University of Southern California

ASTE 572 Resistojet Design Project

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Summary

This project involved the design of a resistojet for stationkeeping and attitude control maneuvers. The resistojet designed was a small thruster approximately 10 cm in length and 3 cm in diameter. The resistojet used gaseous hydrogen propellant heated over a tungsten coil at ~2000K and expanded through a converging-diverging nozzle with an area ratio of 100. The system was powered by a 2500W DC power supply operating at 1000A and 2.5V. The resistojet provided a thrust force of 1.00N with a specific impulse of 551 seconds at normal operating conditions. When paired with a propellant tank containing 32kg of gaseous hydrogen on a 1000-kg spacecraft, the system was able to provide 163 m/s of velocity change (ΔV). In this configuration, the system would be able to provide highly efficient propulsion for gross attitude control and station-keeping, for operations such as re-tasking sensors, desaturating reaction wheels, and minimizing orbital perturbations.

Propellant

Gaseous hydrogen was selected as the propellant for this application. Hydrogen has numerous characteristics that make it favorable as a propellant choice, namely 1) its low molecular weight and high gas constant which contribute to its high specific impulse, and 2) its high thermal conductivity and resultant high heat transfer coefficient which enable it to effectively cool the resistive element through convection. In this design, gaseous hydrogen stored at high pressure (approx. 500 bar) is passed through a pressure regulator and injected into the chamber at low pressure (1.5 bar). Injection velocity is 5 m/s and mass flow rate is 0.2 g/s. Chamber inlet conditions are depicted in Table 1 below (properties shown for the cross section at length x_0 as depicted in Figure 2a).

Table 1: Propellant Properties at Chamber Inlet

Chamber Inlet Conditions		
Mass Flow Rate [kg/s]	$\dot{m}$	0.0002
Pressure [atm]	P_0	1.50
Density [kg/m^3]	ρ_0	0.1273
Temperature [kg/m^3]	T_0	290
Chamber Diameter [m]	D_c	0.02
Chamber Area [m^2]	A_c	0.0003142
Speed [m/s]	u_0	5
Speed of Sound [m/s]	a_0	1284.31
Mach number	M_0	0.0039
Ratio of Specific Heats	γ	1.3789
Constant Pressure Specific Heat [J/kg·K]	C_p	15011.58
Dynamic Viscocisty [kg/m·s]	M	8.76E-06
Thermal Conductivity [W/m·K]	k	0.1897
Reynolds Number	Re	1453.65
Prantdl Number	Pr	0.6929

Propellant specific heat, viscosity, and thermal conductivity have been modeled as a function of temperature. This enables calculation of the Reynolds number, Prandtl number, and convection coefficient specific to the temperature conditions at the time. Specific heat, viscosity, and thermal conductivity were modeled by using point parameters at temperatures ranging from 250K to 2000K and conducting a least-squares regression using a polynomial fit. The properties were assumed to vary with temperature only. The table of point parameters used is below, Table 2. Each property is graphed as a function of temperature from 250K-2000K in Appendix A, Figures A-1 through A-3.

Table 2: Hydrogen Properties at Varying Temperatures

Temperature [K]	Specific Heat [J/kg·K]	Dynamic Viscosity [kg/m·s]	Thermal Conducivity [W/m·K]
250	15330	0.0000079	0.176
300	14850	0.00000895	0.194
400	14550	0.0000109	0.231
500	14520	0.0000127	0.269
600	14550	0.0000143	0.305
800	14700	0.0000174	0.375
1000	14980	0.0000203	0.445
1500	16050	0.0000268	0.622
2000	18180	0.0000326	0.892

Chamber Design

A single coiled tungsten resistive element will heat the propellant inside the heating chamber. Tungsten was chosen as the heater element primarily due to its high melting temperature, over 3000K. The chamber in which the tungsten element sits is an Inconel-625 cylinder 7 cm in length with a 3 cm outer diameter and 2 cm inner diameter. The tungsten coil will form a single spiral axially along the length of the chamber, with a total coil length of 28.27 cm along a 6 cm stretch of the chamber. The coil will be 0.5 cm thick, with a 0.25 cm gap between the coil and the wall of the chamber, and a 0.5 cm diameter cylindrical gap in the middle of the chamber axially. The coil will be wrapped in an insulator where it meets the skin of the chamber to prevent unwanted charging of the chamber and ensure an airtight seal. The chamber will be fed gaseous hydrogen from several orifices in the front and will be open to vacuum at the nozzle end. The chamber and coil (or filament) geometry are sketched in Figures 2a and 2b. The chamber geometrical characteristics are listed in Table 3.

Figure 2a: Resistojet sketch, top-down view

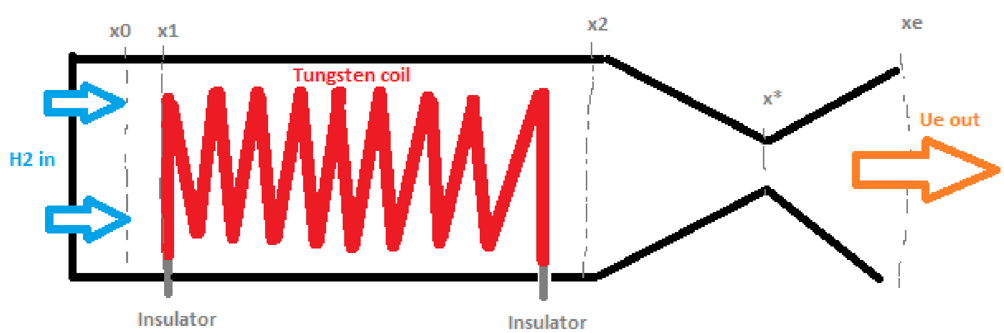

Figure 2b: Resistojet chamber sketch, axial view

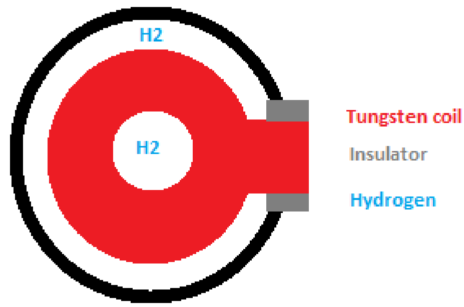

Table 3: Heating Chamber Geometry

Chamber		
D_chamber	0.02	m
D_heater	0.015	m
D_filament	0.005	m
Filament spacing (radial)	0.005	m
Filament spacing (axial)	0.005	m
L_filament(total)	0.282743339	m
L_heater	0.06	m
L_chamber	0.07	m
A_chamber	0.000314159	m^2
A_heater (elements only)	0.00015708	m^2
A_chamber minus heater elements	0.00015708	m^2
A_heater, surface	0.004441322	m^2
S_T	0.01	m

Propellant gas is injected into the chamber at low pressure and low speed. Chamber pressure stabilizes at about 1.5 atm, with flow velocities of 5 m/s at entry, increasing to 20 m/s prior to entering the nozzle, due to flow restriction and heat addition by the heating elements. Pressure drop along the chamber was estimated using the Darcy-Weisbach formula and the Colebrook equation to equal 19.06 N/m^2, low enough to be neglected in calculations when compared to the 1.5 atm (153,000 N/m^2) chamber pressure.

Referencing the sketch in Figure 2a, the simplified model of the flow presented in this analysis proceeds as follows: from a pressure regulator outside the chamber, the H_2 gas propellant enters the chamber at 1.5 atm and 5 m/s, with initial conditions shown for the cross section at chamber length x_0. At x_1, the propellant undergoes isentropic flow restriction due to the geometry of the heater elements but has not yet had any heat addition. From x_1 to x_2, heat addition occurs axially at constant pressure, with both the gas and the heating element increasing in temperature as they approach x_2. At x_2, the flow restriction from the heating elements is removed, and the gas proceeds isentropically through the converging-diverging nozzle, reaching M=1 at the throat at

x^*, and exiting the nozzle at x_e. Chamber conditions at x_1 are shown next to chamber conditions at x_0 in Table 4 below.

Table 4: Propellant Properties at x_0 and x_1

Parameter		x_0	x_1
Mass Flow Rate [kg/s]	$\dot{m}$	0.0002	0.0002
Pressure [atm]	P_0	1.50	1.50
Density [kg/m^3]	ρ_0	0.1273	0.1273
Temperature [kg/m^3]	T_0	290	290
Chamber Diameter [m]	D_c	0.02	0.01
Chamber Area [m^2]	A_c	0.0003142	0.00015708
Speed [m/s]	u_0	5	10
Speed of Sound [m/s]	a_0	1284.31	1284.30
Mach number	M_0	0.0039	0.007786
Ratio of Specific Heats	γ	1.3789	1.3789
Constant Pressure Specific Heat [J/kg·K]	C_p	15011.58	15011.58
Dynamic Viscocisty [kg/m·s]	M	8.76E-06	8.76-06
Thermal Conductivity [W/m·K]	k	0.1897	0.1897
Reynolds Number	Re	1453.65	2907.33
Prantdl Number	Pr	0.6929	0.6929

The maximum temperature of the chamber and nozzle occurs in the chamber in line with the end of the heating element. The inner wall temperature there reaches a peak of 1069 K, hot but well below Inconel-625's maximum working temperature of 1366K, providing a nearly 300 K buffer (21%). To calculate wall temperatures, vacuum radiation heat flux was set equal to both the conductive heat flux in the Inconel-625 wall, as well as the convective heat flux to the wall from the hydrogen gas with a maximum mean temperature of 1138 K, and substitution was used to solve. A summary of the chamber materials and heating characteristics is provided in Table 5.

Table 5: Chamber materials and heating parameters

Parameter	Value
Chamber material	Inconel-625
Max working temp	1366 K
Thermal conductivity	12.3 W/m·K
Wall thickness	.005 m
Location of max temp	x_2
Max temp	1069 K
Heat in (q^{ii}) at max temp location	37,686 W/m^2
Coolant	H_2 gas
Convective coefficient (h)	556 W/m^2·K
Chamber outer wall max temp	1061 K
Inconel emissivity (est.)	0.5
LEO free stream temperature	394 K

Heating Element

This project used a single tungsten coil heating element as previously described. The resistivity and specific heat of tungsten varies widely with temperature. As a result, equations for both resistivity and specific heat as a function of temperature were developed for tungsten and used to improve the accuracy of the analysis. Thermal conductivity of tungsten was assumed constant at 98 W/m·K. Hydrogen properties were also calculated as a function of temperature. Flow was generally considered turbulent, though Reynolds numbers values were lower than might have been realistic given the configuration of the heating element and the significant turbulence its presence would likely cause. Thermal analysis of the ohmic heating and convection cooling balance used the tungsten element with a constant 2500W heat output which was dissipated by convection cooling from the hydrogen gas. Radiation heat flux from the tungsten element was considered negligible, though radiation from the thruster as a whole was used to calculate Inconel wall temperatures (as described above and shown in Table 5). Temperatures of the tungsten wall and the hydrogen gas, as well as flow parameters, were calculated and integrated at every .001 m of tungsten element. The maximum material temperature of 2154 K occurs in the center of the tungsten element at its rearmost point in the chamber, just before the nozzle. This is coincident with the hottest point of the hydrogen gas, at 1138 K. This occurs because the hydrogen propellant and coolant is constantly heating at it proceeds axially along the element, and the element grows hotter along with the propellant. The tungsten element's maximum steady state temperature of 2154 K is well below the tungsten melting temperature of 3695 K, a margin of almost 1500 K. A depiction of the hydrogen gas and tungsten filament temperatures is shown in Figure 3 below. Table 6 shows key parameters of the heat transfer analysis.

Figure 3: Hydrogen and Tungsten Temperatures

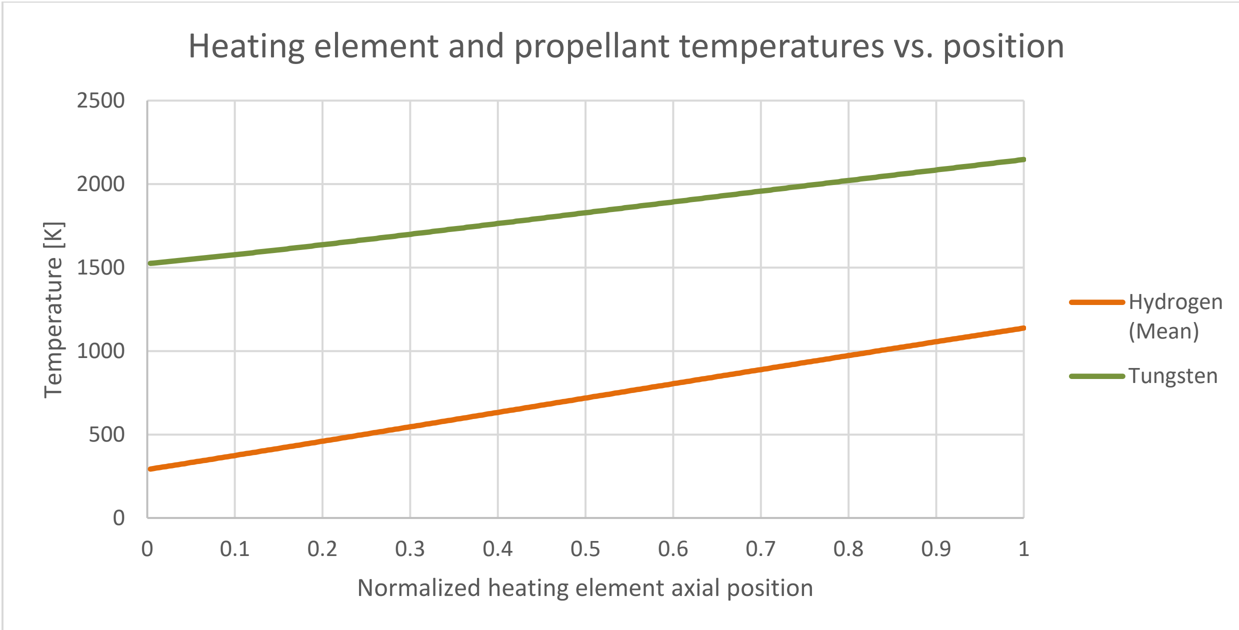

Table 6: Heat transfer analysis parameters

Parameter	Value
Heater material	Tungsten
Melting temp	3693 K
Thermal conductivity	98 W/m·K
Specific heat, C_p	132-198 J/kg·K
Heater wall temperature	1525-2147 K
Heater center temperature (max)	2154 K
Coolant	H_2 gas
Constant Pressure Specific Heat, C_p	14,462-15,307 J/kg·K
Dynamic Viscocisty, μ	8.76E-06 – 2.22E-05 kg/m·s
Thermal Conductivity, k	0.1897-0.4859 W/m·K
Reynolds Number, Re	1147-2907
Prandtl Number, Pr	0.67-0.69
Convective coefficient, h	455-556 $W/m^2 \cdot K$
Coolant temperature	293-1138 K
Heat in, q	2500 W
Heat flux, q^{ii}	5.63E05 W/m^2

Electrothermal

For lab testing purposes, the tungsten filament is heated by Sorensen DCR20-1000A, a 20KW DC power supply system capable of up to 20V and 1000A. This power supply uses standard AC input of 460 VAC at 30 or 60 Hz. For flight, a miniaturized 1000A power supply would be used with capability only up to 3V required. The high current enables the tungsten to heat up more quickly, achieving 2500W thermal in 56 seconds with 1000A at 2.5V. Voltage or current can be turned up or down along with introducing coolant mass flow to control temperature.

Nozzle Design

As propellant approaches the nozzle, it begins approximately isentropic flow through the converging portion, throat, and then diverging portions of the nozzle. Flow goes from medium levels of pressure and high temperature but low speed at the entrance to the nozzle, to choked flow at lower temperature and pressure at the throat, to supersonic flow at the nozzle exit. After constant pressure (non-isentropic) heat addition in the chamber, the propellant assumes new levels of stagnation temperature, pressure, and density at the entrance to the nozzle (position x_2 in Figure 2a). Mass flow, stagnation pressure, and throat area have been selected to ensure that the nozzle reaches choked flow at the throat. The thruster was designed with a conical nozzle with an expansion ratio of 100, and a nozzle divergence correction 0.9 for the conical nozzle has been applied to the final equivalent exhaust velocity. Numerous chamber and nozzle parameters are depicted in Table 7.

Table 7: Nozzle parameters

Parameter	Value
Mass Flow Rate, $\dot{m}$ [kg/s]	0.0002
Ratio of specific heats, γ	1.3687
Area Ratio	100
Stagnation Pressure, P_2 [atm]	1.50
Stagnation Density, ρ_2 [kg/m^3]	0.0324
Stagnation Temperature, T_2 [K]	1137
Chamber Area, A_c m^2	0.000314
Throat Pressure, P* [atm]	0.80
Throat Density, ρ* [kg/m^3]	0.0205
Throat Temperature, T* [K]	961
Throat Area, A* m^2	4.19E-06
Throat Mach, M*	1.0
Exit Pressure, P_2 [atm]	0.00044
Exit Density, ρ_2 [kg/m^3]	8.58E-05
Exit Temperature, T_2 [K]	128
Exit Area, A_e	0.000419
Exit Mach, M_e	6.56
Ambient Pressure, P_a [atm]	0.0

Performance

The thruster performance characteristics are listed in Table 8. Specific impulse is 551 seconds with a thrust of 1.0 N, nearly doubling the performance of an identical thruster with unheated propellant (309s Isp, 0.56N). This performance is ideal for a highly efficient “middle ground” thruster that sits solidly between the large thrust, low efficiency nature of chemical propulsion systems and the extremely high efficiencies but correspondingly extremely low thrust of electrostatic thrusters.

Table 8: Performance Characteristics

Parameter	Value
Mass Flow Rate, $\dot{m}$ [kg/s]	0.0002
Equivalent Exhaust Velocity, U_{eq} [m/s]	5005
Specific Impulse, I_{sp} [s]	551
Thrust Force, F_{th} [N]	1.00
Thrust Coefficient, C_F	1.57
Characteristic Velocity, c*	3188
Jet Power, P_{jet} [W]	2506
Thrust Efficiency, η_{th}	0.73

Summary

This paper has detailed an electric resistojet thruster with high efficiency using storable gaseous hydrogen propellant. Though the propulsion system is promising, work remains to optimize this design for space vehicle use. The low density of hydrogen and high mass of hydrogen tanks (typically more than 12 kg tankage per 1 kg of H_2 for small terrestrial systems) means that the vehicle size must be relatively large, limiting the ΔV the thruster can provide to 100-400 m/s. Using cryogenic liquid hydrogen fuel, which is double the propellant density of pressurized gaseous hydrogen, does not considerably alleviate the issue, as the specific impulse is reduced due to the lower exit temperature, the tank factor is still approximately the same for small systems, and if long-term storage in space is desired, additional cooling equipment must be added and kept powered during flight. It is possible that this problem could be alleviated through the use of lighter, type 5 hydrogen tanks, or through a larger system with a larger tank and lower tank factor, but it is not clear that the efficiency advantages of this resistojet would directly scale to a larger system. Future research should focus on alternative heater configurations that would scale this efficiency to liquid hydrogen systems, as well as scaling the system to a larger size in order to lower the tank factor and improve spacecraft ΔV.

Appendix A: Additional Figures and Tables

Figure A-1: Constant-Pressure Specific Heat of Hydrogen from 250K to 2000K

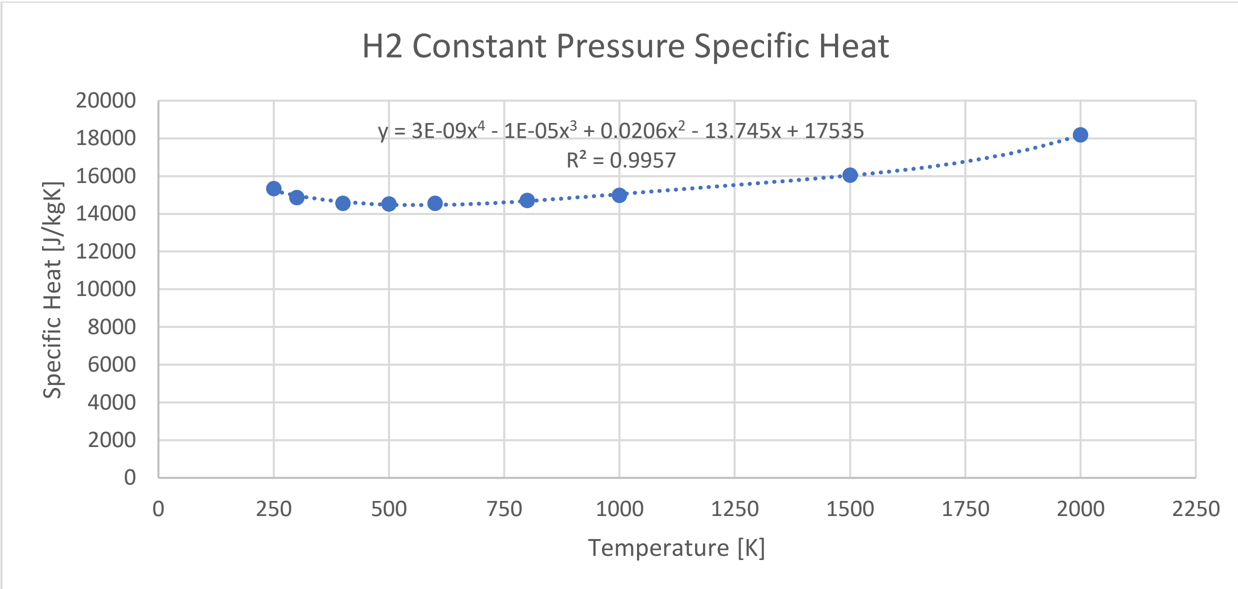

Figure A-2: Thermal Conductivity of Hydrogen from 250K to 2000K

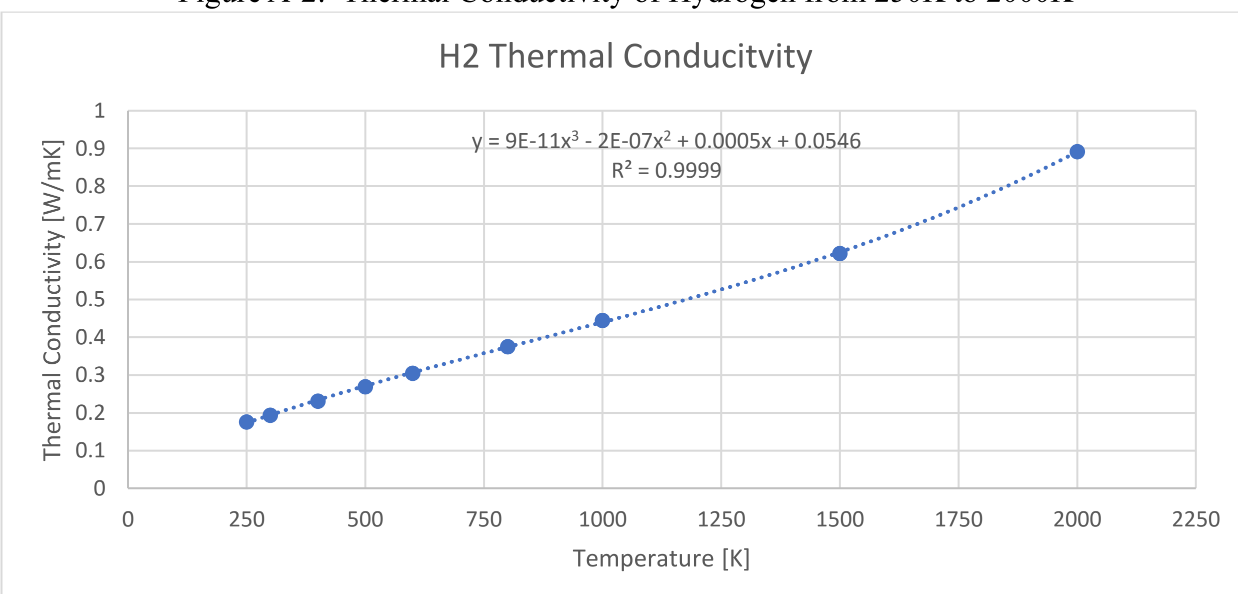

Figure A-3: Dynamic viscosity of Hydrogen from 250K to 2000K

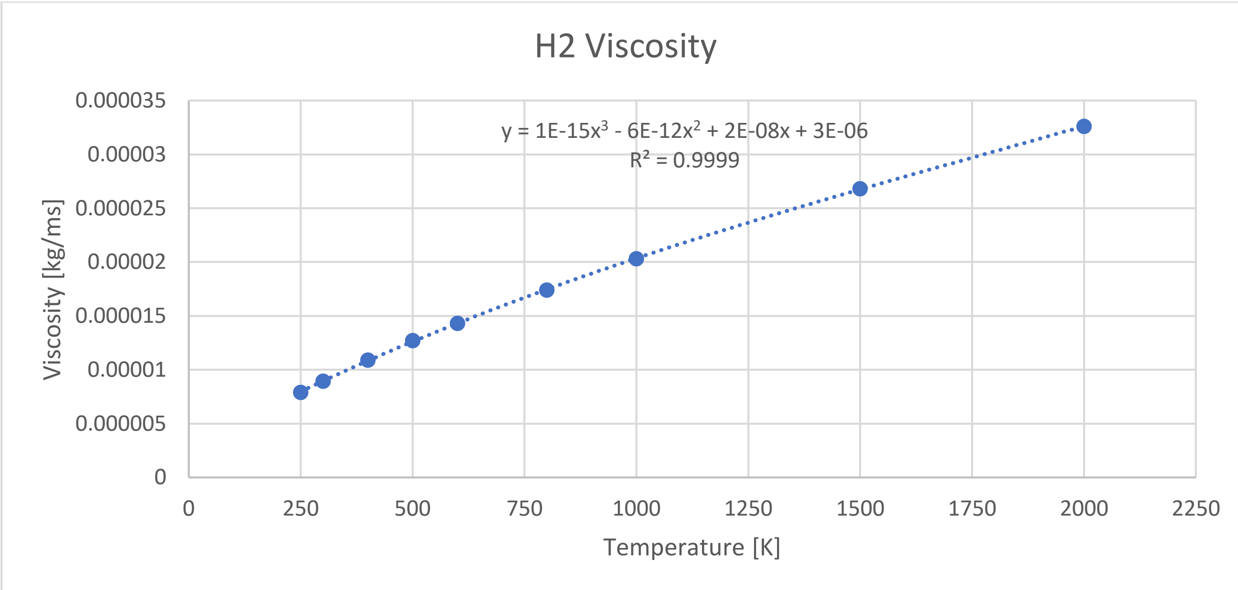

Figure A-4: Resistivity of Tungsten from 250K to 3000K