s (power and recirculati	2.431E-05	2.431E-05	2.431E-05	2.431E-05
Evaporator effective length, cm	2.540	2.540	2.540	2.540
Evaporator vapor velocity, m/s	2.511	1.371	2.511	1.371
Evaporator vapor Reynolds number	86.854	84.259	86.854	84.259
Evaporator vapor pressure drop, laminar flow, P	0.137	0.077	0.137	0.077

Contraction

Neglect, Laminar flow

BASE effective length, cm	6.414	6.414	6.414	6.414
BASE vapor velocity, m/s	18.985	10.367	18.985	10.367
BASE vapor Reynolds number	238.814	231.680	238.814	231.680
BASE vapor pressure drop, laminar flow, Pa	19.720	11.100	19.720	11.100

Vapor pressure drop inside BASE, Pa	19.856	11.177	19.856	11.177
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Liquid Pressure Drop

Liquid recirculation mass flow, kg/s	1.944E-05	1.944E-05	1.944E-05	1.944E-05
BASE wick	E-1 Nickel	E-1 Nickel	-200+325	-200+325
Permeability, m ²	2.000E-11	2.000E-11	5.000E-12	5.000E-12
Pore Size, m	2.500E-05	2.500E-05	2.000E-05	2.000E-05
Wick Pumping Capability, Pa	10936.000	10536.000	13670.000	13170.000

BASE Wick Pressure Drop

BASE effective length, m	0.064	0.064	0.064	0.064
BASE wick cross-sectional area, m ²	4.540E-05	4.540E-05	4.540E-05	4.540E-05
BASE wick pressure drop, Pa	317.774	304.432	1271.095	1217.727
BASE gravity pressure drop, Pa	780.661	768.611	780.661	768.611
Total Pressure drop in BASE wick, Pa	1098.434	1073.043	2051.755	1986.338

Excess pumping capability , Pa	9837.566	9462.957	11618.245	11183.662
BASE-to-Evaporator Transition Wick Pressure Drop				
Transition wick length, m	0.00556	0.00556	0.00556	0.00556
Liquid flow area, m ²	2.534E-05	2.534E-05	2.534E-05	2.534E-05
Transition Wick	Pretend	Pretend	Pretend	Pretend
Permeability, m ²	1.000E-12	1.000E-12	1.000E-12	1.000E-12
Pore Size, m	1.000E-05	1.000E-05	1.000E-05	1.000E-05
Wick Pumping Capability, Pa	2.734E+04	2.734E+04	2.734E+04	2.734E+04
Transition wick pressure drop, Pa	986.450	945.033	986.450	945.033
Evaporator Wick Pressure Drop				
Evaporator wick effective length, m	0.025	0.025	0.025	0.025
Evaporator Liquid Flow Area, m ²	7.473E-05	7.473E-05	7.473E-05	7.473E-05
Transition Wick	Pretend	Pretend	Pretend	Pretend
Permeability, m ²	1.000E-12	1.000E-12	1.000E-12	1.000E-12
Pore Size, m	1.000E-05	1.000E-05	1.000E-05	1.000E-05
Wick Pumping Capability, Pa	2.734E+04	2.734E+04	2.734E+04	2.734E+04
Evaporator pressure drop, Pa	1529.187	1464.983	1529.187	1464.983
Liquid pressure drop, recirculating loop, Pa	2833.410	2714.448	3786.731	3627.743
Total pressure drop, recirculating loop, Pa	4024.257	3878.541	4977.578	4791.836
Excess evaporator wick pumping capability, Pa	23315.743	23461.459	22362.422	22548.164

Condenser Loop

Condenser + Evaporator Length, m	0.212	0.212	0.212	0.212
Condenser + Evaporator Length, in	8.362	8.362	8.362	8.362

Vapor Pressure Drop, Pa	13893.594	25837.807	13893.594	25837.807
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Condenser Wick

Assume that the Condenser wick must withstand liquid flow pressure drop, and gravitational drop for condenser length

Number of cable arteries	1	1	1	1
Condenser mass flow rate, kg/s	4.861E-06	4.861E-06	4.861E-06	4.861E-06
Condenser length, m	0.162	0.162	0.162	0.162
Condenser gravitational pressure drop, Pa	1355.980	1355.980	1355.980	1355.980

Condenser Wick	-50+100	-50+100	-50+100	-50+100
Permeability, m ²	3.800E-11	3.800E-11	3.800E-11	3.800E-11
Pore Size, m	5.500E-05	5.500E-05	5.500E-05	5.500E-05
Wick Pumping Capability, Pa	6061.818	6061.818	6061.818	6061.818

Condenser flow effective length, m	0.0196	0.0196	0.0196	0.0196
Condenser wick liquid pressure drop, Pa	10.958	10.958	10.958	10.958

Condenser pressure drops, Pa	1366.938	1366.938	1366.938	1366.938
Excess condenser pumping capability, Pa	4694.880	4694.880	4694.880	4694.880

Evaporator Wick

Number of cable arteries	1	1	1	1
Condenser mass flow rate, kg/s	4.861E-06	4.861E-06	4.861E-06	4.861E-06
Evaporator length, m	0.051	0.051	0.051	0.051
Evaporator gravitational pressure drop, Pa	390.330	384.306	390.330	384.306
	614.656			

Evaporator Wick	Pretend	Pretend	Pretend	Pretend
Permeability, m ²	1.000E-12	1.000E-12	1.000E-12	1.000E-12
Pore Size, m	1.000E-05	1.000E-05	1.000E-05	1.000E-05
Wick Pumping Capability, Pa	27340.000	26340.000	27340.000	26340.000

Assume coiled cable artery at the top of the AMTEC cell evaporator

Total mass flow rate, kg/s	2.431E-05	2.431E-05	2.431E-05	2.431E-05
Evaporator wick effective length, m	0.025	0.025	0.025	0.025
Evaporator Liquid Flow Area, m ²	7.473E-05	7.473E-05	7.473E-05	7.473E-05
Evaporator pressure drop, Pa	1911.483	1831.229	1911.483	1831.229

Assume cable artery down one side of the AMTEC cell evaporator

Pressure drop due to recirculating flow, Pa	1529.187	1464.983	1529.187	1464.983
Condenser mass flow rate, kg/s	4.861E-06	4.861E-06	4.861E-06	4.861E-06
Effective flow length, m	0.0157	0.0157	0.0157	0.0157
Liquid flow area, m ²	6.452E-05	6.452E-05	6.452E-05	6.452E-05
Recirculation pressure drop, Pa	13.692	13.118	54.770	52.470
Total pressure drop, both flows, Pa	1542.879	1478.100	1583.956	1517.453

Cable Artery Pressure Drop

Cable type	0.080" braid	0.080" braid	Phase 1 Cable	Phase 1 Cable
Permeability, m ²	7.308E-11	7.308E-11	6.860E-10	6.860E-10
Pore Size, m	4.834E-05	4.834E-05	1.200E-04	1.200E-04
Wick pumping capability at 700C, Pa	5668.77	5668.77	2283.33	2283.33
Diameter, in	0.08	0.08	0.25	0.25
Diameter, m	0.0020	0.0020	0.0064	0.0064
Area, m ²	3.243E-06	3.243E-06	3.167E-05	3.167E-05
Number of cables	1	1	1	1
Total flow area, m ²	3.243E-06	3.243E-06	3.167E-05	3.167E-05
Gravitational pressure drop in condenser, Pa	1241.681	1222.515	1241.681	1222.515
Effective length, m	0.212	0.212	0.212	0.212
Condenser mass flow rate, kg/s	4.861E-06	4.861E-06	4.861E-06	4.861E-06
Cable Liquid Flow Pressure Drop, Pa	1448.361	1448.361	15.800	15.800
Total Pressure drop for the Cable, Pa	2815.299	2815.299	1382.738	1382.738
Excess cable pumping capability, Pa	2853.471	2853.471	900.595	900.595
Vapor pressure drop, Pa	13893.594	25837.807	13893.594	25837.807
Total gravitational pressure drop, Pa	1746.310	1740.285	1746.310	1740.285
Liquid flow pressure drop, coiled cable artery, Pa	3370.802	3290.547	1938.241	1857.987
Liquid flow pressure drop, straight cable artery, P	3002.198	2937.419	1610.715	1544.211

Total condenser pressure drop, coiled cable arter	19010.707	30868.640	17578.146	29436.079
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Total condenser pressure drop, straight cable art	18642.102	30515.511	17250.619	29122.303
Excess wick pumping capability, coiled cable art	8329.293	-4528.640	9761.854	-3096.079

Evaporator Sonic Limit

Use equation for choked flow with varying areas, Shapiro, eq. 4-17

Sodium Specific Heat Ratio	1.67
Gas Constant, J/kg-mole K	8314.40
Sodium Molecular Weight, kg/kg-mole	22.99
Sodium Gas Constant, J/kg K	361.66
Sonic Limit Coefficient	0.03821

BASE Wick I.D., cm	0.635
Cross-Sectional Area for Vapor Flow, m ²	3.167E-05

Sodium Properties

Based on Fluprop

Range: 450-1100 C

Temperature, C	450.000	455.000	460.000	465.000
Temperature, K	723.000	728.000	733.000	738.000
Evap. Na Latent Heat, J/kg	4.322E+06	4.316E+06	4.311E+06	4.306E+06
Evap. Na Vapor Pressure, Pa	169.978	191.329	215.009	241.232
Sonic Limit, W	33.059	37.039	41.431	46.270

Title: AMTEC Vapor Fed Cell

Calculated by: W. Anderson Date: 2/9/92

Checked by: _____ Date: _____

Reviewed by: _____ Date: _____

Project: _____

Page 14 of _____

Revise the vapor pressure drop calculations - add a purge tube inside the BASE wick

$\frac{1}{16}$ " O.D. Tube = 0.0625 "

$$\text{Flow Area} = \frac{\pi}{4} (D_{\text{sa}}^2 - D_{\text{tube}}^2) \frac{10^4 \text{ cm}^2}{\text{in}^2} = 2.72 \times 10^{-5} \text{ m}^2$$

$$\text{Perimeter} = \pi (D_{\text{S.D.}} + D_{\text{O.D.}}) = 2.41 \text{ cm}$$

$$\text{Hydraulic Diameter} = \frac{4A}{P} = 0.451 \text{ cm}$$

Use hydraulic diameter in the pressure drop calculations

Title: AmTEC Proof of Concept Cell
BASE Wick Temperature and Fluid
Flow

Calculated by: W. Anderson Date: 2/9/93
 Checked by: _____ Date: _____
 Reviewed by: _____ Date: _____

Project: _____

Page 1 of _____

Objective: Estimate the temperature drop between the interior of the BASE wick and the interior of the BASE Tube.

$P_i = 700^\circ\text{C}$

BASE wick O.D. 0.418" to 0.344"

BASE TUBE I.D. 0.470" I.D.

BASE Tube Length = 3" = 0.076m.

$$K_{\text{nickel}} = 84 \frac{\text{W}}{\text{m K}}$$

$$K_{\text{Na}} = 60 \frac{\text{W}}{\text{m K}}$$

$$K_{\text{wick}} = (0.4)(60) + (0.6)(84) = 74.4$$

Heat Flux $q = 50 \text{ W}$

Radial Heat Transfer

$$q = \frac{2\pi K L}{\ln(r_2/r_1)} \Delta T, \quad \Delta T = \frac{q \ln(r_2/r_1)}{2\pi K L}$$

$$\Delta T_{\text{wick}} = \frac{(50) \ln \frac{0.4}{0.33}}{(2\pi)(74.4)(0.076)} = 0.271^\circ\text{C}$$

$$\Delta T_{\text{gap max}} = \frac{50 \ln \frac{0.47}{0.34}}{(2\pi)(74.4)(0.076)} = 0.456^\circ\text{C}$$

less than 1°C

APPENDIX B

700°C VAPOR-FED AMTEC CELL PARTS DRAWINGS

SECTION A-A

MATERIAL:
304L S.S.
(1 3/4" O.D. TUBE x .120" WALL TUBE(2.010" I.D.))

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 - .015 +30' -30' .XXX=+.005 - .005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
			DRAWN	EHD	DATE	TITLE 700°C WICK PUMPED - AMTEC CELL - HOT ZONE CANNISTER	
TREATMENT			CHECKED				
			APPROVED			SIZE A	
FINISH			APPROVED				
			APPROVED			DWG. NO. A-11-1140-2	
SIMILAR TO	ACT. WT.	CALC. WT.	CUSTOMER				
			SCALE		RELEASE DATE		SHEET

NOTE 1:
 VERIFY SIZE OF
 FREE STANDING WICK
 BEFORE DRILLING
 450 Ø HOLE.

SECTION A-A

MATERIAL: 304L S.S.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
			DRAWN EHD			
TREATMENT			CHECKED		TITLE 700°C WICK PUMPED - AMTEC CELL - TRANSITION CAP	
			APPROVED			
FINISH			APPROVED		SIZE A	
			CUSTOMER		DWG. NO. A-11-1140-3	
SIMILAR TO	ACT. WT.	CALC. WT.			SCALE	RELEASE DATE
					SHEET

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
			DRAWN EHD 10/27/92			
TREATMENT			CHECKED		TITLE 700°C WICK PUMPED - AMTEC CELL - TRANSITION TUBE	
			APPROVED			
FINISH			APPROVED		SIZE A	DWG. NO. A-11-1140-4
			CUSTOMER		SCALE	RELEASE DATE
SIMILAR TO	ACT. WT.	CALC. WT.

MATERIAL: 304L S.S. (1 3/4" O.D. x .120 WALL (1.510 I.D.))

REVISIONS				UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30° -30° .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
LTR.	DESCRIPTION	DATE	APPROVED	TREATMENT	DRAWN	EHD	CHECKED	TITLE 700°C WICK PUMPED - AMTEC CELL - EVAPORATOR		
				FINISH	APPROVED			SIZE	DWG. NO.	REV
				SIMILAR TO	ACT. WT.	CALC. WT.	CUSTOMER	B	B-11-1140-5	A
								SCALE	RELEASE DATE	SHEET

.125 ϕ THRU ON A
1.107 ϕ HOLE CIRCLE

.250 ϕ THRU
ON CENTERS

.062 ϕ THRU ON A
.550 ϕ HOLE CIRCLE

$\begin{matrix} +.000 \\ -.005 \end{matrix}$
1.570 ϕ
(NTS)

.250 ϕ THRU
ON A 1.250 ϕ
HOLE CIRCLE

MATERIAL: 304L S.S.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
			DRAWN EHD	10/27/92		
TREATMENT			CHECKED		TITLE 700°C WICK PUMPED - AMTEC CELL - EVAPORATOR CAP	
			APPROVED			
FINISH			APPROVED		SIZE A	DWG. NO. A-11-1140-6
			CUSTOMER		SCALE	RELEASE DATE
SIMILAR TO	ACT. WT.	CALC. WT.	SHEET

① SEE "AMPS" DWG.
#TC1001 10-06-92
REV A

.023

.023

ADD WELD
MOAT

SECTION A-A

MATERIAL:

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
			DRAWN EHD			
TREATMENT			CHECKED		TITLE 700°C WICK PUMPED - AMTEC CELL - MODIFIED AMTEC TUBE FLANGE	
			APPROVED			
FINISH			APPROVED		SIZE A	
			APPROVED		DWG. NO. A-11-1140-7	
SIMILAR TO	ACT. WT.	CALC. WT.	CUSTOMER		SCALE	RELEASE DATE
						SHEET

MATERIAL: 304L S.S.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
			DRAWN EHD				
TREATMENT			CHECKED		TITLE 700°C WICK PUMPED - AMTEC CELL - CONDENSER CANISTER		
			APPROVED				
FINISH			APPROVED		SIZE A		
			APPROVED				
SIMILAR TO		ACT. WT.	CALC. WT.	CUSTOMER	DWG. NO. A-11-1140-8		SHEET
					SCALE	RELEASE DATE

NOTE:
SEE DRAWING
A-11-1140-24
FOR CAP BEFORE
AND DURING
SINTERING.

MATERIAL: 304L S.S.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
			DRAWN EHD 10/27/92			
TREATMENT			CHECKED		TITLE 700°C WICK PUMPED - AMTEC CELL - CONDENSER CAP (AFTER SINTERING)	
			APPROVED			
			APPROVED			
FINISH			APPROVED		SIZE A	DWG. NO. A-11-1140-9
SIMILAR TO	ACT. WT.	CALC. WT.	CUSTOMER		SCALE	RELEASE DATE
						SHEET

MATERIAL: 5/32" x .028" WALL S.S. TUBING

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
			DRAWN EHD	DATE 5/5/93			
TREATMENT			CHECKED		TITLE 700°C WICK PUMPED - AMTEC CELL - ARTERY TUBING		
			APPROVED				
FINISH			APPROVED		SIZE A DWG. NO. A-11-1140-10		
			CUSTOMER				
SIMILAR TO	ACT. WT.	CALC. WT.			SCALE	RELEASE DATE	SHEET

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX-+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
			DRAWN	EHD			
TREATMENT			CHECKED		TITLE WICK PUMPED - AMTEC CELL - FREE STANDING WICK		
			APPROVED				
FINISH			APPROVED		SIZE A		
			APPROVED		DWG. NO. A-11-1140-11		
SIMILAR TO	ACT. WT.	CALC. WT.	CUSTOMER		SCALE _____		RELEASE DATE
					SHEET		

APPENDIX C

800°C VAPOR-FED AMTEC CELL CALCULATIONS

Title: AMTEC VAPOR-FED CELL
800°C DESIGN

Calculated by: JE Lundquist Date: 5-20-93
 Checked by: John B. ... Date: 6/7/93
 Reviewed by: _____ Date: _____

Project: 11-1140 AMTEC

Page 1 of 2

Purpose : Determine the minimum wall thickness for a square evaporator fabricated from niobium.

Analysis : Niobium Y.T.S. = 20 ksi at 800°C

[REF: TELEDYNE WAH CHANG BROCHURE ON NIOBIUM]

KOARKE + YOUNG, 5th Ed, p. 386, Table 26-1.

$$\sigma_{\text{MAX}} = \frac{\beta q b^2}{t_{\text{WALL}}^2}$$

ASSUMPTION: TREAT AS SIMPLY SUPPORTED BEAM.

$$h = 1.25 \text{ in}$$

$$W = 1.62 \text{ in}$$

$$t_{\text{WALL}} = \sqrt{\frac{\beta q b^2}{\sigma_{\text{MAX}}}}$$

Title: _____

800°C DESIGN

Calculated by: JE Lindemuth Date: 5-20-93

Checked by: _____ Date: _____

Reviewed by: _____ Date: _____

Project: 11-1140 AMTELPage 2 of 2

$$\frac{a}{b} = \frac{h}{w} = \frac{1.25 \text{ IN}}{1.62 \text{ IN}} = 0.77$$

$$R+Y, p. 386 \quad \frac{a}{b} = 0.77 \Rightarrow \beta = 0.287$$

$$\text{CONSERVATIVE} \quad q = P = 14.7 \text{ psi} - 0 \text{ psi} = 14.7 \text{ psi}$$

$$b^2 = w^2 =$$

$$\sigma_{\text{MAX}} = \frac{6}{10} (\text{Y.T.S.}) = \frac{6}{10} (20 \text{ ksi}) = 12 \text{ ksi}$$

$$t_{\text{WALL}} = \sqrt{\frac{(\beta)(14.7 \text{ psi})(1.62 \text{ IN})^2}{12 \times 10^3 \text{ psi}}}$$

$$t_{\text{WALL}} = 0.030 \text{ IN}$$

CONCLUSION: MINIMUM EVAPORATOR WALL THICKNESS

IS 0.030 IN.

Table 5 – Physical Properties

Niobium alloy heat pipe
used for high
temperature heat
transfer

BEND DUCTILITY:

C-103 sheet will pass a -320°F , 90° ,
2T bend in both parent metal and
weldment

<i>Modulus of elasticity</i>	Temperature $^{\circ}\text{F}$	PSI
	Room Temperature	13.1×10^6
	2200	9.3×10^6

WC-103 is fully recrystallized by heat treating one to two hours at 2400°F with more than 80% cold work. WC-103 products include:

- Sheet .030" thick, grain size ASTM 6 minimum
- Plate 1-1/2" thick, extruded, and rolled, grain size ASTM 4-6
- Round bar 3-1/4" diameter, forged and machined, grain size ASTM 3-5

Hardness: Arc melting ingot 130-145 BHN

Recrystallized product: 130-145 DPH

WC-103 alloy can be easily fabricated and worked. Forging, rolling, and swaging are accomplished by general sheet metal working methods; in fact, the low rate of work hardening facilitates these operations by reducing spring-back. WC-103 may be machined by the usual techniques, although the surface galling tendency makes it similar to lead or soft copper.

TIG is the best welding method. Electron beam welding is also excellent, but the necessary equipment is not always available. For TIG, properly designed trailer shields and backup grooves with adequate gas flow, can produce welds of a quality equal to those made with electron beam equipment.

MECHANICAL PROPERTIES

Figures 1 and 2 contain mechanical properties data that has been used successfully as design criteria for over 20 years, while providing necessary safety margins.

Figure 1. Guaranteed mechanical properties of WC-103 recrystallized one hour at 2400°F .

Figure 2. Linear coefficient of thermal expansion and enthalpy.

WELDING

A pickling operation should be conducted before and after welding as well as before and after heat treating. If pickling is performed, welding of niobium alloys can be readily accomplished by both the TIG and electron beam processes. It is recommended that all copper tooling should have a hard chrome plating approximately 0.002" thick without a nickel strike. This prevents copper contamination which causes brittle welds. For TIG, properly designed trailer shields and backup grooves with adequate gas flow can give weldments a quality equal to welds made with electron beam equipment. Where possible, the argon and helium should be passed through hot zirconium

TABLE 26 Formulas for flat plates with straight boundaries and constant thickness

NOTATION: The notation for Table 24 applies with the following modifications: a and b refer to plate dimensions, and when used as subscripts for stress, they refer to the stresses in directions parallel to the sides a and b , respectively. σ is a bending stress which is positive when tensile on the bottom and compressive on the top if loadings are considered vertically downward. R is the reaction force normal to the plate surface exerted by the boundary support on the edge of the plate (pounds per inch). r'_0 is the equivalent radius of contact for a load concentrated on a very small area and is given by $r'_0 = \sqrt{1.6r_0^2 + t^2} - 0.675t$ if $r_0 < 0.5t$ and $r'_0 = r_0$ if $r_0 > 0.5t$

Case no., shape, and supports	Case no., loading	Formulas and tabulated specific values										
1. Rectangular plate; all edges simply supported	1a. Uniform over entire plate	(At center) $\text{Max } \sigma = \sigma_b = \frac{\beta q b^2}{t^2}$ and $\text{max } \gamma = \frac{-\alpha q b^4}{Et^3}$										
		(At center of long sides) $\text{Max } R = \gamma q b$										
		a/b	1.0	1.2	1.4	1.6	1.8	2.0	3.0	4.0	5.0	∞
		β	0.2874	0.3762	0.4530	0.5172	0.5688	0.6102	0.7134	0.7410	0.7476	0.7500
		α	0.0444	0.0616	0.0770	0.0906	0.1017	0.1110	0.1335	0.1400	0.1417	0.1421
		γ	0.420	0.455	0.478	0.491	0.499	0.503	0.505	0.502	0.501	0.500
(Ref. 21 for $\nu = 0.3$)												
	1b. Uniform over small concentric circle of radius r_0 (note definition of r'_0)	(At center) $\text{Max } \sigma = \frac{3W}{2\pi t^2} \left[(1 + \nu) \ln \frac{2b}{\pi r'_0} + \beta \right]$ $\text{Max } \gamma = \frac{-\alpha W b^2}{Et^3}$										
		a/b	1.0	1.2	1.4	1.6	1.8	2.0	∞			
		β	0.435	0.650	0.789	0.875	0.927	0.958	1.000			
		α	0.1267	0.1478	0.1621	0.1715	0.1770	0.1805	0.1851			
(Ref. 21 for $\nu = 0.3$)												

(Ref. 21 for $\nu = 0.3$)(Ref. 21 for $\nu = 0.3$)

[CHAP. 10]

ROUTING - REQUEST

Please

- ☐ READ
☐ HANDLE
☐ APPROVE
 and
☐ FORWARD
☐ RETURN

TO:

WGA	JEL
PMD	JHR
RED	JET
SDG	
NJG	DME
IDL	ONE

1c. Uniform over central rectangular area

(At center)	$\text{Max } \sigma = \sigma_b = \frac{\beta W}{t^2}$						where $W = qa_1b_1$
$a = b$								
b_1/h	0	0.2	0.4	0.6	0.8	1.0	0	0.2	
0		1.82	1.38	1.12	0.93	0.76		2.0	

Title: AMTEC VAPOR-FED CELL
800°C DESIGN

Calculated by: JE Lindquist Date: 5-18-93
 Checked by: K. Horn Date: 6/7/93
 Reviewed by: _____ Date: _____

Project: 11-1140 AMTEC

Page 1 of 1

Purpose: Determine incident heat flux on the evaporator of the 800°C AMTEC cell.

Analysis: Heat source: General Purpose Heat Source operating at 1100°C (1373 K)

AMTEC evaporator 800°C (1073 K)

Assumed emissivity: 0.8

$$\frac{Q}{A} = F_{12} \sigma [T_{GPHS}^4 - T_{EVAP}^4]$$

ASSUME $F_{12} = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$

INFINITE PARALLEL PLANES
 ROSENOW + Choi, p 347

$$= \frac{1}{\frac{1}{.8} + \frac{1}{.8} - 1} = 0.667$$

$$\begin{aligned} \frac{Q}{A} &= (0.667) (5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4) [(1373 \text{ K})^4 - (1073 \text{ K})^4] \\ &= 8.4 \times 10^4 \text{ W/m}^2 = 8.4 \text{ W/cm}^2 \end{aligned}$$

CONCLUSION: Incident heat flux is 8.4 W/cm²

Title: AMTEC VAPOR-FED CELL
800°C DESIGN

Calculated by: JE Lundemuth Date: 5-6-93

Checked by: K. Horvath, K. Cummings Date: 10/2/93

Reviewed by: _____ Date: _____

Project: 11-1140 AMTEC

Page 1 of 21

Purpose: Develop a wick design for a vapor-fed AMTEC cell that will operate near 800°C .

β'' -Alumina Solid Electrode (BASE)

Design Requirements :

Evaporator Temperature : 800°C

Condenser Temperature 400°C

Working Fluid: Sodium (Na)

BASE Characteristics :

Power out/area 0.20 W/cm^2

Current Flux $0.50 \text{ } \frac{\text{A}}{\text{cm}^2}$

Na Flow Rate 1.00 g/hr/A

Assumed Cell Efficiency (η) 0.06

BASE Dimensions:

Outer Diameter (d) $1.50 \text{ cm} = 0.59 \text{ in}$

Total Length (l_{TOT}) $6.50 \text{ cm} = 2.56 \text{ in}$

INACTIVE Length (li) 0.50 cm = 0.20 in

Active Length (l_a) $6.50\text{ cm} - 2(0.50\text{ cm})$
 $= 5.50\text{ cm} = 2.16\text{ in}$

Area (A) = $\pi d l_2 = 25.92 \text{ cm}^2$

Moly Sleeve Length (l_m) $2.50 \text{ cm} = 0.98 \text{ in}$

BASE + Sleeve Length ($l_{TOT} + l_m$) $9.00\text{cm} = 3.54\text{in}$

EFFECTIVE BASE + Sleeve

$$\text{Length, } L_{\text{eff}} = \frac{5.50 \text{ cm}}{2} + 0.50 \text{ cm} + 2.50 \text{ cm} \\ = 5.75 \text{ cm} = 2.26 \text{ in}$$

Estimate electrical power output: $P_{OUT} = (0.20 \frac{W}{cm^2})(25.92 cm^2) = 5.18 W$

Estimate design power in: $P_{in} = \frac{P_{out}}{\eta} = \frac{5.18W}{0.06} = 86.33W$

Current Flow: $I = (A)(J_A) = (25.92 \text{ cm}^2)(0.50 \text{ A/cm}^2) = 13.0 \text{ A}$

Title: AMTEC VAPOR-FED CELL
800°C DESIGN

Calculated by: JL Lunden Date: 5-6-93
 Checked by: _____ Date: _____
 Reviewed by: _____ Date: _____

Project: 11-1140 AMTEC

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Title: 800°C DESIGN
 Project: 11-1140 AMTEC

Calculated by: JF Lindemuth Date: 5-6-93
 Checked by: _____ Date: _____
 Reviewed by: _____ Date: _____

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Sodium flow rate through BASE

$$\dot{m}_{BASE} = (13.0A)(1.00 \text{ g/hr/A}) = 13.0 \text{ g/hr} = 3.61 \times 10^{-6} \text{ kg/s}$$

Since $\eta = 0.06$, Na flow rate through BASE is 6% of total flow

$$\dot{m}_{TOTAL} = \frac{\dot{m}_{BASE}}{\eta} = 216.7 \text{ g/hr} = 6.02 \times 10^{-5} \text{ kg/s}$$

Recirculating flow

$$\dot{m}_{RECIRC} = (.94) \dot{m}_{TOTAL} = 203.7 \text{ g/hr} = 5.66 \times 10^{-5} \text{ kg/s}$$

BASE Wick Dimensions:

Outer Diameter (d)	1.04 cm = 0.41 in
Thickness	0.18 cm = 0.07 in
Inner Diameter	0.68 cm = 0.27 in
Length of Sleeve Support and Evap. Wall Thick.	2.50 cm = 0.98 in
BASE-to-Evap. Transition Wick Thick.	0.96 cm = 0.38 in
BASE Wick Length = L_{TOT}	9.00 cm + 2.50 cm + 0.96 cm = 12.46 cm = 4.91 in
EFF. BASE Wick Length = L_{EFF}	5.75 cm + 2.50 cm + 0.96 cm = 9.21 cm = 3.63 in

Title: _____

800°C DESIGN

Calculated by: JP Zindemuth

Date: 5-18-93

Checked by: _____

Date: _____

Reviewed by: _____

Date: _____

Project: 11-1140 AMTEC

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BASE-to-Evaporator Transition Wick Dimensions:

Thickness (t) 0.96 cm = 0.38 IN

Width (w) 4.11 cm = 1.62 IN

Length (l) 4.11 cm = 1.62 IN

BASE Wick I.D. 0.68 cm = 0.27 IN

(x) Embedded Cable Length 1.27 cm = 0.50 IN

Distance to Cable (d) 0.44 cm = 0.17 IN

Number of Cables $N_{\text{TRANS CABLE}} = 5$

Cable Diameter 0.20 cm = 0.08 IN

Spacing between cables (y) 0.50 cm = 0.20 IN

$$A_{\text{TRANS}} = t w = (.96 \text{ cm} \times 4.11 \text{ cm}) = 3.95 \text{ cm}^2 = 3.95 \times 10^{-4} \text{ m}^2$$

Title: AMTEC VAPOR-FED CELL
800°C DESIGNCalculated by: GE Lindemuth Date: 5-6-93

Checked by: _____ Date: _____

Reviewed by: _____ Date: _____

Project: 11-1140 AMTECPage 5 of 21**Condenser Sodium Properties**

Liquid Density: Foust, pg 13, Stone's equation

Vapor Pressure: Foust, pg 56

Surface Tension: Foust, pg 36

Liquid Viscosity: Foust, pg 23: for $T < 500\text{ C}$

Condenser Temperature, C 400.000

Condenser Temperature, K 673.000

Condenser Na Latent Heat, J/kg 4.374E+06

Condenser Na Liquid Density, kg/m^3 856.221Condenser Na Vapor Density, kg/m^3 2.203E-04

Condenser Na Liquid Thermal Conductivity, W/ 70.379

Condenser Na Liquid Viscosity, cP ($T < 500\text{C}$) 0.285Condenser Na Liquid Viscosity, kg/m s 2.846E-04

Condenser Na Vapor Viscosity, cP 0.016

Condenser Na Vapor Viscosity, kg/m s 1.638E-05

Condenser Na Vapor Pressure, Pa 47.195

Condenser Na Surface Tension, N/m 0.167

Evaporator Sodium Properties

Liquid Density: Foust, pg 13, Stone's equation

Vapor Pressure: Foust, pg 56

Surface Tension: Foust, pg 36

Liquid Viscosity: Foust, pg 23: for $T > 500\text{ C}$

Range: 450-1100 C

Evap. Operating Temperature, C 800.000

Evap. Operating Temperature, K 1073.000

Evap. Na Latent Heat, J/kg 3.961E+06

Evap. Na Liquid Density, kg/m^3 759.835Evap. Na Vapor Density, kg/m^3 0.1257

Evap. Na Liquid Thermal Conductivity, W/m C 57.432

Evap. Na Liquid Viscosity, cP 0.162

Evap. Na Liquid Viscosity, kg/m s 1.622E-04

Evap. Na Vapor Viscosity, cP 0.022

Evap. Na Vapor Viscosity, kg/m s 2.165E-05

Evap. Na Vapor Pressure, Pa 45317.576

Evap. Na Surface Tension, N/m 0.127

Title: _____

800°C DESIGN

Calculated by: J.E. LundermuthDate: 5-6-93

Checked by: _____

Date: _____

Reviewed by: _____

Date: _____

Project: 11-1140 FMTECPage 6 of 21EVAPORATOR Wick DIMENSIONS

THICKNESS (t)

$$1.27 \text{ cm} = 0.50 \text{ in.}$$

LENGTH (l)

$$3.78 \text{ cm} = 1.49 \text{ in.}$$

WIDTH (w)

$$4.11 \text{ cm} = 1.62 \text{ in.}$$

9 VAPOR CHANNELS @

$$0.15 \text{ cm} \times 0.15 \text{ cm} \times 3.78 \text{ cm}$$

$$(0.06 \text{ in} \times 0.06 \text{ in} \times 1.49 \text{ in})$$

1 SIDE CHANNEL
(see p. 2)

$$4.11 \text{ cm} \times 1.27 \text{ cm} \times 0.33 \text{ cm}$$

$$(1.62 \text{ in} \times 0.50 \text{ in} \times 0.13 \text{ in})$$

Recirculating Loop Pressure Drops

$$L_{\text{EVAP}} = 3.17 \text{ cm} = 1.25 \text{ in.}$$

$$L_{\text{BASE}} + L_{\text{EVAP}} = 12.46 \text{ cm} + 3.17 \text{ cm} = 15.63 \text{ cm} = 0.1563 \text{ m}$$

Gravity $\Delta P_{\text{GRAV}} = \rho_{\text{LIQ}} g h = (759.8 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.1563 \text{ m})$

$$\Delta P_{\text{GRAV}} = 1165 \text{ Pa}$$

Recirculating Loop - Vapor Pressure Drop

$$L_{\text{EFF}} = \frac{3.78 \text{ cm}}{2} = 1.89 \text{ cm} = 0.0189 \text{ m}$$

$$\dot{m}_{\text{VAP}} = \dot{m}_{\text{TOTAL}} = 6.02 \times 10^{-5} \text{ kg/s}$$

Vapor channel

$$A_{\text{VC}} = (.15 \text{ cm})^2 = 0.0225 \text{ cm}^2 = 2.25 \times 10^{-6} \text{ m}^2$$

$$P_{\text{VC}} = 4(.15 \text{ cm}) = 0.60 \text{ cm} = 6.00 \times 10^{-3} \text{ m}$$

$$D_h = \frac{4A_{\text{VC}}}{P_{\text{VC}}} = 1.50 \times 10^{-3} \text{ m}$$

Number of vapor channels, $N_{\text{VC}} = 9$

Title: 8000C DESIGN
 Project: 11-1140 RMTGC

Calculated by: JE Lundermuth Date: 5-6-93
 Checked by: _____ Date: _____
 Reviewed by: _____ Date: _____

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Vapor velocity $V_{VC} = \frac{\dot{m}_{VAP}}{\rho_v N_{VC} A_{VC}} = \frac{(6.02 \times 10^{-5} \text{ kg/s})}{(.1257 \text{ kg/m}^3)(9)(2.25 \times 10^{-6} \text{ m}^2)}$

$= 23.7 \text{ m/s}$ IN VAPOR CHANNELS

Reynolds Number $Re = \frac{\rho_v V_{VC} D_H}{\mu_v} = \frac{(.1257 \text{ kg/m}^3)(23.7 \text{ m/s})(1.50 \times 10^{-3} \text{ m})}{2.2 \times 10^{-5} \text{ Pa}\cdot\text{s}}$

$= 203$ LAMINAR

VAPOR CHANNEL - VAPOR PRESS. DROP

$\Delta P_{VC, VAP} = \frac{32 L_{EFF} \mu_v V_{VC}}{D_H^2} = \frac{(32)(.0189 \text{ m})(2.2 \times 10^{-5} \text{ Pa}\cdot\text{s})(23.7 \text{ m/s})}{(1.50 \times 10^{-3} \text{ m})^2}$

$\Delta P_{VC, VAP} = 140 \text{ Pa}$

SIDE CHANNEL

$N_{SC} = 1$

$A_{SC} = (0.33 \text{ cm})(4.11 \text{ cm}) = 1.36 \text{ cm}^2 = 1.36 \times 10^{-4} \text{ m}^2$

all of mass flow
in side channel

$P_{SC} = 2(0.33 \text{ cm} + 4.11 \text{ cm}) = 8.88 \text{ cm} = 0.0888 \text{ m}$

$D_H = \frac{4 A_{SC}}{P_{SC}} = 6.13 \times 10^{-3} \text{ m}$

$\dot{m} = \dot{m}_{VAP} = 6.02 \times 10^{-5} \text{ kg/s}$

VAPOR VELOCITY

$V_{SC} = \frac{\dot{m}_{VAP}}{\rho_v N_{SC} A_{SC}} = \frac{6.02 \times 10^{-5} \text{ kg/s}}{(.1257 \text{ kg/m}^3)(1)(1.36 \times 10^{-4} \text{ m}^2)} = 3.5 \text{ m/s}$ IN SIDE CHANNELS

Title: 800 °C DESIGN

Project: 11-1140 AMTEC

Calculated by: JC Lendemuth Date: 5-6-93

Checked by: _____ Date: _____

Reviewed by: _____ Date: _____

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$$\text{Reynolds Number } Re = \frac{(.1257 \text{ kg/m}^3)(3.5 \text{ m/s})(6.13 \times 10^{-3} \text{ m})}{2.2 \times 10^{-5} \text{ Pa}\cdot\text{s}}$$

$$= 123 \text{ LAMINAR}$$

$$L_{EFF} = 1.27 \text{ cm} = 0.0127 \text{ m}$$

SIDE CHANNEL - VAPOR PRESSURE DROP

$$\Delta P_{SC \text{ VAP}} = \frac{32 L_{EFF} \mu V_{SC}}{D_N^2} = \frac{32 (0.0127 \text{ m}) (2.2 \times 10^{-5} \text{ Pa}\cdot\text{s}) (3.5 \frac{\text{m}}{\text{s}})}{(6.13 \times 10^{-3} \text{ m})^2}$$

$$\Delta P_{SC \text{ VAP}} = 0.8 \text{ Pa}$$

EVAPORATOR VAPOR SPACE

All of the mass flow is used $m_{VAP} = m_{TOTAL}$
 $= 6.02 \times 10^{-5} \text{ kg/s}$

$$A_{VAP} = (4.11 \text{ cm})^2 = 16.89 \text{ cm}^2 = 1.69 \times 10^{-3} \text{ m}^2$$

$$P_{VAP} = 2(4.11 \text{ cm} + 4.11 \text{ cm}) = 16.44 \text{ cm} = 0.164 \text{ m}$$

$$D_H = \frac{4 A_{VAP}}{P_{VAP}} = 0.0412 \text{ m}$$

$$V = \frac{6.02 \times 10^{-5} \text{ kg/s}}{(.1257 \text{ kg/m}^3)(1.69 \times 10^{-3} \text{ m}^2)} = 0.28 \text{ m/s} \text{ IN EVAP. VAPOR SPACE}$$

$$Re = \frac{(.1257 \text{ kg/m}^3)(.28 \text{ m/s})(0.0412 \text{ m})}{2.2 \times 10^{-5} \text{ Pa}\cdot\text{s}} = 66 \text{ LAMINAR}$$

Title: 800 °C DESIGN
 Project: 11-1140 FMTEC

Calculated by: JE Landemuth Date: 5-6-93
 Checked by: _____ Date: _____
 Reviewed by: _____ Date: _____

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$$L_{EFF} = [1.25 \text{ IN} - 2(.188 \text{ IN}) - .50 \text{ IN}] = 0.374 \text{ IN} = 9.50 \times 10^{-3} \text{ m}$$

Evaporator vapor space pressure drop

$$\Delta P_{EVAP \text{ VAP}} = \frac{(32)(.0095 \text{ m})(2.2 \times 10^{-5} \text{ Pa} \cdot \text{s})(0.28 \text{ m/s})}{(.0412 \text{ m})^2}$$

$$\Delta P_{EVAP \text{ VAP}} = 0.001 \text{ Pa} \quad \text{neglect}$$

BASE wick vapor space

All of the mass flow is used $\dot{m}_{VAP} = \dot{m}_{TOTAL} = 6.02 \times 10^{-5} \frac{\text{kg}}{\text{s}}$

$$\text{BASE WICK I.D.} = 0.68 \text{ cm} \quad \text{p. 3}$$

$$\text{PURGE TUBE O.D.} = 0.16 \text{ cm} = 0.062 \text{ IN}$$

$$L_{EFF} = 9.21 \text{ cm} = 0.0921 \text{ m} \quad \text{p. 3}$$

$$A_{BASE \text{ VAP}} = \frac{\pi}{4} [(.68 \text{ cm})^2 - (.16 \text{ cm})^2] \\ = 0.343 \text{ cm}^2 = 3.43 \times 10^{-5} \text{ m}^2$$

$$P_{BASE \text{ VAP}} = \pi (.68 \text{ cm} + .16 \text{ cm}) = 2.64 \text{ cm} = 0.0264 \text{ m}$$

$$D_H = \frac{4A_{BASE \text{ VAP}}}{P_{BASE \text{ VAP}}} = 5.20 \times 10^{-3} \text{ m}$$

$$V_{BASE} = \frac{6.02 \times 10^{-5} \text{ kg/s}}{(.1257 \text{ kg/m}^3)(3.43 \times 10^{-5} \text{ m}^2)} = 14.0 \text{ m/s}$$

IN BASE
WICK VAPOR SPACE

$$Re = \frac{(.1257 \text{ kg/m}^3)(14.0 \text{ m/s})(5.20 \times 10^{-3} \text{ m})}{2.2 \times 10^{-5} \text{ Pa} \cdot \text{s}} = 416 \text{ LAMINAR}$$

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$$\Delta P_{\text{BASE VAP}} = \frac{32(.0921\text{m})(2.2 \times 10^{-5}\text{Pa}\cdot\text{s})(14.0\text{m/s})}{(5.20 \times 10^{-3}\text{m})^2}$$

$$\Delta P_{\text{BASE VAP}} = 34\text{ Pa}$$

$$\begin{aligned} (\Delta P_{\text{VAF}})_{\text{TOT}} &= \Delta P_{\text{YC VAP}} + \Delta P_{\text{SC VAP}} + \Delta P_{\text{EVAP VAP}} + \Delta P_{\text{BASE VAP}} \\ &= 140\text{ Pa} + 0.8\text{ Pa} + 0\text{ Pa} + 34\text{ Pa} = 175\text{ Pa} \end{aligned}$$

There will also be a pressure drop due to the contraction between the evaporator and BASE cell. This is neglected, since the flow is laminar and vapor pressure drops are small.

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RECIRCULATING LOOP - LIQUID PRESSURE DROPS

BASE WICK

$$L_{EFF} = 9.21 \text{ cm} = 0.0921 \text{ m} \quad p. 3$$

Flow Cross-Sectional Area

$$A_{BASE} = \frac{\pi}{4} (D_o^2 - D_i^2) = \frac{\pi}{4} [(0.410 \text{ in})^2 - (0.270 \text{ in})^2] = 0.075 \text{ in}^2 \\ = 4.82 \times 10^{-5} \text{ m}^2$$

Assume -50+100 MESH POWDER

$$K = 3.8 \times 10^{-11} \text{ m}^2$$

$$r_c = 5.5 \times 10^{-5} \text{ m}$$

$$\dot{m} = \frac{K \rho A}{\mu L} \frac{dP}{dx}$$

$$\dot{m} = \dot{m}_{RECIRC} = 5.66 \times 10^{-5} \text{ kg/s}$$

$$\Delta P_{BASE} = \frac{(\dot{m}_{RECIRC}) \mu L_{EFF}}{K \rho A_{BASE}} = \frac{(5.66 \times 10^{-5} \text{ kg/s})(1.62 \times 10^{-4} \text{ Pa.s})(0.0921 \text{ m})}{(3.8 \times 10^{-11} \text{ m}^2)(759.8 \frac{\text{kg}}{\text{m}^3})(4.82 \times 10^{-5} \text{ m}^2)}$$

$$\Delta P_{BASE} = 607 \text{ Pa}$$

$$(\Delta P_{GRAV})_{BASE} = \rho g h = (759.8 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(12.46 \text{ cm})(\frac{1 \text{ m}}{100 \text{ cm}})$$

$$(\Delta P_{GRAV})_{BASE} = 929 \text{ Pa}$$

$$h = L_{TOT} = 12.46 \text{ cm} \quad p. 3$$

$$(\Delta P_{TOT})_{BASE} = (\Delta P_{GRAV})_{BASE} + \Delta P_{BASE} = 929 \text{ Pa} + 607 \text{ Pa} = 1536 \text{ Pa}$$

WICK CAPABILITY

$$P_c = \frac{2\sigma}{r_c} = \frac{2(0.127 \text{ N/m})}{5.5 \times 10^{-5} \text{ m}} = 4618 \text{ Pa}$$

EXCESS CAPABILITY

$$4618 \text{ Pa} - 1536 \text{ Pa} = 3082 \text{ Pa} \quad \text{O.K.}$$

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BASE-to-Evaporator Transition Wick

$$t = 0.96 \text{ cm} = 9.60 \times 10^{-3} \text{ m} \quad \text{p. 4}$$

$$d = 0.44 \text{ cm} = 4.40 \times 10^{-3} \text{ m} \quad \text{p. 4}$$

$$D = 0.68 \text{ cm} = 6.80 \times 10^{-3} \text{ m} \quad \text{p. 4}$$

Spacing between cables
 $0.50 \text{ cm} = 0.20 \text{ in} \quad \text{p. 4}$

$$A_{\text{TRANS}} = 3.95 \times 10^{-4} \text{ m}^2 \quad (\text{p. 4})$$

$$x = 1.27 \text{ cm} = 0.0127 \text{ m} \quad \text{p. 4}$$

ASSUME - 50 + 100 mesh $K = 3.8 \times 10^{-11} \text{ m}^2$
 $r_c = 5.5 \times 10^{-5} \text{ m}$

$$L_{\text{EFF}} = \frac{1.27 \text{ cm}}{2} + 0.44 \text{ cm} = 1.08 \text{ cm} = 0.0108 \text{ m}$$

$$\Delta P_{\text{TRANS}} = \frac{(\dot{m}_{\text{RECIRC}}) \mu_0 L_{\text{EFF}}}{K \rho_l A_{\text{TRANS}}}$$

$$= \frac{(5.66 \times 10^{-5} \text{ kg/s})(1.62 \times 10^{-4} \text{ Pa}\cdot\text{s})(0.0108 \text{ m})}{(3.8 \times 10^{-11} \text{ m}^2)(759.8 \text{ kg/m}^3)(3.95 \times 10^{-4} \text{ m}^2)}$$

$$\Delta P_{\text{TRANS}} = 9 \text{ Pa}$$

$$(\Delta P_{\text{TOT}})_{\text{TRANS}} = (\Delta P_{\text{TOT}})_{\text{BASE}} + \Delta P_{\text{TRANS}} = 1536 \text{ Pa} + 9 \text{ Pa} = 1545 \text{ Pa} \quad \text{p. 11}$$

WICK CAPABILITY: $P_c = 4618 \text{ Pa} \quad \text{p. 11}$

EXCESS CAPABILITY $4618 \text{ Pa} - 1545 \text{ Pa} = 3073 \text{ Pa} \quad \text{O.K.}$

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BASE-to-Evaporator Liquid Return Cable

$$a = 3.17 \text{ cm} = 1.25 \text{ in}$$

$$b = 1.27 \text{ cm} = 0.50 \text{ in}$$

$$c = 1.91 \text{ cm} = 0.75 \text{ in}$$

$$t = 1.27 \text{ cm} \quad \text{p. 6}$$

$$w = 4.11 \text{ cm} \quad \text{p. 6}$$

$$l = 3.78 \text{ cm} \quad \text{p. 6}$$

Cable diameter $0.20 \text{ cm} = 0.08 \text{ in}$
 Number of Cables = 5

$$A_{\text{CABLE}} = \pi/4 D^2 = \pi/4 (.20 \text{ cm})^2 = 3.14 \times 10^{-2} \text{ cm}^2 = 3.14 \times 10^{-6} \text{ m}^2$$

Cable properties: $K = 7.31 \times 10^{-11} \text{ m}^2$ $r_c = 4.83 \times 10^{-5} \text{ m}^2$

$$L_{\text{EFF}} = \frac{1}{2}(1.27 \text{ cm}) + 1.27 \text{ cm} + 1.91 \text{ cm} + 1.27 \text{ cm} + \frac{1}{2}(3.17 \text{ cm})$$

$$= 6.67 \text{ cm} = 0.0667 \text{ m}$$

$$\Delta P_{\text{CABLE}} = \frac{(\text{in RECIRC}) \mu_L L_{\text{EFF}}}{K \rho_L A_{\text{CABLE}} N_{\text{CABLE}}} = \frac{(5.66 \times 10^{-5} \frac{\text{kg}}{\text{s}})(1.62 \times 10^{-4} \text{ Pa} \cdot \text{s})(0.0667 \text{ m})}{(7.31 \times 10^{-11} \text{ m}^2)(759.8 \frac{\text{kg}}{\text{m}^3})(3.14 \times 10^{-6} \text{ m}^2)(5)}$$

$$\Delta P_{\text{CABLE}} = 701 \text{ Pa}$$

$$(\Delta P_{\text{GRAV}})_{\text{CABLE}} = \rho_L g h = (759.8 \frac{\text{kg}}{\text{m}^3})(9.81 \frac{\text{m}}{\text{s}^2})(12.96 \text{ cm} + 1.91 \text{ cm})(\frac{1 \text{ m}}{100 \text{ cm}}) = 1071 \text{ Pa}$$

$$(\Delta P_{\text{TOT}})_{\text{CABLE}} = (\Delta P_{\text{GRAV}})_{\text{CABLE}} + \Delta P_{\text{CABLE}} + \Delta P_{\text{TRANS}} + \Delta P_{\text{BASE}}$$

$$(\Delta P_{\text{TOT}})_{\text{CABLE}} = 1071 \text{ Pa} + 701 \text{ Pa} + 9 \text{ Pa} + 607 \text{ Pa} = 2388 \text{ Pa}$$

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WICK CAPABILITY $P_c = \frac{2\sigma}{r_c} = \frac{2(.127 \text{ N/m})}{4.83 \times 10^{-5} \text{ m}} = 5259 \text{ Pa}$

Excess Capability $5259 \text{ Pa} - 2388 \text{ Pa} = 2871 \text{ Pa} \text{ O.K.}$

Static Wicking Height for cable $\frac{2\sigma}{r_c} = \rho_l g h$

$$h = \frac{2\sigma}{\rho_l g r_c} = \frac{2(.127 \text{ N/m})}{(759.8 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(4.83 \times 10^{-5} \text{ m})}$$

$h = 0.71 \text{ m} = 70.6 \text{ cm} = 27.7 \text{ in} \text{ O.K.}$

Evaporator Wick Pressure Drop

$$L_{EFF} = \left(\frac{1}{2}\right) \sqrt{\left(\frac{.20 \text{ in}}{2}\right)^2 + \left[\left(\frac{.08 \text{ in}}{2} + .26 \text{ in}\right)\right]^2} = \frac{1}{2} \sqrt{.10} = 0.16 \text{ in}$$

$$= 0.40 \text{ cm} = 4.0 \times 10^{-3} \text{ m}$$

$$A = (4.11 \text{ cm})(3.78 \text{ cm}) = 15.54 \text{ cm}^2 = 1.55 \times 10^{-3} \text{ m}^2$$

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HYPOTHETICAL WICK PROPERTIES, EXTRAPOLATED FROM
 MEASURED WICK PROPERTIES TO SMALLER SIZES (see p.16)

$$K = 4 \times 10^{-13} \text{ m}^2 \quad r_c = 5 \times 10^{-6} \text{ m}$$

$$\Delta P_{\text{EVAP}} = \frac{\dot{m}_{\text{RECIRC}} M_L L_{\text{EFF}}}{K \rho_l A} = \frac{(5.66 \times 10^{-5} \text{ kg/s})(1.62 \times 10^{-4} \text{ Pa}\cdot\text{s})(4.0 \times 10^{-3} \text{ m})}{(4 \times 10^{-13} \text{ m}^2)(759.8 \frac{\text{kg}}{\text{m}^3})(1.55 \times 10^{-3} \text{ m}^2)}$$

$$\Delta P_{\text{EVAP}} = 78 \text{ Pa}$$

The total liquid pressure drop in the recirculating loop

$$\begin{aligned} (\Delta P_{\text{LIQ}})_{\text{TOT}} &= \Delta P_{\text{BASE}} + \Delta P_{\text{TRANS}} + \Delta P_{\text{CABLE}} + \Delta P_{\text{EVAP}} \\ &= 607 \text{ Pa} + 9 \text{ Pa} + 701 \text{ Pa} + 78 \text{ Pa} \end{aligned}$$

$$(\Delta P_{\text{LIQ}})_{\text{TOT}} = 1395 \text{ Pa}$$

$$\begin{aligned} \Delta P_{\text{TOTAL}} &= \overset{(\text{p.6})}{\Delta P_{\text{GRAV}}} + (\Delta P_{\text{VAP}})_{\text{TOT}} + (\Delta P_{\text{LIQ}})_{\text{TOT}} \\ &= 1165 \text{ Pa} + 175 \text{ Pa} + 1395 \text{ Pa} \end{aligned}$$

$$\Delta P_{\text{TOTAL}} = 2735 \text{ Pa}$$

$$\text{WICK CAPABILITY} \quad P_c = \frac{2\sigma}{r_c} = \frac{2(0.127 \text{ N/m})}{5 \times 10^{-6} \text{ m}} = 50,800 \text{ Pa}$$

$$\text{EXCESS CAPABILITY} \quad 50,800 \text{ Pa} - 2735 \text{ Pa} = 48,065 \text{ Pa}$$

O.K.

Figure 26. Permeability versus Pore Radius for Spherical Nickel Powders.

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Condenser Loop Pressure Drops

Gravity

$$h = 8.67 \text{ in} = 22.0 \text{ cm} \\ = 0.22 \text{ m}$$

$$\Delta P_{\text{GRAV}} = \rho g h \\ = (856.2 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.22 \text{ m})$$

$$\Delta P_{\text{GRAV}} = 1848 \text{ Pa}$$

FOR CABLE ARTERY

$$L_{\text{EFF}} = \frac{2.065 \text{ in}}{2} + 2.0 \text{ in} + 2.615 \text{ in} + 3.238 \text{ in} \\ + 0.75 \text{ in} + 2.0 \text{ in} + \frac{1.25 \text{ in}}{2} \\ \uparrow \text{ p 13} \\ = 12.26 \text{ in} = 31.14 \text{ cm} = 0.31 \text{ m}$$

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Three different wicks to be considered in the condenser loop:

1. Condenser wick
2. Cable artery
3. Evaporator wick

Condenser Wick

$$D_{COND} = 1.625 \text{ IN}$$

$$t_{WICK} = 0.050 \text{ IN}$$

$$D_{CABLE} = 0.125 \text{ IN}$$

$$N = \text{NUMBER OF CABLE ARTERIES} = 1$$

$$\text{LENGTH BETWEEN ARTERIES} = \frac{\pi D_{COND}}{2N} = \frac{\pi D_{COND}}{2}$$

$$L_{EFF} = \frac{\pi D_{COND}}{4N} = \frac{\pi D_{COND}}{4} = \frac{\pi (1.625 \text{ IN})}{4} = 1.28 \text{ IN} = 0.0324 \text{ m}$$

$$L_{COND} = 2.065 \text{ IN} = 0.0525 \text{ m}$$

$$A_{FLOW} = L_{COND} t_{WICK} = (2.065 \text{ IN})(0.050 \text{ IN}) = 0.103 \text{ IN}^2 = 6.66 \times 10^{-5} \text{ m}^2$$

The condenser wick must have sufficient pumping capability to withstand

1. Liquid flow pressure drop in condenser wick
2. Gravitational wicking for the entire condenser.

$$\Delta P_{GRAV} = 1848 \text{ Pa}$$

$$\text{ASSUME A } -50 \text{ } +100 \text{ WICK} \quad K = 3.8 \times 10^{-11} \text{ m}^2 \quad r_c = 5.5 \times 10^{-5} \text{ m}$$

$$\text{WICK CAPABILITY} \quad P_c = \frac{2\sigma}{r_c} = \frac{2(1.67 \text{ N/m})}{5.5 \times 10^{-5} \text{ m}} = 6073 \text{ Pa}$$

$$\dot{m}_{CONDENSER} = \dot{m}_{BASE} = 3.61 \times 10^{-6} \text{ kg/s}$$

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$$\Delta P_{\text{COND WICK}} = \frac{(3.61 \times 10^{-6} \text{ kg/s})(2.85 \times 10^{-4} \text{ Pa}\cdot\text{s})(0.0324 \text{ m})}{(3.8 \times 10^{-11} \text{ m}^2)(856.2 \text{ kg/m}^3)(6.66 \times 10^{-5} \text{ m}^2)}$$

$$= 15 \text{ Pa}$$

$$(\Delta P_{\text{COND WICK}})_{\text{TOT}} = \Delta P_{\text{GRAV}} + \Delta P_{\text{COND WICK}} = 1848 \text{ Pa} + 15 \text{ Pa} = 1863 \text{ Pa}$$

$$\text{EXCESS CAPABILITY} = 6073 \text{ Pa} - 1863 \text{ Pa} = 4210 \text{ Pa} \quad \text{o.k.}$$

CABLE ARTERY

The cable artery must sustain the following pressure drops

1. Liquid flow in the condenser wick.
2. Liquid flow in the cable artery
3. Gravitational wicking for the entire condenser

Cable $K = 7.31 \times 10^{-11} \text{ m}^2$ $r_c = 4.83 \times 10^{-5} \text{ m}$ Diameter = 0.080 in
 = 0.203 cm

Pumping capability

$$P_c = \frac{2(1.127 \text{ N/m})}{4.83 \times 10^{-5} \text{ m}} = 5259 \text{ Pa} @ 800^\circ\text{C}$$

$$L_{\text{EFF}} = 0.31 \text{ m} \quad \text{p. 17}$$

$$A = \frac{\pi}{4} (0.20 \text{ cm})^2 = 0.0314 \text{ cm}^2 = 3.14 \times 10^{-6} \text{ m}^2$$

$$\Delta P_{\text{CABLE}} = \frac{(3.61 \times 10^{-6} \text{ kg/s})(2.85 \times 10^{-4} \text{ Pa}\cdot\text{s})(0.31 \text{ m})}{(7.31 \times 10^{-11} \text{ m}^2)(856.2 \text{ kg/m}^3)(3.14 \times 10^{-6} \text{ m}^2)} = 1623 \text{ Pa}$$

CABLE PRESSURE DROP

$$(\Delta P_{\text{CABLE}})_{\text{TOT}} = \Delta P_{\text{GRAV}} + \Delta P_{\text{COND WICK}} + \Delta P_{\text{CABLE}} = 1848 \text{ Pa} + 15 \text{ Pa} + 1623 \text{ Pa} = 3486 \text{ Pa}$$

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$$\text{EXCESS CAPABILITY} = 5259 \text{ Pa} - 3486 \text{ Pa} = 1773 \text{ Pa} \quad \text{o.k.}$$

EVAPORATOR WICK-CONDENSER FLOW

The evaporator wick must sustain the following pressure drops

1. Gravity in the evaporator and condenser = 1907 Pa
2. Vapor Pressure in condenser and recirculating loops.
3. Liquid flow in the condenser wick = 14 Pa
4. Liquid flow in the cable artery = 1776 Pa
5. Liquid flow in the evaporator wick.

Difference in vapor pressures

$$\Delta P_{\text{VAPOR}} = P_{800^\circ\text{C}} - P_{400^\circ\text{C}} = 45,318 \text{ Pa} - 47 \text{ Pa} \\ = 45,271 \text{ Pa}$$

Evaporator wick pressure drop $m = m_{\text{TOTAL}} = 6.02 \times 10^{-5} \frac{\text{kg}}{\text{s}}$

$$\Delta P_{\text{EVAP WICK}} = \frac{(6.02 \times 10^{-5} \frac{\text{kg}}{\text{s}})(1.62 \times 10^{-4} \text{ Pa} \cdot \text{s})(4.0 \times 10^{-3} \text{ m})}{(4 \times 10^{-13} \text{ m}^2)(759.8 \frac{\text{kg}}{\text{m}^3})(1.55 \times 10^{-3} \text{ m}^2)} \\ = 83 \text{ Pa}$$

$$\Delta P_{\text{TOTAL}} = \Delta P_{\text{GRAV}} + \Delta P_{\text{VAPOR}} + \Delta P_{\text{COND WICK}} + \Delta P_{\text{CABLE}} + \Delta P_{\text{EVAP WICK}} \\ = 1848 \text{ Pa} + 45,271 \text{ Pa} + 15 \text{ Pa} + 1623 \text{ Pa} + 83 \text{ Pa} \\ = 48,840 \text{ Pa}$$

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Project: 11-1140 AMTECPage 21 of 21WICK CAPABILITY $P_c = 50,800 \text{ Pa}$ p. 14EXCESS CAPABILITY = $50,800 \text{ Pa} - 48,840 \text{ Pa} = 1960 \text{ Pa}$ CONCLUSION:RECIRCULATING LOOP TOTAL PRESSURE DROP: 2735 Pa CONDENSER LOOP TOTAL PRESSURE DROP: $48,840 \text{ Pa}$ EVAPORATOR WICK CAPABILITY: $50,800 \text{ Pa}$

HYPOTHETICAL EVAPORATOR WICK PROPERTIES:

$$K = 4 \times 10^{-13} \text{ m}^2$$

$$r_c = 5 \times 10^{-6} \text{ m}$$

Project: 11-1140
Wick-Pumped, Vapor-Fed AMTEC Cell Design
800 C Design, Inverted Wick

AMTEC800.XLS

5/20/1993

Design Calculations for a Wick Pumped AMTEC cell design

Assume:

Remote Condenser
Cable Artery Liquid Return from Condenser and BASE Wicks
Inverted Evaporator Wick

11-1140

5/6/93

JEL

Wick Pumped AMTEC Cell Design Calculations

Objective: Develop a wick design for a vapor-fed AMTEC cell that will operate near 800 C

The Amtec cell has two main regions: (1) a high pressure, high temperature region with the evaporator connected to the BASE tube, and (2) a low temperature, low pressure condenser region. Heat supplied to the evaporator vaporizes sodium, which travels to the BASE region and condenses. There are two sodium circulation patterns that must be accounted for when designing the AMTEC wick. First, roughly 80-95 percent of the sodium supplies heat to the BASE tube, then is wicked back to the evaporator in the high pressure region.

The remaining sodium (5-20%, based on the assumed 5-20% efficiency), passes through the BASE, generating electricity. This sodium then vaporizes and travels to the condenser, which has a temperature of typically 400 C, and a vapor pressure near zero (50 Pa or less). This sodium must be wicked back to the evaporator, which has a vapor pressure above 12,000 Pa. This is accomplished with a relatively coarse cable artery in the condenser, which is embedded in the fine sintered powder of the evaporator wick.

The current conceptual design uses four different wicks:

1. A relatively coarse wick in the condenser, to collect the sodium.
2. Cable arteries to return sodium from the condenser to the evaporator and from the BASE to the evaporator.
3. A fine wick in the evaporator, that can supply the pumping capability to return the liquid
4. A relatively coarse wick in the BASE.

The current conceptual design has a free-standing wick in the BASE, with a gap between the wick and the BASE. This is done for several reasons: First, this removes problems with differential thermal expansion between the wick and the BASE tube, which is relatively brittle. Second, separating the wick from the BASE should help to minimize the thermal stress on the BASE during start-up, when the thermal front moves down the wick.

CONSTANTS

Stefan-Boltzman const., W/cm^2K^4	5.67E-12
Sodium Gas Constant, R, J/kg K	361.64
Na Ratio of Specific Heats, gamma	1.67
Gravitational Acceleration, m/s^2	9.81

DESIGN ASSUMPTIONS

Evaporator Temperature, C	800.00
Condenser Temperature, C	400.00
Ambient Temperature, C	20.00
Working Fluid	Sodium

ASSUMED BASE CHARACTERISTICS

BASE Power out/area, W/cm^2	0.20
BASE current flux, A/cm^2	0.50
Sodium flow rate, g/hr/Amp	1.00
Assumed cell efficiency:	0.06

BASE DIMENSIONS

BASE Outside Diameter, cm	1.50
BASE Outside Diameter, in	0.59
BASE Total Length, cm	6.50
BASE Total Length, in	2.56
BASE Inactive Length, each end, cm	0.50
BASE Active length, cm	5.50
BASE Active length, in	2.17
Moly Sleeve Length, cm	2.50
Moly Sleeve Length, in	0.98
BASE + Sleeve Length, cm	9.00
BASE + Sleeve Length, in	3.54
BASE area, cm^2	25.92

Sodium Flow Rates

Estimated Electrical Output, W	5.18
Estimated Design Power into AMTEC cell, W	86.39
Current, A	12.96
Sodium flow rate through BASE, g/hr	12.96

Sodium flow rate through BASE, kg/s	3.60E-06
Total sodium flow rate, g/hr	215.98
Total sodium flow rate, kg/s	6.00E-05
Recirculating sodium flow rate, g/hr	203.03
Recirculating sodium flow rate, kg/s	5.64E-05

Condenser Sodium Properties

Range: 450-1100 C

Gas Constant, J/kg-mole K	8314.40					
Sodium Molecular Weight, kg/kg-mole	22.99					
Sodium Gas Constant, R, J/kg K	361.66					
Na Ratio of Specific Heats, gamma	1.67					
Condenser Temperature, C	400.00	450.00	500.00	550.00	600.00	650.00
Condenser Temperature, K	673.00	723.00	773.00	823.00	873.00	923.00
Condenser Na Latent Heat, J/kg	4.374E+06	4.322E+06	4.270E+06	4.218E+06	4.166E+06	4.115E+06
Condenser Na Liquid Density, kg/m^3	856.22	844.27	832.27	820.25	808.21	796.14
Condenser Na Vapor Density, kg/m^3	2.203E-04	6.339E-04	1.692E-03	4.188E-03	9.615E-03	2.047E-02
Condenser Na Liquid Thermal Conductivity, W/m C	72.20	69.75	67.30	64.85	62.40	59.95
Condenser Na Liquid Viscosity, cP	0.285	0.263	0.246	0.225	0.208	0.193
Condenser Na Liquid Viscosity, kg/m s	2.846E-04	2.634E-04	2.460E-04	2.246E-04	2.076E-04	1.934E-04
Condenser Na Vapor Viscosity, cP	0.02	0.02	0.02	0.02	0.02	0.02
Condenser Na Vapor Viscosity, kg/m s	1.638E-05	1.708E-05	1.777E-05	1.845E-05	1.911E-05	1.977E-05
Condenser Na Vapor Pressure, Pa	47.20	169.98	517.51	1373.56	3254.28	7011.38
Condenser Na Surface Tension, N/m	0.167	0.162	0.157	0.152	0.147	0.142
Condenser Na Liq. Specific Heat, cal/g C	0.305	0.303	0.302	0.300	0.300	0.300
Condenser Na Liq. Specific Heat, W-s/kg C	1277.98	1268.61	1261.55	1256.80	1254.35	1254.22

Evaporator Sodium Properties

Range: 450-1100 C

Gas Constant, J/kg-mole K	8314.40					
Sodium Molecular Weight, kg/kg-mole	22.99					
Sodium Gas Constant, R, J/kg K	361.66					
Na Ratio of Specific Heats, gamma	1.67					
Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Evaporator Na Latent Heat, J/kg	4.115E+06	4.063E+06	4.012E+06	3.961E+06	3.910E+06	3.859E+06

Evaporator Na Liquid Density, kg/m ³	796.14	784.05	771.95	759.83	747.72	735.60
Evaporator Na Vapor Density, kg/m ³	0.020	0.040	0.074	0.126	0.198	0.289
Evaporator Na Liquid Thermal Conductivity, W/m C	59.95	57.50	55.05	52.60	50.15	47.70
Evaporator Na Liquid Viscosity, cP	0.193	0.181	0.171	0.162	0.154	0.147
Evaporator Na Liquid Viscosity, kg/m s	1.934E-04	1.814E-04	1.711E-04	1.622E-04	1.544E-04	1.475E-04
Evaporator Na Vapor Viscosity, cP	0.0198	0.0204	0.0210	0.0217	0.0223	0.0228
Evaporator Na Vapor Viscosity, kg/m s	1.977E-05	2.041E-05	2.104E-05	2.165E-05	2.226E-05	2.285E-05
Evaporator Na Vapor Pressure, Pa	7011.38	13940.79	25885.00	45317.58	75400.90	120011.87
Evaporator Na Surface Tension, N/m	0.142	0.137	0.132	0.127	0.122	0.117
Evaporator Na Lq. Specific Heat, cal/g C	0.300	0.300	0.301	0.303	0.305	0.308
Evaporator Na Lq. Specific Heat, W-s/kg C	1254.22	1256.40	1260.89	1267.69	1276.80	1288.22

System Dimensions**BASE**

BASE O.D., cm	1.50
BASE Total Length, cm	6.50
BASE Inactive Length, each end, cm	0.50
BASE Active Length, cm	5.50
Moly Sleeve Length, cm	2.50
BASE + Sleeve Length, cm	9.00
Effective BASE/Sleeve Length, cm	5.75
Effective BASE/Sleeve Length, in	2.26

BASE Wick (Free-Standing Wick)

BASE Wick O.D., cm (must be less than BASE I.D.)	1.04
BASE Wick O.D., in	0.41
BASE Wick Thickness, cm	0.18
BASE Wick Thickness, in	0.07
BASE Wick I.D., cm	0.68
BASE Wick I.D., in	0.27
Vapor Space Purge Tube O.D., cm	0.16
Vapor Space Purge Tube O.D., in	0.06
BASE + Sleeve Length, cm	9.00
Effective BASE/Sleeve Length, cm	5.75
Length of Sleeve Support + Evap. Wall Thick., cm	2.50
Length of Sleeve Support + Evap. Wall Thick., in	0.98
BASE-to-Evaporator Transition Wick Thickness, cm	0.96

BASE-to-Evaporator Transition Wick Thickness, in	0.38
Total BASE Wick Length, cm	12.46
Total BASE Wick Length, in	4.91
Effective BASE Wick Length, cm	9.21
Effective BASE Wick Length, in	3.63
Cross-Sectional Area for Liquid Flow, m ²	4.863E-05
Cross-Sectional Area for Vapor Flow, m ²	3.431E-05
Perimeter for Vapor Flow, m	2.639E-02
Hydraulic Diameter for Vapor Flow, m ²	5.200E-03

BASE-to-Evaporator Transition Wick

Transition Wick Thickness, cm	0.96
Transition Wick Thickness, in	0.38
Transition Wick Width, cm	4.11
Transition Wick Width, in	1.62
Transition Wick Length, cm	4.11
Transition Wick Length, in	1.62
BASE Wick I.D., cm	0.68
Embedded Cable Length, cm	1.27
Embedded Cable Length, in	0.50
Distance from BASE Wick to Cable Artery, cm	0.44
Distance from BASE Wick to Cable Artery, in	0.17
Effective Length for Transition Wick, cm	1.08
Effective Length for Transition Wick, in	0.42
Number of Cable Arteries	5
Cable Artery Diameter, cm	0.20
Cable Artery Diameter, in	0.08
Spacing Between Cables, cm	0.50
Spacing Between Cables, in	0.20
Trans. Wick Cross-Sectional Area for Liquid Flow, m ²	3.95E-04

BASE-to-Evaporator Cable Arteries

Cable Artery Diameter, cm	0.20
Cable Artery Diameter, in	0.08
Number of Cable Arteries	5
Embedded Cable Length, cm	1.27
Cable Artery Horizontal Extension, cm	1.27

Cable Artery Horizontal Extension, in	0.50
Cable Artery Vertical Extension, cm	1.91
Cable Artery Vertical Extension, in	0.75
Total Cable Artery Length, outside evaporator, cm	5.72
Total Cable Artery Length, outside evaporator, in	2.25
Cable Artery Effective Length, outside evap., cm	5.09
Cable Artery Effective Length, outside evap., in	2.00

Evaporator - Square

Inner Evaporator Width, cm	4.11
Inner Evaporator Width, in	1.62
Inner Evaporator Length, cm	4.11
Inner Evaporator Length, in	1.62
Inner Evaporator Height, cm	3.17
Inner Evaporator Height, in	1.25

Evaporator Wick - Rectangular

Evaporator Wick Width, cm	4.11
Evaporator Wick Width, in	1.62
Evaporator Wick Length, cm	3.78
Evaporator Wick Length, in	1.49
Evaporator Wick Thickness, cm	1.27
Evaporator Wick Thickness, in	0.50
Cross-Sectional Area for Liquid Flow, m ²	1.55E-03
Evaporator Vapor Channel Width, cm	0.15
Evaporator Vapor Channel Width, in	0.06
Evaporator Vapor Channel Height, cm	0.15
Evaporator Vapor Channel Height, in	0.06
Evaporator Vapor Channel Length, cm	3.78
Evaporator Vapor Channel Length, in	1.49
Cross-Sectional Area for Vapor Channel Vapor Flow, m ²	2.25E-06
Perimeter for Vapor Channel Vapor Flow, m	6.00E-03
Hydraulic Diameter for Vapor Channel Vapor Flow, m	1.50E-03
Number of Vapor Channels	9
Evaporator Side Channel Width, cm	4.11
Evaporator Side Channel Width, in	1.62
Evaporator Side Channel Length, cm	0.33

Evaporator Side Channel Length, in	0.13
Evaporator Side Channel Height, cm	1.27
Evaporator Side Channel Height, in	0.50
Cross-Sectional Area for Side Channel Vapor Flow, m ²	1.36E-04
Perimeter for Side Channel Vapor Flow, m	8.88E-02
Hydraulic Diameter for Side Channel Vapor Flow, m	6.11E-03
Number of Side Channels	1
Evaporator Vapor Space Width, cm	4.11
Evaporator Vapor Space Width, in	1.62
Evaporator Vapor Space Length, cm	4.11
Evaporator Vapor Space Length, in	1.62
Evaporator Vapor Space Height, cm	0.94
Evaporator Vapor Space Height, in	0.37
Cross-Sectional Area for Evap. Vapor Space Flow, m ²	1.69E-03
Perimeter for Evaporator Vapor Space Flow, m	1.64E-01
Hydraulic Diameter for Evaporator Vapor Space Flow, m	4.11E-02
Heat Input Area, cm ²	16.89
Heat Flux, W/cm ² (Est. Design Power In/Heat Input Area)	5.11
GPHS Temperature, K	1373.00
Evaporator Temperature, K	1073.00
Assumed Emissivity	0.80
Incident Heat Flux, W/cm ²	10.11
Evaporator Cable Arteries (from BASE)	
Cable Artery Diameter, cm	0.20
Number of Cable Arteries	5
Cable Artery Length in Evaporator, cm	3.17
Cable Artery Length in Evaporator, in	1.25
Cable Artery Effective Length, inside evap., cm	1.59
Cable Artery Effective Length, inside evap., in	0.62
Total Cable Artery Length, outside evaporator, cm	5.72
Cable Artery Effective Length, outside evap., cm	5.09
Total Cable Artery Length, cm	8.89
Total Cable Artery Length, in	3.50
Total Cable Artery effective Length, cm	6.67
Total Cable Artery effective Length, in	2.63

Cable Artery Cross-sectional Area for Liquid Flow, m ²	3.14E-06
Distance from Evaporator Edge to Cable, cm	0.66
Distance from Evaporator Edge to Cable, in	0.26

Condenser Wick

Condenser I.D., cm	4.13
Condenser I.D., in	1.63
Condenser Length, cm	5.25
Condenser Length, in	2.07
Condenser Wick Thickness, cm	0.13
Condenser Wick Thickness, in	0.05
Condenser Wick I.D., cm	3.87
Condenser Wick I.D., in	1.52
Number of Cable Arteries	1
Condenser Cable Artery Diameter, cm	0.20
Condenser Cable Artery Diameter, in	0.08
Condenser Wick Effective Length, cm	3.24
Condenser Wick Effective Length, in	1.28
Cross-Sectional Area for Liquid Flow, m ²	6.83E-05

Condenser Cable Artery

Condenser Cable Artery Diameter, cm	0.20
Condenser Cable Artery Diameter, in	0.08
Number of Condenser Cable Arteries	1
Condenser Length, cm	5.25
Cable Artery Effective Length, inside condenser, cm	2.63
Cable Artery Effective Length, inside condenser, in	1.03
Cable Artery Horizontal Extension, cm	5.08
Cable Artery Horizontal Extension, in	2.00
Number of Horizontal Extensions	2
Length of Hot Zone 1, cm	6.64
Length of Hot Zone 1, in	2.61
Length of Hot Zone 2, cm	8.22
Length of Hot Zone 2, in	3.24
Cable Artery Vertical Extension at Evaporator, cm	1.91
Cable Artery Vertical Extension at Evaporator, in	0.75
Total Cable Artery Vertical Length, cm	22.02

Total Cable Artery Vertical Length, in	8.67
Total Cable Artery Length, outside evaporator, cm	32.18
Total Cable Artery Length, outside evaporator, in	12.67
Cable Artery Effective Length, outside evaporator, cm	29.56
Cable Artery Effective Length, outside evaporator, in	11.64

Evaporator Cable Artery (from condenser)

Condenser Cable Artery Diameter, cm	0.20
Number of Condenser Cable Arteries	1
Cable Artery Length Extension, cm	3.17
Cable Artery Length Extension, in	1.25
Number of Cable Arteries	1
Total Cable Artery Length, inside evaporator, cm	3.17
Total Cable Artery Length, inside evaporator, in	1.25
Cable Artery Effective Length, inside evaporator, cm	1.59
Cable Artery Effective Length, inside evaporator, in	0.62
Total Cable Artery Length, outside evaporator, cm	32.18
Cable Artery Effective Length, outside evaporator, cm	29.56
Total Cable Artery Length, cm	35.35
Total Cable Artery Length, in	13.92
Total Cable Artery Effective Length, cm	31.14
Total Cable Artery Effective Length, in	12.26
Cable Artery Cross-Sectional Area for Liquid Flow, m ²	3.14E-06

RECIRCULATING LOOP PRESSURE DROPS**Gravitational Pressure Drop**

Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Total BASE Wick Length, cm	12.46	12.46	12.46	12.46	12.46	12.46
Total BASE Wick Length, m	0.12	0.12	0.12	0.12	0.12	0.12
Evaporator Height, cm	3.17	3.17	3.17	3.17	3.17	3.17
Evaporator Height, m	3.17E-02	3.17E-02	3.17E-02	3.17E-02	3.17E-02	3.17E-02
BASE + Evaporator Height, m	0.16	0.16	0.16	0.16	0.16	0.16
Gravitational Acceleration, m/s ²	9.81	9.81	9.81	9.81	9.81	9.81
Na Liquid Density, kg/m ³	796.14	784.05	771.95	759.83	747.72	735.60
Recirculating Loop Gravitational Pressure Drop, Pa	1220.72	1202.18	1183.63	1165.06	1146.48	1127.90

Vapor Pressure Drop**Vapor Channels**

Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Number of Vapor Channels	9	9	9	9	9	9
Vapor Channel Length, cm	3.78	3.78	3.78	3.78	3.78	3.78
Effective Vapor Channel Length, cm	1.89	1.89	1.89	1.89	1.89	1.89
Effective Vapor Channel Length, m	1.89E-02	1.89E-02	1.89E-02	1.89E-02	1.89E-02	1.89E-02
Cross-Sectional Area for Vapor Channel Vapor Flow, m ²	2.25E-06	2.25E-06	2.25E-06	2.25E-06	2.25E-06	2.25E-06
Vapor Mass Flow Rate (=Total Mass Flow Rate), kg/s	6.00E-05	6.00E-05	6.00E-05	6.00E-05	6.00E-05	6.00E-05
Evaporator Na Vapor Density, kg/m ³	0.020	0.040	0.074	0.126	0.198	0.289
Vapor Channel Vapor Velocity, m/s	144.72	73.29	40.02	23.56	14.96	10.24
Hydraulic Diameter for Vapor Channel Vapor Flow, m	1.50E-03	1.50E-03	1.50E-03	1.50E-03	1.50E-03	1.50E-03
Evaporator Na Vapor Viscosity, kg/m s	1.98E-05	2.04E-05	2.10E-05	2.17E-05	2.23E-05	2.28E-05
Vapor Channel Reynold's Number	224.83	217.77	211.27	205.26	199.69	194.52
Vapor Channel Vapor Pressure Drop, Pa	768.92	402.03	226.30	137.15	89.50	62.90

Side Channels

Number of Side Channels	1	1	1	1	1	1
Side Channel Height, cm	1.27	1.27	1.27	1.27	1.27	1.27
Effective Side Channel Length, m	1.27E-02	1.27E-02	1.27E-02	1.27E-02	1.27E-02	1.27E-02
Cross-Sectional Area for Side Channel Vapor Flow, m ²	1.36E-04	1.36E-04	1.36E-04	1.36E-04	1.36E-04	1.36E-04
Side Channel Vapor Velocity, m/s	21.61	10.94	5.98	3.52	2.23	1.53
Hydraulic Diameter for Side Channel Vapor Flow, m	6.11E-03	6.11E-03	6.11E-03	6.11E-03	6.11E-03	6.11E-03
Side Channel Reynold's Number	136.72	132.43	128.47	124.82	121.43	118.29
Side Channel Vapor Pressure Drop, Pa	4.65	2.43	1.37	0.83	0.54	0.38

Evaporator Vapor Space

Evaporator Vapor Space Height, cm	0.94	0.94	0.94	0.94	0.94	0.94
Effective Evaporator Vapor Space Length, m	9.40E-03	9.40E-03	9.40E-03	9.40E-03	9.40E-03	9.40E-03
Cross-Sectional Area for Evap. Vapor Space Flow, m ²	1.69E-03	1.69E-03	1.69E-03	1.69E-03	1.69E-03	1.69E-03
Evaporator Vapor Space Vapor Velocity, m/s	1.73	0.88	0.48	0.28	0.18	0.12
Hydraulic Diameter for Evaporator Vapor Space Flow, m	4.11E-02	4.11E-02	4.11E-02	4.11E-02	4.11E-02	4.11E-02

Evaporator Vapor Space Reynold's Number	73.85	71.53	69.39	67.42	65.59	63.89
Evaporator Vapor Space Vapor Pressure Drop, Pa	6.11E-03	3.19E-03	1.80E-03	1.09E-03	7.11E-04	4.99E-04
BASE Wick Vapor Space						
Effective BASE Wick Length, cm	9.21	9.21	9.21	9.21	9.21	9.21
Effective BASE Wick Length, m	9.21E-02	9.21E-02	9.21E-02	9.21E-02	9.21E-02	9.21E-02
Cross-Sectional Area for Vapor Flow, m ²	3.43E-05	3.43E-05	3.43E-05	3.43E-05	3.43E-05	3.43E-05
BASE Wick Vapor Space Vapor Velocity, m/s	85.42	43.26	23.62	13.91	8.83	6.05
Hydraulic Diameter for Vapor Flow, m ²	5.20E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03	5.20E-03
BASE Wick Vapor Space Reynold's Number	460.07	445.62	432.31	420.01	408.62	398.04
BASE Wick Vapor Space Vapor Pressure Drop, Pa	184.04	96.22	54.16	32.83	21.42	15.05
Total Recirculating Loop Vapor Pressure Drop, Pa	957.62	500.69	281.83	170.80	111.46	78.33

There will also be a vapor pressure drop due to the contraction between the evaporator and the BASE cell. This is neglected, since the flow is laminar and the vapor pressure drops are small.

Wick Properties

Candidate Evaporator Wicks: Sintered Niobium

Sieve Size	Hypothetical1	Hypothetical2
Permeability, m ²	4.00E-13	1.00E-13
Pore Size, m	5.00E-06	2.00E-06
Na Surface Tension at 800C, N/m	0.127	0.127
Wick pumping capability at 800C, Pa	50680.00	126700.00

Candidate BASE, Transition, and Condenser Wicks: Sintered Nickel

Sieve Size	-50+100	-100+150	-200+325	E-1 Nickel
Permeability, m ²	3.800E-11	1.500E-11	5.000E-12	2.000E-11
Pore Size, m	5.500E-05	3.900E-05	2.000E-05	2.500E-05
Wick pumping capability at 800C, Pa	4607.27	6497.44	12670.00	10136.00

Candidate Cable Properties

Cable type	Phase1 Cable 0.080" braid
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Cable Artery Diameter, cm	0.64	0.20
Cable Artery Diameter, in	0.25	0.08
Permeability, m ²	6.86E-10	7.31E-11
Pore Size, m	1.20E-04	4.83E-05
Cable pumping capability at 800C, Pa	2111.67	5246.38

Liquid Pressure Drop**BASE Wick - Sieve Size: -50+100**

Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Total BASE Wick Length, cm	12.46	12.46	12.46	12.46	12.46	12.46
Total BASE Wick Length, m	0.12	0.12	0.12	0.12	0.12	0.12
Effective BASE Wick Length, cm	9.21	9.21	9.21	9.21	9.21	9.21
Effective BASE Wick Length, m	9.21E-02	9.21E-02	9.21E-02	9.21E-02	9.21E-02	9.21E-02
Cross-Sectional Area for BASE Wick Liquid Flow, m ²	4.86E-05	4.86E-05	4.86E-05	4.86E-05	4.86E-05	4.86E-05
Liquid Mass Flow Rate (=Recirc. Mass Flow Rate), kg/s	5.64E-05	5.64E-05	5.64E-05	5.64E-05	5.64E-05	5.64E-05
Evaporator Na Liquid Density, kg/m ³	796.14	784.05	771.95	759.83	747.72	735.60
Evaporator Na Liquid Viscosity, kg/m s	1.93E-04	1.81E-04	1.71E-04	1.62E-04	1.54E-04	1.47E-04
Evaporator Na Surface Tension, N/m	0.142	0.137	0.132	0.127	0.122	0.117
BASE Wick Permeability, m ²	3.80E-11	3.80E-11	3.80E-11	3.80E-11	3.80E-11	3.80E-11
BASE Wick Pore Size, m	5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05
BASE Wick Pumping Capability, Pa	5152.73	4970.91	4789.09	4607.27	4425.45	4243.64
BASE Wick Liquid Pressure Drop, Pa	682.85	650.32	623.01	599.92	580.28	563.49
BASE Wick Gravitational Pressure Drop, Pa	973.14	958.36	943.57	928.77	913.96	899.14
Total BASE Wick Pressure Drop, Pa	1655.99	1608.68	1566.58	1528.69	1494.23	1462.63
Excess BASE Wick Pumping Capability, Pa	3496.74	3362.23	3222.51	3078.58	2931.22	2781.01

BASE-to-Evaporator Transition Wick - Sieve Size: -50+100 and 0.080" Dia. Cable Arteries

Effective Length for Transition Wick, cm	1.08	1.08	1.08	1.08	1.08	1.08
Effective Length for Transition Wick, m	1.08E-02	1.08E-02	1.08E-02	1.08E-02	1.08E-02	1.08E-02
Trans. Wick Cross-Sectional Area for Liquid Flow, m ²	3.95E-04	3.95E-04	3.95E-04	3.95E-04	3.95E-04	3.95E-04
Transition Wick Permeability, m ²	3.800E-11	3.800E-11	3.800E-11	3.800E-11	3.800E-11	3.800E-11
Transition Wick Pore Size, m	5.500E-05	5.500E-05	5.500E-05	5.500E-05	5.500E-05	5.500E-05
Transition Wick Pumping Capability, Pa	5152.73	4970.91	4789.09	4607.27	4425.45	4243.64

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Total BASE Wick Pressure Drop, Pa	1655.99	1608.68	1566.58	1528.69	1494.23	1462.63
Transition Wick Liquid Pressure Drop, Pa	9.82	9.36	8.96	8.63	8.35	8.11
Total Transition Wick Pressure Drop, Pa	1665.81	1618.04	1575.55	1537.32	1502.58	1470.74
Excess Transition Wick Pumping Capability, Pa	3486.91	3352.87	3213.54	3069.95	2922.87	2772.90

BASE-to-Evaporator Liquid Return Cable Artery - 0.080" Dia. Cable Arteries

Number of Cable Arteries	5	5	5	5	5	5
Total BASE Wick Length, m	0.12	0.12	0.12	0.12	0.12	0.12
Cable Artery Vertical Length, cm	1.91	1.91	1.91	1.91	1.91	1.91
Cable Artery Vertical Length, m	1.91E-02	1.91E-02	1.91E-02	1.91E-02	1.91E-02	1.91E-02
Total BASE Wick + Cable Artery Vertical Length, m	0.14	0.14	0.14	0.14	0.14	0.14
Total Cable Artery effective Length, cm	6.67	6.67	6.67	6.67	6.67	6.67
Total Cable Artery effective Length, m	6.67E-02	6.67E-02	6.67E-02	6.67E-02	6.67E-02	6.67E-02
Cable Artery Cross-sectional Area for Liquid Flow, m ²	3.14E-06	3.14E-06	3.14E-06	3.14E-06	3.14E-06	3.14E-06
Cable Artery Permeability, m ²	7.31E-11	7.31E-11	7.31E-11	7.31E-11	7.31E-11	7.31E-11
Cable Cable Pore Size, m	4.83E-05	4.83E-05	4.83E-05	4.83E-05	4.83E-05	4.83E-05
Cable Artery Pumping Capability, Pa	5867.49	5660.46	5453.42	5246.38	5039.34	4832.30
BASE Wick Liquid Pressure Drop, Pa	682.85	650.32	623.01	599.92	580.28	563.49
Transition Wick Liquid Pressure Drop, Pa	9.82	9.36	8.96	8.63	8.35	8.11
Cable Artery Liquid Pressure Drop, Pa	795.90	757.98	726.16	699.25	676.35	656.77
Cable Artery Gravitational Pressure Drop, Pa	1122.31	1105.27	1088.21	1071.14	1054.06	1036.97
Total Cable Artery Pressure Drop, Pa	2610.89	2522.93	2446.35	2378.94	2319.03	2265.34
Excess Cable Artery Pumping Capability, Pa	3256.60	3137.53	3007.07	2867.44	2720.31	2566.96
Cable Artery Static Wicking Height, m	0.75	0.74	0.72	0.70	0.69	0.67
Cable Artery Static Wicking Height, cm	75.13	73.59	72.01	70.38	68.70	66.96

Evaporator Wick - Sieve Size: Hypothetical 1

Distance from Evaporator Edge to Transition Cable, cm	0.66	0.66	0.66	0.66	0.66	0.66
Cable Artery Diameter, cm	0.20	0.20	0.20	0.20	0.20	0.20
Distance from Evaporator Edge to Cable Center, cm	0.76	0.76	0.76	0.76	0.76	0.76
Distance from Evaporator Edge to Cable Center, m	7.60E-03	7.60E-03	7.60E-03	7.60E-03	7.60E-03	7.60E-03
Spacing Between Cables, cm	0.50	0.50	0.50	0.50	0.50	0.50
Spacing Between Cables, m	5.00E-03	5.00E-03	5.00E-03	5.00E-03	5.00E-03	5.00E-03

Effective Length for Evaporator Wick, m	4.00E-03	4.00E-03	4.00E-03	4.00E-03	4.00E-03	4.00E-03
Cross-Sectional Area for Liquid Flow, m ²	1.55E-03	1.55E-03	1.55E-03	1.55E-03	1.55E-03	1.55E-03
Evaporator Wick Permeability, m ²	4.00E-13	4.00E-13	4.00E-13	4.00E-13	4.00E-13	4.00E-13
Evaporator Wick Pore Size, m	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Evaporator Wick Pumping Capability, Pa	56680.00	54680.00	52680.00	50680.00	48680.00	46680.00
BASE Wick Liquid Pressure Drop, Pa	682.85	650.32	623.01	599.92	580.28	563.49
Transition Wick Liquid Pressure Drop, Pa	9.82	9.36	8.96	8.63	8.35	8.11
Cable Artery Liquid Pressure Drop, Pa	795.90	757.98	726.16	699.25	676.35	656.77
Evaporator Wick Liquid Pressure Drop, Pa	88.20	84.00	80.47	77.49	74.95	72.78
Total Recirculating Loop Liquid Pressure Drops, Pa	1576.78	1501.65	1438.61	1385.29	1339.93	1301.15
Total Recirculating Loop Pressure Drops, Pa	3755.11	3204.53	2904.06	2721.15	2597.87	2507.38
Excess Recirculating Loop Pumping Capability, Pa	52924.89	51475.47	49775.94	47958.85	46082.13	44172.62

CONDENSER LOOP PRESSURE DROPS**Gravitational Pressure Drop**

Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Condenser Temperature, C	400.00	400.00	400.00	400.00	400.00	400.00
Condenser Temperature, K	673.00	673.00	673.00	673.00	673.00	673.00
Total Cable Artery Vertical Length, cm	22.02	22.02	22.02	22.02	22.02	22.02
Total Cable Artery Vertical Length, m	0.22	0.22	0.22	0.22	0.22	0.22
Gravitational Acceleration, m/s ²	9.81	9.81	9.81	9.81	9.81	9.81
Condenser Na Liquid Density, kg/m ³	856.22	856.22	856.22	856.22	856.22	856.22
Condenser Loop Gravitational Pressure Drop, Pa	1849.58	1849.58	1849.58	1849.58	1849.58	1849.58

Vapor Pressure Drop

Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Evaporator Na Vapor Pressure, Pa	7011.38	13940.79	25885.00	45317.58	75400.90	120011.87
Condenser Temperature, C	400.00	400.00	400.00	400.00	400.00	400.00
Condenser Temperature, K	673.00	673.00	673.00	673.00	673.00	673.00
Condenser Na Vapor Pressure, Pa	47.20	47.20	47.20	47.20	47.20	47.20

Condenser Loop Vapor Pressure Drop, Pa	6964.19	13893.59	25837.81	45270.38	75353.70	119964.67
Liquid Pressure Drop						
Condenser Wick - Sieve Size: -50+100						
Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Condenser Temperature, C	400.00	400.00	400.00	400.00	400.00	400.00
Condenser Temperature, K	673.00	673.00	673.00	673.00	673.00	673.00
Condenser Wick Effective Length, cm	3.244	3.244	3.244	3.244	3.244	3.244
Condenser Wick Effective Length, m	0.032	0.032	0.032	0.032	0.032	0.032
Cross-Sectional Area for Liquid Flow, m ²	6.83E-05	6.83E-05	6.83E-05	6.83E-05	6.83E-05	6.83E-05
Liquid Mass Flow Rate (=Base Mass Flow Rate), kg/s	3.60E-06	3.60E-06	3.60E-06	3.60E-06	3.60E-06	3.60E-06
Condenser Na Liquid Density, kg/m ³	856.22	856.22	856.22	856.22	856.22	856.22
Condenser Na Liquid Viscosity, kg/m s	2.85E-04	2.85E-04	2.85E-04	2.85E-04	2.85E-04	2.85E-04
Condenser Na Surface Tension, N/m	0.167	0.167	0.167	0.167	0.167	0.167
Condenser Wick Permeability, m ²	3.80E-11	3.80E-11	3.80E-11	3.80E-11	3.80E-11	3.80E-11
Condenser Wick Pore Size, m	5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05
Condenser Wick Pumping Capability, Pa	6061.818	6061.818	6061.818	6061.818	6061.818	6061.818
Condenser Gravitational Pressure Drop, Pa	1849.58	1849.58	1849.58	1849.58	1849.58	1849.58
Condenser Wick Liquid Pressure Drop, Pa	14.97	14.97	14.97	14.97	14.97	14.97
Total Condenser Wick Pressure Drop, Pa	1864.54	1864.54	1864.54	1864.54	1864.54	1864.54
Excess Condenser Wick Pumping Capability, Pa	4197.275	4197.275	4197.275	4197.275	4197.275	4197.275
Condenser-to-Evaporator Liquid Return Cable Artery - 0.080" Dia. Cable Artery						
Number of Condenser Cable Arteries	1	1	1	1	1	1
Total Cable Artery Effective Length, cm	31.14	31.14	31.14	31.14	31.14	31.14
Total Cable Artery Effective Length, m	0.31	0.31	0.31	0.31	0.31	0.31
Cable Artery Cross-Sectional Area for Liquid Flow, m ²	3.14E-06	3.14E-06	3.14E-06	3.14E-06	3.14E-06	3.14E-06
Cable Artery Permeability, m ²	7.31E-11	7.31E-11	7.31E-11	7.31E-11	7.31E-11	7.31E-11
Cable Cable Pore Size, m	4.83E-05	4.83E-05	4.83E-05	4.83E-05	4.83E-05	4.83E-05
Evaporator Na Surface Tension, N/m	0.142	0.137	0.132	0.127	0.122	0.117
Cable Artery Pumping Capability, Pa	5867.49	5660.46	5453.42	5246.38	5039.34	4832.30
Condenser Gravitational Pressure Drop, Pa	1849.58	1849.58	1849.58	1849.58	1849.58	1849.58

Condenser Wick Liquid Pressure Drop, Pa	14.97	14.97	14.97	14.97	14.97	14.97
Condenser Cable Artery Liquid Pressure Drop, Pa	1622.73	1622.73	1622.73	1622.73	1622.73	1622.73
Total Condenser Cable Artery Pressure, Pa	3487.27	3487.27	3487.27	3487.27	3487.27	3487.27
Excess Cable Artery Pumping Capability, Pa	2380.23	2173.19	1966.15	1759.11	1552.07	1345.03
Evaporator Wick - Sieve Size: Hypothetical 1						
Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Condenser Temperature, C	400.00	400.00	400.00	400.00	400.00	400.00
Condenser Temperature, K	673.00	673.00	673.00	673.00	673.00	673.00
Effective Length for Evaporator Wick, m	4.00E-03	4.00E-03	4.00E-03	4.00E-03	4.00E-03	4.00E-03
Cross-Sectional Area for Liquid Flow, m^2	1.55E-03	1.55E-03	1.55E-03	1.55E-03	1.55E-03	1.55E-03
Liquid Mass Flow Rate (=Total Mass Flow Rate), kg/s	6.00E-05	6.00E-05	6.00E-05	6.00E-05	6.00E-05	6.00E-05
Evaporator Na Liquid Density, kg/m^3	796.14	784.05	771.95	759.83	747.72	735.60
Evaporator Na Liquid Viscosity, kg/m s	1.93E-04	1.81E-04	1.71E-04	1.62E-04	1.54E-04	1.47E-04
Evaporator Na Surface Tension, N/m	0.142	0.137	0.132	0.127	0.122	0.117
Evaporator Wick Permeability, m^2	4.00E-13	4.00E-13	4.00E-13	4.00E-13	4.00E-13	4.00E-13
Evaporator Wick Pore Size, m	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Evaporator Wick Pumping Capability, Pa	56680.00	54680.00	52680.00	50680.00	48680.00	46680.00
Condenser Wick Liquid Pressure Drop, Pa	14.97	14.97	14.97	14.97	14.97	14.97
Condenser Cable Artery Liquid Pressure Drop, Pa	1622.73	1622.73	1622.73	1622.73	1622.73	1622.73
Evaporator Wick Liquid Pressure Drop, Pa	93.83	89.36	85.61	82.44	79.74	77.43
Total Condenser Loop Liquid Pressure Drops, Pa	1731.52	1727.05	1723.30	1720.13	1717.43	1715.12
Total Condenser Loop Pressure Drops, Pa	10545.29	17470.22	29410.68	48840.08	78920.71	123529.37
Excess Condenser Loop Pumping Capability, Pa	46134.71	37209.78	23269.32	1839.92	-30240.71	-76849.37
ABSOLUTE PRESSURES IN SYSTEM						
Evaporator Temperature, C	650.00	700.00	750.00	800.00	850.00	900.00
Evaporator Temperature, K	923.00	973.00	1023.00	1073.00	1123.00	1173.00
Condenser Temperature, C	400.00	400.00	400.00	400.00	400.00	400.00

Condenser Temperature, K	673.00	673.00	673.00	673.00	673.00	673.00
Recirculating Loop Pressure Drops						
Wick Pumping Capability, Pa	56680.00	54680.00	52680.00	50680.00	48680.00	46680.00
Gravitational Pressure Drop, Pa	1220.72	1202.18	1183.63	1165.06	1146.48	1127.90
Vapor Pressure Drop, Pa	957.62	500.69	281.83	170.80	111.46	78.33
Liquid Pressure Drops, Pa	1576.78	1501.65	1438.61	1385.29	1339.93	1301.15
Total Pressure Drops, Pa	3755.11	3204.53	2904.06	2721.15	2597.87	2507.38
Absolute Pressure at End of Evaporator, Pa	52924.89	51475.47	49775.94	47958.85	46082.13	44172.62
Power Loop Pressure Drops						
Wick Pumping Capability, Pa	56680.00	54680.00	52680.00	50680.00	48680.00	46680.00
Gravitational Pressure Drop, Pa	1849.58	1849.58	1849.58	1849.58	1849.58	1849.58
Vapor Pressure Drop, Pa	6964.19	13893.59	25837.81	45270.38	75353.70	119964.67
Liquid Pressure Drops, Pa	1731.52	1727.05	1723.30	1720.13	1717.43	1715.12
Total Pressure Drops, Pa	10545.29	17470.22	29410.68	48840.08	78920.71	123529.37
Absolute Pressure at End of Evaporator, Pa	46134.71	37209.78	23269.32	1839.92	-30240.71	-76849.37

SONIC LIMIT**Evaporator Sonic Limit**

Use equation for choked flow with varying areas, Shapiro, eq. 4-17

Sodium Specific Heat Ratio	1.67
Gas Constant, J/kg-mole K	8314.40
Sodium Molecular Weight, kg/kg-mole	22.99
Sodium Gas Constant, J/kg K	361.66
Sonic Limit Coefficient	0.03821

BASE Wick I.D., cm	0.68
Cross-Sectional Area for Vapor Flow, m ²	3.431E-05

Sodium Properties

Range: 450-1100 C

Based on Fluprop

Temperature, C	400.00	425.00	450.00	475.00	500.00	525.00
Temperature, K	673.00	698.00	723.00	748.00	773.00	798.00
Evap. Na Latent Heat, J/kg	4.374E+06	4.348E+06	4.322E+06	4.296E+06	4.270E+06	4.244E+06
Evap. Na Vapor Pressure, Pa	47.20	91.68	169.98	302.25	517.51	856.31
Sonic Limit, W	10.43	19.78	35.81	62.23	104.18	168.63

AMTEC Wick-Pumped Cell
Recirculating Loop Pressure Drops
Condenser Temperature: 400 C

AMTEC Wick-Pumped Cell
Power Loop Pressure Drops
Condenser Temperature: 400 C

Title: AMTEC VAPOR-FED CELL
SECOND 800°C DESIGN

Calculated by: J.E. Landemuth Date: 5-21-93
 Checked by: John R. Adams Date: 6/8/93
 Reviewed by: _____ Date: _____

Project: 11-1140 AMTEC

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Purpose: Determine the feasibility of the following
 vapor-fed AMTEC cell design operating
 near 800°C.

Geometry:

Title: SECOND 800°C DESIGNCalculated by: JE Lindemuth Date: 5-21-93

Checked by: _____ Date: _____

Reviewed by: _____ Date: _____

Project: 11-1140 AMTECPage 2 of 8

REFERENCE: AMTEC VAPOR-FED CELL 800°C DESIGN
dated 5-6-93.

Sodium properties + some cell dimensions are
drawn from this reference.

Recirculating Loop Pressure Drops

Gravitational Drop: $\Delta P_{\text{GRAV}} = 1165 \text{ Pa}$ [REF, p. 6]

Vapor Pressure Drop:

Vapor Channel: $\Delta P_{\text{VC VAP}} = 140 \text{ Pa}$ [REF, p. 7]

Side Channel: $\Delta P_{\text{SC VAP}} = 0.8 \text{ Pa}$ [REF, p. 8]

Evaporator Vapor Space: $\Delta P_{\text{EVAP VAP}} = 0.001 \text{ Pa}$ [REF, p. 9]

BASE Wick Vapor Space:

O.D. = 1.04 cm = 0.41 in

Thick = 0.25 cm = 0.10 in

I.D. = 0.54 cm = 0.21 in

Purge Tube O.D. = 0.16 cm = 0.062 in

$L_{\text{EFF}} = 0.0921 \text{ m}$ [REF, p. 3]

$$A_{\text{BASE VAP}} = \frac{\pi}{4} [(0.54 \text{ cm})^2 - (0.16 \text{ cm})^2] = 0.209 \text{ cm}^2 \\ = 2.09 \times 10^{-5} \text{ m}^2$$

Title: _____

Calculated by: JE Lindemuth Date: 5-21-93SECOND 800°C DESIGN

Checked by: _____ Date: _____

Project: 11-1140 AMTEC

Reviewed by: _____ Date: _____

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$$P_{\text{BASE VAP}} = \pi (.54 \text{ cm} + .16 \text{ cm}) = 2.20 \text{ cm} \\ = 0.022 \text{ m}$$

$$D_H = \frac{4A}{P} = 3.80 \times 10^{-3} \text{ m}$$

$$V_{\text{BASE VAP}} = 22.9 \text{ m/s}$$

$$Re = 497$$

$$\Delta P_{\text{BASE VAP}} = 103 \text{ Pa}$$

$$(\Delta P_{\text{VAP}})_{\text{TOT}} = 140 \text{ Pa} + 0.8 \text{ Pa} + 0 \text{ Pa} + 103 \text{ Pa} = 244 \text{ Pa}$$

Liquid Pressure Drop:

BASE WICK: $A_{\text{BASE}} = \frac{\pi}{4} [(1.04 \text{ cm})^2 - (.59 \text{ cm})^2]$

$$= 0.620 \text{ cm}^2 = 6.20 \times 10^{-5} \text{ m}^2$$

$$\dot{m} = \dot{m}_{\text{TOTAL}} = 6.02 \times 10^{-5} \text{ kg/s}$$

$$P_c = 50,800 \text{ Pa} [\text{REF, p. 15}]$$

5 μm Powder

$$K = 4 \times 10^{-13} \text{ m}^2 \quad r_c = 5 \times 10^{-6} \text{ m}$$

$$(\Delta P_{\text{GRAV}})_{\text{BASE}} = 929 \text{ Pa} \\ [\text{REF, p. 11}]$$

$$\Delta P_{\text{BASE}} = 47,667 \text{ Pa}$$

$$(\Delta P_{\text{TOT}})_{\text{BASE}} = 47,667 \text{ Pa} + 929 \text{ Pa} = 48,596 \text{ Pa}$$

TRANSITION WICK 1:

$$t = 0.95 \text{ cm} = 0.37 \text{ in}$$

$$W = 4.11 \text{ cm} = 1.62 \text{ in}$$

$$l = \frac{1}{2} (1.62 \text{ in} - .21 \text{ in}) = 0.71 \text{ in} \\ = 1.79 \text{ cm}$$

Title: _____

SECOND 800°C DESIGN

Calculated by: JE Lindemuth Date: 5-21-93

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Project: 11-1140 AMTECPage 4 of 8

$$A_{TRANS1} = tW = 3.90 \text{ cm}^2 = 3.90 \times 10^{-4} \text{ m}^2$$

$$L_{EFF} = l = 1.79 \text{ cm} = 0.0179 \text{ m}$$

$$\dot{m} = 1/2 \dot{m}_{TOT} = 3.01 \times 10^{-5} \text{ kg/s}$$

$$P_c = 50,800 \text{ Pa}$$

5 μm Powder

$$K = 4 \times 10^{-13} \text{ m}^2$$

$$r_c = 5 \times 10^{-6} \text{ m}$$

$$\Delta P_{TRANS1} = 736 \text{ Pa}$$

$$(\Delta P_{TOT})_{TRANS1} = (\Delta P_{TOT})_{BASE} + \Delta P_{TRANS1}$$

$$= 49,332 \text{ Pa}$$

TRANSITION Wick 2:

$$t = 0.51 \text{ cm} = 0.20 \text{ in}$$

$$W = 3.78 \text{ cm} = 1.49 \text{ in}$$

$$l = 1.25 \text{ in} - 0.50 \text{ in} - 0.37 \text{ in}$$

$$= 0.38 \text{ in} = 0.97 \text{ cm}$$

$$A_{TRANS2} = tW = 1.93 \text{ cm}^2 = 1.93 \times 10^{-4} \text{ m}^2$$

$$L_{EFF} = l = 0.97 \text{ cm} = 0.0097 \text{ m}$$

$$P_c = 50,800 \text{ Pa}$$

$$\dot{m} = 1/2 \dot{m}_{TOT} = 3.01 \times 10^{-5} \text{ kg/s}$$

5 μm Powder

$$K = 4 \times 10^{-13} \text{ m}^2$$

$$r_c = 5 \times 10^{-6} \text{ m}$$

$$\Delta P_{TRANS2} = 806 \text{ Pa}$$

$$(\Delta P_{GRAV})_{TRANS2} = (\Delta P_{GRAV})_{CABLE} = 1071 \text{ Pa} \quad [\text{REF, p 13}]$$

Title: SECOND 800°C DESIGN
 Project: 11-1140 AMT&C

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$$(\Delta P_{TOT})_{TRANS2} = (\Delta P_{GRAV})_{TRANS2} + \Delta P_{TRANS2} + \Delta P_{TRANS1} + \Delta P_{BASE}$$

$$P_c = 50,800 \text{ Pa}$$

$$= 1071 \text{ Pa} + 806 \text{ Pa} + 736 \text{ Pa} + 47,667 \text{ Pa} = 50,280 \text{ Pa}$$

EVAPORATOR WICK:

$$t = 1.27 \text{ cm} = 0.50 \text{ in}$$

$$w = 4.11 \text{ cm} = 1.62 \text{ in}$$

$$l = 3.78 \text{ cm} = 1.49 \text{ in}$$

$$L_{EFF} = \sqrt{\left(\frac{1.62 \text{ in}}{2}\right)^2 + (0.5 \text{ in})^2} = 0.95 \text{ in} = 0.0242 \text{ m}$$

$$A_{EVAP} = t l = 4.80 \text{ cm}^2 = 4.80 \times 10^{-4} \text{ m}^2$$

$$\dot{m} = \frac{1}{2} \dot{m}_{TOT} = 3.01 \times 10^{-5} \text{ kg/s}$$

$$P_c = 50,800 \text{ Pa} \quad [\text{REF, p. 15}]$$

5 μm Powder (EXTRAPOLATED)

$$K = 4 \times 10^{-13} \text{ m}^2$$

$$r_c = 5 \times 10^{-6} \text{ m}$$

[REF, p. 15]

$$\Delta P_{EVAP} = 809 \text{ Pa}$$

$$\begin{aligned} (\Delta P_{LIQ})_{TOT} &= \Delta P_{BASE} + \Delta P_{TRANS1} + \Delta P_{TRANS2} + \Delta P_{EVAP} \\ &= 47,667 \text{ Pa} + 736 \text{ Pa} + 806 \text{ Pa} + 809 \text{ Pa} \\ &= 50,018 \text{ Pa} \end{aligned}$$

$$\begin{aligned} \Delta P_{TOTAL} &= \Delta P_{GRAV} + (\Delta P_{VAR})_{TOT} + (\Delta P_{LIQ})_{TOT} \\ &= 1165 \text{ Pa} + 244 \text{ Pa} + 50,018 \text{ Pa} = 51,427 \text{ Pa} \end{aligned}$$

$$\text{EXCESS CAPABILITY} = 50,800 \text{ Pa} - 51,427 \text{ Pa} = -627 \text{ Pa}$$

Title: SECOND 800°C DESIGN
 Project: 11-1140 AMTEC

Calculated by: JE Landemuth Date: 5-21-93
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CONDENSER LOOP PRESSURE DROPS

Gravitational Drop: $\Delta P_{\text{GRAV}} = 1848 \text{ Pa}$ [REF, p.17]

Vapor Pressure Drop: $\Delta P_{\text{VAP}} = 45,271 \text{ Pa}$ [REF, p.20]

Liquid Pressure Drop

Condenser Wick $\Delta P_{\text{COND WICK}} = 15 \text{ Pa}$ } [REF, pp 18-19]
 - 50 + 100 MESH POWDER $P_c = 6073 \text{ Pa}$ }

Cable Artery: $L_{\text{EFF}} = \frac{2.065 \text{ IN}}{2} + 2.75 \text{ IN} = 3.78 \text{ IN}$
 $= 0.096 \text{ m}$

$P_c = 5259 \text{ Pa}$ [REF, p. 19]

$\Delta P_{\text{CABLE}} = 503 \text{ Pa}$

$h = 2.065 \text{ IN} + 2.75 \text{ IN} = 4.82 \text{ IN}$
 $= 0.122 \text{ m}$

$(\Delta P_{\text{GRAV}})_{\text{CABLE}} = 1025 \text{ Pa}$

$(\Delta P_{\text{TOT}})_{\text{CABLE}} = 1025 \text{ Pa} + 503 \text{ Pa} = 1528 \text{ Pa}$

BASE Wick: $\Delta P_{\text{BASE}} = 47,667 \text{ Pa}$ p. 3 ABOVE

Transition Wick 1: $\Delta P_{\text{TRANS 1}} = 736 \text{ Pa}$ p. 4 ABOVE

Title: _____

Calculated by: JE Lundemuth Date: 5-21-93SECOND 800°C DESIGN

Checked by: _____ Date: _____

Project: 11-1140 AMTEC

Reviewed by: _____ Date: _____

Page 7 of 8Transition Wick 2: $\Delta P_{TRANS2} = 44 \text{ Pa}$ p. 4 ABOVE $P_c = 50,800 \text{ Pa}$ p. 3 ABOVE

$$(\Delta P_{TOT})_{TRANS2} = \underset{\substack{\uparrow \\ \text{p. 6}}}{\Delta P_{GRAV}} + \underset{\substack{\text{WICK}}}{\Delta P_{COND}} + \Delta P_{CABLE}$$

$$+ \Delta P_{BASE} + \Delta P_{TRANS1} + \Delta P_{TRANS2}$$

$$= 1848 \text{ Pa} + 15 \text{ Pa} + 503 \text{ Pa}$$

$$+ 47,667 \text{ Pa} + 736 \text{ Pa} + 806 \text{ Pa}$$

$$= 51,575 \text{ Pa}$$

EVAPORATOR WICK: $\Delta P_{EVAP} = 809 \text{ Pa}$ p. 5 ABOVE $P_c = 50,800 \text{ Pa}$ [Ref p. 15]

$$(\Delta P_{LIQ})_{TOT} = \underset{\substack{\text{WICK}}}{\Delta P_{COND}} + \Delta P_{CABLE} + \Delta P_{BASE} + \Delta P_{TRANS1} + \Delta P_{TRANS2} + \Delta P_{EVAP}$$

$$= 15 \text{ Pa} + 503 \text{ Pa} + 47,667 \text{ Pa} + 736 \text{ Pa} + 806 \text{ Pa} + 809 \text{ Pa}$$

$$= 50,536 \text{ Pa}$$

$$\Delta P_{TOTAL} = \Delta P_{GRAV} + \Delta P_{VAP} + (\Delta P_{LIQ})_{TOT}$$

$$= 1848 \text{ Pa} + 45,271 \text{ Pa} + 50,536 \text{ Pa} = 97,655 \text{ Pa}$$

$$\text{EXCESS CAPABILITY} = 50,800 \text{ Pa} - 97,655 \text{ Pa}$$

$$= -46,855 \text{ Pa}$$

Title: SECOND 800°C DESIGN
Project: 11-1140 AMTEC

Calculated by: JE Lindemuth Date: 5-21-93
Checked by: _____ Date: _____
Reviewed by: _____ Date: _____

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Conclusion:

RECIRCULATING LOOP TOTAL PRESSURE DROP: 51,427 Pa

Condenser Loop Total Pressure Drop: 97,655 Pa

Evaporator Wick Capability: 50,800 Pa

Hypothetical Evaporator Wick Properties:

$$K = 4 \times 10^{-13} \text{ m}^2$$

$$r_c = 5 \times 10^{-6} \text{ m}^2$$

Appendix D

800°C Wick-Pumped AMTEC System Design

AMTEC System Design

11-1140

May 15, 1997

Design an AMTEC system powered by a series of GPHS bricks.

The model currently neglects the following

1. Pressure drops in the low pressure region (pressure drop between the outside of the the BASE and the condenser through the heat shield. This will increase the effective condenser temperature, and reduce the efficiency.
2. Temperature drop through the BASE.

AMTEC Voltage-Current Characteristics

Ref: R. K. Sievers and C. P. Bankston, "Radioisotope Powered Alkali Metal Thermoelectric Converter Design," Proc., 23rd IECEC, Vol. 3., pp. 159-167, Denver, Colorado, July 31-August 5, 1988.

$$V_{\text{OpenCircuit}}(T_{\text{Base}}, T_{\text{Cond}}) := \left(\frac{\text{GasConstant} \cdot T_{\text{Base}}}{\text{Faraday}} \right) \cdot \ln \left[\frac{\text{NaVaporPressure}(T_{\text{Base}})}{\text{NaVaporPressure}(T_{\text{Cond}}) \cdot \left(\frac{T_{\text{Base}}}{T_{\text{Cond}}} \right)^{0.5}} \right]$$

$$V_{\text{OpenCircuit}}(1073 \cdot \text{K}, 423 \cdot \text{K}) = 1.583 \cdot \text{volt}$$

Equation for the BASE resistivity taken from:

C. P. Bankston, Alkali Metal Thermoelectric Conversion (AMTEC) Technology Status Review, Space Nuclear Power Systems, 1986, ed. M. S. El-Genk and M. D. Hoefer, Copyright Orbit Book Co., Malabar, Florida, 1987.

$$R_{\text{BASE}}(t_{\text{BASE}}, T) := \left(\frac{t_{\text{BASE}}}{\text{cm}} \right) \cdot \left(\frac{T}{\text{K}} \right) \cdot \left(4.03 \cdot 10^{-4} \cdot \exp\left(\frac{1420 \cdot \text{K}}{T}\right) + 3.24 \cdot 10^{-7} \cdot \exp\left(\frac{4725 \cdot \text{K}}{T}\right) \right) \cdot \text{ohm} \cdot \text{cm}^2$$

G is a dimensionless geometry factor, taken from Sievers and Bankston

$$G := 40$$

Pressure drop associated with the porous electrode

$$P_d(T_{\text{Base}}, J) := \frac{0.75 \cdot G \cdot J}{\text{Faraday}} \cdot \left(\frac{\text{NaMolecWeight} \cdot \text{GasConstant} \cdot T_{\text{Base}}}{2 \cdot \pi} \right)^{0.5}$$

BASE Voltage/Current Density Equation

See Sievers, R. K., and Bankston, C. P., "Radioisotope Powered Alkali Metal Thermoelectric Converter Design for Space Systems", Proceedings of the 23rd Annual IECEC, Vol. 3, pp. 159-167, Denver, Colorado, July 31-August 5, 1988.

$$V_B(J, T_{\text{Base}}, T_{\text{Cond}}, t_{\text{BASE}}) := \left(\frac{\text{GasConstant} \cdot T_{\text{Base}}}{\text{Faraday}} \right) \cdot \ln \left[\frac{\text{NaVaporPressure}(T_{\text{Base}})}{\text{NaVaporPressure}(T_{\text{Cond}}) \cdot \left(\frac{T_{\text{Base}}}{T_{\text{Cond}}} \right)^{0.5} \dots} \right] - J \cdot R_{\text{BASE}}(t_{\text{BASE}}, T_{\text{Base}}) + \left(2 \cdot \pi \cdot \text{NaMolecWeight} \cdot \text{GasConstant} \cdot T_{\text{Base}} \right)^{0.5} \cdot \frac{J}{\text{Faraday}} + P_d(T_{\text{Base}}, J)$$

High Temperature Wick Fed Cell Geometry

BASE

$$t_{\text{BASE}} := 0.11 \cdot \text{cm}$$

$$ID_{\text{BASE}} := 0.500 \cdot \text{in}$$

$$ID_{\text{BASE}} = 1.27 \cdot \text{cm}$$

$$OD_{\text{BASE}} := ID_{\text{BASE}} + 2 \cdot t_{\text{BASE}}$$

$$OD_{\text{BASE}} = 1.49 \cdot \text{cm}$$

AMTEC System Design

Initially the BASE Length was 10 cm. Increase it until the required hot shoe is the same size as the cylinder O.D. Note that we also need to increase the length of the cylinder.

$$L_{\text{TotalBASE}} := 13.5 \cdot \text{cm}$$

$$L_{\text{TotalBASE}} = 5.315 \cdot \text{in}$$

$$L_{\text{InactiveBASE}} := 0.2 \cdot \text{in}$$

$$L_{\text{BASE}} := L_{\text{TotalBASE}} - L_{\text{InactiveBASE}}$$

Length covered by the electrode

$$L_{\text{BASE}} = 12.992 \cdot \text{cm}$$

$$A_{\text{BASE}} := \pi \cdot \text{OD}_{\text{BASE}} \cdot L_{\text{BASE}}$$

$$A_{\text{BASE}} = 60.815 \cdot \text{cm}^2$$

$$V_{\text{BASE}} := \frac{\pi}{4} \cdot (\text{OD}_{\text{BASE}}^2 - \text{ID}_{\text{BASE}}^2) \cdot L_{\text{TotalBASE}}$$

$$V_{\text{BASE}} = 6.438 \cdot \text{cm}^3$$

$$\text{Mass}_{\text{BASE}} := \rho_{\text{BASE}} \cdot V_{\text{BASE}}$$

$$\text{Mass}_{\text{BASE}} = 25.108 \cdot \text{gm}$$

$$L_{\text{SupportStructure}} := .7 \cdot \text{in}$$

Current Collector

Current is collected by a copper screen over the electrode. The current is carried to Molybdenum wires, and then carried to a copper cable which takes the current through a high temperature feed-through.

Molybdenum Wire

$$\text{OD}_{\text{MolyWire}} := 0.015 \cdot \text{in}$$

AMTEC System Design

$$\text{NoTurns}_{\text{Internal}} := 118 \cdot \frac{L_{\text{BASE}}}{4.492 \cdot \text{cm}} \quad \text{NoTurns}_{\text{Internal}} = 341.286$$

Molybdenum wire is used as the internal current collector, and is also used to attach the copper screen to the outside of the BASE tube. Normalize to the number of turns to the number in the cell with a 4.5 cm length.

$$\text{NoTurns}_{\text{External}} := 35 \cdot \frac{L_{\text{BASE}}}{4.492 \cdot \text{cm}} \quad \text{NoTurns}_{\text{External}} = 101.229$$

$$L_{\text{MolyWire}} := \pi \cdot (\text{NoTurns}_{\text{Internal}} \cdot \text{ID}_{\text{BASE}} + \text{NoTurns}_{\text{External}} \cdot \text{OD}_{\text{BASE}})$$

$$L_{\text{MolyWire}} = 1835.52 \cdot \text{cm}$$

$$\text{Vol}_{\text{MolyWire}} := \frac{\pi}{4} \cdot \text{OD}_{\text{MolyWire}}^2 \cdot L_{\text{MolyWire}}$$

$$\text{Mass}_{\text{MolyWire}} := \rho_{\text{Moly}} \cdot \text{Vol}_{\text{MolyWire}} \quad \text{Mass}_{\text{MolyWire}} = 21.387 \cdot \text{gm}$$

High Temperature Feedthrough

$$\text{Mass}_{\text{Feedthrough}} := 10 \cdot \text{gm}$$

Copper Cable

Use a relatively small cable in the cell, and a larger cable outside.

$$\text{OD}_{\text{CopperCable}} := 0.090 \cdot \text{in}$$

$$L_{\text{CopperCable}} := \frac{L_{\text{TotalBASE}}}{2} + 0.5 \cdot \text{in} \quad L_{\text{CopperCable}} = 3.157 \cdot \text{in}$$

Use an effective length for the copper in contact with the BASE. Include copper on the outside of the cell

$$\text{Vol CopperCable} := \frac{\pi}{4} \cdot \text{OD CopperCable}^2 \cdot \text{L CopperCable}$$

$$\text{Mass CopperCable} := \rho_{\text{Copper}} \cdot \text{Vol CopperCable} \quad \text{Mass CopperCable} = 2.963 \cdot \text{gm}$$

$$\text{OD OuterCable} := 0.15 \cdot \text{in}$$

$$\text{L OuterCable} := 4 \cdot \text{in}$$

Use an effective length for the copper in contact with the BASE. Include copper on the outside of the cell

$$\text{Vol OuterCable} := \frac{\pi}{4} \cdot \text{OD OuterCable}^2 \cdot \text{L OuterCable}$$

$$\text{Mass OuterCable} := \rho_{\text{Copper}} \cdot \text{Vol OuterCable} \quad \text{Mass OuterCable} = 10.425 \cdot \text{gm}$$

Resistances

$$\text{Resistance InnerCable} := \frac{\text{Resis Cu} \cdot \text{L CopperCable}}{\left(\frac{\pi}{4} \cdot \text{OD CopperCable}^2 \right)}$$

$$\text{Resistance InnerCable} = 0.0013 \cdot \text{ohm}$$

$$\text{Resistance OuterCable} := \frac{\text{Resis Cu} \cdot \text{L OuterCable}}{\left(\frac{\pi}{4} \cdot \text{OD OuterCable}^2 \right)}$$

$$\text{Resistance OuterCable} = 0.0006 \cdot \text{ohm}$$

AMTEC System Design

$$\text{Resistance}_{\text{CopperCable}} := \text{Resistance}_{\text{InnerCable}} + \text{Resistance}_{\text{OuterCable}}$$

$$\text{Resistance}_{\text{CopperCable}} = 0.0019 \cdot \text{ohm}$$

$$\text{Resistance}_{\text{InnerCable}} \cdot A_{\text{BASE}} = 0.077 \cdot \text{ohm} \cdot \text{cm}^2$$

$$R_{\text{BASE}}(t_{\text{BASE}}, 973 \cdot \text{K}) = 0.19 \cdot \text{ohm} \cdot \text{cm}^2$$

$$R_{\text{Contact}} := \frac{0.080 \cdot \text{ohm} \cdot \text{cm}^2}{A_{\text{BASE}}}$$

$$R_{\text{Contact}} = 0.001 \cdot \text{ohm}$$

Calculate the resistance in the molybdenum wires on the outside (the inside ones are connected by sodium, and the resistance can be neglected). There are multiple wraps, with an effective length of the circumference divided by 4.

$$\text{No}_{\text{MolyPaths}} := 2 \cdot \text{NoTurns}_{\text{External}}$$

Two electric paths for each wrap

$$A_{\text{All_Moly}} := \text{No}_{\text{MolyPaths}} \cdot \left(\frac{\pi}{4} \cdot \text{OD}_{\text{MolyWire}}^2 \right)$$

$$A_{\text{All_Moly}} = 0.231 \cdot \text{cm}^2$$

$$\text{Resistance}_{\text{MolyCable}} := \frac{\text{Resis}_{\text{Mo}} \cdot \left(\frac{\pi \cdot \text{OD}_{\text{BASE}}}{4} \right)}{A_{\text{All_Moly}}}$$

$$\text{Resistance}_{\text{MolyCable}} = 9.521 \cdot 10^{-5} \cdot \text{ohm}$$

$$\text{Resistance}_{\text{MolyCable}} \cdot A_{\text{BASE}} = 0.006 \cdot \text{ohm} \cdot \text{cm}^2$$

Cell Dimensions

$$OD_{Cell} := 1.25 \cdot \text{in}$$

$$t_{Cell} := 0.020 \cdot \text{in}$$

$$ID_{Cell} := OD_{Cell} - 2 \cdot t_{Cell}$$

$$ID_{Cell} = 1.21 \cdot \text{in}$$

Initial cell length was 6 inches. Increase the length as we increase the BASE length, and for the required condenser area.

$$L_{HeatPipe} := 0.5 \cdot \text{in}$$

$$L_{Shield} := 1 \cdot \text{in}$$

$$L_{SupportStructure} = 1.778 \cdot \text{cm}$$

$$L_{Condenser} := 3.5 \cdot \text{in}$$

$$L_{Cell} := L_{HeatPipe} + L_{SupportStructure} + L_{BASE} + L_{Shield} + L_{Condenser}$$

$$L_{Cell} = 10.815 \cdot \text{in}$$

$$A_{CrossSectCylinder} := \frac{\pi}{4} \cdot (OD_{Cell}^2 - ID_{Cell}^2)$$

$$A_{CrossSectCylinder} = 0.499 \cdot \text{cm}^2$$

$$Vol_{CellCylinder} := \frac{\pi}{4} \cdot (OD_{Cell}^2 - ID_{Cell}^2) \cdot L_{Cell}$$

$$Mass_{CellCylinder} := \rho_{Stainless} \cdot Vol_{CellCylinder}$$

$$Mass_{CellCylinder} = 115.051 \cdot \text{gm}$$

$$t_{\text{endcap}} := 0.050 \cdot \text{in}$$

$$A_{\text{endcap}} := \frac{\pi}{4} \cdot \text{OD}_{\text{Cell}}^2$$

$$A_{\text{endcap}} = 7.917 \cdot \text{cm}^2$$

$$\text{Vol}_{\text{endcap}} := \frac{\pi}{4} \cdot \text{OD}_{\text{Cell}}^2 \cdot t_{\text{endcap}}$$

$$\text{Mass}_{\text{endcap}} := \rho_{\text{Stainless}} \cdot \text{Vol}_{\text{endcap}}$$

$$\text{Mass}_{\text{endcap}} = 8.446 \cdot \text{gm}$$

$$\text{Vol}_{\text{LowerCap}} := \frac{\pi}{4} \cdot (\text{OD}_{\text{Cell}}^2 - \text{OD}_{\text{BASE}}^2) \cdot t_{\text{endcap}}$$

$$\text{Mass}_{\text{LowerCap}} := \rho_{\text{Stainless}} \cdot \text{Vol}_{\text{LowerCap}}$$

$$\text{Mass}_{\text{LowerCap}} = 6.586 \cdot \text{gm}$$

$$\text{OD}_{\text{Nb_Tube}} := 0.212 \cdot \text{in}$$

Interior Niobium tube

$$t_{\text{Nb_Tube}} := 0.012 \cdot \text{in}$$

$$\text{ID}_{\text{Nb_Tube}} := \text{OD}_{\text{Nb_Tube}} - 2 \cdot t_{\text{Nb_Tube}}$$

$$\text{ID}_{\text{Nb_Tube}} = 0.188 \cdot \text{in}$$

$$L_{\text{Nb_Tube}} := L_{\text{BASE}} + L_{\text{SupportStructure}}$$

$$\text{Vol}_{\text{Nb_Tube}} := \frac{\pi}{4} \cdot (\text{OD}_{\text{Nb_Tube}}^2 - \text{ID}_{\text{Nb_Tube}}^2) \cdot L_{\text{Nb_Tube}}$$

$$\text{Mass}_{\text{Nb_Tube}} := \rho_{\text{Nb}} \cdot \text{Vol}_{\text{Nb_Tube}}$$

$$\text{Mass}_{\text{Nb_Tube}} = 6.157 \cdot \text{gm}$$

Condenser and Return Artery

$$t_{\text{CondWick}} := 0.250 \cdot \text{in}$$

$$\phi_{\text{CondWick}} := 0.850 \quad \text{Condenser wick porosity}$$

$$\text{Vol SolidCondWick} := (1 - \phi_{\text{CondWick}}) \cdot \frac{\pi}{4} \cdot \text{ID}_{\text{Cell}}^2 \cdot t_{\text{CondWick}}$$

$$\text{Mass SolidCondwick} := \rho_{\text{Nickel}} \cdot \text{Vol SolidCondWick} \quad \text{Mass SolidCondwick} = 6.289 \cdot \text{gm}$$

$$\text{Vol PoreCondWick} := \phi_{\text{CondWick}} \cdot \frac{\pi}{4} \cdot \text{ID}_{\text{Cell}}^2 \cdot t_{\text{CondWick}} \quad \text{Vol PoreCondWick} = 4.004 \cdot \text{cm}^3$$

$$\text{OD}_{\text{ReturnArtery}} := 0.125 \cdot \text{in}$$

$$A_{\text{Artery}} := \frac{\pi}{4} \cdot \text{OD}_{\text{ReturnArtery}}^2 \quad A_{\text{Artery}} = 0.079 \cdot \text{cm}^2$$

$$L_{\text{ReturnArtery}} := L_{\text{Condenser}} \quad L_{\text{ReturnArtery}} = 3.5 \cdot \text{in}$$

$$\phi_{\text{ReturnArtery}} := 0.15 \quad \text{Cable artery porosity}$$

$$\text{Vol ReturnArtery} := (1 - \phi_{\text{ReturnArtery}}) \cdot \frac{\pi}{4} \cdot \text{OD}_{\text{ReturnArtery}}^2 \cdot L_{\text{ReturnArtery}}$$

$$\text{Mass ReturnArtery} := \rho_{\text{Nickel}} \cdot \text{Vol ReturnArtery} \quad \text{Mass ReturnArtery} = 5.325 \cdot \text{gm}$$

$$\text{Vol PoreReturnArtery} := \phi_{\text{ReturnArtery}} \cdot \frac{\pi}{4} \cdot \text{OD}_{\text{ReturnArtery}}^2 \cdot L_{\text{ReturnArtery}} \quad \text{Vol PoreReturnArtery} = 0.106 \cdot \text{cm}^3$$

$$t_{\text{ArterySheath}} := 0.010 \cdot \text{in} \quad \text{Cable Artery Sheath wall thickness}$$

$$\text{OD}_{\text{ArterySheath}} := \text{OD}_{\text{ReturnArtery}} + 2 \cdot t_{\text{ArterySheath}} \quad \text{OD}_{\text{ArterySheath}} = 0.145 \cdot \text{in}$$

$$A_{\text{ArterySheath}} := \frac{\pi}{4} \cdot (\text{OD}_{\text{ArterySheath}}^2 - \text{OD}_{\text{ReturnArtery}}^2) \quad A_{\text{ArterySheath}} = 0.027 \cdot \text{cm}^2$$

$$\text{Vol}_{\text{ArterySheath}} := \frac{\pi}{4} \cdot (\text{OD}_{\text{ArterySheath}}^2 - \text{OD}_{\text{ReturnArtery}}^2) \cdot L_{\text{ReturnArtery}}$$

$$\text{Mass}_{\text{ArterySheath}} := \rho_{\text{Nickel}} \cdot \text{Vol}_{\text{ArterySheath}} \quad \text{Mass}_{\text{ArterySheath}} = 2.165 \cdot \text{gm}$$

Niobium wick

$$t_{\text{Nb_Wick}} := 0.020 \cdot \text{in}$$

$$\text{OD}_{\text{Nb_Wick}} := \text{OD}_{\text{Nb_Tube}} + 2 \cdot t_{\text{Nb_Wick}} \quad \text{OD}_{\text{Nb_Wick}} = 0.252 \cdot \text{in}$$

$$\phi_{\text{Nb_Wick}} := 0.42$$

$$\text{Vol}_{\text{Solid_Nb_Wick}} := (1 - \phi_{\text{Nb_Wick}}) \cdot \frac{\pi}{4} \cdot (\text{OD}_{\text{Nb_Wick}}^2 - \text{OD}_{\text{Nb_Tube}}^2) \cdot L_{\text{Nb_Tube}}$$

$$\text{Mass}_{\text{Solid_Nb_Wick}} := \rho_{\text{Nb}} \cdot \text{Vol}_{\text{Solid_Nb_Wick}} \quad \text{Mass}_{\text{Solid_Nb_Wick}} = 6.904 \cdot \text{gm}$$

$$\text{Vol}_{\text{Pore_Nb_Wick}} := \phi_{\text{Nb_Wick}} \cdot \frac{\pi}{4} \cdot (\text{OD}_{\text{Nb_Wick}}^2 - \text{OD}_{\text{Nb_Tube}}^2) \cdot L_{\text{Nb_Tube}}$$

$$\text{Vol Pore_Nb_Wick} = 0.583 \cdot \text{cm}^3$$

$$\text{Vol Pore_Wicks} := \text{Vol PoreCondWick} + \text{Vol PoreReturnArtery} + \text{Vol Pore_Nb_Wick}$$

$$\text{Vol Pore_Wicks} = 4.693 \cdot \text{cm}^3$$

$$\text{Mass Sodium} := \text{NaLiquidDensity}(350 \cdot ^\circ\text{C} + \text{K_To_}^\circ\text{C}) \cdot \text{Vol Pore_Wicks} \quad \text{Mass Sodium} = 4.076 \cdot \text{gm}$$

Heat Pipe Mass

Note: The outer cylinder of the heat pipe is included in the length of the cylinder above.

$$\text{Mass HeatPipeCap} := \text{Mass endcap} \quad \text{Mass HeatPipeCap} = 8.446 \cdot \text{gm}$$

$$t_{\text{HeatPipeWick}} := 0.100 \cdot \text{in}$$

$$\phi_{\text{HeatPipeWick}} := 0.42 \quad \text{Wick porosity}$$

$$\text{Vol SolidHeatPipeWick} := (1 - \phi_{\text{HeatPipeWick}}) \cdot \frac{\pi}{4} \cdot \text{ID}_{\text{Cell}}^2 \cdot t_{\text{HeatPipeWick}}$$

$$\text{Mass SolidHeatPipeWick} := \rho_{\text{Nickel}} \cdot \text{Vol SolidHeatPipeWick} \quad \text{Mass SolidHeatPipeWick} = 9.727 \cdot \text{gm}$$

$$\text{Vol NaHeatPipeWick} := (\phi_{\text{HeatPipeWick}}) \cdot \frac{\pi}{4} \cdot \text{ID}_{\text{Cell}}^2 \cdot t_{\text{HeatPipeWick}}$$

$$\text{Mass NaHeatPipeWick} := \text{NaLiquidDensity}(800 \cdot ^\circ\text{C} + \text{K_To_}^\circ\text{C}) \cdot \text{Vol NaHeatPipeWick} \quad \text{Mass NaHeatPipeWick} = 0.602 \cdot \text{gm}$$

Single Cell Mass

$$\text{Mass CellCylinder} = 115.051 \cdot \text{gm}$$

$$\text{Mass endcap} = 8.446 \cdot \text{gm}$$

$$\text{Mass LowerCap} = 6.586 \cdot \text{gm}$$

$$\text{Mass Nb_Tube} = 6.157 \cdot \text{gm}$$

$$\text{Mass HeatPipeCap} = 8.446 \cdot \text{gm}$$

$$\text{Mass Envelope} := \text{Mass endcap} + \text{Mass CellCylinder} + \text{Mass LowerCap} + \text{Mass Nb_Tube} + \text{Mass HeatPipeCap}$$

$$\text{Mass Envelope} = 144.687 \cdot \text{gm}$$

$$\text{Mass Sodium} = 4.076 \cdot \text{gm}$$

$$\text{Mass NaHeatPipeWick} = 0.602 \cdot \text{gm}$$

$$\text{Mass SolidCondwick} = 6.289 \cdot \text{gm}$$

$$\text{Mass ReturnArtery} = 5.325 \cdot \text{gm}$$

$$\text{Mass ArterySheath} = 2.165 \cdot \text{gm}$$

$$\text{Mass Solid_Nb_Wick} = 6.904 \cdot \text{gm}$$

$$\text{Mass SolidHeatPipeWick} = 9.727 \cdot \text{gm}$$

$$\begin{aligned} \text{Mass Wicks} := & \text{Mass SolidCondwick} + \text{Mass ReturnArtery} + \text{Mass ArterySheath} \dots \\ & + \text{Mass Solid_Nb_Wick} + \text{Mass Sodium} + \text{Mass SolidHeatPipeWick} + \text{Mass NaHeatPipeWick} \end{aligned}$$

$$\text{Mass Wicks} = 35.088 \cdot \text{gm}$$

AMTEC System Design

$$\text{Mass MolyWire} = 21.387 \cdot \text{gm}$$

$$\text{Mass CopperCable} = 2.963 \cdot \text{gm}$$

$$\text{Mass OuterCable} = 10.425 \cdot \text{gm}$$

$$\text{Mass Feedthrough} = 10 \cdot \text{gm}$$

$$\text{Mass BASE} = 25.108 \cdot \text{gm}$$

$$\text{Mass ElectricSystem} = \text{Mass CopperCable} + \text{Mass OuterCable} + \text{Mass Feedthrough} + \text{Mass MolyWire} + \text{Mass BASE}$$

$$\text{Mass ElectricSystem} = 69.883 \cdot \text{gm}$$

$$\text{Mass Envelope} = 144.687 \cdot \text{gm}$$

$$\text{Mass Wicks} = 35.088 \cdot \text{gm}$$

$$\text{Mass ElectricSystem} = 69.883 \cdot \text{gm}$$

$$\text{Mass Cell} = \text{Mass Envelope} + \text{Mass Wicks} + \text{Mass ElectricSystem}$$

$$\text{Mass Cell} = 249.658 \cdot \text{gm}$$

Operating Conditions

$$T_{\text{BASE}} := 800 \cdot ^\circ\text{C} + K_{\text{To}} \cdot ^\circ\text{C}$$

$$T_{\text{cond}} := 350 \cdot ^\circ\text{C} + K_{\text{To}} \cdot ^\circ\text{C}$$

$$V_{\text{OpenCircuit}}(T_{\text{BASE}}, T_{\text{cond}}) = 0.735 \cdot \text{volt}$$

Lead Losses

$$\Delta V_{\text{CopperCable}}(J) := (J \cdot A_{\text{BASE}}) \cdot \text{Resistance}_{\text{CopperCable}}$$

$$\Delta V_{\text{ContactResistance}}(J) := (J \cdot A_{\text{BASE}}) \cdot R_{\text{Contact}}$$

$$\Delta V_{\text{MolyCable}}(J) := (J \cdot A_{\text{BASE}}) \cdot \text{Resistance}_{\text{MolyCable}}$$

$$\Delta V_{\text{LeadLosses}}(J) := \Delta V_{\text{CopperCable}}(J) + \Delta V_{\text{ContactResistance}}(J) + \Delta V_{\text{MolyCable}}(J)$$

$$J_{\text{Max}} := 2 \cdot \frac{\text{amp}}{\text{cm}^2} \quad \text{Initial guess for maximum current}$$

$$J_{\text{Max}} := \text{root}(V_{\text{B}}(J_{\text{Max}}, T_{\text{BASE}}, T_{\text{cond}}, t_{\text{BASE}}) - \Delta V_{\text{LeadLosses}}(J_{\text{Max}}), J_{\text{Max}})$$

$$J_{\text{Max}} = 1.648 \cdot \frac{\text{amp}}{\text{cm}^2}$$

$$K_{\text{Max}} := 100$$

$$k := 0, 1 \dots K_{\text{Max}}$$

$$J_k := \frac{k}{K_{Max}} \cdot J_{Max}$$

$$V_{Base_k} := V_B(J_k, T_{BASE}, T_{cond}, t_{BASE})$$

$$V_{Base_{10}} = 0.687 \text{ •volt}$$

$$\Delta V_{CopperCable}(J_{10}) = 0.0186 \text{ •volt}$$

$$\Delta V_{ContactResistance}(J_{10}) = 0.0132 \text{ •volt}$$

$$\Delta V_{MolyCable}(J_{10}) = 0.001 \text{ •volt}$$

$$V_{Loss_k} := \Delta V_{LeadLosses}(J_k)$$

$$V_{Loss_{10}} = 0.033 \text{ •volt}$$

$$V_{Out_k} := V_{Base_k} - V_{Loss_k}$$

$$V_{Out_{10}} = 0.654 \text{ •volt}$$

$$Power_{BASE_k} := J_k \cdot V_{Out_k} \cdot A_{BASE}$$

$$I_{BASE_k} := J_k \cdot A_{BASE}$$

Output Voltage and Voltage across the BASE

Power versus Current Density

Cell Efficiency

Start with the heat required for the sodium circulation. This can be broken into two parts:

1. The latent heat for evaporation at T_{Base}
2. The specific heat for going from T_{Cond} to T_{Base} .

Heat Flux

$$q_{Na_Flow_k} := \frac{J_k \cdot NaMolecWeight}{Faraday} \cdot \left[NaLatentHeat(T_{BASE}) + c_{p_Na_Liq} \left(\frac{T_{BASE} + T_{cond}}{2} \right) \cdot (T_{BASE} - T_{cond}) \right]$$

$$q_{Na_Flow_{50}} = 0.987 \cdot \frac{watt}{cm^2}$$

$$Q_{Na_Flow_k} := q_{Na_Flow_k} \cdot A_{BASE}$$

$$Q_{Na_Flow_{50}} = 60.043 \cdot watt$$

$$J_{10} = 0.165 \cdot \frac{amp}{cm^2}$$

$$Q_{Na_Flow_{10}} = 12.009 \cdot watt$$

Parasitic Heat Losses

The high temperature wick-fed design has a high temperature feed-through, and a cylinder temperature equal to the BASE temperature.

The following are parasitic losses:

1. Radiation from the BASE cylinder to the heat shield (and then to the condenser)
2. Radiation from the BASE top to the heat shield (and then to the condenser)
3. Conduction through the return artery
4. Conduction up the cylinder wall from the high temperature region to the low temperature condenser. Note that the wall thickness is minimized to reduce this loss as much as possible.

There are also a number of smaller losses that can be neglected: radiation directly from the BASE to the condenser through the flow passage and other small leaks.

Radiation to the Heat Shield and Condenser

The outer cylinder, BASE, and the top of the BASE are all at about the same temperature. These surfaces will act like a black body with an area equal to the area of the heat shield.

Ref: R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer*, Third Edition, Hemisphere Publishing Company, Washington, D.C., pg. 372-373, 1992.

The radiation from the BASE/enclosure to the shield can be written as

$$\frac{Q}{A_{BASE}} \cdot \left(\frac{1}{1} + \frac{1}{\epsilon_{HeatShield}} - 1 \right) = \text{StefanBoltzmann} \cdot (T_{BASE}^4 - T_{Shield}^4)$$

where we have assumed that the BASE/enclosure acts like a Black Body.

The radiation from the shield to the condenser can be written as:

$$\frac{Q}{A_{BASE}} \cdot \left(\frac{1}{\epsilon_{HeatShield}} + \frac{1}{\epsilon_{Condenser}} - 1 \right) = \text{StefanBoltzmann} \cdot (T_{Shield}^4 - T_{cond}^4)$$

Adding the two equations,

$$\frac{Q}{A_{BASE}} \cdot \left(\frac{1}{1} + \frac{2}{\epsilon_{HeatShield}} + \frac{1}{\epsilon_{Condenser}} - 2 \right) = \text{StefanBoltzmann} \cdot (T_{BASE}^4 - T_{cond}^4)$$

Solving for the heat transfer

$$Q_{Radiation} = \frac{\text{StefanBoltzmann} \cdot A_{BASE} \cdot (T_{BASE}^4 - T_{cond}^4)}{\left(\frac{1}{1} + \frac{2}{\epsilon_{HeatShield}} + \frac{1}{\epsilon_{Condenser}} - 2 \right)}$$

$$Q_{Radiation} = 13.978 \cdot \text{watt}$$

Conduction through the return artery and sheath

$$A_{\text{Artery}} = 0.079 \cdot \text{cm}^2$$

$$L_{\text{ReturnArtery}} = 3.5 \cdot \text{in}$$

$$K_{\text{ReturnArtery}} := \phi_{\text{ReturnArtery}} \cdot \text{NaThermalCond} \left(\frac{T_{\text{BASE}} + T_{\text{cond}}}{2} \right) + (1 - \phi_{\text{ReturnArtery}}) \cdot k_{\text{Steel}}$$

$$K_{\text{ReturnArtery}} = 23.399 \cdot \frac{\text{watt}}{\text{m} \cdot \text{K}}$$

$$Q_{\text{ReturnArtery}} := (K_{\text{ReturnArtery}} \cdot A_{\text{Artery}} + k_{\text{Steel}} \cdot A_{\text{ArterySheath}}) \cdot \left(\frac{T_{\text{BASE}} - T_{\text{cond}}}{L_{\text{ReturnArtery}}} \right)$$

$$Q_{\text{ReturnArtery}} = 1.163 \cdot \text{watt}$$

Conduction From the Hot Outer Cylinder to the Condenser

$$Q_{\text{ConductCylinder}} := (k_{\text{Steel}} \cdot A_{\text{CrossSectCylinder}}) \cdot \left(\frac{T_{\text{BASE}} - T_{\text{cond}}}{L_{\text{ReturnArtery}}} \right)$$

$$Q_{\text{ConductCylinder}} = 4.114 \cdot \text{watt}$$

$$Q_{\text{ReturnArtery}} = 1.163 \cdot \text{watt}$$

$$Q_{\text{ConductCylinder}} = 4.114 \cdot \text{watt}$$

$$Q_{\text{Radiation}} = 13.978 \cdot \text{watt}$$

$$Q_{\text{Parasitic}} := Q_{\text{ReturnArtery}} + Q_{\text{ConductCylinder}} + Q_{\text{Radiation}}$$

$$Q_{\text{Parasitic}} = 19.255 \cdot \text{watt}$$

$$\text{Efficiency}_k := \frac{\text{Power}_{\text{BASE}_k}}{\text{Power}_{\text{BASE}_k} + Q_{\text{Na_Flow}_k} + Q_{\text{Parasitic}}}$$

$$J_{10} = 0.165 \cdot \frac{\text{amp}}{\text{cm}^2}$$

$$\text{Efficiency}_{10} = 0.173$$

AMTEC Cell Efficiency

Maximum Power

$K_{\text{maxpower}} := \begin{cases} \text{for } k \in 1, 2 \dots K_{\text{Max}} \\ K1 \leftarrow k \text{ if } \text{Power}_{\text{BASE}_k} > \text{Power}_{\text{BASE}_{k-1}} \\ K_{\text{maxpower}} \leftarrow K1 \end{cases}$

$$K_{\text{maxpower}} = 49$$

$$\text{Efficiency}_{K_{\text{maxpower}}} = 0.185 \quad I_{\text{BASE}_{K_{\text{maxpower}}}} = 49.113 \cdot \text{amp} \quad J_{K_{\text{maxpower}}} = 0.808 \cdot \frac{\text{amp}}{\text{cm}^2}$$

$$\text{Power}_{\text{BASE}_{K_{\text{maxpower}}}} = 17.701 \cdot \text{watt} \quad V_{\text{Out}_{K_{\text{maxpower}}}} = 0.36 \cdot \text{volt}$$

Maximum Efficiency

The cell will be designed to operate at the maximum efficiency.

$K_{\text{maxeff}} := \begin{cases} \text{for } k \in 1, 2 \dots K_{\text{Max}} \\ K1 \leftarrow k \text{ if } \text{Efficiency}_k > \text{Efficiency}_{k-1} \\ K_{\text{maxeff}} \leftarrow K1 \end{cases}$
Find the point of maximum efficiency

$$K_{\text{maxeff}} = 26$$

$$\text{Efficiency}_{\text{Cell}} := \text{Efficiency}_{K_{\text{maxeff}}} \quad \text{Efficiency}_{\text{Cell}} = 0.215$$

$$\text{Current}_{\text{Cell}} := I_{\text{BASE}_{K_{\text{maxeff}}}} \quad \text{Current}_{\text{Cell}} = 26.06 \cdot \text{amp}$$

AMTEC System Design

$$\text{CurDensity}_{\text{Cell}} := J_{K_{\text{maxeff}}} \quad \text{CurDensity}_{\text{Cell}} = 0.429 \cdot \frac{\text{amp}}{\text{cm}^2}$$

$$\text{Power}_{\text{Cell}} := \text{Power}_{\text{BASE}_{K_{\text{maxeff}}}} \quad \text{Power}_{\text{Cell}} = 13.822 \cdot \text{watt}$$

$$\text{Voltage}_{\text{Cell}} := V_{\text{Out}_{K_{\text{maxeff}}}} \quad \text{Voltage}_{\text{Cell}} = 0.53 \cdot \text{volt}$$

$$\text{ThermalPower}_{\text{Cell}} := \frac{\text{Power}_{\text{Cell}}}{\text{Efficiency}_{\text{Cell}}} \quad \text{ThermalPower}_{\text{Cell}} = 64.299 \cdot \text{watt}$$

Cell Heat Pipe

Estimate the size of the hot shoe required to supply the power to each AMTEC cell. Assume an effective emissivity of 0.75 between the GPHS and the hot shoe.

$$\epsilon_{\text{HotShoeEff}} := 0.75$$

$$T_{\text{GPHS}} := 1100 \cdot ^\circ\text{C} + K_{\text{To}_\circ\text{C}} \quad T_{\text{GPHS}} = 1373.16 \cdot \text{K}$$

$$\text{ThermalPower}_{\text{Cell}} = 64.299 \cdot \text{watt}$$

$$A_{\text{HotShoe}} := \frac{\text{ThermalPower}_{\text{Cell}}}{\text{StefanBoltzmann} \cdot \epsilon_{\text{HotShoeEff}} (T_{\text{GPHS}}^4 - T_{\text{BASE}}^4)} \quad A_{\text{HotShoe}} = 6.783 \cdot \text{cm}^2$$

$$D_{\text{HotShoe}} := \sqrt{\frac{4 \cdot A_{\text{HotShoe}}}{\pi}} \quad D_{\text{HotShoe}} = 2.939 \cdot \text{cm}$$

$$D_{\text{HotShoe}} = 1.157 \cdot \text{in} \quad \text{OD}_{\text{Cell}} = 1.25 \cdot \text{in}$$

AMTEC Cell Condenser

Estimate the condenser required to reject the waste heat.

$$T_{\text{Sink}} := K_{\text{To}} \cdot ^\circ\text{C}$$

$$Q_{\text{WasteHeat}} := \text{ThermalPower}_{\text{Cell}} - \text{Power}_{\text{Cell}} \quad Q_{\text{WasteHeat}} = 50.477 \cdot \text{watt}$$

$$A_{\text{Condenser}} := \frac{\text{ThermalPower}_{\text{Cell}}}{\text{StefanBoltzmann} \cdot \epsilon_{\text{Rejection}} \cdot (T_{\text{cond}}^4 - T_{\text{Sink}}^4)} \quad A_{\text{Condenser}} = 86.76 \cdot \text{cm}^2$$

$$A_{\text{endcap}} = 7.917 \cdot \text{cm}^2$$

$$\text{OD}_{\text{Cell}} = 3.175 \cdot \text{cm}$$

$$L_{\text{Condenser}} := \frac{A_{\text{Condenser}} - A_{\text{endcap}}}{\pi \cdot \text{OD}_{\text{Cell}}} \quad L_{\text{Condenser}} = 7.904 \cdot \text{cm} \quad L_{\text{Condenser}} = 3.112 \cdot \text{in}$$

Note: this number should agree with the length specified above.

AMTEC System Design

The system would be powered by 18 GPHS modules, with a total thermal power of 4500 watts.

$$\text{Power}_{\text{SingleGPHS}} := 250 \cdot \text{watt}$$

$$\text{No}_{\text{GPHS}} := 18$$

$$\text{TotalThermalPower} := \text{No}_{\text{GPHS}} \cdot \text{Power}_{\text{SingleGPHS}}$$

$$\text{TotalThermalPower} = 4500 \cdot \text{watt}$$

Multiply and divide by 4 to get a number divisible by 4.

$$\text{No}_{\text{AMTEC_Cells}} := 4 \cdot \text{floor} \left(\frac{\text{TotalThermalPower}}{\text{ThermalPower}_{\text{Cell}}} \right)$$

$$\text{No}_{\text{AMTEC_Cells}} = 68$$

$$\text{ElectricPower} := \text{No}_{\text{AMTEC_Cells}} \cdot \text{Power}_{\text{Cell}}$$

$$\text{ElectricPower} = 939.88 \cdot \text{watt}$$

AMTEC System Geometry

Examine the required AMTEC cell spacing. Assume:

1. The GPHS cells are in a single column.
2. The cells are located around all 4 sides of the GPHS stack.

$$W_{\text{GPHS}} := 9.4 \cdot \text{cm}$$

$$L_{\text{GPHS}} := 9.97 \cdot \text{cm}$$

$$H_{\text{GPHS}} := 5.38 \cdot \text{cm}$$

$$H_{\text{GPHS}} = 2.118 \cdot \text{in}$$

AMTEC System Design

$$H_{Stack} := No_{GPHS} \cdot H_{GPHS}$$

$$H_{Stack} = 96.84 \cdot \text{cm}$$

$$H_{Stack} = 38.126 \cdot \text{in}$$

How much of the total area will the cells take up?

$$H_{CellString} := \frac{No_{AMTEC_Cells}}{4} \cdot OD_{Cell}$$

$$H_{CellString} = 21.25 \cdot \text{in}$$

AMTEC System Mass

Use masses from the Sievers and Bankston paper, with revised cell weights.

$$Mass_{GPHS} := 26.1 \cdot \text{kg}$$

$$Mass_{Multifoil} := 3.6 \cdot \text{kg}$$

$$Mass_{Al_Structure} := 4.4 \cdot \text{kg}$$

$$Mass_{Ceramic_Supports} := 4.6 \cdot \text{kg}$$

$$Mass_{AMTEC_Cells} := No_{AMTEC_Cells} \cdot Mass_{Cell}$$

$$Mass_{AMTEC_Cells} = 16.977 \cdot \text{kg}$$

$$Mass_{System} := Mass_{GPHS} + Mass_{Multifoil} + Mass_{Al_Structure} + Mass_{Ceramic_Supports} + Mass_{AMTEC_Cells}$$

$$Mass_{System} = 55.677 \cdot \text{kg}$$

$$SystemSpecificPower := \frac{ElectricPower}{Mass_{System}}$$

$$SystemSpecificPower = 16.881 \cdot \frac{\text{watt}}{\text{kg}}$$

Thermal Conductivities

$$k_{\text{Steel}} \approx 16.3 \cdot \frac{\text{watt}}{\text{m} \cdot \text{K}}$$

Emissivities

$$\varepsilon_{\text{BASE}} \approx 0.700 \quad \text{BASE tube}$$

$$\varepsilon_{\text{Stainless}} \approx 0.40 \quad \text{Interior of the stainless tube}$$

$$\varepsilon_{\text{Condenser}} \approx 0.05 \quad \text{Condenser (partially sodium covered)}$$

$$\varepsilon_{\text{HeatShield}} \approx 0.20 \quad \text{Heat Shield}$$

$$\varepsilon_{\text{Rejection}} \approx 0.9 \quad \text{Outside surface of the condenser (Iron titanate)}$$

Densities

$$\rho_{\text{Moly}} \approx 10220 \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{\text{BASE}} \approx 3900 \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{\text{Nickel}} \approx 8900 \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{\text{Stainless}} \approx 8400 \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{\text{Copper}} = 9000 \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{\text{CuScreen}} = 68 \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{\text{Nb}} = 8570 \cdot \frac{\text{kg}}{\text{m}^3}$$

Electric Resistivities

$$\text{Resis}_{\text{Cu}} = 6.514 \cdot 10^{-6} \cdot \text{ohm} \cdot \text{cm}$$

$$\text{Resis}_{\text{Mo}} = 1.878 \cdot 10^{-5} \cdot \text{ohm} \cdot \text{cm}$$

Constants

$$\text{Zero} = 0.$$

$$\text{K_To_}^{\circ}\text{C} = 273.16 \cdot \text{K} \quad \quad \quad ^{\circ}\text{C} = \text{K}$$

$$^{\circ}\text{F} = \text{R}$$

$$\text{R_To_}^{\circ}\text{F} = \text{K_To_}^{\circ}\text{C} - 32 \cdot ^{\circ}\text{F}$$

$$\text{AtmosphericPressure} = 101350 \cdot \text{Pa}$$

$$\text{BoltzmannConstant} = 1.3805 \cdot 10^{-23} \cdot \frac{\text{joule}}{\text{K}}$$

$$\text{StefanBoltzmann} = 5.670 \cdot 10^{-8} \cdot \frac{\text{watt}}{\text{m}^2 \cdot \text{K}^4}$$

$$\text{Avogadro} \equiv 6.0225 \cdot 10^{26} \cdot \frac{1}{\text{mole}} \quad \text{Avogadro's number, kg-mole}$$

$$\text{Faraday} \equiv 96500 \cdot 1000 \cdot \frac{\text{coul}}{\text{mole}} \quad \text{Faraday Constant, kg-mole}$$

Fluid Properties

Sodium

May 24, 1994

Fluid Properties for Sodium.

Reference: *Handbook of Thermodynamic and Transport Properties of Alkali Metals*, Roland W. Ohse, Editor, Blackwell Scientific Publications, Boston, MA, 1985.

O. J. Foust, Editor, *Sodium-NaK Engineering Handbook, Volume 1: Sodium Chemistry and Physical Properties*, Gordon and Breach, Inc., New York, New York, 1972.

$$\text{GasConstant} \equiv 8314.4 \cdot \frac{\text{joule}}{\text{mole} \cdot \text{K}} \quad \text{joule/kg-mole K}$$

$$\text{NaMolecWeight} \equiv 22.9898 \cdot \frac{\text{kg}}{\text{mole}} \quad \text{CRC Handbook of Tables for Applied Engineering Science}$$

$$\text{NaGasConstant} \equiv \frac{\text{GasConstant}}{\text{NaMolecWeight}}$$

$$\gamma_{\text{Na}} \equiv 1.67 \quad \text{Sodium Specific Heat Ratio}$$

Melting temperature, Ohse, pg. 334

$$T_{\text{Nmelt}} \equiv 370.90 \cdot \text{K}$$

$$\text{NaMoleculeMass} \equiv \frac{\text{NaMolecWeight}}{\text{Avogadro}}$$

$$\text{NaMoleculeMass} = 0.382 \cdot 10^{-25} \cdot \text{kg}$$

Critical Properties, Ohse, page 99

$$\text{NaCriticalTemperature} \equiv 2507 \cdot \text{K}$$

$$\text{NaCriticalPressure} \equiv 26.16 \cdot 10^6 \cdot \text{Pa}$$

$$\text{NaCriticalDensity} \equiv 209.7 \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\text{NaZCritical} \equiv \frac{\text{NaCriticalPressure}}{\text{NaCriticalDensity} \cdot \text{NaGasConstant} \cdot \text{NaCriticalTemperature}}$$

$$\text{NaZCritical} = 0.138$$

$$\rho_{\text{NaCrit}} \equiv \frac{\text{NaCriticalPressure}}{\text{NaZCritical} \cdot \text{GasConstant} \cdot \text{NaCriticalTemperature}}$$

$$\rho_{\text{NaCrit}} = 9.121 \cdot \text{m}^{-3}$$

$$\text{NaVCritical} \equiv \frac{1}{\rho_{\text{NaCrit}}}$$

$$\text{NaVCritical} = 0.1096 \cdot \text{m}^3 \quad \text{m}^3/\text{kg-mole, or } 110 \text{ cm}^3/\text{gram-mole}$$

Sodium Vapor Pressure Curve. Ohse, pg. 351, $864 < \text{Kelvin} < 2361$

$$\text{NaVaporPressure}(\text{Kelvin}) \equiv \left(\frac{\text{K}}{\text{Kelvin}} \right)^{0.3869} \cdot \exp \left[11.2916 - \left(\frac{12532.694 \cdot \text{K}}{\text{Kelvin}} \right) \right] \cdot 10^6 \cdot \text{Pa}$$

Na Surface Tension: Ohse, pg. 692

$$\text{NaSurfaceTension}(\text{Kelvin}) \equiv 0.1979 \cdot \frac{\text{newton}}{\text{m}} - 1.01 \cdot 10^{-4} \cdot \frac{\text{newton}}{\text{m}} \cdot \frac{1}{\text{K}} \cdot (\text{Kelvin} - T_{\text{Namelt}})$$

L = 1, 2.. 20

Sodium Liquid Density: Ohse, pg. 459, $T_{\text{melt}} < T(\text{K}) < 2500$

$$\text{NaLiquidDensity}(\text{Kelvin}) \equiv 1000 \cdot \left[0.89660679 + 0.51613430 \cdot \frac{1}{\text{K}} \cdot \left(\frac{\text{Kelvin}}{1000} \right) \dots \right] \cdot \frac{\text{kg}}{\text{m}^3}$$

$$+ - 1.8297218 \cdot \frac{1}{\text{K}^2} \cdot \left(\frac{\text{Kelvin}}{1000} \right)^2 + 2.2016247 \cdot \frac{1}{\text{K}^3} \cdot \left(\frac{\text{Kelvin}}{1000} \right)^3 \dots$$

$$+ - 1.3975634 \cdot \frac{1}{\text{K}^4} \cdot \left(\frac{\text{Kelvin}}{1000} \right)^4 + 0.44866894 \cdot \frac{1}{\text{K}^5} \cdot \left(\frac{\text{Kelvin}}{1000} \right)^5 \dots$$

$$+ - .057963628 \cdot \frac{1}{\text{K}^6} \cdot \left(\frac{\text{Kelvin}}{1000} \right)^6$$

Thermal conductivity from Foust, pg. 46, Evangelisti and Isacchini Equation, 105 to 832°C

$$\text{NaThermalCond}(\text{Kelvin}) \equiv 100 \cdot \frac{\text{watt}}{\text{m} \cdot \text{K}} \cdot \left[0.918 - 4.9 \cdot 10^{-4} \cdot \frac{1}{\text{K}} \cdot (\text{Kelvin} - K_{\text{To_}^\circ\text{C}}) \right]$$

Sodium Dynamic Liquid Viscosity, Ohse, page 771, $T_{\text{melt}} < T(\text{K}) < 2000$, Pa*sec

$$\text{NaMuLiquid}(\text{Kelvin}) \equiv \left(\frac{\text{Kelvin}}{\text{K}} \right)^{-0.3958} \cdot \exp \left(-6.4406 + \frac{556.835 \cdot \text{K}}{\text{Kelvin}} \right) \cdot \frac{\text{kg}}{\text{m} \cdot \text{sec}}$$

Sodium Dynamic Vapor Viscosity, Ohse, pg. 822, assume $x_2=0$, kg/m*sec

$$\text{NaMuVapor}(\text{Kelvin}) \equiv \left[213.1 + 0.165 \cdot \left(\frac{\text{Kelvin}}{\text{K}} - 1000 \right) \right] \cdot 10^{-7} \cdot \frac{\text{kg}}{\text{m} \cdot \text{sec}}$$

Sodium Vapor Density, kg/m³

For now, assume an ideal gas: see Ohse, Section 6.6 later

NaZFactor $\equiv$ 1.0

$$\text{NaVaporDensity (Kelvin)} = \frac{\text{NaVaporPressure (Kelvin)}}{\text{NaZFactor} \cdot \frac{\text{GasConstant}}{\text{NaMolecWeight}} \cdot \text{Kelvin}}$$

Sodium Sound Speed, m/s

For now, assume an ideal gas

$$\text{NaSoundSpeed (Kelvin)} = \sqrt{\gamma_{\text{Na}} \cdot \frac{\text{GasConstant}}{\text{NaMolecWeight}} \cdot \text{Kelvin}}$$

Latent Heat, J/kg

Ohse, page 351

At T=1154.8 K, H=100.486*10³ joule/gram-mole.

Using the Watson relation

Ref: R. C. Reid, J. M. Prausnitz, and T. K. Sherwood, *The Properties of Liquids and Gases*, Third Edition, page 210, McGraw Hill, N.Y., N.Y., 1977.

$$\text{NaLatentHeat (Kelvin)} \equiv 100.486 \cdot 10^3 \cdot \frac{\text{joule}}{\text{mole}} \cdot \frac{1000}{\text{NaMolecWeight}} \cdot \left[\frac{1 - \frac{\text{Kelvin}}{\text{NaCriticalTemperature}}}{1 - \frac{1154.8 \cdot \text{K}}{\text{NaCriticalTemperature}}} \right]^{0.38}$$

Liquid Sodium Specific Heat

$T_{\text{melt}} < T < 1600 \text{ K}$

Ohse, pg. 426. Original version in gram-moles

$$c_{p_Na_Liq}(\text{Kelvin}) = \left[40.656 - 2.6410 \cdot 10^{-2} \cdot \left(\frac{\text{Kelvin}}{\text{K}} \right) + 1.4363 \cdot 10^{-5} \cdot \left(\frac{\text{Kelvin}}{\text{K}} \right)^2 \right] \cdot \frac{\text{joule}}{\text{mole} \cdot \text{K}} \cdot \left[\frac{1}{\left(\frac{\text{NaMolecWeight}}{1000} \right)} \right]$$

$$c_{p_Na_Liq}(917 \cdot \text{K}) = 1.24 \cdot 10^3 \frac{\text{joule}}{\text{kg} \cdot \text{K}}$$