

# Dielectric Properties of Lunar Simulant Materials

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## Abstract

To guide development of microwave process technology that could be used during *in situ* construction on the Moon, basic dielectric measurements of  $\epsilon'$  and  $\epsilon''$  to high temperatures were acquired on 21 lunar simulants and related materials. In order to confidently use these data one needs to understand the data's strengths and weaknesses. Therefore, a major point of this publication is to provide insight into the comparative significance of such things as sample pre-treatments, experimental variables, compositional differences, mixes of materials, and other considerations affecting this type of data. This work also is intended to be a permanent, public archive of data on which other workers can build.

The dielectric measurements were performed using the cavity perturbation method. Measurements were taken over a temperature range between room temperature to  $\sim 1000$  °C or higher, and provided the real and imaginary components of permittivity at six frequencies. Each set of measurements were provided in reports and data in ASCII files. In addition to the measurements the reports contained substantial ancillary information, such as photos and details of each run. The utility of the reported values was limited by the varying density of the pellets used in the measurement. Therefore, all of the  $\epsilon'$  and  $\epsilon''$  measurements at the frequency of 2466 MHz have been scaled to a constant density, 1.75 g/cc. For each material this document contained the original and scaled  $\epsilon'$ ,  $\epsilon''$ , and the computed Half Power Depth versus temperature, the original Microwave Properties North reports, plots of scaled  $\epsilon'$  and  $\epsilon''$  versus temperature, and brief commentary. The plots were organized to aid analysis within the groups and across the datasets. To gain additional insight into the processes happening at the elevated temperatures of the dielectric measurements, differential scanning calorimetry (DSC) data on several of the simulant materials was also included.

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# 1 Introduction

Multiple efforts are underway around the globe to use microwave energy to enable construction on the Moon while only using lunar regolith (Meng et al, 2011; Gatto et al., 2024; Lim et al. 2023; Liu et al., 2025; Farries et al., 2021; Kim et al., 2025). To understand, develop effective processes, and scale up the work, including building systems, with microwave sources, dielectric data is required that indicate how microwave energy interacts with various lunar materials. A fundamental measurement of materials response to microwave and radio frequency energy is the complex relative permittivity. This data must be obtained for lunar regolith and high-fidelity simulants over a range of temperatures that can be expected on the Moon and during processing.

Data for the cryogenic-to-room temperature portion of that temperature range have been published for lunar regolith and several simulants (Barmatz et al., 2011, 2013, 2023). Herein we presented data for the temperature range from room temperature to  $> 1,000$  °C. Our data were 21 sets of measurements acquired on a total of 12 lunar regolith simulant materials. The samples included mare simulants, highland simulants, and some materials related to components of a simulant. For each data set we provided the real and imaginary portions of the complex relative permittivity (Von Hippel, 1954) versus temperature at the frequency of 2466 MHz. We also provided the Half Power Depth (HPD) versus temperature. HPD was an estimated depth at which half of the incident microwave radiation was absorbed. We also included plots of similar materials, plot material comparisons, and listed some observations drawn from the datasets.

Measurements were done by Microwave Properties North (MPN)<sup>1</sup>, their methodology is given in Appendix A. Many of the simulants were measured multiple times. The materials measured and some details of the measurements were given in tabular form in Table 5.1. MPN produced a document detailing the experimental conditions, their observations, graphs of the data, tabulated measurements, and in some cases photographs. Each of these reports is included in this publication in Appendix E. Table 5.1 also provided the reference designation used within MPN, the name of the MPN report, and an index, such as “A8”, used in this report. The data tables in Appendix C and E are in the order of the measurements given in Table 5.1. In this document when it was necessary to refer to a specific measurement, we used the index or the MPN reference designation.

To function inside their measurement system, MPN must compress a sample into pellets. New pellets were made for each run. For practical reasons the pellets were not pressed to consistent bulk densities. Further, measurement reduction to the desired values is sensitive to a sample’s bulk density. Therefore, an error was introduced when comparing dielectric data using values reported in the MPN reports, if the densities weren’t exactly the same. Also, the pellet densities were outside the range of bulk densities for *in situ* lunar material within a meter of the surface. To address these points, we have scaled all data sets to a bulk density of 1.75 g/cc, a density within the range of near surface lunar regolith. The method of scaling employed the Looyenga equation (Looyenga, 1965), which is provided below. The scaling was done using Microsoft Excel VBA code, which is included as Appendix B. The VBA code also produced the Half

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<sup>1</sup> Use of company names shall not be construed as endorsements. They are provided for the purpose of completeness of information.

Power Depth values. Appendix C provides the measurements at 2466 MHz generated by MPN and the scaled values for each material measured.

To gain more insight into the processes that occur at high temperatures, we have included some Differential Scanning Calorimetry (DSC) data on three of the simulant materials. The DSC data are in Appendix D.

For clarity, this paper is concerned at all points with the Relative Complex Permittivity,  $\epsilon^*$ , defined as

$$\epsilon^* = \epsilon_r' - (j^* \times \epsilon_r'')$$

Where  $j^*$  is the square root of negative 1,  $\sqrt{-1}$ . The principal values reported in this document are  $\epsilon_r'$  and  $\epsilon_r''$ . These two values are referred to as the real and imaginary part of the permittivity, or relative permittivity and dielectric loss. For more information on complex permittivity, see Von Hippel (1954).

What this paper provides is internally consistent measurements of the significant lunar regolith simulants developed specifically for the National Aeronautics and Space Administration (NASA). It may be possible to extend this work to other simulants using inference, based primarily on composition, or using some form of computer learning, for example Ellison (2021).

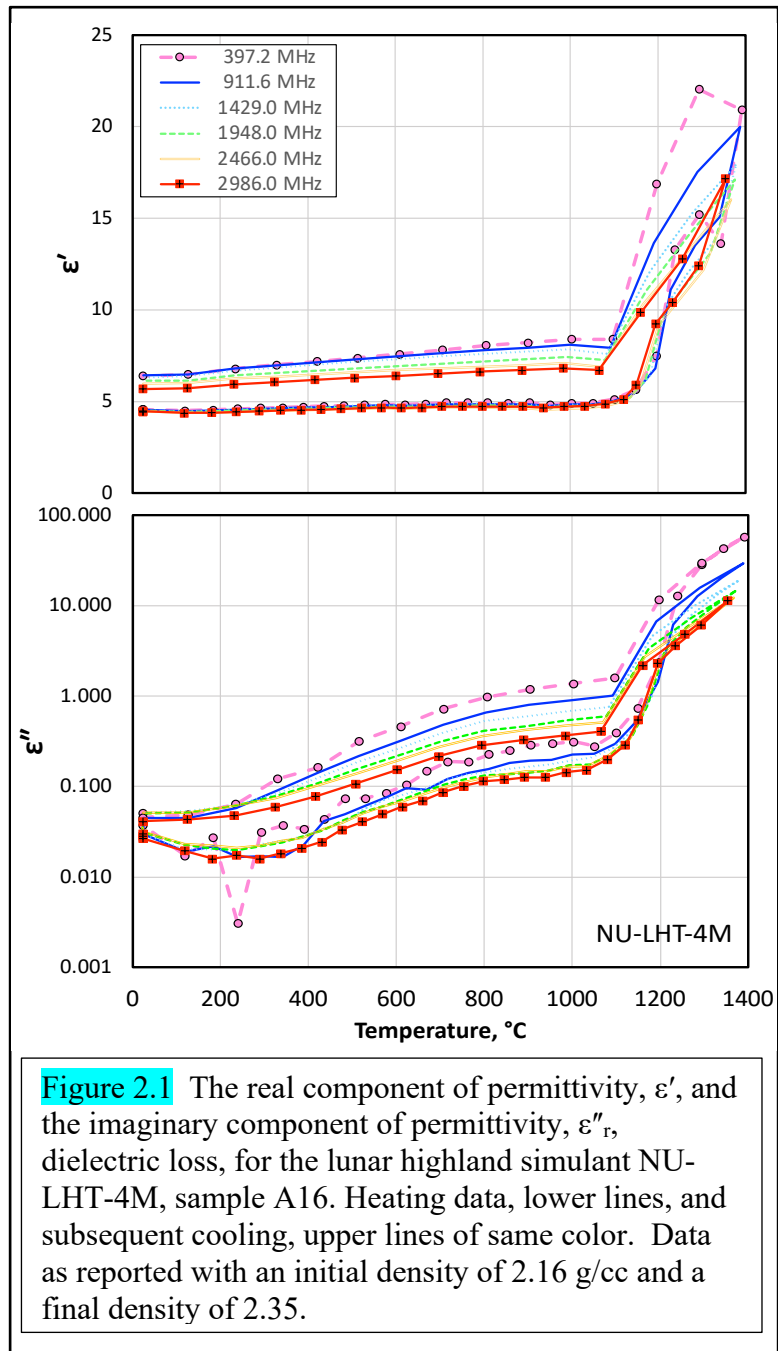
Finally, we emphasize the point this document and the measurement technology used are by no means complete answers to engineering a system using microwaves. For example the question of how the sample mass fills space, e.g. pressed pellets vs. drill core, is not explored, Section 3.2 of Forster et al. (2023). What this paper provides is internally consistent measurements of the significant lunar regolith simulants developed specifically for the National Aeronautics and Space Administration (NASA).

## 2 Introduction to Interpretations of Dielectric Measurements of Lunar Simulants

### 2.1 Basics

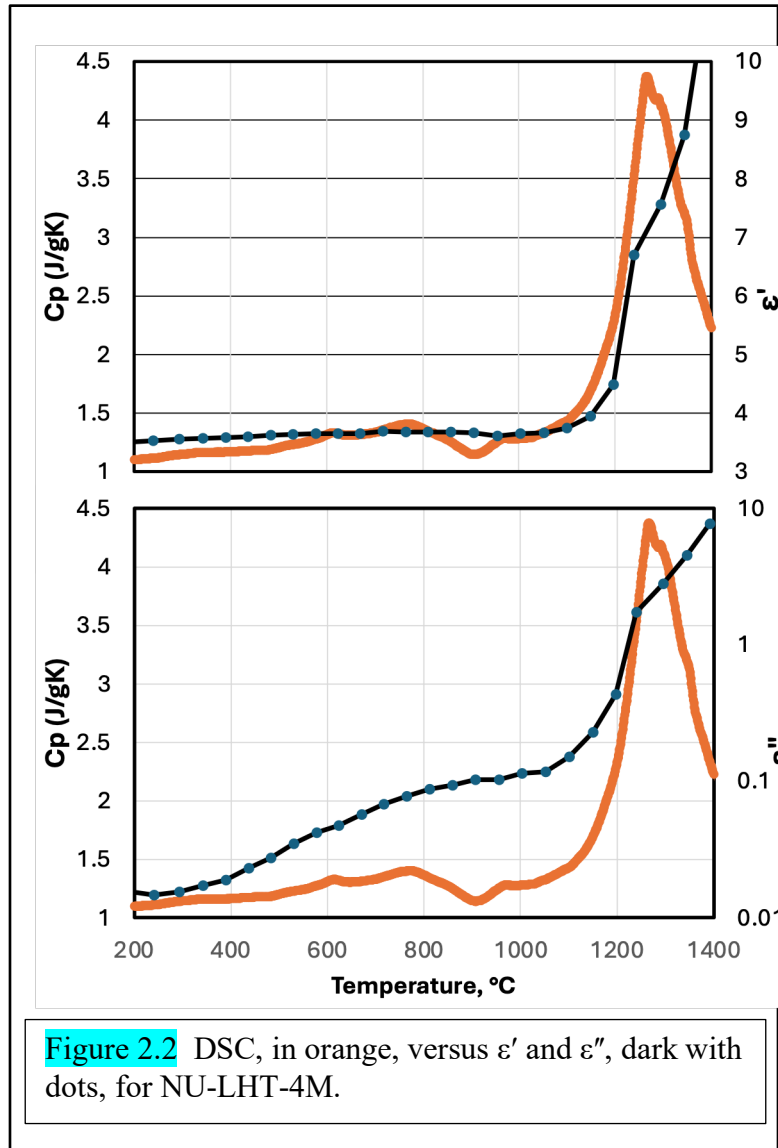
Figure 2.1 showed two dominant features. First, MPN measured both the heating leg and the cooling leg during data acquisition. Typically, the heating leg was measured at smaller temperature increments than the cooling leg. In Figure 2.1 the cooling leg has significantly higher values of  $\epsilon'$  and  $\epsilon''$  than the heating leg, which could be seen by following the same color line from room temperature to maximum temp and back to room temperature. The second major feature was the sharp increases in both  $\epsilon'$  and  $\epsilon''$  near 1100 °C. This could be explained by the onset of melting, denoted as  $T_m$  in DSC data. This was shown by nearly parallel sharp increases in both datasets in Figure 2.2. It was also seen in Figure 2.3. It could be understood that the dielectric response was greater in both the permittivity (which measures polarization) and dielectric loss during a phase change from solid to viscous liquid because the liquid allowed easier movement for dipole alignment. Other factors besides melting could also cause this type of behavior in the dielectric data, and care must be taken, as done here,

to validate using other techniques such as DSC and XRD studies. Upon cooling, the higher permittivity and loss in Figure 2.1 indicated that a glass phase may have been quenched in, retaining a more polarizable structure. It was important to note that sample size, heating, and cooling rates could have an impact on the structure of regolith and simulants which can be thought of as ceramic and glass materials.



Thermal runaway was a phenomenon reported by workers heating simulant materials with microwaves (Lim et al., 2021). The sharp increase in the relative complex permittivity that occurred at melting was a contributing factor to the phenomenon

It could be seen in Figure 2.2 that there was a second dielectric inflection at 1200 °C, with a slowing of the rate of increase of  $\epsilon'$  and  $\epsilon''$  after the 1100 °C melting onset. This could be caused by a decrease in viscosity of the liquid phase which could decrease the lag in dipole alignment. There were many polarization mechanisms that could be activated or drop out at different temperatures. Regolith and simulants were composites of various materials which undergo complex interactions during heating. Dielectric measurements could only be used to understand the bulk behavior. Even with imperfect understanding of the mechanisms at play, the dielectric data along with an understanding of the thermal properties and chemistry gave a powerful foundation for modeling and microwave process development.



The offset between the initial and the cooling leg was often permanent when changes such as melting and quenching occur, see, Figure 6.3.2. If the temperature at which total melting,  $T_m$ , is not reached, all other things being unchanged, the cooling data would largely plot on top of the heating data.

## 2.2 Non-Lunar Minerals

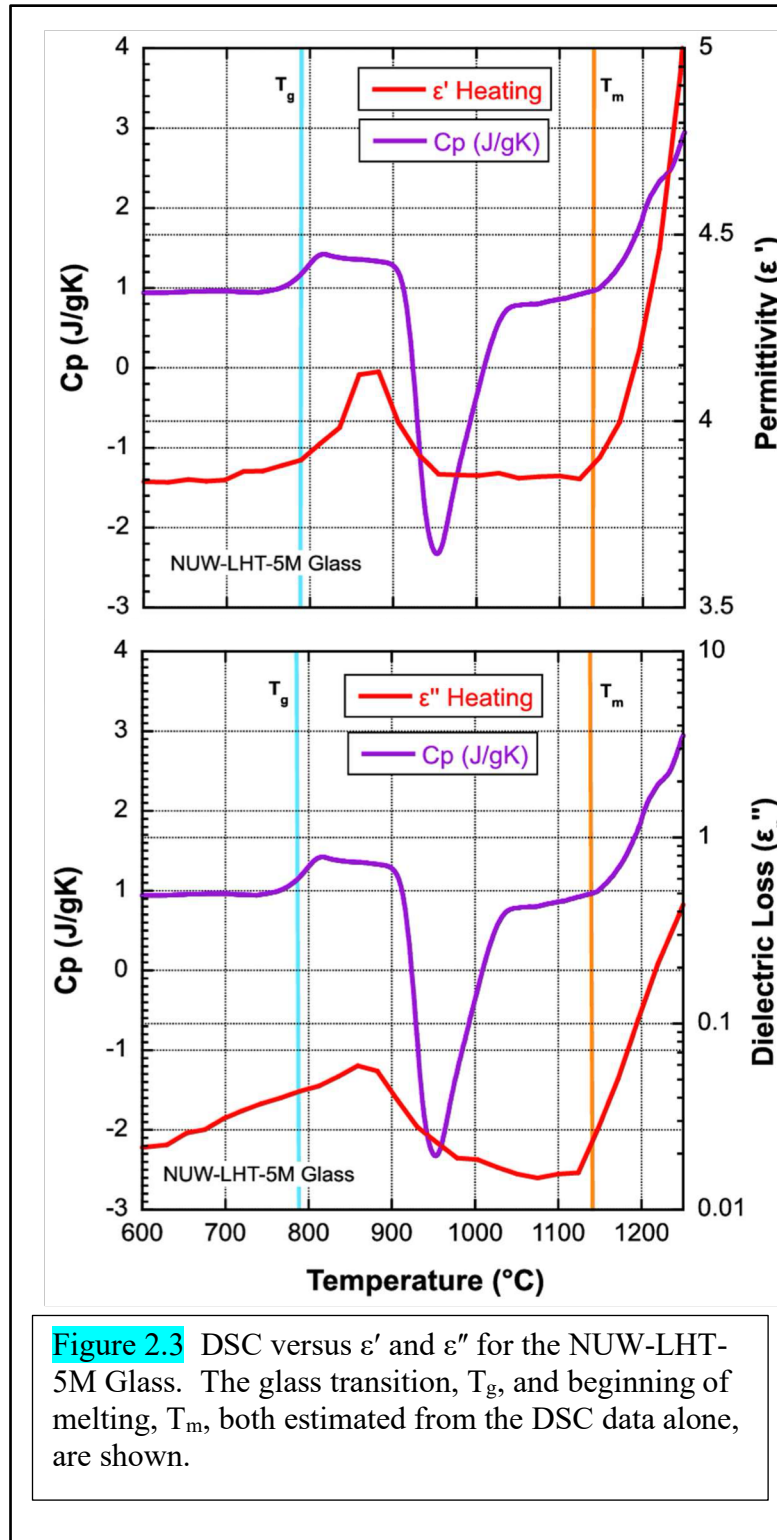
However, there were characteristics of simulant materials that commonly interfere with the simple case. One was the presence of non-lunar minerals in the material. Non-lunar minerals were ubiquitous in all natural, terrestrially sourced, geologic materials. The specific mineralogy, their abundance, and their spatial distribution were controlled by the geologic history of the materials and the processes used to produce simulant from the feedstocks. Usually, these non-lunar minerals had very different dielectric and thermal profiles compared to the lunar-like

mineralogy that made up the bulk of the simulant. For example, many non-lunar phases (such as clay minerals) were transformed to new phases and lose volatiles, typically  $\text{H}_2\text{O}$  or  $\text{OH}^-$  at temperatures below any change in the lunar-like phases. Multiple such features could occur because multiple non-lunar minerals were usually present, each having a different thermal behavior. If glass was not present in a simulant, features in dielectric measurements below  $\sim 1000^\circ\text{C}$  would very probably involve non-lunar mineralogy. At lower temperatures the non-lunar minerals could start changing as low as  $\sim 300^\circ\text{C}$ , for clays. All of the changes in the non-lunar phases were non-reversible.

Some techniques have been tested to reduce the impact of non-lunar minerals. Multiple runs of JSC-1A, see Section 6.6 below, were made specifically to test some of the methods. The dielectric data presented herein was sensitive to even a small percentage of non-lunar constituents. What was referred to as the standard technique (Wilkerson et al, 2023) is now the recommended method to reduce the influence of non-lunar phases in the simulants.

### 2.3 Mixtures

Other than some of the synthetic materials reported in this document, for example see Figure 2.3, all of the simulants reported herein, and even many of the natural feedstocks used to make the simulants were complex mixtures. The effects of non-lunar minerals inherited from the feedstocks has already been noted above. Larger scale mixtures, as used in CSM-LHT-1G, could have such a great impact, the influence of each constituent cannot be individually resolved.



**Figure 2.3** DSC versus  $\epsilon'$  and  $\epsilon''$  for the NUW-LHT-5M Glass. The glass transition,  $T_g$ , and beginning of melting,  $T_m$ , both estimated from the DSC data alone, are shown.

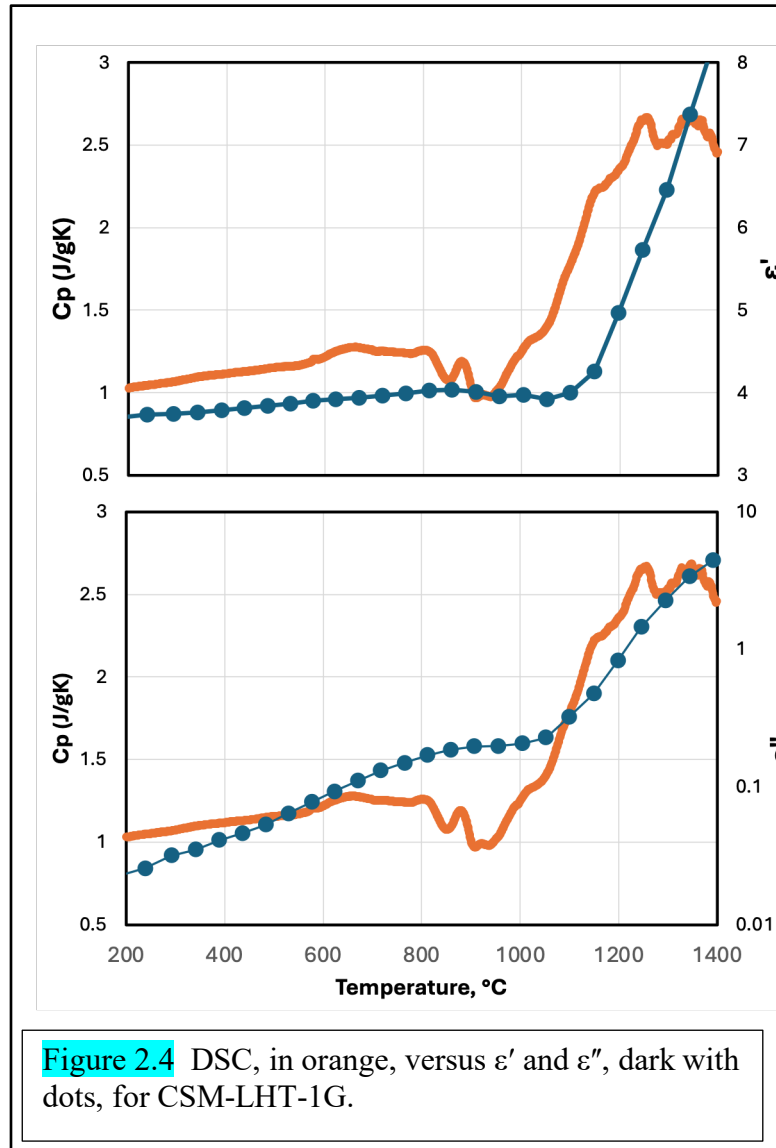
In Figure 2.4 the melting temperature seen in the DSC data did not directly coincide with a feature in the dielectric data. This is attributed to the influence of the Merriam Crater feedstock in the DSC data. That material had a substantially lower melting point than that of the crystalline material, GreenSpar, which was an anorthosite with an An value of approximately 78. This early melting material strongly affected the DSC, suggesting with having a lesser influence in the dielectric measurement.

## 2.4 Density

Sample density was important as density affected the conversion of raw measurements to useful data. Pellet density was obtained by measuring pellet mass, length, and diameter; all three measurements could change during processing. Therefore, pellets were measured before and after the dielectric measurements.

In lunar simulant materials the before and after densities could change for several reasons. The high temperature alteration of the non-lunar minerals could cause the pellets to lose weight and to change volumetrically, either increasing or decreasing. Both phenomena may occur at the same time. Another known change occurred because the simulant could shrink when a sample enters the sintering regime. Experiments at Kennedy Space Center showed both JSC-1A and CSM-LHT-1G initially lost approximately 5% of their length (linear shrinkage) (Sibille et al., 2023). On further heating the simulants expanded. The shrinkage has been tentatively explained by surface tension of the initial melt pulling particles closer together.

How to apportion any change in density over the thermal history of the measurements is not a science. In this work attribution of density change was done by MPN in consultation with the senior author. The attributions used for each measurement could be found in the respective MPN report. Practically, change to the attribution profile report has a small impact in the reported data.



**Figure 2.4** DSC, in orange, versus  $\epsilon'$  and  $\epsilon''$ , dark with dots, for CSM-LHT-1G.

Density corrections, discussed in detail in the following section, were important for comparing data from different simulants and treatments.

## 2.5 Atmosphere

As a practical matter the atmosphere the materials were exposed to during heating may be important. This is currently a topic of active research. Table 5.1 reported the atmosphere used for each run, either “Argon” or “vacuum”. “Argon” was done using Ultra-High Purity (UHP) Argon. Vacuum at the pump was <1 millitorr. Examination of the photos in the MPN reports for the JSC-1A runs, A8 – A12, and the Merriam Crater feedstock used for JSC-1A, A-14, found the runs in an argon atmosphere, as opposed to vacuum, exhibit intense discoloration, reddening, due to oxidation of some of the Fe minerals. The source of the oxygen was unknown. Runs A17 vs A19 of NUW-LHT-5M also showed the difference between argon atmosphere vs. vacuum. Colors in the runs for CSM-LHT-1G cannot be compared because in run A4 the sample substantially melted. A difficulty to rigorously assessing significance of “argon” vs “vacuum” was the lack of a one-to-one comparison. All of the possible pairs of runs have other variables that might confuse analysis, such as different maximum temperatures and/or pre-treatments. The best test the current data provided for testing the difference between the two environments was examination of Figure 6.1, NUW-LHT-5M. Run A17 used vacuum; runs A18 and A19 were done with argon. It can be seen that the heating legs of the three runs fell quite close to each other, especially if the baseline comparison was highland simulant versus mare simulant, Figure 7.4. The generality of this observation was probably limited because NUW-LHT-5M has significantly lower Fe content compared to JSC-1A.

## 2.6 Summary

When acquired on lunar regolith simulant materials, the dielectric data from MPN may show features related to:

- a) removal of H<sub>2</sub>O between 100 °C and 250 °C,
- b) the destruction of one or more non-lunar minerals, frequently accompanied with devolatilization,
- c) glass softening in glass-bearing material,
- d) melting,
- e) change in pellet density,
- f) irreversibility of b, c, and d.

These will be explained in following sections. The most critical information from dielectric properties as a function of temperature for using microwaves to process lunar regolith into landing pads, berms, and structural components were the magnitude of the permittivity, dielectric loss and the combination of loss and permittivity in the half power depth. This gave data for insight and modeling of the microwave self-heating capabilities for regolith as a function of temperature.

### 3 Scaling from Measured Density to a Common Density

Material density during the measurement process was practically constrained by the need for the pellets to be sturdy enough to withstand handling and processing in the instrument. Addition of binders of any kind was not desirable, as these would either change the propagation of microwave energy through a pellet or chemically alter at the temperatures used, or both. Pellets were created by pressing the material in a uniaxial cell. For each sample the pressure used was in the MPN report.

For this study the resulting pellets had a density between 1.5 and 3.0 g/cc. Most of the samples were made into pellets with densities close to 2.0. The variation in density presented two problems when trying to use the data. First, in almost all cases the density used was outside the range of interest for *in situ* lunar regolith, thus reducing the applicability of the data to actual conditions. Second, as previously noted, density was a significant factor in the mathematical reduction of the measured values to the relative complex permittivities we report. In other words, comparison between two samples was difficult because an apparent difference may be caused by different densities in the pellets, not just differences between materials.

Therefore, we have scaled all of our data to a single density. To make the data directly comparable to lunar conditions, we used a value 1.75 g/cc, which was a reasonable value in the near subsurface of the Moon. Other densities were easily estimated by simple scaling as reported in Rickman et al. (2024a), which one can review for additional discussion on this topic. In this document, other than Figure 2.1 and the contents of the MPN reports,  $\epsilon'$  and  $\epsilon''$  values have been scaled to the 1.75 g/cc value.

The method of scaling to 1.75 g/cc used an equation derived from the work of Looyenga (1965). For comparison of the Looyenga to other mixing models see Tempke et a. (2020). Eq. 2, gave the complex permittivity,  $\epsilon^*$ , (which has both real (Re),  $\epsilon'$ , and imaginary (Im),  $\epsilon''$ , components), at any required but unmeasured density,  $\rho_{req}$ . Densities are in g/cm<sup>3</sup>. All values of  $\epsilon^*$ ,  $\epsilon'$ , and  $\epsilon''$  were at a temperature,  $T$ , and frequency,  $f$ . Computations required known, in this case measured, values of  $\epsilon'_{T,f}$  and  $\epsilon''_{T,f}$  at an initial density,  $\rho_s$ .  $\rho_T$  was obtained from the initial and final densities with the evolution of  $\rho$  given in the MPN report. Note, equation two as written here was a correction of equation 2 as written in Rickman et al. (2024a) TM 20240007310.

$$\text{eq. 1. } \rho_{ratio_T} = \frac{\rho_T}{\rho_s}$$

$$\text{eq. 2. } \epsilon_{T,f}^* = \left[ \frac{\rho_{req} \times \rho_{ratio_T}}{\rho_T} \left[ \left[ \epsilon'_{T,f} - j \times \epsilon''_{T,f} \right]^{\frac{1}{3}} - 1 \right] + 1 \right]^3$$

$$\text{eq. 3. } \epsilon'_{T,f} = \text{Re}[\epsilon_{T,f}^*]$$

$$\text{eq. 4. } \epsilon''_{T,f} = -\text{Im}[\epsilon_{T,f}^*]$$

This equation was implemented into Microsoft Excel VBA code, which is included in Appendix B.

## 4 Computation of Half Power Depth

For most people we assumed that looking at the values of real and imaginary parts of the complex permittivity was not meaningful. Therefore, we included a value termed half power depth (HPD). HPD was the theoretical depth, in millimeters, on an infinite half plane, at which half of the energy input would be absorbed. In other words, HPD gave insight into how microwaves penetrated a material vs. how they dissipated (are absorbed) via dielectric loss which caused heating. HPD was computed by eq. 6. Note, this version of Equation 6 was corrected from the version previously published in Rickman et al. (2024a).

$$\text{eq. 5} \quad \tan\delta_{T,f} = \frac{\epsilon''_{T,f}}{\epsilon'_{T,f}}$$

$$\text{eq. 6} \quad \text{HPD}_{T,f} = \left(\frac{\ln(2)}{2}\right) \times \left[ \frac{c}{2\pi f} \times \left[ \frac{2}{\left[ \sqrt{(1+(\tan\delta_{T,f})^2)} - 1 \right] \epsilon'_{T,f}} \right]^{\frac{1}{2}} \right]$$

where: T = temperature.

f = frequency in Hz.

C = speed of light in millimeters/second,  $2.998 \times 10^{11}$ .

Equation 6 was implemented inside the same Microsoft Excel VBA code, in Appendix B, used to apply the Looyenga equation.

The HPD values should not be confused with the engineering practicality of using microwave radiation on the Moon for construction processes. There was far more to the question of such practicality than HPD alone (e.g. thermal behavior of regolith). What the data herein provided was a rigorous comparison between the HPD of Mare and Highland simulants, and information on the relationship between temperature and HPD. These were important inputs to developing process strategies and solving the engineering problem.

We also noted that  $\tan\delta$  by itself could be a useful metric.  $\tan\delta$ , which is computationally simple to obtain, could be used as an *ad hoc* guide by comparing the  $\tan\delta$  of a material whose heating characteristics were unknown with the  $\tan\delta$  of materials whose performance was known, Table 2 of Rickman, Hutcheon, and Shulman (2024).

## 5 Data Organization

The relative complex permittivity of 22 materials from room temperature to or above 1,000 °C were measured. Of these measurements 21 were included in this report<sup>2</sup>. Table 5.1 gave basic information for each measurement. The key to Table 5.1 was after the table.

Each of the data sets recorded a single thermal run consisting of heating from room temperature to a maximum temperature followed by cooling back to room temperature, except for A7 (SHUL2117 JSC-1A) and A13 (CERL0960 JSC-1AC). Runs A7 and A13 went to a high temperature, cooled, and then were heated again before returning to room temperature. Each of the 21 runs required between ~ 8 and ~24 hours.

From the original ASCII values supplied by MPN, for each data set we have extracted the index temperature, relative  $\epsilon'$ , relative  $\epsilon''$ , the elapsed time (LAPST), temperature at the precise time of measurement, all at the frequency 2466 MHz. These data were needed to compute the scaled values. Note there was a small difference between the index temperature and the precise temperature at the time of measurement. For plotting, the difference which peaked at <5% at 1400 °C, was not further considered herein and the index temperature was used. This was done because the precise temperature varies with frequency, making comparison between frequency cumbersome. We also have extracted the computed half power depth from the original values. All of the data directly from MPN used densities obtained from measurements of pellet mass, length and diameter both before and after the run. Density affected the data reduction to obtain the permittivity values, for reasons previously discussed. The assumed density – temperature relationship during a run was included in the MPN report. For various reasons the density profiles used herein for A13, A19 were slightly different from the ones provided in the MPN reports. In Appendices C we include the  $\epsilon'$ ,  $\epsilon''$ , and HPD for both the original values and the values after scaling to a density of 1.75 g/cc. Appendices C and E are provided for those who need the numeric values or must understand the MPN data in greater detail.

It was from the scaled data the following plots have been made. Most of these graphs used hollow markers at each data point for the heating leg and solid markers for the cooling leg.

The remainder of this report will consider the plots without substantial use of the numeric values. This was done because the exact translation of the measurements from a simulant to a corresponding lunar sample is, at this time, unknown. Until measurements on lunar samples become available, with the existing data it was the relationships between the materials that was of primary importance.

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<sup>2</sup> During run SHUL2234, done using JSC-1A, the pellets broke apart at some unknown point.

Table 5.1. Material, run conditions, index, MPN identifier, and report file name

Material	Pre-treatment	Temp °C	Notes	Gas	Density		Index	Microwave Properties North Designations	
					Start	End		MPN ID	Report Name
Anorthite synthetic	NP	1100	-	Vacuum	1.57	1.53	A1	SHUL2149	MPN-231_Shulman_3_Anorthite A-006.docx
CSM-LHT-1G	D250	1100	-	Vacuum	2.14	2.07	A2	SHUL2281	MPN-257_Shulman_CSM-LHT-1G_1 .docx
	B1	1100	-	Vacuum	2.06	2.04	A3	SHUL2282	MPN-257_Shulman_CSM-LHT-1G_2 .docx
	B1	1400	-	Argon	2.12	2.38	A4	MPN02286	MPN-258_MPN_CSM-LHT-1G_heat-treated .docx
Diopside synthetic	NP	1100	1	Vacuum	1.65	1.64	A5	SHUL2152	MPN-231_Shulman_3_Diopside D-009.docx
Diopside w/ actinolite	D140	1100	2	Vacuum	3.09	3.02	A6	MPN02181	MPN-242_MPN_Diopside with Actinolite .docx
Enstatite	D140	1100	2	Vacuum	2.96	2.89	A7	MPN02180	MPN-242_MPN_Enstatite_Mirabel Springs,Mt St Helena CA.docx
JSC-1A	B500/RR	1100	3	Argon	1.97	1.89	A8	SHUL2117	MPN-218_Shulman_1_JSC-1A.docx
	B500	1100	3	Argon	2.02	2.02	A9	SHUL2119	MPN-218_Shulman_2_JSC-1A.docx
	B3	1100	-	Vacuum	2.08	2.14	A10	SHUL2146	MPN-231_Shulman_3_JSC-1A(A).docx
	B2	1100	-	Vacuum	2.16	2.18	A11	SHUL2147	MPN-231_Shulman_3_JSC-1A (B).docx
JSC-1AC	NP/RR	1100	-	Argon	2.09	2.19	A13	CERL0960	CERALINK NYSERDA_10.doc
Merriam Crater	D200	1100	-	Vacuum	2.1	2.17	A14	SHUL2179	MPN-241_Shulman_4_Merriam Crater Basalt .docx
NU-LHT-2M	D200/15	1230	-	Argon	1.89	1.62	A15	SHUL2127	MPN-218_Shulman_1_NU-LHT-2M_mod.docx
NU-LHT-4M	NP	1400	-	Argon	2.16	2.35	A16	MPN02284	MPN-258_MPN_NU-LHT-4M .docx
NUW-LHT-5M	D200/15	1100	-	Vacuum	2.12	2.02	A17	NASA2358	MPN-285_NUW-LHT-5M_Rickman_1mm.docx
	B1	1150	-	Argon	2.12	2.06	A18	NASA2360	MPN-285_NUW-LHT-5M_Rickman_2mm.docx
	B1	1250	3	Argon	2.09	2.2	A19	NASA2361	MPN-285_NUW-LHT-5M_Rickman_3m.docx
NUW-LHT-5M Glass	NP	1000	-	Argon	1.9	1.81	A20	MPN023101	MPN-292_MPN_Glass for 5M Simulant_Creedon_Washington Mills.docx
	NP	1150	-	Argon	2.0	2.03	A21	MPN023100	MPN-292_MPN_Glass for 5M Simulant_Creedon_Washington Mills.docx
	NP	1300	-	Argon	2.04	2.34	A22	MPN023109	MPN-294_MPN_5M Glass to 1300C_Creedon_Washington Mills .docx

## Key

### Pretreat

#### Code Description

B1	Standard Bakeout: 750 °C, Heat in Argon, 2 hr dwell Argon/ 4%H2, Cooled Argon
B2	Same as B1 except all Argon/4% H2
B3	Same as B1 except all Argon
B500	500 °C 6 hr, Argon, Dried 140 °C 2 hr
D140	Dried 2 hr 140 °C
D200/15	Dried 15 min 200 °C
D200	Dried 1 hr 200 °C
D250	Dried 1 hr 250 °C
NP	No Pretreatment
RR	Re-run of the sample directly after first run

Temp: The approximate peak temperature

Notes: 1 - (Mg,Ca)Si<sub>2</sub>O<sub>6</sub>. Includes 1.3 wt% forsterite, Mg<sub>2</sub>(SiO<sub>4</sub>), by XRD

2 – Drill core, not powder

3 – Oxidized, brick-red after measurement

Gas: The environment around the sample during measurement. It was either “Argon”, Ultra-High Purity Argon, or “Vacuum”, <1 millitorr

Density: In g/cc, the starting and end density

Index: Reference identity for this report

MPN: Microwave Properties North internal tracking ID and customer report name

## 6 Variations Within Groups

The 21 measurements included have been grouped for this document; this grouping enabled comparisons to be made within similar materials. The exception was the Feedstocks group, which compiled plots for some of the feedstocks used to make simulants. As not all of the feedstocks have been measured, this group also included some materials similar to components in the simulants. Four groups, see Table 6.1, were replicates of a single material: NUW-LHT-5M, NUW-LHT-5M Glass, JSC-1A, and CSM-LHT-1G. These are discussed first. Following, we discussed groups of highly similar materials: NU-LHT-2M and NU-LHT-4M together, several feedstock related materials, and Merriam Crater feedstock vs. JSC-1AC vs. JSC-1A samples. A subsequent section of this document discusses comparisons between groups.

Each run in a group was acquired for reasons that were not consistent across the groups. For example, the NUW-LHT-5M runs were done to explore the rapid rise at melting; the JSC-1A runs were done to evaluate the effects of different bake out procedures. But the groups provided more information than just the reason they were acquired. The most important conclusion that can be drawn from the variation within a group was the dielectric measurements were highly consistent, once the density of each measurement was scaled to a single value. An equally important corollary to this is differences that were observed between two materials were the result of real differences.

Table 6.1 Number of measurements in each group

Group	n
NUW-LHT-5M	3
NUW-LHT-5M Glass	3
NU-LHT-2M & -4M	2
JSC-1A	4
JSC-1AC	1
Feedstocks	5
CSM-LHT-1G	3

## 6.1 NUW-LHT-5M

NUW-LHT-5M is a simulant intended to reproduce, to the limit practical, an average Apollo 16 highland sample, see NASA Technical Publication TP-20240007991 (Rickman et al., 2024b). Three runs were done, peaking at 1100 °C, 1150 °C, and 1250 °C, Figure 6.1.1. The tight clustering of the runs during heating (open symbols), each done with pellets made for that run, demonstrated the high reproducibility of the measurements after the values were scaled using the Looyenga equation. Reproducibility was best confirmed by comparing A18 and A19 which had identical pre-treatments and both were run in argon. A slightly lower permittivity and loss was observed when comparing these with A17 measured in vacuum; however, there wasn't sufficient data to determine if the difference in atmosphere was solely responsible for the observed difference.

In Figure 6.1.1, on cooling (filled symbols), there was a drastic difference in permittivity between A18 and A19. These samples had different maximum heating temperatures. This suggested that a change occurred during the run as the samples are heated. The difference was also evident in the dielectric loss, but was less drastic in part because of the log plotting scale. The strong increases in both  $\epsilon'$  and  $\epsilon''$  beyond ~1150 °C were likely caused by the onset of melting. This was corroborated by DSC data, Figure 6.1.2, and shown in more detail in Section 14.1 of Rickman et al. (2024b). Additionally, the feature in

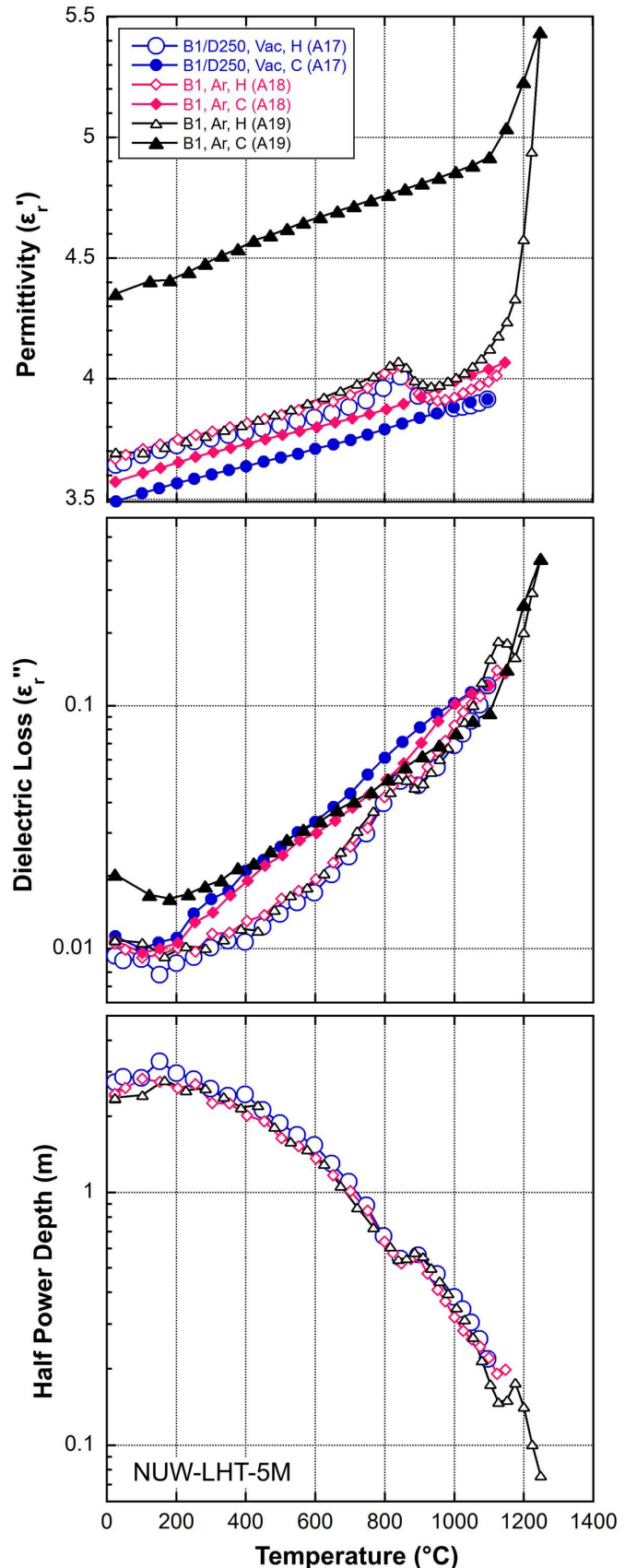


Figure 6.1.1.  $\epsilon'$ ,  $\epsilon''$ , and HPD for the lunar highland simulant NUW-LHT-5M. The HPD cooling leg is not plotted.

dielectric properties at  $\sim 850$  °C (upon heating only) was likely related to the  $T_g$ , the glass softening temperature, or softening of the NUW-LHT-5M glass before it crystallized at  $\sim 950$  °C (see Figure 6.1.2). Glass softening offered more opportunities for movement, both for polarization and polarization lag (dielectric loss). This feature was not observed on cooling, indicating that different structures were locked in.

It was interesting to note that permittivity was higher on cooling only for the sample with higher temperature (run A19), while the others all showed lower permittivity on cooling. In contrast, for dielectric loss all samples were higher on cooling than heating. Permittivity is a measure of polarization, so higher permittivity in A19 after undergoing melting, means the product has cooled to contain more dipoles, but also more lag of dipoles switching in the field.

Other analytical methods, such as XRD and SEM/EDS are needed in addition to DSC to understand the material reactions and products. It should also be noted that heating and cooling rates and sample size will impact these reactions. It is clear that changes caused by heating were permanent for all cases even when not heated to the regime of melting.

DSC data by Austin Patridge and Alan Whittington of University of Texas at San Antonio were included in Section 14.1 of Rickman et al. (2024b). The strong exothermic drop in  $C_p$  at  $\sim 950$  °C indicates crystallization, while the sharp endothermic peak indicated the onset of melting at  $\sim 1150$  °C. Glass transition,  $T_g$ , the onset of glass softening, was a second order phase transition which showed up on DSC plots as gradual changes, like the small features at  $\sim 850$  °C.

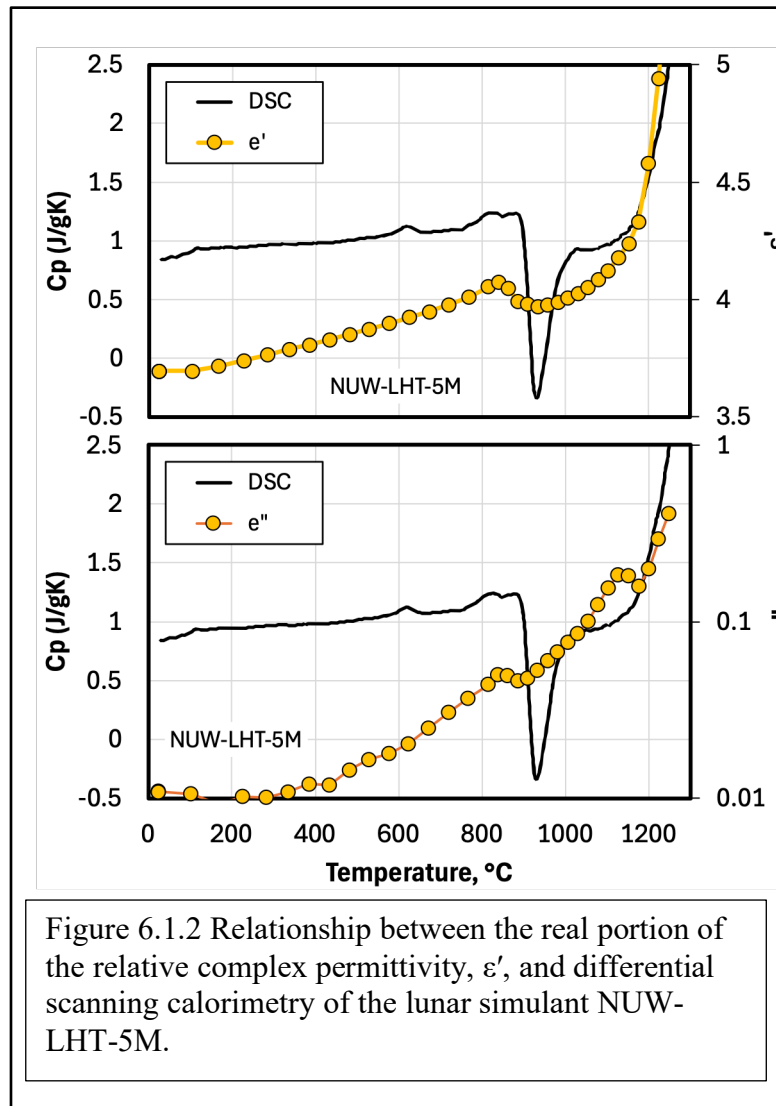


Figure 6.1.2 Relationship between the real portion of the relative complex permittivity,  $\epsilon'$ , and differential scanning calorimetry of the lunar simulant NUW-LHT-5M.

## 6.2 NUW-LHT-5M Glass

NUW-LHT-5M Glass is a synthetic glass made by Washington Mills for the NUW-LHT-5M simulant. This glass is 40 wt% of the simulant. Additional information about the glass may be found in Rickman et al. (2024b). This simulant glass was also used (at 15 wt%) in the lunar highland simulant CSM-LHT-1G.

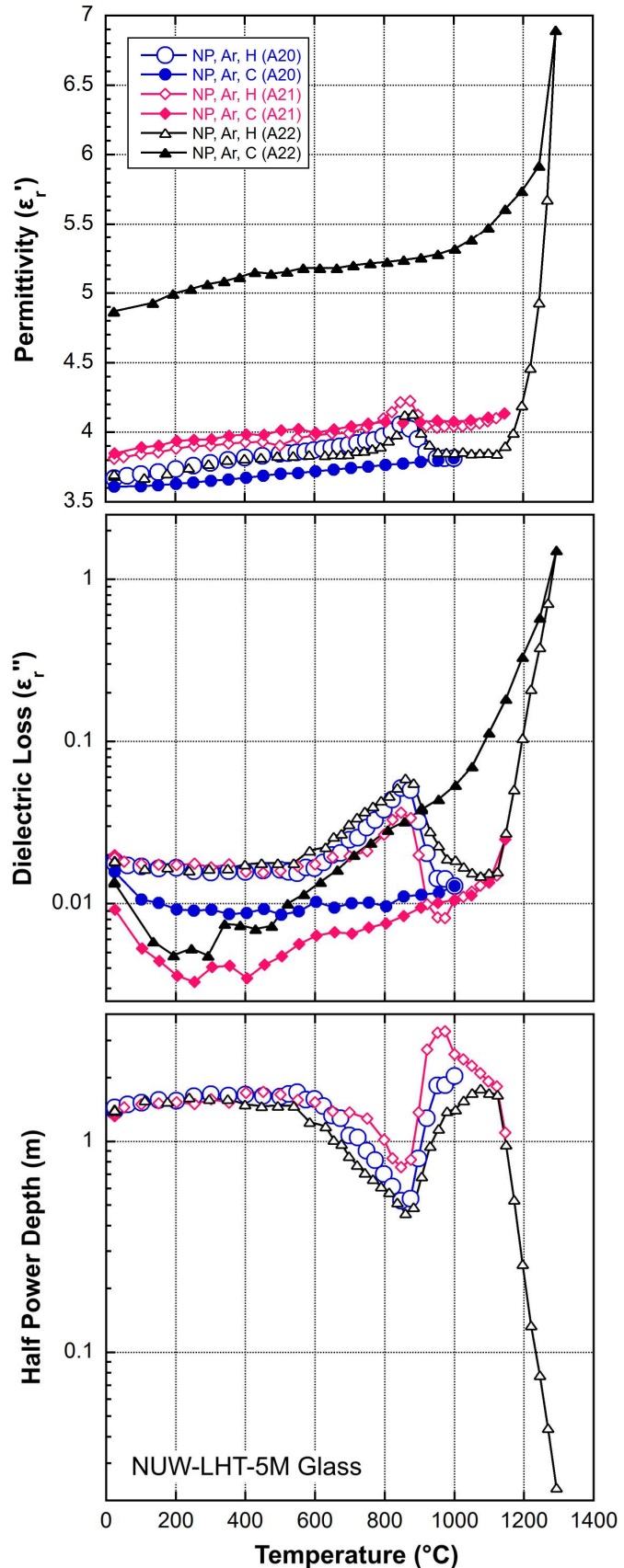
Table 6.2 gives the target composition of the NUW-LHT-5M glass. Industrial grades (>98% purity) of SiO<sub>2</sub> (quartz sand), calcined Al<sub>2</sub>O<sub>3</sub>, dead burned MgO, CaO (quick lime), Fe<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub> (rutile) were used to manufacture the synthetic glass.

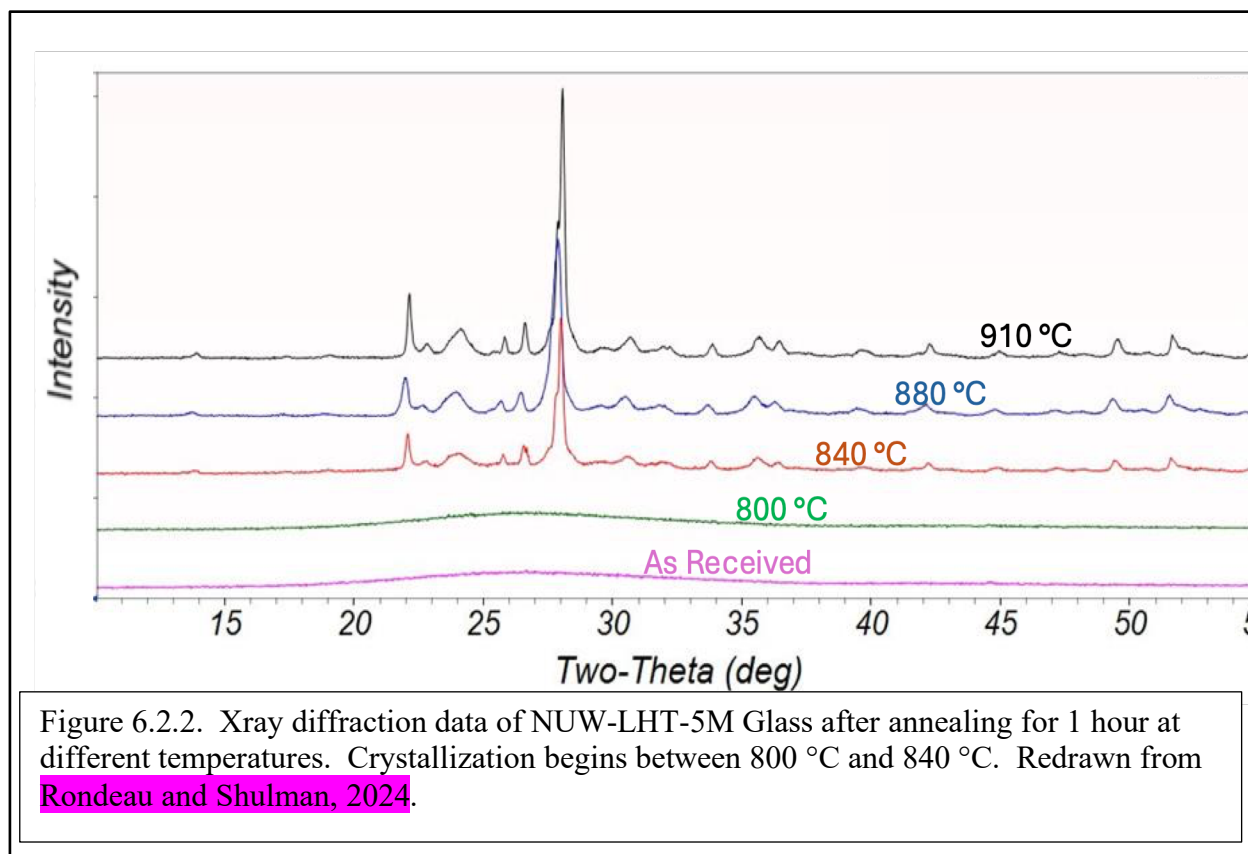
A21 was heated just above the beginning of melting, as seen by comparison with A22 and the cooling curve of A21 being very slightly above the heating curve.

Table 6.2 NUW-LHT-5M Glass target composition.

Material	NUW-LHT-5M Formulation Target
SiO <sub>2</sub>	45.29%
Al <sub>2</sub> O <sub>3</sub>	27.27%
Fe <sub>2</sub> O <sub>3</sub>	5.18%
MgO	5.87%
CaO	15.83%
TiO <sub>2</sub>	0.56%

Figure 6.2.1  $\epsilon'$ ,  $\epsilon''$ , and HPD for the glass used in the lunar highland simulant material NUW-LHT-5M.





Based on Figure 6.2.2 and the DSC data in Figure 6.2.3, the feature in Figure 6.2.1 centered between 800 °C and 900 °C is associated with the glasses' crystallization.

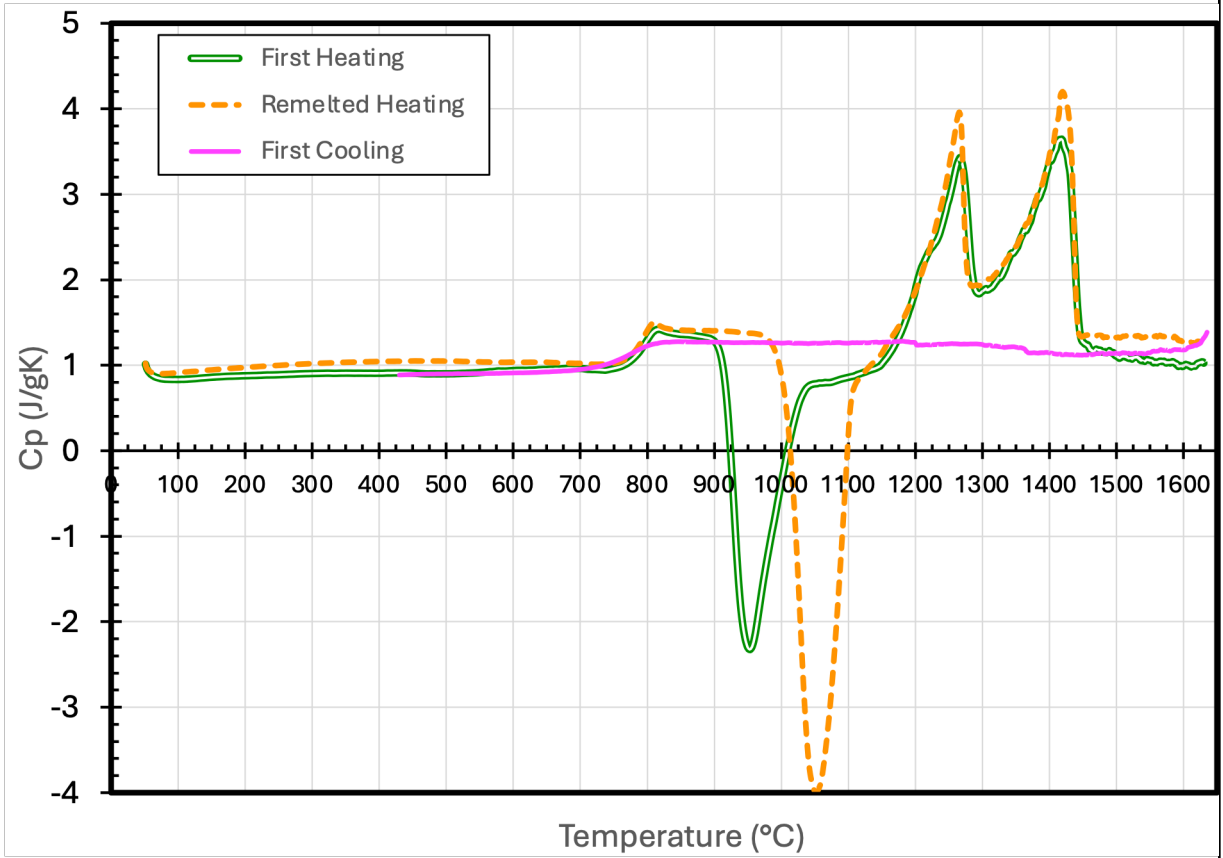


Figure 6.2.3. DSC of NUW-LHT-5M Glass. See Section 14 in Rickman et al. (2024b) for more information.

### 6.3 JSC-1A

JSC-1A is a mare simulant produced in 2005 - 2006 by Dr. James Carter, for Orbitec under a NASA contract. Its feedstock was a basaltic volcanic ash from the Merriam Crater cinder quarry east of Flagstaff, AZ. It is the most studied of all lunar simulants.

Four samples of JSC-1A were run by MPN; each to explore run variables and preprocessing variations of bake out conditions, Figure 6.3.1. The purpose of a pre-treatment was to subdue the effects of the non-lunar minerals in the simulant. This latter emphasis was an element in the work that led to Wilkerson et al. (2023). That work, as does A11 in this plot, demonstrated the effect of heating the simulant in an inert atmosphere, UPH argon, to 750 °C, then holding that temperature and adding H<sub>2</sub> gas to the otherwise inert atmosphere, then finally cooling to room temperature while maintaining the argon. This treatment is now referred to as the Standard Treatment or the Standard Bake Out (B1). A11 shows the result of applying the Standard Treatment to JSC-1A.

Sample A8 and A9, which were minimally pre-treated, have strong deflection starting near 600 °C. This was attributed to the non-lunar minerals in the simulant. The non-lunar minerals, which included clays, carbonates, and sulfates, are very different from the lunar minerals. Although the non-lunar minerals are a small percentage of the total mass, those minerals are on the surface of the particles or free as very small particles. For a detailed investigation of the non-lunar minerals

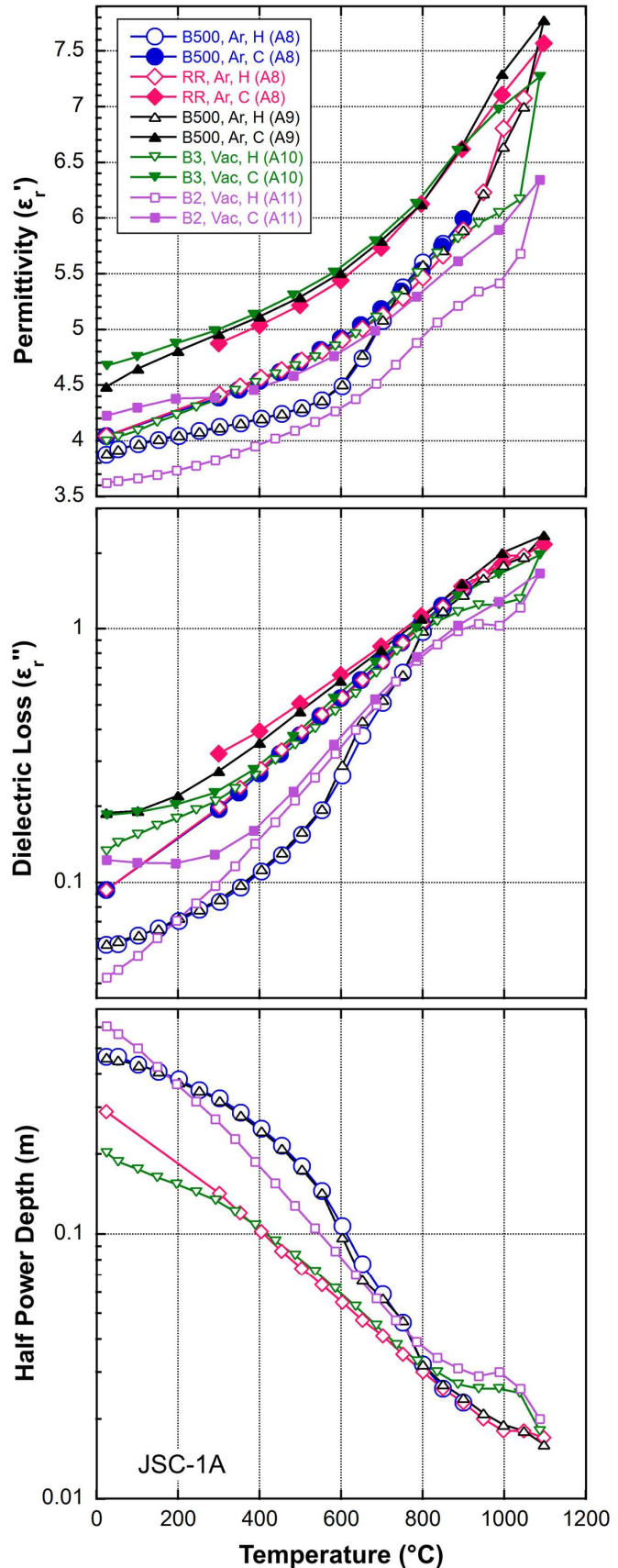


Figure 6.3.1  $\epsilon'$ ,  $\epsilon''$ , and HPD for the lunar mare simulant JSC-1A.

in JSC-1A see Petkov et al. (2025).

In run A8 the simulant was heated to 900 °C, allowed to cool to room temperature, then reheated to ~1100 °C, and again allowed to cool to room temperature, Figure 6.3.2. The first heating leg exhibited the beginning of non-lunar mineral destruction near 600 °C. That was shown to be irreversible by returning the material to room temperature and reheating. The second heating overlays the first cooling, showing no more changes occurred up to 900 °C. The second heating, to ~1100 °C, caused another irreversible change between ~950 °C and 1000 °C. This change is not explained here. The observation that the second cooling is above the second heating is caused by the beginning of melting in the simulant by the peak temperature of the run. This agrees with other data on the simulant, for example Rickman et al. (2024b) give the  $T_m$  of JSC-1A as 1020 °C.

Figure 6.3.3 gives both the DSC and the dielectric values for the simulant.

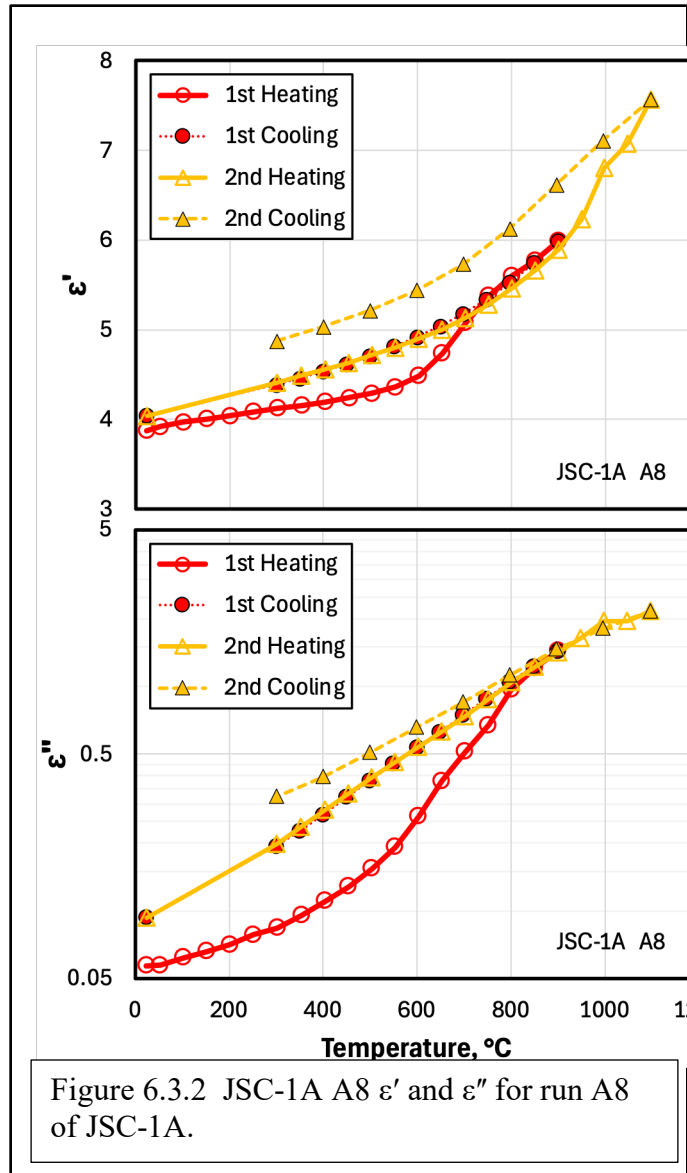
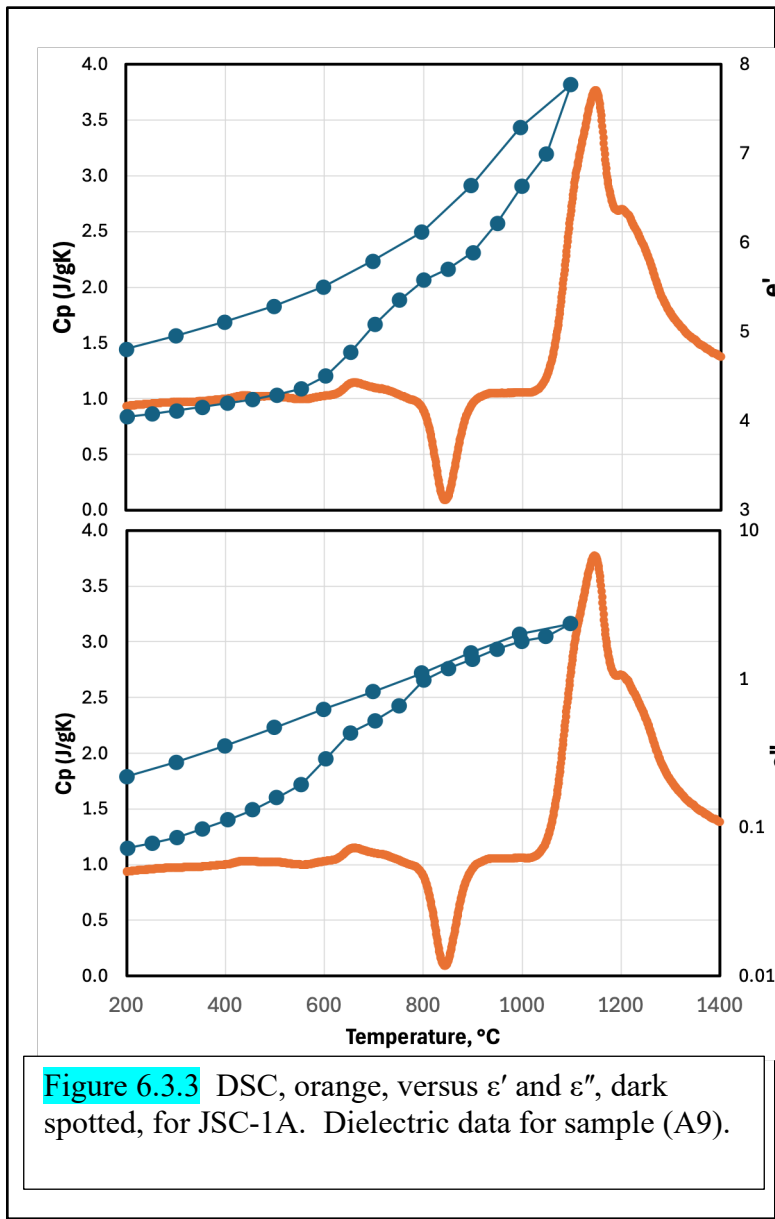


Table 6.1 Measurement conditions for the JSC-1A samples run for this study.  $\epsilon'$  &  $\epsilon''$  are at room temperature and scaled to 1.75 g/cc.

	SHUL2146	SHUL2119	SHUL2117	SHUL2147
$\epsilon'$ & $\epsilon''$	3.998 0.1327	3.888 0.0573	3.876 0.0568	3.620 0.0422
Environment	Vacuum	Argon	Argon	Vacuum
Pre-treatment	750 °C Ar	500 °C Ar	500 °C Ar	750 °C Ar & H2
Pellets baked	no	140 °C Ar	140 °C Ar	no
Pressure, PSI	32,000	20,000	20,000	32,000
Initial Density	2.08	2.02	1.97	2.16
Final Density	2.14	2.02	1.89	2.18
Oxidation	Moderate	Heavy	Heavy	Minimal
Peak Temp	1100 °C	1100 °C	1100 °C	1100 °C



**Figure 6.3.3** DSC, orange, versus  $\epsilon'$  and  $\epsilon''$ , dark spotted, for JSC-1A. Dielectric data for sample (A9).

## 6.4 CSM-LHT-1G

CSM-LHT-1G is a mix of the constituents in Table 6.4. This simulant was intended as a stop gap that existed before NUW-LHT-5M was produced. Its design emphasized using material readily available, Greenland anorthosite (GreenSpar) and Merriam Crater basaltic ash, a small amount of commercially available augite, and the same glass as used in NUW-LHT-5M.

Table 6.4 Make up of CSM-LHT-1G by weight.

Source	%
GreenSpar (Anorthosite)	55
Merriam Crater	24
Augite	6
NUW-LHT-5M Glass	15
sum =	100

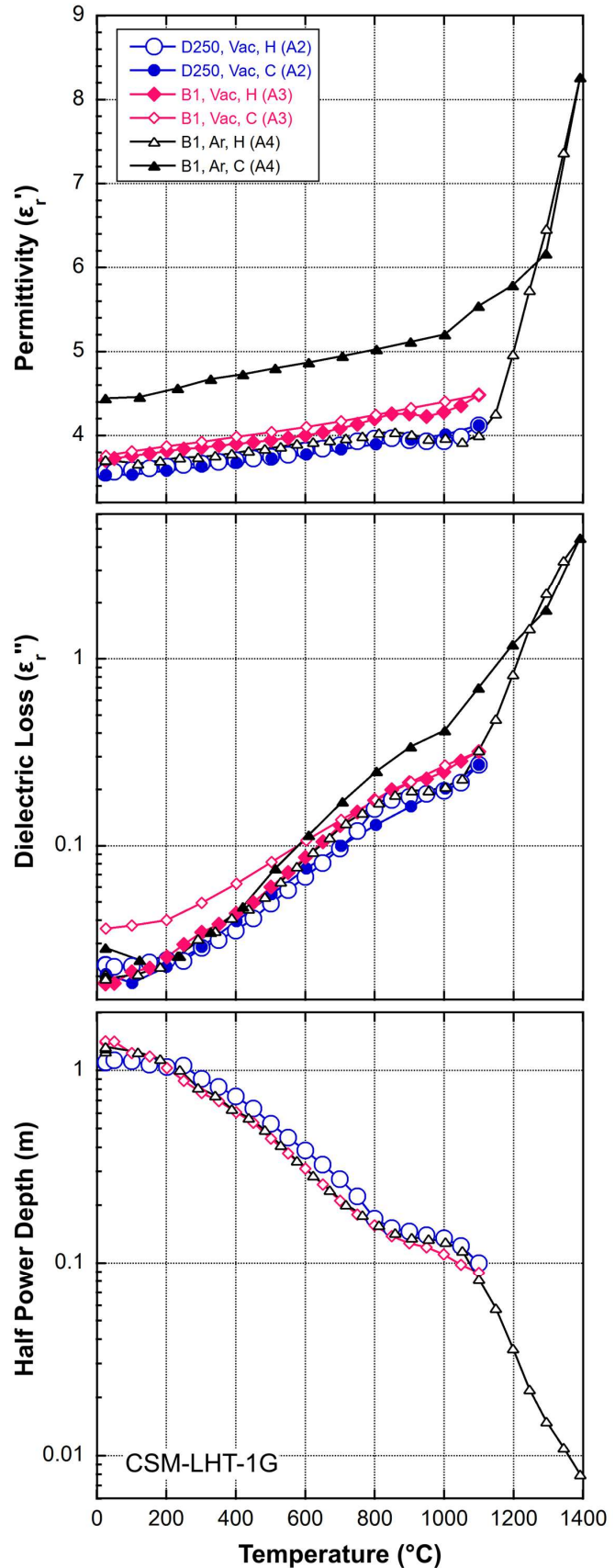


Figure 6.4  $\epsilon'$ ,  $\epsilon''$ , and HPD for the lunar highland simulant CSM-LHT-1G.

## 6.5 Feedstocks and Related Materials

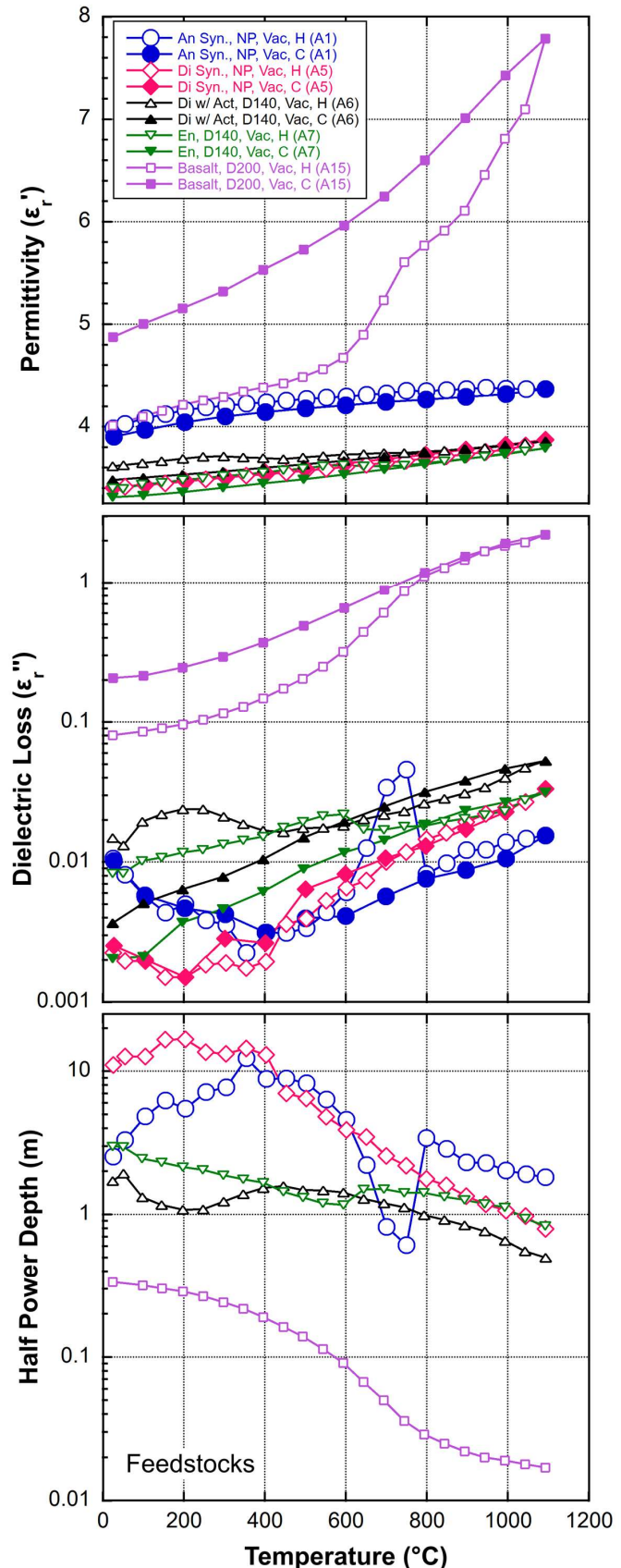
One of the intentions of this work was to understand the relationships between the dielectric properties of a full simulant compared to constituents of the simulant. Toward that end, in addition to the data on NUW-LHT-5M Glass, measurements were made of Merriam Crater basaltic ash, synthetic anorthite, synthetic diopside, natural diopside, and natural enstatite. These, plus olivine which was not studied, are by far the dominant minerals in the lunar regolith.

Of the materials included in this section, only the basalt (A15) is a true feedstock used in a simulant. The other materials are essentially mono-mineralic materials similar to the mineralogy of the lunar simulants. Readers are cautioned that the actual simulant feedstocks are complex rocks which contain varying amounts of minerals more or less similar to the minerals included here.

### 6.5.1 Merriam Crater

Merriam Crater near Flagstaff, Arizona (35.3370, -111.2889) is the source of the feedstocks used to make JSC-1A, JSC-1AC, and other simulants we have not studied. The ash has been quarried for road metal for some time, and the quarry operation is quite obvious in the satellite images. (These are the extremely black areas around the base of the cone.). The quarry provided the material we use in the lunar simulants.

Figure 6.5  $\epsilon'$ ,  $\epsilon''$ , and HPD for feedstocks and related materials used in lunar simulants.



Geologically, the Merriam Crater materials are considered basaltic volcanic ash. While there are known variations in the ash spewed by the volcano, for our purposes the ashes are fairly consistent. Because the eruptions that created the volcanic cone occurred ~20,000 years ago, the ash has weathered some. In consequence, the deposit has developed a small amount of weathering minerals, which are non-lunar in character.

The estimated amount of non-lunar minerals is close to 1 wt%, but varies.

### 6.5.2 Synthetic anorthite

This material, as well as the synthetic diopside discussed below, was made by Dr. Shulman and students at Alfred University. As the lunar plagioclase is dominated by An95 anorthite, as a first step an An100 compositions,  $\text{CaAl}_2\text{Si}_2\text{O}_8$ , was targeted for synthesis<sup>3</sup>. This composition is in contrast with the significantly lower, An70 – An83, compositions of the lunar simulants. The synthesis of anorthite and diopside were part of a developmental effort to fabricate a completely synthetic lunar simulant.

The melting point of pure anorthite is ~1550 °C, therefore the lack of a melting signature in our data, which reached ~1100 °C was not surprising.

These data showed a significantly higher values of  $\epsilon'$  for the synthetic anorthite compared to the diopside values. This is unexplained here.  $\epsilon''$  for the synthetic anorthite are a one-to-two orders of magnitude below that of the Merriam Crater basaltic ash, a material with significant plagioclase.

### 6.5.3 Synthetic diopside

The synthesis of pure diopside, a clinopyroxene, is considerably more difficult than that of An100 anorthite, as previous attempts have demonstrated. The material used for dielectric measurements were made by Shulman and students at Alfred University. The synthesized material was shown to be  $(\text{Mg,Ca})\text{Si}_2\text{O}_6$ , with 1.3 wt% forsterite,  $\text{Mg}_2(\text{SiO}_4)$ , by XRD.

As with the synthetic anorthite, the melting temperature of the mineral was substantially higher than ~1100 °C reached in the permittivity measurements.

### 6.5.4 Diopside with actinolite

The material measured was cored out of a large crystalline mass by MPN. See the MPN report “MPN-242\_MPN\_Diopside with Actinolite.docx” for photos of the crystalline mass and the cores taken from it. The report also included TGA and DTG data for the material. This work was done by Dr. Peter Hayward, Eutechnics Consulting Inc., Box 718, 3 Monck Place, Pinawa, Manitoba, Canada R0E 1L0. The following is an interpretation of the mineralogy, photographs, TGA, and DTG data.

The exact composition of the sample processed by MPN is unknown.

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<sup>3</sup> The An number for plagioclase minerals is obtained from  $100 \cdot [\text{Ca}/(\text{Ca}+\text{Na})]$  in the formula.

Diopside is a solid solution silicate mineral in which Ca, Mg, and Fe substitute within the general formula of  $(\text{Mg,Fe})\text{CaSi}_2\text{O}_6$ . The range of substitution is restricted. Its colors are confined in the green – dark green range. Actinolite is also a solid solution silicate with a very similar formula, except it contains  $\text{OH}^-$  radicals,  $\text{Ca}_2(\text{Mg,Fe})\text{Si}_8\text{O}_{22}(\text{OH})_2$ . In the photos of the prepared core the red – purple areas are some of the actinolite, though they may be caused by the iron-rich end member of the solid solution, tremolite. It was likely the samples also included minor amounts of other minerals, such as carbonates and clays along the grain/crystal boundaries. The observations that there was an irreversible reaction starting near  $250^\circ\text{C}$  and continue to approximately  $350^\circ\text{C}$  was strong evidence of this. This temperature range was compatible with dehydration of clays and possibly other minerals, though not with the evolution of something from diopside or actinolite. Based on TGA and DTA something, possibly carbonate and/or biotite/muscovite, started to transform between  $650^\circ\text{C}$  and  $850^\circ\text{C}$ . The weight loss might also be tied to dehydrations of the actinolite. The result in a 4% weight loss in the sample, which is was a larger percentage than expected from just the actinolite.

#### 6.5.5 Enstatite

Enstatite is an orthopyroxene, approximately  $\text{MgSiO}_3$ . Another solid solution silicate, Fe can substitute for up to 50% of the Mg. The exact Mg/Fe ratio in the measured sample was unknown.

The sample was also a core from a large crystalline mass purchased from a commercial vendor of mineral samples. In addition to the dielectric measurements, it was studied by DTA and DTG. The following interpretation was driven by the photographs, DTA, and DTG data which are in the MPN report, “MPN-242\_MPN\_Enstatite\_Mirabel Springs, Mt St Helena CA.docx”

The hand sample showed this rock was very likely picked up off a mine dump. The iron staining was dominantly on the surface of the sample, not through the fresh face. Note, there was some staining inside the sample.

The hand sample exhibited large, blocky crystals. This increased the probability that the analyzed core was dominantly enstatite.

The color of the core sample showed ~2% - 5 % impurity. The sample clearly oxidized in the thermal processing, and the color/tint/hue suggested the oxidized iron was on the surface of the crystalline enstatite. This added further weight to the probable high purity of the sample and agrees with the 2 – 5% estimate.

The TGA showed 1/10th the range of the diopside sample. The DTA, once the interstitial  $\text{H}_2\text{O}$  was removed, showed multiple phases were present in small amounts. These facts further limited the abundance and nature of the impurities.

As with the anorthite and diopsides, the melting point of enstatite was much above the  $\sim 1100^\circ\text{C}$  limit of the run at MPN.

## 6.6 JSC-1AC

JSC-1AC (Allan et al., 2013) is the coarser version of the simulant JSC-1A; it has the same composition and the same production history. The only difference between the two simulants is the particle size distribution.

Compared to the other runs covered in this report, all of which measured six frequencies, this run measured two frequencies, 912 and 2466 MHz. Otherwise there was no appreciable difference in the technology used.

This run followed the same logic as was used for the A8 run with JSC-1A; the material was heated, cooled, and re-heated, and re-cooled. In this run the two heating runs both reached  $\sim 1079^\circ\text{C}$ ; which temperature, as can be seen by the cooling lines being above the heating lines, was above the melting point of the simulant. Inspection of Figure 6.6.1 suggests the melting temperature of the material is similar to that of JSC-1A. The sample was not totally melted, as can be seen by the photograph in the MPN report “CERALINK NYSERDA\_10.doc”.

Both  $\epsilon'$  and  $\epsilon''$  show a decrease between  $\sim 900^\circ\text{C}$  and  $\sim 1000^\circ\text{C}$ . The cause of this was unknown. It was an irreversible reaction after the simulant was heated to the peak temperature. The feature was not present in either the JSC-1A or Merriam Crater basaltic ash data.

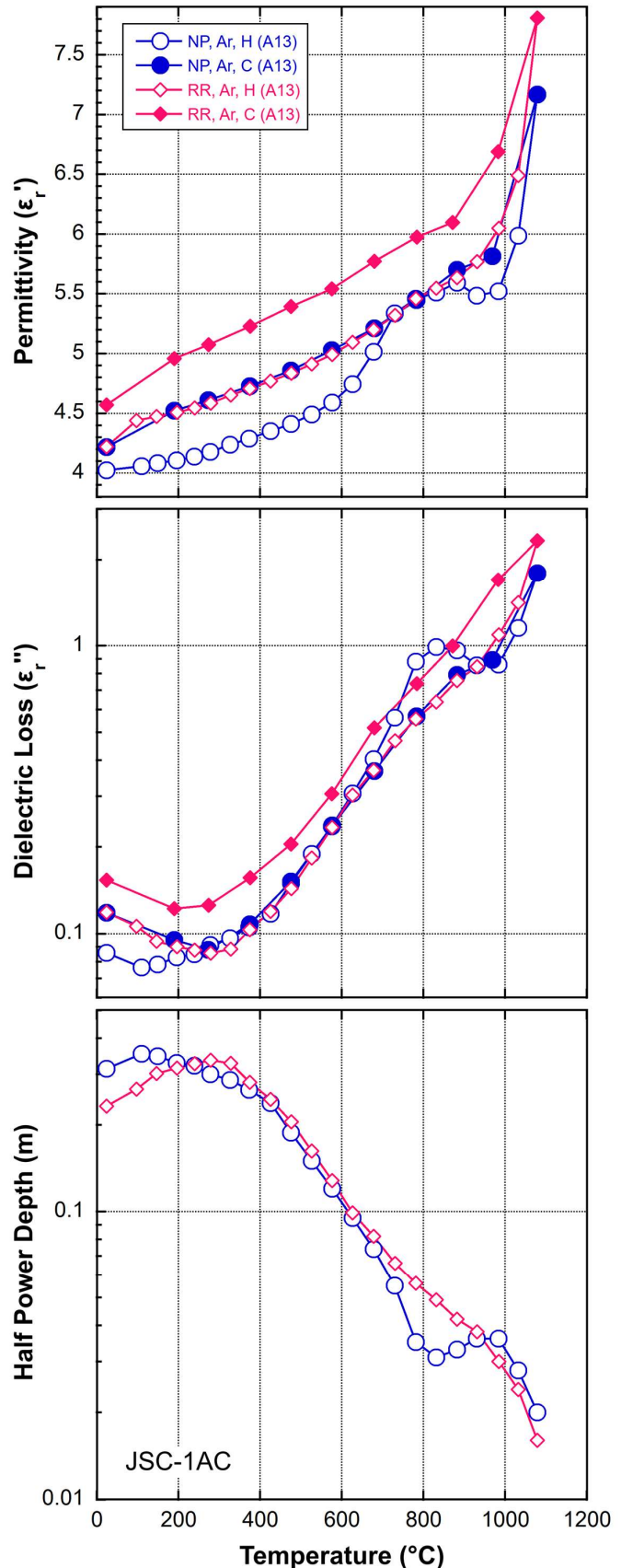


Figure 6.6  $\epsilon'$ ,  $\epsilon''$ , and HPD for JSC-1AC.pdf

## 6.7 NU-LHT-2M and NU-LHT-4M

These are earlier generations of the simulants NUW-LHT-5M. NU-LHT-2M was produced first and was followed by NU-LHT-4M. The two simulants were intended to be highly similar, using the same feedstocks from the same sources and processed the same way. The primary difference between these two was the included glass; NU-LHT-2M included 5 wt% “good” glass and 30 wt% pseudo-agglutinate glass. NU-LHT-4M did not include the “good” glass and the pseudo-agglutinate was 35 wt% of the total mass.

“Good” glass was a high quality, visibly uniform, dark glass. The pseudo-agglutinate was a very impure glass of varying color with abundant included particles of crystalline feedstocks and previously made glass (Rickman et al., 2013).

Therefore, the difference between the two plotted values was caused by the 5 wt% change in the nature of the glasses, which was a surprising sensitivity. The “good” glass was apparently causing the rise in  $\epsilon'$  and  $\epsilon''$  centered near 900 °C. In contrast the  $\epsilon'$  of the pseudo-agglutinate-bearing NU-LHT-4M was almost flat up to the rise associated with melting.

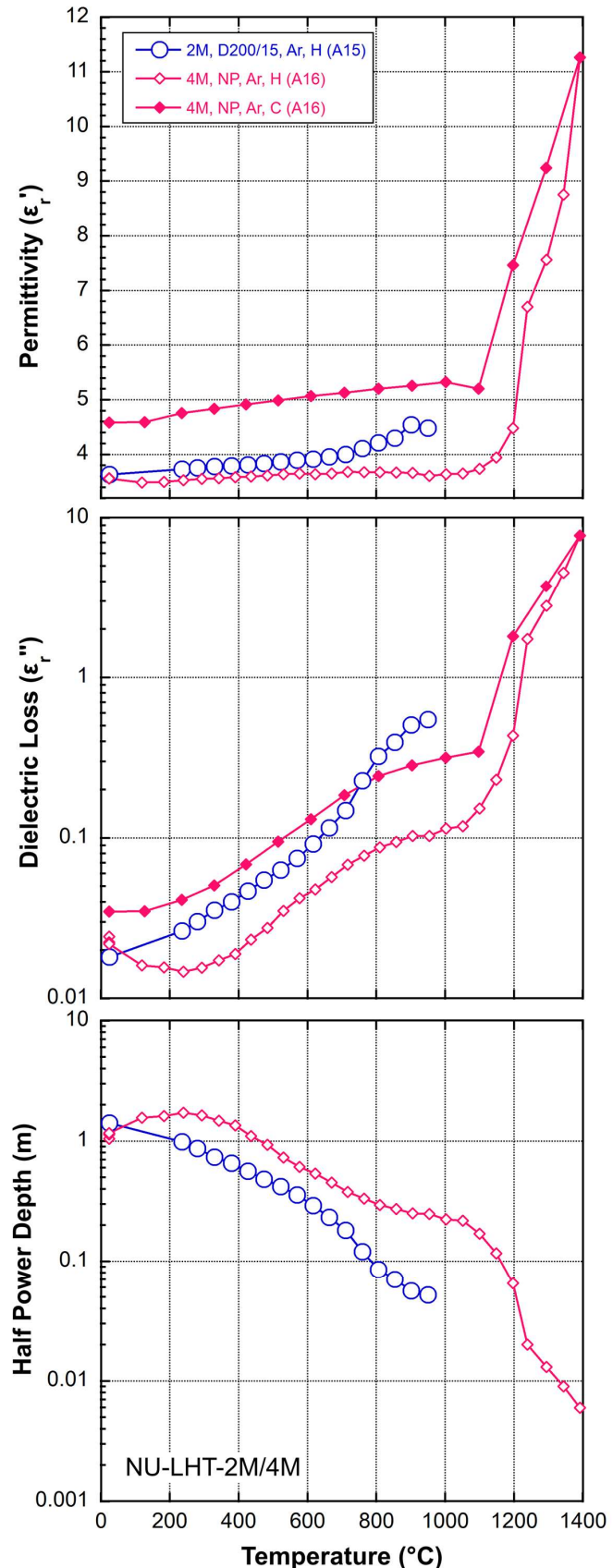


Figure 6.7  $\epsilon'$ ,  $\epsilon''$ , and HPD for NU-LHT-2M & NU-LHT-4M.pdf

## 7 Variation Between Groups

The figures in this section combined data from different materials to enable study of questions such as the relationships between the constituents of a simulant versus the simulant, or the relationships between simulants that were supposed to be applicable for a common usage. The individual measurements, for example A5 and A18, were discussed in the preceding section.

### 7.1 NUW-LHT-5M vs Feedstock Materials

A feature between 800 °C to 900 °C in the simulant appeared to come from the glass component of the simulant. As shown above, this feature was associated with a glass transition. In detail there was also a difference in the simulant and glass curves between ~900 °C to ~1100 °C. This may be the crystallization in the glass.

The crystalline components of the simulant were all solid solution minerals, able to contain various amounts of Ca, Fe, and Mg, or Ca and Na, depending on the specific mineral. Although fairly precise values for these elements are known for the simulant (Rickman et al., 2024b), and for the synthetic minerals, the chemistry of the natural diopside and enstatite used here were unknown.

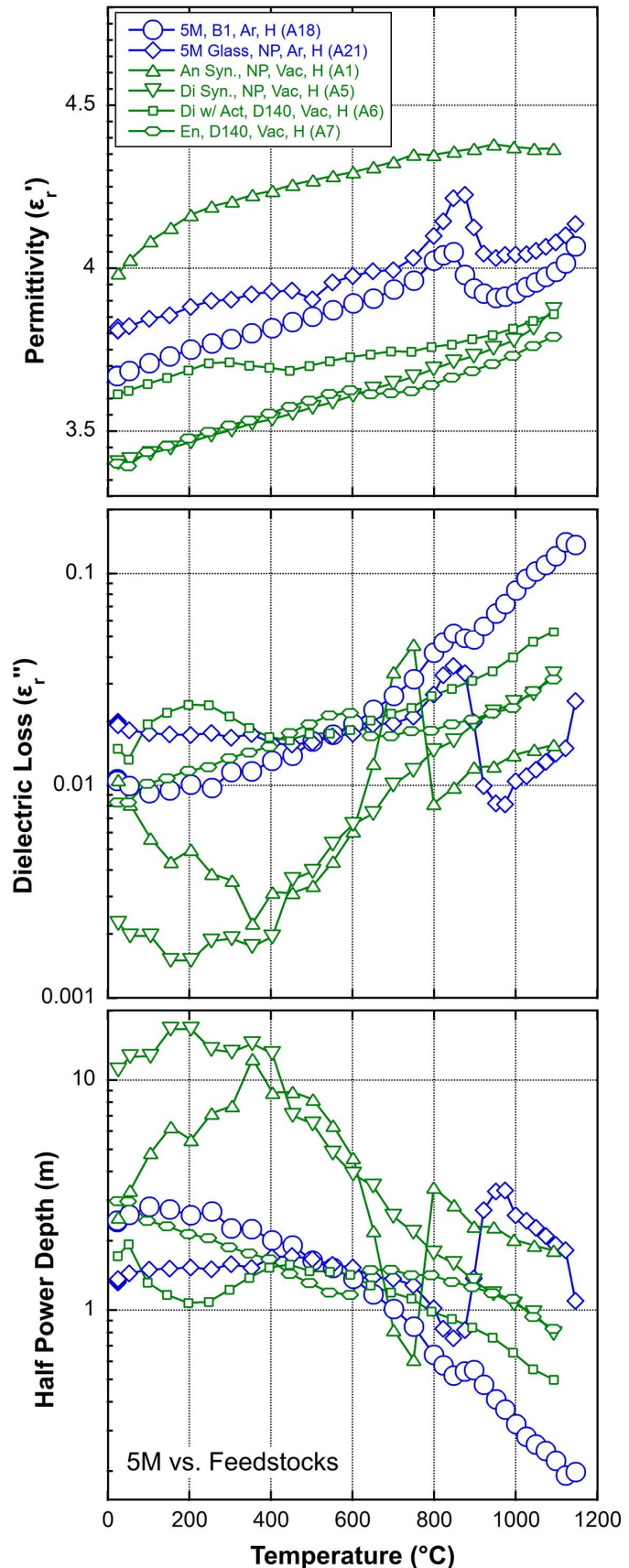


Figure 7.1  $\epsilon'$ ,  $\epsilon''$ , and HPD for NUW-LHT-5M vs Its Feedstocks.

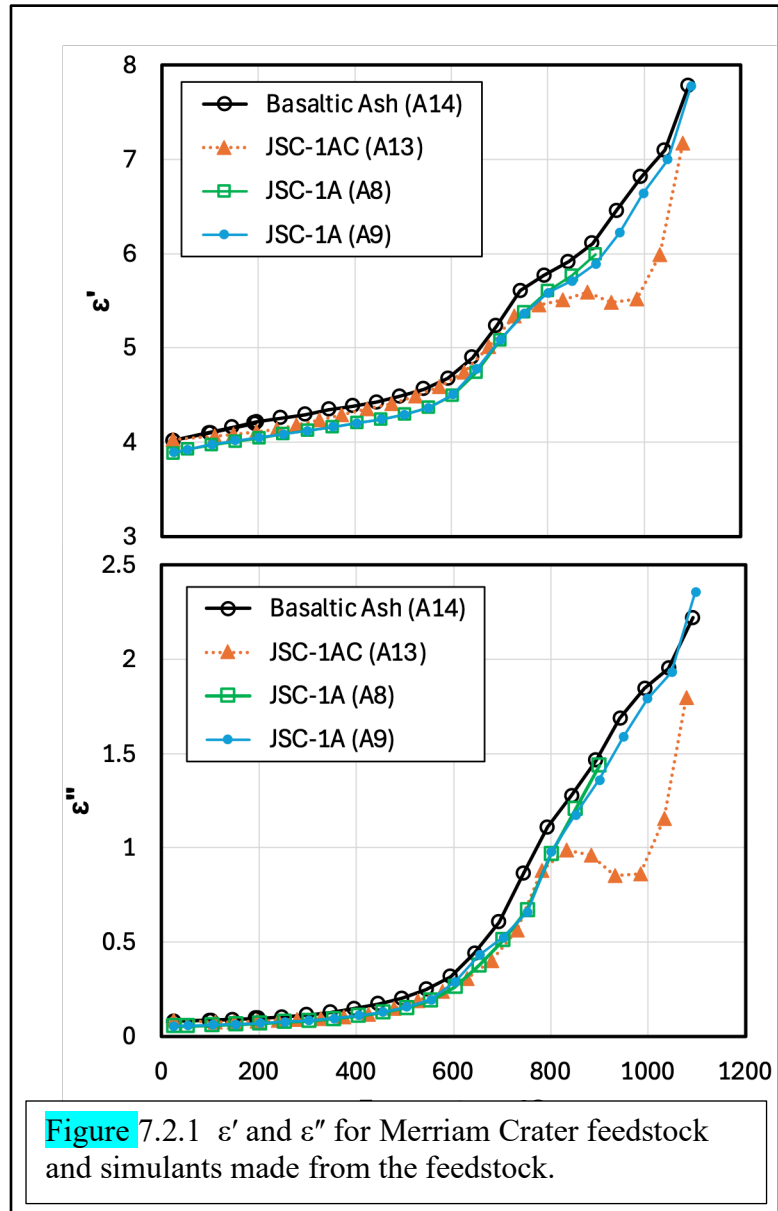
## 7.2 Merriam Crater, JSC-1AC, and JSC-1A

Merriam Crater basaltic ash was used as the only feedstock to make JSC-1A and JSC-1AC.

Differences between the runs are not likely to be due to compositional difference, which chemical data shows varies at the 1% level or less, or pre-treatments, rather particle size and pre-treatments should be considered. Of the materials in the plot, the fine sand used in A14 was the coarsest, with JSC-1AC being the next coarsest. While there was an organization of the three in the  $\epsilon'$ , it was very minor. If the observed differences between the data sets are real, which was a conclusion strongly supported by this study, then the minor differences between the materials may be the result of approximately an order of magnitude in particle size differences.

The robustness of this conclusion was limited primarily by the lack of a robust particle size distribution for the basaltic ash, and secondarily by the limited range of particle sizes the measurement system at MPN can use.

This conclusion is significant to NASA as it put a limit on the need to do particle size sorting on the Moon where microwave heating is to be used.



### 7.3 NU-LHT-2M, NU-LHT-4M, NUW-LHT-5M and CSM-LHT-1G

These highland simulants are very similar in their permittivity values.  $\epsilon'$  show functional difference between the two up to the maximum temperature used with CSM-LHT-1G. There is a difference in the  $\epsilon''$  values, with corresponding differences in the HPD.

Given the quite different feedstocks used to make these simulants, these results provided evidence that, at least for dielectric heating, the significance of differences have not made a major difference. Certainly not when compared to the differences between mare and highland simulants.

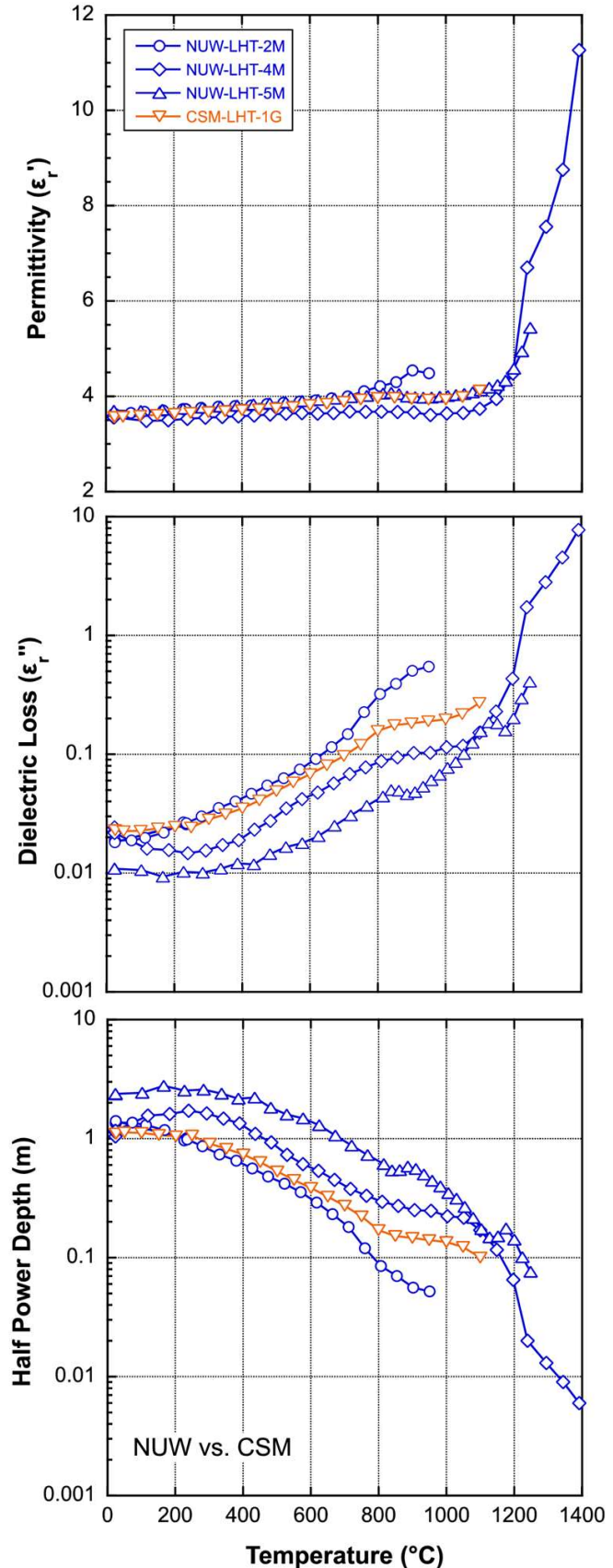


Figure 7.3  $\epsilon'$ ,  $\epsilon''$ , and HPD for highland simulants.

#### 7.4 NU-LHT-series vs JSC-1A series

In both  $\epsilon'$  and  $\epsilon''$  there are clear, strong differences between the permittivity values of the highland and the mare simulants JSC-1A.

$\epsilon'$  of the mare simulant JSC-1A started at a value similar to that of the highland simulants, but diverged as temperature rises.  $\epsilon''$  of the two groups, mare vs. highlands, was distinctly different at room temperature and departs substantially with rising temperature. The resulting difference in half power depth became more than an order of magnitude at 800 °C.

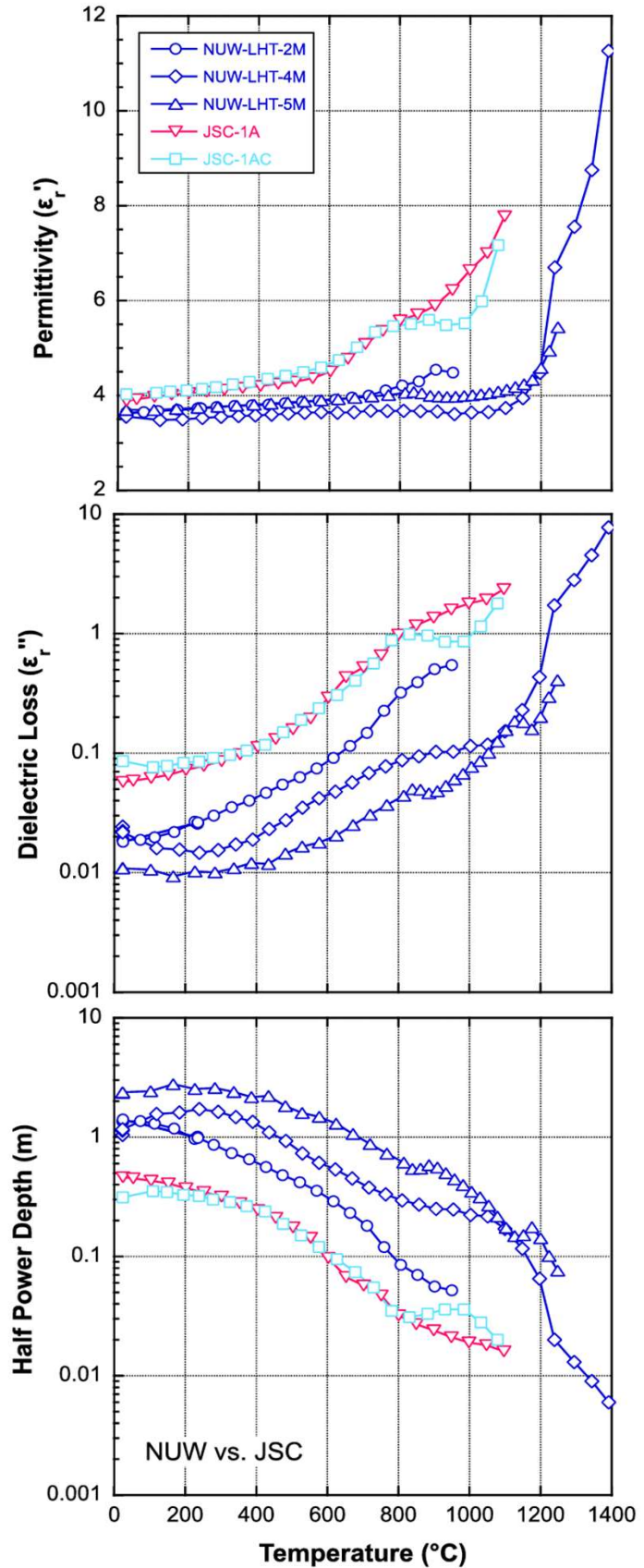


Figure 7.4  $\epsilon'$ ,  $\epsilon''$ , and HPD for NU-LHT-series vs JSC-1A series.pdf

## 8 Scatter in Measurements at Room Temperature

There were practical limits to the accuracy of the measurements provided by MPN. For example the pellet weights, length, diameter, and physical conformity to a consistent geometry were some of the limitations to reproducibility. The pellet masses were small enough, <0.3 g, that uniformity of compositions for mixtures as complex as the simulants could be a factor. Beyond such factors, MPN believed their  $\epsilon'$  values were no better than  $\pm 5\%$  at room temperature, and the  $\epsilon''$  scatter was larger, possibly  $\pm 10\%$ , though the company stated a lack of calibration samples made it hard to evaluate  $\epsilon''$ . They also indicated scatter between replicates increased with temperature. Visual analysis of our plots with replicates definitely supported the reasonableness of their estimate of reproducibility. Nonetheless, the functional bottom line was the measurements were highly reproducible, with minor scatter between replicates, especially up to  $\sim 800^\circ\text{C}$ .

Numerical analyses of reproducibility in the data over the full temperature range were beyond the scope of this work. But the effort to do such analyses, beyond the small efforts done as part of our work, cannot be justified for the purposes originally driving our work.

We have done a simple analysis of reproducibility at room temperature using four groups of measurements. The simulants and the number of repetitions were: NUW-LHT-5M (3) NUW-LHT-5M Glass (3), JSC-1A (4), CSM-LHT-1G (3). Table 8.1 showed for each material the room temperature values of  $\epsilon'$  and  $\epsilon''$  scaled to 1.75 g/cc. Table 8.2 gave information on the observed scatter in the data

Table 8.1 Values at Room Temperature Scaled to 1.75 g/cc

	$\epsilon'$	$\epsilon''$	$\epsilon'$	$\epsilon''$	$\epsilon'$	$\epsilon''$	$\epsilon'$	$\epsilon''$
NUW-LHT-5M Glass	3.688	0.0185	3.818	0.0199	3.670	0.0184	-	-
NUW-LHT-5M	3.694	0.0110	3.670	0.0107	3.651	0.0100	-	-
JSC-1A	3.998	0.1327	3.888	0.0573	3.876	0.0568	3.620	0.0422
CSM-LHT-1G	3.709	0.0206	3.709	0.0184	3.557	0.0231	-	-

Table 8.2 Scatter in  $\epsilon'$  and  $\epsilon''$  from four groups of measurements.

Material	$\epsilon'$				$\epsilon''$			
	Max	Otherwise	Average	$\Delta, \%$	Max	Otherwise	Average	$\Delta, \%$
NUW-LHT-5M Glass	0.15	0.02	3.73	4.0	0.0015	0.0001	0.0189	7.9
NUW-LHT-5M	0.04	0.02	3.67	1.2	0.0009	0.0003	0.0105	9.0
JSC-1A	0.38	0.12	3.85	9.8	0.0905	0.0151	0.0723	125.2
CSM-LHT-1G	0.15	0.00	3.66	4.1	0.0046	0.0022	0.0207	22.4

- Max - maximum difference between two  $\epsilon'$  measurements seen in the material,
- Otherwise - the second largest difference in  $\epsilon'$ ,
- Average - the average value of  $\epsilon'$  for the material, and
- $\Delta, \%$  - the ratio of the maximum difference divided by the average.

Between materials the  $\Delta$  for JSC-1A was roughly 6 times the largest delta in the other three materials. Within just JSC-1A the value of the first sample was 2 ½ to 3 times the other samples. The variation in the range in  $\epsilon''$  of CSM-LHT-1G was also 2 ½ to 3 times the range in NUW-LHT-5M and NUW-LHT-5M Glass. The CSM-LHT-1G range was also higher than the estimated range to be expected provided by MPN. While we hesitated to draw too much focus on the CSM-LHT-1G, the range of  $\epsilon''$  in JSC-1A was definitely unusual in these data.

In contrast to the other three materials, which were each drawn from a single stock, each of the four JSC-1A samples was pre-processed in different ways. This was done as part of an effort to understand the impact of suppressing non-lunar minerals in the simulant, the final results of that work were reported in Wilkerson et al. (2023). The four samples received 1 of 3 treatments before being provided to MPN: (1) powder baked at 500 °C for 6 hours in Ultra-High Purity (UHP) argon, pressed pellets further baked at 140 °C for 2 hours; (2) powder baked at 750 °C UHP argon, pressed pellets not further baked; and (3) powder baked at 750 °C UHP argon and hydrogen, pressed pellets not further baked. Treatment (3) was referred to as the “Standard Bake Out” or “Standard Treatment”. The rationale for the Standard Bake Out was explained in the Wilkerson et al. (2023) paper. This treatment was found to be significantly more successful in removing non-lunar minerals from the simulant. The first and last JSC-1A samples were also exposed to different environments during the measurements. The first and last sample in Table 8.2 were run in vacuum. The middle two samples were run in UHP argon.

In Table 8.2 the left most JSC-1A sample,  $\epsilon' = 3.998$ , received treatment (2). The center samples,  $\epsilon' = 3.888$  and  $3.876$ , received treatment (1). The right most sample,  $\epsilon' = 3.620$ , received treatment (3). It was clear there were distinct differences in the  $\epsilon'$  values as a function of pre-treatment. The relatively strong effect of the standard treatment was seen by eliminating it from the analysis in Table 1.1.2. When that was done the max difference between samples drops to 0.122, otherwise = 0.11, average = 3.92, and the  $\Delta = 3.1\%$ , a value in line with the other three materials. Therefore, based on this analysis, at least the variation of  $\epsilon'$  at room temperature that we observe was significantly less than the  $\pm 5\%$  value given by MPN.

Here we attributed differences between runs to the pre-treatment, despite the measurement environments were also changed. We did this because the three samples each of CSM-LHT-1G and NUW-LHT-5M were also the two different environments, but showed no obvious pattern in  $\epsilon''$  with respect to run environment.

## 9 Conclusions

It was our intention to have provided a thorough statement of what has been learned about and from the data reported herein. Because the measurement process and the materials are both complex, grasping the information is not simple. We therefore provided the following simple statements summarizing significant points.

- 1) After scaling to a single density using the Looyenga equation, the data produced by Microwave Properties North was highly consistent sample to sample. This was true for both the  $\epsilon'$  and the  $\epsilon''$  values.
- 2) The beginning of melting in the simulants corresponded with a rapid rise in  $\epsilon'$  and  $\epsilon''$ .
- 3) Simulants are complex mixtures. In many cases the complexity of these mixtures made it problematic to definitively and precisely attribute, using dielectric data alone, a measured feature to a single cause.
- 4) Non-lunar minerals, even in very small amounts, distinctly affect the permittivity measurements. These minerals introduced spurious signals into the intended measurements. These spurious signals did not reoccur after cooling. Further, the choice of pre-treatment protocol could have distinct impact on the values measured. It was recommended that the standard treatment, per Wilkerson et al. (2023) be a default choice for pre-treatment.
- 5) Surface bound H<sub>2</sub>O (Rickman et al. 2025) could make a small but detectable difference in the measurements at the lower initial temperatures. For some purposes its removal by preliminary baking at ~200 °C was recommended.
- 6) With respect to dielectric measurements, high quality, i.e. glass with few imperfections, was apparently very different from the glass made as pseudo-agglutinate for NU-LHT-2M and NU-LHT-4M. The significance of this to lunar material was unknown.
- 7) Particle size, within the limits of the pellets used by Microwave Properties North, did not significantly affect the permittivity values. For reference Carrier (2003), and the superior Chambers and DeStefano (2025), compiled the available particle size distribution data for lunar regolith. The former is the distribution which current, as of 2025, lunar simulants are patterned after.
- 8) There was a correlation between DSC heat capacity and these permittivity measurements; both reflected the material's ability to respond to energy input, but under differing mechanisms. At a simple level, dielectric response depended on the material's ability to store electric energy at a given frequency, whereas DSC measured the total energy absorbed as heat, regardless of frequency. Also, the simulants were generally too complicated to work out this relationship.
- 9) There are many features in these data we did not attempt to explain.

- 10) The highland simulants, NU-LHT-2M, NU-LHT-4M, NUW-LHT-5M, and CSM-LHT-1G all had similar permittivity behavior. However, caution was warranted when using simulants which contain components with very different behaviors, for example a Merriam Crater and a high calcium anorthosite. Such a combination might do well in dielectric measurements and be problematic under a different type of measurement.
- 11)  $\epsilon'$  of the mare simulant JSC-1A started at a value similar to that of the highland simulants, but diverged upward as temperature rises.  $\epsilon''$  of the two groups, mare vs. highlands, was distinctly different at room temperature and further departed with rising temperature. The resulting difference in half power depth became more than an order of magnitude at 800 °C.
- 12) Substantial oxidation in some of the samples has occurred, but the significance was not clear.
- 13) Pellet density had a substantial effect on the reported values of  $\epsilon'$  and  $\epsilon''$ . These data showed that density can change during a run. There were multiple processes that accounted for the evolution of pellet density during a run, and these processes could act at different temperatures. Which processes, and the magnitude of their effect, varied with the material. How the changing density was distributed with respect to temperature affected details of the reported permittivity values to a minor extent
- 14) If a sample was heated above its  $T_m$ , density evolution would effectively stop when the sample was cooled below  $T_m$ . If a sample did not exceed  $T_m$ , evolution of density would largely stop when the sample reached the peak temperature.
- 15) As noted by reviewer John Forster, the data presented here are useful in modeling of several properties, such as thermal and electromagnetic behavior.

## 10 Credits

This work is the product of extensive collaborations over five years. All of the authors have made substantial contributions, without each of which this document would be significantly different. Much of the dielectric work was performed through a NASA contract with Dr. Holly Shulman, LLC (now Blue Star Advanced Manufacturing, LLC). The JSC-1AC measurements originated through Dr. Shulman's previous company, Ceralink Inc. Mr. Roque Santiago and Mr. Alex Teijeira did much of the graphing, such as those in Section 7. These graphs were essential to the analyses of the data. The DSC measurements were done by Austin Patridge under the direction of Alan Whittington, Dept. of Earth and Planetary Sciences, U. of Texas at San Antonio, TX. All of the dielectric measurements were made by Microwave Properties North, and some of that work was done at their expense. The remainder of the work was done through NASA dedicated contracts. The senior author did the density scaling, provided knowledge about the simulants, and organized the work. He also benefited greatly from extensive, and often patient, discussions provided by the other authors. This report has benefited from the reviews of Michael Fiske, John Forster, and Rostislav Kovtun. The senior author thanks his wife, Pamela, for editing the document as well as the support and encouragement in climbing this hill.

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## Appendix A. Dielectric Measurement Methodology and Key to Data Sheets from Microwave Properties North (MPN)

The perturbation technique as used by MPN consists of measurements at a pre-fixed number (n) of frequencies at each measurement time. The measurement times are determined by the Labview data collection code, which the operator sets up before measurements start. In practice a stack of pellets in a tube sealed from outside atmosphere is heated in a conventional furnace and periodically transferred from the furnace to the instrument for measurement. At no time is the sample exposed to atmosphere, either flowing Ultra-high Purity Argon or vacuum surrounds the sample.

The measurement sequence for each new sample starts with the requisite empty holder measurements (at room temperature, at each frequency) which the data analysis code gives specific names, fh and Qh.

All the following measurements are placed in two large matrices, named “f” and “Q”.

The “run” then starts with a pre-determined sequence of measurements for the calibration samples (at room temperature), which the data analysis code places at the beginning of the “f” and “Q” matrices. The number of calibrators measured is “NCal”. The measurements on the holder with sample in it start with the sequence number (NCal +1 ). After the sample measurements are complete, the sample is (if possible) emptied out of the holder, and the holder is measured in steps up to the maximum temperature used in the sample measurements. The number of these empty measurements is labeled “Nempties”.

The total number of f and Q “measurements” at each frequency in a run is labelled “nd”.

In the written report for the measurement run, the following variables are used.

Subscript “md” - sequence number, i.e. iteration count, for measurement, which excludes the initial calibrations and the final high temperature empty holder measurements – and is mainly used to display the “sample related” physical values :

lsamp<sub>md</sub> - sample length ( millimeters) in holder  
 dsamp<sub>md</sub> - sample diameter in holder ( millimeters)  
 samdns<sub>md</sub> - sample density ( grams/cc) , computed, pores included  
 samvol<sub>md</sub> - sample volume ( cubic millimeters) in holder  
 sammas<sub>md</sub> - sample mass (grams)

Subscript “mm” - sequence number – used to calculate and display sample properties. Usually “mm” goes from “NCal+1” sequentially up to (nd-Nempties).

$\epsilon'_{mm, n}$  - real component at frequency n,  $\epsilon$  prime  
 $\epsilon''_{mm, n}$  - “imaginary” component at frequency n,  $\epsilon$  double prime  
 $T_{Smm}$  - furnace temperature (°C) immediately before the sample is dropped into the cavity

## Appendix A. Dielectric Measurement Methods

$T_{mm,n}$  - actual sample temperature ( °C -calculated) at the time each frequency is measured  
 $t_{laps\ mm}$  - elapsed time since the first sample room temperature measurement (in hours)

The frequencies used are specified in the table “Legend for Data Plots”.

Samples are rapidly (< 1 second translation time) moved from the furnace to the cavity position, measured in ~ 3 seconds (all 6 frequencies), and returned to the furnace. Approximately 3 seconds are needed to measure at 6 frequencies. The furnace temperature,  $T_{Smm}$ , is measured at the initiation of each “measurement”. The value of the temperature for each frequency for each measurement in the sequence is calculated using previously determined cooling rates. The determined values of  $\epsilon'_{mm,n}$  and  $\epsilon''_{mm,n}$  can be plotted against  $T_{Smm}$  or against the specific temperature values for each frequency. Only at temperatures above 1000 °C is there significant cooling over the 3 seconds between the 1<sup>st</sup> and 6<sup>th</sup> frequency measurements. Thermal monitoring for NU-HT-4M showed a nominal drop in temperature during a measurement of 4.7% at 1300 °C.

Sample runs consist of a stepwise cycle to maximum temperature and then a stepwise return back down to room temperature. Heating rates typically are between 2 and 5 degrees per minute. A typical time vs temperature plot is given in Figure A.1. During the temperature increase, the furnace temperature is controlled such that it ramps up to the next desired temperature (usually in 5 minutes or so) and then holds the temperature (does a “soak”) at the desired temperature for another 4 or 5 minutes to allow for temperature uniformity in the sample) before the measurement is made.

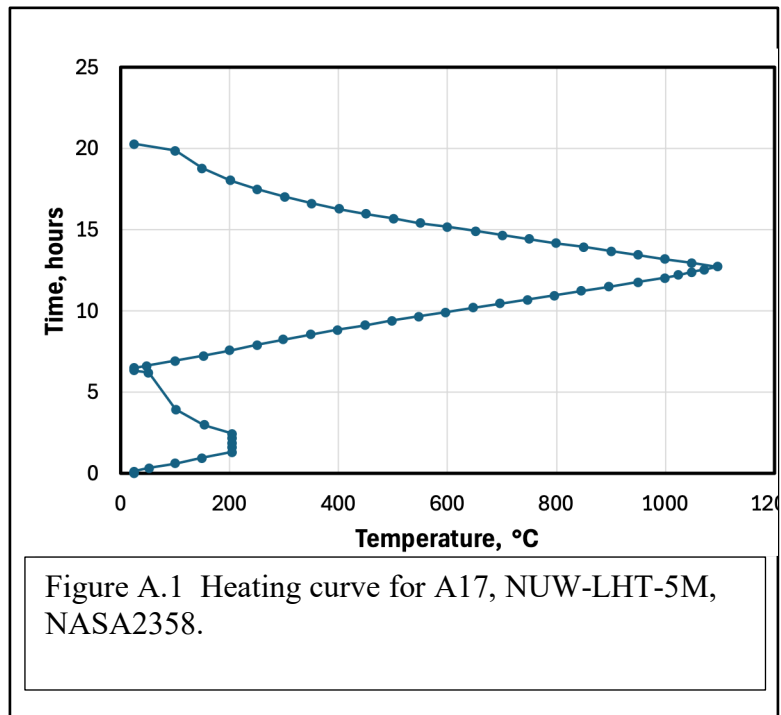


Figure A.1 Heating curve for A17, NUW-LHT-5M, NASA2358.

In the decreasing temperature part of the cycle, the furnace is brought down to the next required sample (using a programmed controller) so undershoot is minimized. Again, once the desired temperature is attained, a 5 minute hold at the desired sample is done, after which the measurement is made. These measurements have an inherently longer cooling time before the soak is initiated.

Characteristically, the  $\epsilon''$  ramp-up values (heating) versus temperature are lower than the subsequent ramp down values at the same temperature. This difference is much larger at high temperatures. This delta may be a measure of the frequency dependent sensitivity of the new

## Appendix A. Dielectric Measurement Methods

glass vs. beginning phase(s). This pattern is typical of disordered materials, like glasses or heavily defected crystalline material.

Equivalent Free Electron Conductivity:  $\sigma_{eq_{mm,n}} := \epsilon''_{mm,n} \cdot 2 \cdot \pi \cdot f_n \cdot \epsilon_0$  in Siemens/meter.

$\sigma_{eq_{mm,n}}$  - ac conductivity at frequency "n", equivalent

$TrPwr_{mm,n}$  - Power transmitted through an interface by a normal plane wave into the material of infinite depth. I.e. a measure of reflectance.

Half power depth is a theoretical value based on a plane wave going into plane surface.

Computation of Arrhenius thermal dependence values, activation energy, black lines are fits to the data using a specific band gap. Note: These plots are against T in Kelvin.

For more information on the technique of measurement see Details of Technique:  
<http://www.magma.ca/~hutcheon/technique/appendix3.htm>

## Appendix B. Scaling and Half Power Depth Code

This Microsoft Excel VBA code will compute  $\epsilon'$ ,  $\epsilon''$ , and Half Power Depth to scale the measured data to a given sample bulk density. Density is in g/cc. This version sets the new density to 1.75.

Option Explicit ' Force explicit variable declaration

```
' Ron Hutcheon of Microwave Properties North measures e' and e'' without controlling the
' bulk density of the compressed pellets used to measure over a range of temperatures.
' This code computes new e' and e'' at a user defined bulk density in g/cc. The desired
' density can be changed using variable "rho_Required".
'
' The basic equation used for the scaling is the Looyenga (1965) equation.
'
' Program logic:
' 1 - Check, is the current workbook relevant to this code. If so copy the contents of
' sheet "2466" into sheet "Scaled to XXXX". XXXX is used in these comments to stand
' for the required density set in the variable rho_Required.
' 2 - Ask the user for the temperature of the inflection point, termed "T_Inflexion".
' 3 - Data ranges are specified. The contents of each range is given in the following
' "Dim" statements.
' 4 - Compute the adjusted densities and record these in column J
' 5 - Using the Looyenga equation compute e' and e'' at the desired density.
' 6 - The scaled e' and e'' will be written to "Scaled to XXXX"
' 7 - The Half Power Depth is computed for the scaled e' and e''
' 8 - The workbook is saved
'
' Input file layout:
' Two sheets must be present, "All" and "2466"
' If sheet "Scaled to XXXX" is present, it will be deleted
' Data in sheet "2466" are in columns D through I. See "Dim" statements for column
' definitions.
' Data table starts in row 7.
' The start and end densities are in (4,E) and (4,F), respectively.
'
' Code developed by Douglas L. Rickman, May - July, 2025
'
' Measured data and output are allocated storage from these columns:
Dim rngD As Range ' Range() of data in column D - Index Temperature
Dim rngE As Range ' Range() of data in column E - e' - Permittivity real component
Dim rngF As Range ' Range() of data in column F - e'' - Permittivity imaginary component
Dim rngG As Range ' Range() of data in column G - HPD - Half Power Depth
Dim rngH As Range ' Range() of data in column H - LAPST - Elapsed time
```

## Appendix B. Scaling and Half Power Depth Code

```

Dim rngI As Range      ' Range() of data in column I - Actual (Measured) temp
Dim rngJ As Range      ' Range() of data in column J - Density, corrected
Dim rngK As Range      ' Range() of data in column K - e' Scaled (Output)
Dim rngL As Range      ' Range() of data in column L - e' Scaled (Output)
Dim rngM As Range      ' Range() of data in column M - Half Power Depth (Output)

Dim Density_Min    As Variant ' in (4,E) Note: Density_Min can be less than Density_Max
Dim Density_Max    As Variant ' In (4,F)
Dim Density_Delta  As Variant ' Computed from Density Min and Max
Dim T_Inflexion    As Variant ' Temp at which e' begins to rise rapidly
Dim ErrorFlag      As Boolean

Dim rho_Required As Double    ' Desired density to scale measured values to.

Dim LastRow As Integer        ' Row number of the last row holding data
Dim NRows As Integer          ' Number of rows of data
Dim maxTemp As Double         ' Maximum temperature in column D; currently not used

Dim Compute_Density As Integer

' Bugs in VBA found during development using
' macOS 15.5, Microsoft 365, Excel for Mac Version 16.95 (25030928)
' A "Variant" type variable can not be tested against a "Double" type variable

Sub ScaleDensityMain()
' *****
' ***** Program Control Flags *****
' *****

rho_Required = 1.75      ' desired bulk density
Compute_Density = 0     ' if = 1, then compute. Otherwise density
'                        ' does not change with temperature, and
'                        ' T_Inflexion is not requested. Option 1
'                        ' is not fully implemented and checked out
'
' *****
' *****

' Function of the Compute_Density flag:

' I successfully tested Compute_Density = 1 using file "NASA2361.xlsm". I can not vouch
' for other cases.
' Operations when Compute_Density <> 1:
' 1 - Density_ Max = Density_Min + 0.0001

```

## Appendix B. Scaling and Half Power Depth Code

```
' 2 - T_Inflexion is not requested from the user. It is set to 99999.
' Compute_Density is used in GetUserInputs().
' Testing with Compute_Density = 1 and = 0 show no difference at the precision output.
' This does not make sense to me, yet.

ErrorFlag = False

' This subroutine uses the ErrorFlag to handle one type of error.
CreateSheet ErrorFlag
If ErrorFlag = True Then 'Put this after Subs that can return an error.
'     MsgBox "Problem Detected. Ending MAIN", , "Problem in CreateSheet()"
Exit Sub
End If

' Safety checks
If Range("H6").Value <> "LAPST" Then
'     MsgBox "The string |LAPST| was not found where it should be! Aborting", , "Bad News In Main!"
Exit Sub
End If

If IsNumeric(Range("E4")) = False Or IsEmpty(Range("F4")) = True Then
MsgBox "The Starting Density is not found in cell (E,4)! Aborting", , "Bad News In Main!"
Exit Sub
End If

If IsNumeric(Range("F4")) = False Or IsEmpty(Range("F4")) = True Then
MsgBox "The End Density is not found in cell (E,4)! Aborting", , "Bad News In Main!"
Exit Sub
End If

GetUserInputs
'     MsgBox "Inflexion Temperature = " & T_Inflexion _
'
'     ; "Returned from GetUserInputs()"

' Lable column headings, load data ranges,determine the LastRow, NRows, MaxTemp
LoadDataRanges

ComputeNewDensity T_Inflexion

ComputeNewPermittivity

ComputeHPD

' Center the data in the columns
```

## Appendix B. Scaling and Half Power Depth Code

```
Range(Selection, Selection.End(xlToRight)).Select
Selection.HorizontalAlignment = xlCenter

' Save the workbook
Activeworkbook.Save

End Sub

Private Sub ComputeNewPermittivity()
' Execute the Looyenga Equation. For equation source see:
' Complex Permittivity for NUW-LHT-5M at 2.466 GHZ Over a Range of Densities
' NASA TM 20240007310 by Rickman, Hutcheon, and Shulman

' This logic loops through each measured temperature. THEREFORE,
' **** All computations are at a single temperature, then computations step to ****
' **** the next temperature. ****

' I have used "rho" for "Density" to make it easier to follow the printed equations
' Cube root computation methodology was developed with the aid of the following sites:
'
' Excel statements and checking values:
' https://real-statistics.com/other-mathematical-topics/polar-coordinates-complex-roots/
'
' An online calculator to check values against:
' https://www.omnicalculator.com/math/complex-root#how-to-find-complex-roots-by-hand
'
' Simple expression of algebra operations with complex numbers:
' https://www.dummies.com/article/academics-the-arts/math/pre-calculus/how-to-perform-operations-with-complex-numbers-167803/
'
' More format statements of algebra operations and graphs showing meaning of
' operations;
' also Excel statements
' https://medium.com/@the1howie/complex-numbers-in-excel-8e8f90566310#45d7

' Allocate density variables
' Density is in column "J"
Dim rho_Start As Double ' density at starting Temperature
Dim rho_Temp As Double ' density at the current Temperature, column "J"
Dim rho_Ratio As Double ' ratio (computed density at Temperature N)/(density at

Dim rho_Scaling As Double ' density scaling value

' Programmer's comment:
```

## Appendix B. Scaling and Half Power Depth Code

```

' I have assigned the values of e', e'', r, and theta at each step to distinct
' variables, as it makes debugging much easier. Also, it does not have
' significant negative impacts to memory or speed given the small size of the
' data files.

' Define complex numbers stored in polar format
Dim r As Double           ' magnitude polar coordinate ' Obtained by changing e' and e'' to polar
Dim theta As Double      ' angle polar coordinate     ' Obtained by changing e' and e'' to polar
Dim r_1_3 As Double      ' cube root values in polar format
Dim theta_1_3 As Double  ' cube root values in polar format
Dim r_A As Double        ' Intermediate value
Dim theta_A As Double    ' Intermediate value
Dim r_Power3 As Double   ' r raised to the 3rd
Dim theta_Power3 As Double ' theta raised to the 3rd

' Define complex numbers stored in rectangular format
Dim e_P As Double       ' e prime; measured real component of permittivity.
' a.k.a. the "c" component in rectangular format.
' Value is stored in column "E"
Dim e_PP As Double      ' e double prime; measured imaginary component of permittivity.
' a.k.a. the "d" component in rectangular format.
' Value is stored in column "F"

Dim e_P_1New As Double  ' Used in debugging
Dim e_PP_1New As Double ' Used in debugging
Dim e_P_2New As Double  ' Used in debugging
Dim e_PP_2New As Double ' Used in debugging
Dim e_P_3New As Double  ' Used in debugging
Dim e_PP_3New As Double ' Used in debugging
Dim e_P_4New As Double  ' Used in debugging
Dim e_PP_4New As Double ' Used in debugging
Dim e_P_5New As Double  ' The scaled e'
Dim e_PP_5New As Double ' The scaled e''

Dim i As Integer        ' loop counter

rho_Start = Cells("7", "J") ' density at the start of the run

For i = 7 To NRows ' Step through the Looyenga Equation

' Compute the bulk density scaling value
rho_Temp = Cells(i, "J")
rho_Ratio = rho_Temp / rho_Start
rho_Scaling = (rho_Required * rho_Ratio) / rho_Temp

```

## Appendix B. Scaling and Half Power Depth Code

```

'      Cells(i, "N").Value = rho_Scaling ' This will write the scaling value to column N
'
'      Compute the cube root of the measured e' and e" at temperature(i)
'      Determine the cube root of the complex number (e' + i e")
e_P = Cells(i, "E") ' value of "c", the real component
e_PP = Cells(i, "F") ' value of "d", the imaginary component
'
'      Convert from rectangular to polar
r = Abs(Sqr((e_P ^ 2) + (e_PP ^ 2)))
theta = WorksheetFunction.Atan2(e_P, e_PP)
'
'      Cube root in polar coordinates
r_1_3 = r ^ (1 / 3)
theta_1_3 = theta / 3
'
'      Convert cube root from polar into rectangular form
e_P_1New = r_1_3 * Cos(theta_1_3)
e_PP_1New = r_1_3 * Sin(theta_1_3)
'
'      Subtract 1
e_P_2New = e_P_1New - 1 ' add the real to the real component
e_PP_2New = e_PP_1New ' the imaginary component is unchanged
'
'      Multiply by rho_scaling
e_P_3New = rho_Scaling * e_P_2New
e_PP_3New = rho_Scaling * e_PP_2New
'
'      Add 1
e_P_4New = e_P_3New + 1 ' add the real to the real component
e_PP_4New = e_PP_3New ' the imaginary component is unchanged
'
'      Convert back to polar and raise the complex number by the power of 3
r_A = Abs(Sqr((e_P_4New ^ 2) + (e_PP_4New ^ 2)))
theta_A = WorksheetFunction.Atan2(e_P_4New, e_PP_4New)
r_Power3 = r_A ^ 3
theta_Power3 = theta_A * 3
e_P_5New = r_Power3 * Cos(theta_Power3)
e_PP_5New = r_Power3 * Sin(theta_Power3)
'
'      VBA DOES NOT SUPPORT TRUNC(X,Y) !!!!! Now work around this stupidity!!!
'      Truncate e_P to 4 decimal places and e_PP to 5
e_P_5New = e_P_5New * 10 ^ 4
e_PP_5New = e_PP_5New * 10 ^ 5
e_P_5New = Fix(e_P_5New)
e_PP_5New = Fix(e_PP_5New)
e_P_5New = e_P_5New / 10 ^ 4

```

## Appendix B. Scaling and Half Power Depth Code

```

e_PP_5New = e_PP_5New / 10 ^ 5
' Write scaled e_P and e_PP to active sheet
Cells(i, "K").Value = e_P_5New
Cells(i, "L").Value = e_PP_5New

Next i

End Sub

Sub ComputeNewDensity(T_Inflexion As Variant)
' Code logic:
' It is assumed the change in density occurs above the Inflection Temperature.
' Change is assumed to happen linearly between Time1 and Time2,
' rather than more rapid change as temperature goes up. In the relevant data
' this assumption significantly simplifies the code without too wild an error.

' *****
' I may need to handle the case of Density_Min > Density_Max I must study the data first!!!!
' *****

Dim IndexTemp As Double ' Index Temperature in column D
Dim i As Integer ' loop counter
Dim CoolingFlag As Integer ' Are data in cooling leg? 0 = heating. 1 = cooling
Dim Time1 As Double ' First Time IndexTemp is above T_Inflexion
Dim Time2 As Double ' Last Time IndexTemp is above T_Inflexion
Dim TimeDelta As Double ' Elapsed Time above T_Inflexion
Dim FractionTime As Double ' Fraction of elapsed of total time above T_Inflexion

' Find the start and stop times when Temp is above the Inflection Temperature
For i = 7 To NRows
IndexTemp = Cells(i, "D")
If IndexTemp >= T_Inflexion Then
Time2 = Cells(i, "H")
If Time1 = 0 Then
Time1 = Cells(i, "H")
End If
End If
Next i

TimeDelta = Time2 - Time1

CoolingFlag = 0 ' Temperature has never exceeded T_Inflexion

```

## Appendix B. Scaling and Half Power Depth Code

```
' Distribute density change over time
For i = 7 To NRows 'Data start in row 7
IndexTemp = Cells(i, "D")

' Repeated "if" tests are not efficient, but an insignificant use of resources in this case
If IndexTemp < T_Inflexion Then
Cells(i, "J").Value = Density_Min
End If

If IndexTemp >= T_Inflexion Then
CoolingFlag = 1
FractionTime = (Cells(i, "H") - Time1) / TimeDelta
Cells(i, "J") = Density_Min + (FractionTime * Density_Delta)
Cells(i, "J").NumberFormat = "0.00"
End If

If IndexTemp < T_Inflexion And CoolingFlag = 1 Then
Cells(i, "J").Value = Density_Max
End If

Next i

End Sub

Private Sub CreateSheet(ByRef ErrorFlag As Boolean)

' Check to be sure current workbook is relevant to this code. If so create a new
' sheet, make it the active sheet, rename it to "Scaled to 1.75", save the workbook.

Dim i As Integer ' Loop counter
Dim j As Integer ' Test variable
Dim NSheets As Integer ' Number of sheets in the workbook

j = 0 ' Not strictly necessary, but I like explicit code.

' Check if the current workbook is relevant to this code
For i = 1 To Worksheets.Count
If Worksheets(i).Name = "All" Or Worksheets(i).Name = "2466" Then
j = j + 1
End If
Next i

If j <> 2 Then
MsgBox "The current workbook |" & ActiveWorkbook.Name & "| does not " & _
"have sheets named (All) and/or (2466). Aborting"
End
```

## Appendix B. Scaling and Half Power Depth Code

End If

```
' Check to see if sheet "Scaled to 1.75" exists. If it does delete it
NSheets = Worksheets.Count
For i = 1 To NSheets
If Worksheets(i).Name = "Scaled to " & rho_Required Then
Application.DisplayAlerts = False
Sheets("Scaled to " & rho_Required).Delete
Application.DisplayAlerts = True
i = NSheets ' This will cause the loop to end
End If
Next i
```

```
' Check to see if sheet "Temp" exists. If it does delete it
NSheets = Worksheets.Count
For i = 1 To NSheets
If Worksheets(i).Name = "Temp" Then
Application.DisplayAlerts = False
Sheets("Temp").Delete
Application.DisplayAlerts = True
i = NSheets ' This will cause the loop to end
End If
Next i
```

```
' Make "2466" active and copy it to "Scaled to " & rho_Required
NSheets = Worksheets.Count
For i = 1 To NSheets
If Worksheets(i).Name = "2466" Then
Worksheets("2466").Activate
ActiveSheet.Copy After:=Worksheets(Sheets.Count) 'This also makes the new sheet active
ActiveSheet.Name = "Scaled to " & rho_Required
i = Worksheets.Count
End If
Next i
```

```
'Save the workbook
ActiveWorkbook.Save
```

End Sub

```
Private Sub GetUserInputs()
```

```
' Get the start and stop densities
Density_Min = Cells(4, "E") ' This value could be greater or less than the Density_Max value
Density_Max = Cells(4, "F")
```

## Appendix B. Scaling and Half Power Depth Code

```
If Compute_Density <> 1 Then      ' Ignore input Density_Max
Density_Max = Density_Min + 0.0001
End If

' The following 2 lines were used during program development to allow user inputs
' Density_Min = InputBox("Input the starting the density, g/cc")
' Density_Max = InputBox("Input the final the density, g/cc")

Density_Delta = Density_Max - Density_Min 'This could be negative

If Compute_Density <> 1 Then
T_Inflexion = 99999 ' A temp value for testing
Else
T_Inflexion = InputBox("Input the inflection temperature, centigrade")
End If

' MsgBox "Initial density = " & Density_Min & vbNewLine & _
"Final density = " & Density_Max & vbNewLine & _
"Change in density = " & Density_Delta & vbNewLine & vbNewLine & _
"Inflection Temperature = " & T_Inflexion _
', "At the end of GetUserInputs()"
End Sub

Private Sub LoadDataRanges()
' After loading column headers "Density", "e' Scaled", and "e'' Scaled" are created.
' Variables MaxTemp, LastRow, NRows are determined here.

' Programmer's note:
' Not sure all of these definitions are needed, but they are cheap to create and have
' almost no downside in current hardware.

' Make column headings
Range("J6").Select
ActiveCell.FormulaR1C1 = "Adjusted Density"
With Selection
.HorizontalAlignment = xlCenter
.WrapText = True
End With

Cells(6, "K").Value = "e' Scaled"
Cells(6, "K").HorizontalAlignment = xlCenter

Cells(6, "L").Value = "e'' Scaled"
Cells(6, "L").HorizontalAlignment = xlCenter
```

## Appendix B. Scaling and Half Power Depth Code

```
Range("M6").Select
ActiveCell.FormulaR1C1 = "Adjusted HPD"
With Selection
    .HorizontalAlignment = xlCenter
    .WrapText = True
End With

With Selection
    .HorizontalAlignment = xlCenter
    .WrapText = True
End With

Range("K5:M5").Select
Selection.Merge
ActiveCell.FormulaR1C1 = "Scaled Density " & rho_Required
Selection.HorizontalAlignment = xlCenter

' Load ranges with data
' Column D is done at the end, making it the active column

' rngE = e prime
' Load the variable rngE
Range("E7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngE = Range(Selection.Address)

' rngF = e double prime
' Load the variable rngF
Range("F7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngF = Range(Selection.Address)

' rngG = Half Power Depth
' Load the variable rngG
Range("G7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngG = Range(Selection.Address)

' rngH = the elapsed time
' Load the variable rngH
Range("H7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngH = Range(Selection.Address)

' rngI = the Temperatures
' Load the variable rngI
```

## Appendix B. Scaling and Half Power Depth Code

```
Range("I7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngI = Range(Selection.Address)

'   rngJ = the new densities
'   Load the variable rngJ
Range("J7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngJ = Range(Selection.Address)

'   rngK = e_P_Scaled
'   Load the variable rngK
Range("K7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngK = Range(Selection.Address)

'   rngL = e_PP_Scaled
'   Load the variable rngL
Range("L7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngL = Range(Selection.Address)

'   rngM = Half Powered Depth
'   Load the variable rngL
Range("M7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngL = Range(Selection.Address)

'   rngD = the Index Temperatures
'   Load the variable rngD and get the maximum temperature.
Range("D7").Select
Range(Selection, Selection.End(xlDown)).Select
Set rngD = Range(Selection.Address)

maxTemp = WorksheetFunction.Max(rngD)   ' Maximum value the Index Temperature
LastRow = Selection.Rows.Count         ' The number of the last row of data
NROWS = 6 + LastRow

End Sub

Private Sub ComputeHPD()

Dim Eulers As Double                 ' Euler's number
Dim LogN2 As Double                  ' Natural log of 2
Dim LightSpeed As Double              ' Speed of light per second in millimeters
```

## Appendix B. Scaling and Half Power Depth Code

```

Dim Frequency As Double      ' Frequency used in this work. 2466,000,000 Hz
Dim Constant1 As Double
Dim Constant2 As Double

Dim e_P_Scaled As Double    ' e prime; after scaling to the desired density
' Value is stored in column "K"
Dim e_PP_Scaled As Double   ' e double prime; after scaling to the desired density
' Value is stored in column "L"
Dim tnD As Double          ' ePP / eP
Dim Intermediate As Double  ' This is a running value. It makes debugging easier
Dim HPD As Double          ' Half power depth
Dim i As Integer           ' loop counter

' Determine constants
Eulers = Exp(1)
LogN2 = Log(2) / Log(Eulers)
Constant1 = LogN2 / 2

LightSpeed = 299792458000#   ' Speed of light/second
Frequency = 2466000000#     ' 2466 MHz
Constant2 = LightSpeed / (2 * WorksheetFunction.Pi() * Frequency)

' Compute HPD at each Index Temp
For i = 7 To NRows
e_P_Scaled = Cells(i, "K")
e_PP_Scaled = Cells(i, "L")
tnD = e_PP_Scaled / e_P_Scaled

Intermediate = 1 + (tnD ^ 2)
Intermediate = Sqr(Intermediate)
Intermediate = Intermediate - 1
Intermediate = Intermediate * e_P_Scaled
Intermediate = 2 / Intermediate
Intermediate = Sqr(Intermediate)
HPD = Constant1 * Constant2 * Intermediate
HPD = Fix(HPD)
Cells(i, "M").Value = HPD

Next i

End Sub

```

## Appendix C. Original Measurements and Scaled Values

The following data tables are organized in the order given in Table 5.1. Material, run conditions, index, MPN identifier, and report file name. The  $\epsilon'$ ,  $\epsilon''$ , measured at 2466 MHz, and the corresponding Half Power Depth values reported by MPN are provided and the same values after scaling the density to 1.75 g/cc.

Note there can be small discrepancies between the data shown in the MPN reports and the values shown here. The values used here are from ACSCII files, one for each variable such as  $\epsilon'$ , provided by MPN. The ASCII files have more precision than the tables in the reports and can differ slightly from the printed documents.

The data in the following tables are:

MPN index	- Such as SHUL2149. This links all of the work on a single measurement
MPN document	- Such as "MPN-218_Shulman_2_JSC-1A.docx" Report file by MPN
Index Temp	- A temperature, in degrees centigrade
$\epsilon'$	- Real portion of the relative complex permittivity at frequency 2466 MHz
$\epsilon''$	- Imaginary component of the relative complex permittivity at 2466 MHz
HPD	- Computed Half Power Depth in millimeters.
LAPTS	- Elapsed time in hours
Temp	- Temperature recorded for the specific measurement at the elapsed time.
$\epsilon'$ Scaled	- $\epsilon'$ scaled to a density of 1.75 g/cc
$\epsilon''$ Scaled	- $\epsilon''$ scaled to a density of 1.75 g/cc
Adjusted HPD	- HPD based on scaled $\epsilon'$ and scaled $\epsilon''$

Temp varies with the frequency measured. In our work Index Temp is used rather than the recorded Temp in order that comparisons can be made between the six original difference frequencies. For the frequency report in this document, Index Temp will differ from the "Temp" by an amount that is considered insignificant given other limitations to accuracy in the measurement and the observed rates of change the reported variables with temperature. Study of these data has shown the difference between Index Temp and Temp increase with temperature and are <5% at 1300 °C.

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2149	MPN-231_Shulman_3_Anorthite A-006.docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
25.06	3.547	0.00879	2874	0	24.85	3.9838	0.01058	2530
54.16	3.582	0.00675	3763	0.237	53.81	4.0259	0.00812	3313
104.2	3.629	0.00467	5473	0.492	103.3	4.0826	0.00562	4821
154.4	3.663	0.00362	7094	0.757	152.9	4.1236	0.00436	6246
204	3.696	0.00414	6226	1.03	201.8	4.1634	0.00499	5483
254.5	3.717	0.00318	8125	1.304	251.7	4.1888	0.00384	7148
304.3	3.73	0.00296	8764	1.577	300.9	4.2044	0.00356	7724
354.2	3.747	0.00186	#####	1.859	350.1	4.225	0.00224	12306
403.8	3.757	0.00259	#####	2.148	399	4.237	0.00313	8819
453.3	3.772	0.00259	#####	2.442	447.9	4.2552	0.00312	8867
502.6	3.784	0.00279	9344	2.743	496.6	4.2697	0.00337	8223
552.1	3.795	0.00363	7204	3.069	545.4	4.283	0.00438	6336
601.3	3.804	0.00503	5201	3.428	593.8	4.2938	0.00607	4578
650.9	3.817	0.01045	2507	3.812	642.6	4.3095	0.01262	2206
700.2	3.83	0.02818	931.6	4.254	691.1	4.3252	0.03406	818
749.5	3.849	0.03796	693.3	4.771	739.6	4.3482	0.04589	609
799.1	3.848	0.00678	3879	5.338	788.3	4.347	0.0082	3410
848.4	3.857	0.0081	3254	6.02	836.7	4.3579	0.00978	2862
897.5	3.864	0.01005	2624	6.687	884.9	4.3664	0.01215	2306
946.3	3.875	0.01014	2603	7.324	932.7	4.3797	0.01226	2289
995.5	3.868	0.01145	2304	7.966	980.8	4.3712	0.01384	2025
1045	3.864	0.01215	2171	8.697	1029	4.3664	0.01469	1907
1093	3.864	0.01279	2062	9.38	1076	4.3664	0.01546	1812
995	3.825	0.00878	2989	9.632	980.4	4.3192	0.0106	2629
896.6	3.803	0.00727	3598	9.906	884	4.2926	0.00878	3164
797.8	3.781	0.00628	4153	10.24	787.1	4.266	0.00758	3654
698.6	3.761	0.00471	5519	10.64	689.5	4.2419	0.00569	4854
599.8	3.734	0.00342	7571	11.13	592.3	4.2093	0.00413	6662
500.6	3.709	0.00328	7868	11.73	494.6	4.1791	0.00396	6923
401.4	3.679	0.00261	9864	12.5	396.7	4.1429	0.00314	8693
302.2	3.644	0.00352	7285	13.5	298.8	4.1007	0.00423	6420
202.1	3.597	0.00388	6564	14.95	200	4.044	0.00467	5775
103.5	3.534	0.0048	5252	17.68	102.6	3.9681	0.00578	4622
27.12	3.478	0.00845	2961	21.2	26.58	3.9007	0.01016	2607

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2281	MPN-257_Shulman_CSM-LHT-1G_1.docx				Scaled Density 1.75			
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
25.09	4.442	0.03269	864.9	0	24.87	3.557	0.02305	1097
25.33	4.446	0.03254	869.1	0.08187	25.16	3.5599	0.02294	1103
25.34	4.456	0.03258	869	0.1534	25.16	3.5669	0.02296	1103
50.22	4.462	0.03187	889.1	0.3266	49.91	3.5711	0.02246	1128
100.4	4.488	0.03223	881.6	0.5444	99.47	3.5895	0.0227	1119
151.3	4.516	0.03374	844.8	0.7799	149.8	3.6092	0.02376	1072
201.7	4.543	0.0348	821.6	0.9905	199.5	3.6282	0.02449	1043
249.6	4.571	0.0343	836	1.169	246.9	3.6479	0.02413	1061
301.4	4.597	0.0403	713.7	1.35	298	3.6662	0.02834	906
350.6	4.626	0.04451	648.1	1.526	346.6	3.6866	0.03128	823
400.5	4.654	0.04996	579.3	1.706	395.9	3.7063	0.0351	735
450.6	4.682	0.05808	499.7	1.887	445.3	3.7259	0.04078	634
500.8	4.712	0.06974	417.5	2.071	494.8	3.747	0.04895	530
550.3	4.746	0.08262	353.7	2.254	543.5	3.7709	0.05795	449
600.3	4.812	0.09705	303.2	2.437	592.8	3.8172	0.068	385
649.9	4.85	0.1153	256.3	2.626	641.7	3.8438	0.08074	325
699.9	4.907	0.1382	215	2.813	690.8	3.8837	0.09669	273
749.7	4.976	0.1714	174.5	3.002	739.8	3.9321	0.11979	222
799.7	5.021	0.2249	133.7	3.192	788.9	3.9636	0.15707	170
849.3	5.026	0.2517	119.5	3.377	837.7	3.9672	0.17578	152
899.7	4.991	0.261	114.9	3.568	887.1	3.9427	0.18237	146
949.2	4.971	0.2708	110.5	3.755	935.6	3.9288	0.18927	140
999.7	4.977	0.2809	106.6	3.944	985	3.933	0.19631	135
1049	5.05	0.3116	96.77	4.133	1033	3.9841	0.21752	123
1100	5.245	0.3888	79.07	4.323	1083	4.1203	0.27063	100
1004	5.088	0.2897	104.5	4.569	988.7	4.0105	0.20212	132
904.9	5.003	0.2322	129.2	4.823	892.2	3.9511	0.16222	164
803.9	4.924	0.1844	161.5	5.081	793.1	3.8957	0.12898	205
703.9	4.838	0.1424	207.2	5.357	694.8	3.8354	0.09974	263
603.1	4.752	0.1078	271.2	5.695	595.6	3.7751	0.07561	344
503.1	4.68	0.07845	369.9	6.107	497	3.7246	0.05509	469
402.1	4.606	0.05616	512.6	6.635	397.5	3.6725	0.03948	651
301.5	4.545	0.04089	699.3	7.314	298.1	3.6296	0.02878	887
201	4.474	0.032	886.5	8.287	198.9	3.5796	0.02255	1125
101.6	4.409	0.02608	1080	10.12	100.6	3.5338	0.0184	1370
26.2	4.398	0.02909	967	10.46	25.85	3.526	0.02053	1226

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2282 MPN-257_Shulman_CSM-LHT-1G_2 .docx						Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
24.55	4.451	0.0245	1155	0	24.53	3.7087	0.01842	1402
24.7	4.441	0.02456	1151	0.1472	24.66	3.7011	0.01847	1396
24.74	4.455	0.02423	1168	0.2252	24.69	3.7117	0.01822	1418
50.31	4.473	0.02442	1162	0.3974	50	3.7252	0.01836	1409
100.3	4.516	0.02808	1015	0.6192	99.36	3.7575	0.0211	1232
152.1	4.549	0.02946	971	0.8492	150.5	3.7823	0.02212	1179
201.6	4.591	0.03391	847.6	1.059	199.5	3.8139	0.02545	1029
249.9	4.621	0.03955	729	1.238	247.2	3.8364	0.02967	885
301.8	4.647	0.04599	628.7	1.419	298.4	3.8559	0.03449	763
351.1	4.679	0.05079	571.3	1.592	347	3.8799	0.03808	693
400.8	4.703	0.05808	500.9	1.77	396.1	3.8979	0.04353	608
450.8	4.731	0.06615	441.1	1.949	445.5	3.9189	0.04956	535
501	4.764	0.08008	365.6	2.133	495	3.9436	0.05997	444
550.6	4.802	0.09609	305.9	2.315	543.9	3.9721	0.07193	371
600.4	4.838	0.116	254.3	2.502	592.9	3.9991	0.08679	309
650.5	4.887	0.1405	211.1	2.687	642.3	4.0357	0.10505	256
700.2	4.951	0.1712	174.3	2.874	691.2	4.0836	0.1279	211
749.9	5.019	0.203	148.1	3.061	740	4.1344	0.15153	179
800	5.101	0.2344	129.3	3.247	789.2	4.1957	0.17479	157
849.4	5.184	0.2678	114.1	3.436	837.7	4.2576	0.1995	138
899.8	5.182	0.2921	104.6	3.624	887.2	4.2562	0.2176	127
949.3	5.138	0.3051	99.69	3.81	935.7	4.2234	0.22741	121
999.6	5.209	0.3332	91.93	3.999	984.9	4.2764	0.24814	111
1049	5.315	0.3815	81.11	4.188	1033	4.3554	0.28375	98
1100	5.487	0.4297	73.17	4.375	1083	4.4834	0.31898	89
1003	5.378	0.3611	86.2	4.622	988.4	4.4022	0.26839	104
904.2	5.279	0.2942	104.8	4.877	891.5	4.3284	0.21892	127
803.4	5.17	0.2348	129.9	5.135	792.6	4.2471	0.17494	158
703.5	5.066	0.1842	163.9	5.411	694.4	4.1695	0.13742	199
603	4.976	0.1426	209.9	5.748	595.5	4.1022	0.1065	255
503.1	4.891	0.1094	271.1	6.163	497	4.0387	0.08179	329
402.3	4.818	0.08375	351.6	6.695	397.6	3.9841	0.06267	427
301.8	4.738	0.066	442.4	7.38	298.4	3.9241	0.04944	537
200.7	4.667	0.05328	543.8	8.346	198.6	3.8709	0.03995	660
101.1	4.584	0.0498	576.7	10.17	100.1	3.8086	0.03738	700
25.3	4.518	0.04798	594.3	14.83	25.14	3.7591	0.03605	721

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

MPN02286	MPN-258_MPN_CSM-LHT-1G_heat-treated.docx					Scaled Density 1.75		
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
24.91	4.605	0.02881	1001	0	24	3.7085	0.02058	1254
25.05	4.601	0.02781	1036	0.07616	24.52	3.7056	0.01987	1299
25.07	4.608	0.02725	1058	0.1468	24.54	3.7106	0.01946	1327
118.1	4.546	0.0288	994.2	0.3587	117	3.6663	0.02059	1247
182.1	4.594	0.03143	916	0.5572	180.2	3.7006	0.02246	1148
238.5	4.648	0.03599	804.5	0.7391	235.9	3.7392	0.02569	1009
291.8	4.652	0.04457	650	0.9209	288.5	3.7421	0.03182	815
340.8	4.678	0.04901	592.7	1.086	336.9	3.7606	0.03497	743
389	4.713	0.05776	504.8	1.251	384.4	3.7856	0.04119	633
436.5	4.756	0.0646	453.4	1.416	431.3	3.8163	0.04604	569
483.2	4.794	0.07478	393.3	1.582	477.4	3.8434	0.05327	493
529.3	4.824	0.08998	327.9	1.73	522.8	3.8647	0.06407	411
576.2	4.879	0.1091	272	1.879	569	3.9039	0.07761	341
622.5	4.909	0.1304	228.3	2.01	614.6	3.9253	0.09273	286
669.9	4.934	0.1559	191.4	2.142	661.3	3.9431	0.11082	240
717.1	4.97	0.1854	161.6	2.274	707.7	3.9687	0.13172	202
764.8	5.002	0.2109	142.5	2.406	754.6	3.9915	0.14976	178
811.9	5.057	0.2398	126	2.538	800.8	4.0306	0.17015	158
859	5.069	0.2637	114.7	2.67	847.1	4.0392	0.18707	144
906.9	5.027	0.2782	108.3	2.801	894.1	4.0094	0.19748	136
955.4	4.957	0.2786	107.4	2.933	941.5	3.9597	0.19796	134
1004	4.973	0.2908	103	3.065	988.7	3.9711	0.20658	129
1052	4.905	0.3214	92.61	3.197	1036	3.9229	0.22855	116
1100	5.021	0.4564	66.01	3.329	1077	4.0058	0.32397	82
1149	5.381	0.6761	46.17	3.461	1119	4.2618	0.47747	58
1198	6.379	1.187	28.7	3.593	1153	4.9656	0.82813	36
1246	7.473	2.107	17.59	3.726	1199	5.7329	1.45367	22
1295	8.511	3.295	12.11	3.859	1258	6.4601	2.25254	15
1344	9.812	4.996	8.675	3.991	1320	7.3695	3.38172	11
1392	11.1	6.652	7	4.123	1366	8.2635	4.46592	8
1294	8.096	2.665	14.53	4.257	1259	6.1677	1.82855	18
1197	7.558	1.732	21.46	4.4	1171	5.7873	1.19453	27
1099	7.208	1.013	35.68	4.551	1075	5.5398	0.70114	45
1002	6.727	0.596	58.51	4.716	986.8	5.2041	0.41448	73
903.8	6.602	0.488	70.77	4.899	891	5.1167	0.33982	89
805.7	6.473	0.3586	95.32	5.106	794.8	5.0264	0.25005	120

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

707.5	6.355	0.2469	137.1	5.342	698.3	4.9438	0.17238	173
610.3	6.246	0.1633	205.6	5.617	602.7	4.8676	0.11415	259
513.6	6.151	0.1079	308.7	5.941	507.3	4.8011	0.0755	389
420.2	6.046	0.0673	490.7	6.324	415.3	4.7275	0.04715	618
327.9	5.968	0.04931	665.4	6.783	324.2	4.6728	0.03457	838
233.2	5.812	0.03659	885	7.419	229.8	4.5633	0.0257	1114
123.4	5.664	0.0348	918.4	8.558	121.8	4.4593	0.02449	1156
25.15	5.641	0.04042	789.3	9.912	24.6	4.4431	0.02845	993

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2152	MPN-231_Shulman_3_Diopside D-009.docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
25.2	3.211	0.002032	1.18E+04	0	24.94	3.4027	0.00224	11044
54.66	3.219	0.001786	1.35E+04	0.2358	54.32	3.4116	0.00196	12638
104.2	3.236	0.001785	1.35E+04	0.4884	103.3	3.4303	0.00196	12673
153.9	3.251	-6.09E-05	3.97E+05	0.7555	152.4	3.4468	0.00006	414982
203.8	3.269	0.001369	1.77E+04	1.023	201.7	3.4667	0.0015	16647
253.8	3.288	0.00168	1.45E+04	1.301	251.2	3.4876	0.00185	13538
303.8	3.302	0.001723	1.42E+04	1.577	300.6	3.5031	0.0019	13211
353.5	3.32	0.001587	1.54E+04	1.857	349.6	3.523	0.00175	14384
403.2	3.332	0.001766	1.39E+04	2.141	398.7	3.5362	0.00194	12999
452.8	3.348	0.003275	7494	2.441	447.7	3.5539	0.00361	7003
502.1	3.365	0.00357	6893	2.75	496.4	3.5726	0.00394	6433
551.4	3.379	0.004786	5152	3.084	545	3.5881	0.00528	4811
600.8	3.398	0.005938	4164	3.439	593.7	3.609	0.00655	3889
650.3	3.416	0.006683	3710	3.829	642.5	3.6289	0.00737	3466
699.6	3.432	0.009067	2741	4.266	691	3.6466	0.01001	2558
749	3.45	0.01065	2339	4.809	739.7	3.6665	0.01176	2183
798.4	3.471	0.01316	1899	5.379	788.3	3.6897	0.01453	1772
847.8	3.491	0.01464	1712	6.066	836.8	3.7118	0.01617	1597
897.1	3.507	0.0175	1436	6.767	885.2	3.7294	0.01933	1339
945.9	3.529	0.01999	1261	7.417	933.1	3.7538	0.02209	1176
995.1	3.551	0.02215	1141	7.983	981.2	3.7781	0.02448	1064
1044	3.584	0.0243	1045	8.683	1029	3.8146	0.02686	975
1093	3.636	0.03018	847.5	9.368	1077	3.8721	0.03338	790
994.9	3.59	0.02064	1231	9.618	981.1	3.8212	0.02282	1148
896.3	3.548	0.01553	1626	9.892	884.4	3.7748	0.01716	1518
797.4	3.505	0.01175	2137	10.22	787.2	3.7272	0.01298	1994
698.2	3.465	0.009655	2586	10.62	689.7	3.683	0.01066	2414
599.2	3.427	0.007414	3349	11.1	592.2	3.6411	0.00818	3128
500.3	3.383	0.005777	4271	11.69	494.6	3.5925	0.00637	3990
401.2	3.346	0.002395	1.02E+04	12.43	396.8	3.5516	0.00264	9573
301.5	3.309	0.002566	9507	13.4	298.3	3.5108	0.00283	8879
202.9	3.275	-0.000756	3.21E+04	14.8	200.9	3.4733	0.00083	30113
103.9	3.238	0.001834	1.32E+04	17.43	103	3.4325	0.00202	12300
27.26	3.218	0.002298	1.05E+04	20.26	26.69	3.4105	0.00253	9789

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

MPN02181	MPN-242_MPN_Diopside with Actinolite .docx					Scaled Density 1.75		
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
23.88	7.344	0.04205	864.3	0	24.12	3.6132	0.01484	1717
50.19	7.372	0.03745	972.4	0.2063	49.88	3.6231	0.0132	1933
96.88	7.433	0.0551	663.6	0.505	96.02	3.6446	0.0194	1319
144.6	7.485	0.06258	586.3	0.8126	143.1	3.6629	0.022	1166
197.4	7.552	0.06812	541	0.9996	195.4	3.6864	0.02391	1076
247.1	7.613	0.0679	545	1.181	244.4	3.7078	0.0238	1085
297.6	7.622	0.06019	615.1	1.363	294.3	3.711	0.02109	1225
346.4	7.592	0.05316	695.2	1.537	342.4	3.7005	0.01864	1384
395.7	7.573	0.04798	769.3	1.715	391.1	3.6938	0.01683	1531
445.3	7.547	0.0465	792.3	1.896	440	3.6847	0.01632	1577
493.7	7.59	0.04974	742.8	2.078	487.8	3.6998	0.01744	1479
543.5	7.63	0.05009	739.5	2.26	536.9	3.7138	0.01755	1472
593.7	7.665	0.05195	714.7	2.443	586.4	3.726	0.01818	1423
643.7	7.689	0.05775	644	2.625	635.6	3.7345	0.0202	1283
693.8	7.716	0.06209	600.1	2.808	684.9	3.7439	0.02171	1195
743.5	7.714	0.06613	563.3	2.991	733.8	3.7432	0.02312	1122
792.7	7.755	0.07518	496.8	3.175	782.1	3.7575	0.02626	989
842.8	7.777	0.08124	460.4	3.359	831.3	3.7652	0.02836	917
892.8	7.826	0.08892	422	3.542	880.3	3.7823	0.03101	841
942.6	7.859	0.09852	381.6	3.726	929	3.7938	0.03433	760
992.7	7.916	0.1149	328.4	3.911	978.1	3.8137	0.03999	654
1042	7.985	0.1363	278	4.095	1027	3.8377	0.04736	554
1093	8.046	0.1522	250	4.281	1076	3.8589	0.05281	498
993.4	7.935	0.1335	283	4.534	978.8	3.8203	0.04644	564
894.3	7.831	0.11	341.1	4.788	881.8	3.7841	0.03836	680
794.3	7.721	0.09037	412.4	5.046	783.7	3.7457	0.03159	821
694.8	7.606	0.0713	518.8	5.324	685.8	3.7054	0.025	1032
595.1	7.501	0.05518	665.7	5.661	587.7	3.6685	0.01939	1324
495.2	7.399	0.04255	857.3	6.073	489.2	3.6326	0.01499	1705
395.7	7.3	0.02967	1221	6.589	391.1	3.5977	0.01048	2427
296.1	7.197	0.02219	1621	7.252	292.8	3.5612	0.00786	3219
196.5	7.114	0.01799	1988	8.192	194.4	3.5318	0.00638	3950
99.42	7.032	0.01428	2490	9.859	98.53	3.5026	0.00508	4940
23.97	6.97	0.01031	3435	11.73	24.08	3.4805	0.00367	6817

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

MPN02180	MPN-242_MPN_Enstatite_Mirabel Springs,Mt St Helena CA.docx					Scaled Density 1.75		
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
23.95	6.354	0.02134	1584	0	24.16	3.4008	0.00831	2976
49.95	6.333	0.02132	1583	0.2144	49.65	3.3926	0.00831	2972
96.55	6.444	0.02614	1302	0.5129	95.69	3.4358	0.01016	2446
144.2	6.492	0.02779	1230	0.8214	142.8	3.4545	0.01078	2312
196.9	6.552	0.03018	1138	1.009	194.8	3.4778	0.01169	2139
246.8	6.603	0.03155	1092	1.191	244.1	3.4975	0.01221	2054
297.4	6.655	0.0347	997	1.372	294	3.5176	0.01341	1875
346.2	6.695	0.03701	937.7	1.546	342.2	3.5331	0.01428	1765
395.4	6.748	0.03942	883.7	1.724	390.8	3.5535	0.01519	1664
445.2	6.802	0.04584	763	1.904	439.9	3.5743	0.01764	1437
493.5	6.852	0.05045	695.9	2.085	487.5	3.5936	0.01939	1311
543.4	6.905	0.05556	634.3	2.267	536.8	3.6139	0.02133	1195
593.5	6.936	0.05712	618.4	2.449	586.1	3.6258	0.02191	1165
643.5	6.903	0.04443	793.1	2.631	635.4	3.6132	0.01706	1494
693.7	6.911	0.0443	795.9	2.814	684.8	3.6162	0.017	1500
743.7	6.926	0.04689	752.8	2.997	733.9	3.622	0.01799	1418
792.5	6.977	0.04714	751.4	3.181	781.9	3.6416	0.01806	1417
842.8	7.035	0.0506	703	3.364	831.3	3.6638	0.01936	1325
892.6	7.087	0.05345	668.1	3.547	880.1	3.6837	0.02042	1260
942.5	7.145	0.05702	628.7	3.731	929	3.7058	0.02176	1186
992.4	7.209	0.06063	593.9	3.916	977.8	3.7302	0.0231	1121
1042	7.29	0.073	496.1	4.1	1027	3.7611	0.02776	936
1092	7.364	0.08293	438.8	4.286	1075	3.7892	0.03148	829
993.5	7.222	0.07031	512.6	4.538	978.9	3.7352	0.02678	967
894.3	7.085	0.06102	585	4.792	881.8	3.6829	0.02332	1103
794.4	6.95	0.04843	730.1	5.049	783.8	3.6312	0.01857	1376
694.8	6.82	0.03726	939.9	5.328	685.8	3.5813	0.01433	1771
595.2	6.696	0.03028	1146	5.666	587.8	3.5335	0.01169	2156
495.1	6.575	0.02308	1490	6.08	489.2	3.4867	0.00893	2804
395.5	6.474	0.01586	2152	6.6	390.9	3.4475	0.00616	4042
296.2	6.359	0.01191	2841	7.266	292.9	3.4028	0.00464	5331
196.5	6.252	0.009482	3537	8.211	194.4	3.361	0.0037	6645
99.58	6.165	0.005402	6164	9.896	98.68	3.3269	0.00211	11593
24.02	6.121	0.005217	6360	16.07	24.12	3.3097	0.00204	11960

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2117	MPN-218_Shulman_1_JSC-1A.docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
23.95	6.354	0.02134	1584	0	24.16	3.4008	0.00831	2976
49.95	6.333	0.02132	1583	0.2144	49.65	3.3926	0.00831	2972
96.55	6.444	0.02614	1302	0.5129	95.69	3.4358	0.01016	2446
144.2	6.492	0.02779	1230	0.8214	142.8	3.4545	0.01078	2312
196.9	6.552	0.03018	1138	1.009	194.8	3.4778	0.01169	2139
246.8	6.603	0.03155	1092	1.191	244.1	3.4975	0.01221	2054
297.4	6.655	0.0347	997	1.372	294	3.5176	0.01341	1875
346.2	6.695	0.03701	937.7	1.546	342.2	3.5331	0.01428	1765
395.4	6.748	0.03942	883.7	1.724	390.8	3.5535	0.01519	1664
445.2	6.802	0.04584	763	1.904	439.9	3.5743	0.01764	1437
493.5	6.852	0.05045	695.9	2.085	487.5	3.5936	0.01939	1311
543.4	6.905	0.05556	634.3	2.267	536.8	3.6139	0.02133	1195
593.5	6.936	0.05712	618.4	2.449	586.1	3.6258	0.02191	1165
643.5	6.903	0.04443	793.1	2.631	635.4	3.6132	0.01706	1494
693.7	6.911	0.0443	795.9	2.814	684.8	3.6162	0.017	1500
743.7	6.926	0.04689	752.8	2.997	733.9	3.622	0.01799	1418
792.5	6.977	0.04714	751.4	3.181	781.9	3.6416	0.01806	1417
842.8	7.035	0.0506	703	3.364	831.3	3.6638	0.01936	1325
892.6	7.087	0.05345	668.1	3.547	880.1	3.6837	0.02042	1260
942.5	7.145	0.05702	628.7	3.731	929	3.7058	0.02176	1186
992.4	7.209	0.06063	593.9	3.916	977.8	3.7302	0.0231	1121
1042	7.29	0.073	496.1	4.1	1027	3.7611	0.02776	936
1092	7.364	0.08293	438.8	4.286	1075	3.7892	0.03148	829
993.5	7.222	0.07031	512.6	4.538	978.9	3.7352	0.02678	967
894.3	7.085	0.06102	585	4.792	881.8	3.6829	0.02332	1103
794.4	6.95	0.04843	730.1	5.049	783.8	3.6312	0.01857	1376
694.8	6.82	0.03726	939.9	5.328	685.8	3.5813	0.01433	1771
595.2	6.696	0.03028	1146	5.666	587.8	3.5335	0.01169	2156
495.1	6.575	0.02308	1490	6.08	489.2	3.4867	0.00893	2804
395.5	6.474	0.01586	2152	6.6	390.9	3.4475	0.00616	4042
296.2	6.359	0.01191	2841	7.266	292.9	3.4028	0.00464	5331
196.5	6.252	0.009482	3537	8.211	194.4	3.361	0.0037	6645
99.58	6.165	0.005402	6164	9.896	98.68	3.3269	0.00211	11593
24.02	6.121	0.005217	6360	16.07	24.12	3.3097	0.00204	11960

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2119	MPN-218_Shulman_2_JSC-1A.docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
24.25	4.58	0.07384	388.7	0	24.35	3.8875	0.05734	461
53.28	4.62	0.07576	380.6	0.2385	52.94	3.9186	0.0588	451
103.8	4.69	0.07986	363.7	0.488	102.8	3.9729	0.06193	431
152.3	4.744	0.08472	344.8	0.743	150.7	4.0147	0.06566	409
201.9	4.789	0.09348	314	0.9691	199.7	4.0496	0.07241	372
252.1	4.83	0.1011	291.6	1.202	249.3	4.0814	0.07828	346
302.1	4.877	0.1109	267.2	1.438	298.7	4.1178	0.08582	317
353.9	4.931	0.1266	235.4	1.63	349.8	4.1596	0.09791	279
404.4	4.984	0.1457	205.6	1.818	399.6	4.2006	0.11262	244
454.6	5.04	0.1699	177.2	2.003	449.2	4.2439	0.13124	210
503.6	5.103	0.2054	147.5	2.188	497.5	4.2926	0.15856	175
553.1	5.194	0.2529	120.9	2.37	546.3	4.3629	0.19503	143
602.9	5.379	0.3776	82.42	2.553	595.4	4.5057	0.29064	97
652.5	5.727	0.5642	56.96	2.735	644.2	4.7737	0.4328	67
702	6.135	0.6859	48.51	2.918	692.9	5.0865	0.52425	57
751.6	6.493	0.8652	39.59	3.1	741.6	5.3605	0.65933	47
800.5	6.781	1.29	27.19	3.283	789.7	5.5822	0.9807	32
850.1	6.947	1.546	23	3.466	838.3	5.7102	1.17373	27
899.6	7.184	1.794	20.19	3.649	886.9	5.8919	1.35957	24
948.8	7.616	2.103	17.77	3.831	935.1	6.2212	1.58898	21
998.3	8.169	2.378	16.29	4.014	983.5	6.6403	1.79062	19
1048	8.644	2.57	15.51	4.197	1032	6.9988	1.93002	18
1097	9.677	3.15	13.41	4.382	1080	7.7769	2.35307	16
994.8	9.036	2.67	15.26	4.645	980.2	7.2934	2.00105	18
896.1	8.179	1.996	19.35	4.906	883.5	6.6443	1.50327	23
796.6	7.492	1.445	25.53	5.223	785.9	6.122	1.09313	30
697.5	7.065	1.083	33.03	5.61	688.5	5.7965	0.82176	39
598.3	6.684	0.8188	42.43	6.089	590.8	5.5057	0.62307	50
498.8	6.402	0.6177	55	6.694	492.8	5.2901	0.4711	65
399.3	6.172	0.4639	71.88	7.462	394.6	5.114	0.35448	85
299.8	5.969	0.3583	91.5	8.475	296.5	4.9585	0.27427	108
200.1	5.772	0.2871	112.3	9.942	198	4.8074	0.22016	133
101.5	5.565	0.2492	127	12.67	100.6	4.6484	0.19147	151
23.96	5.353	0.2437	127.4	20.43	24.07	4.4854	0.18763	151
403.6	5.283	0.3486	88.47	12.62	398.9	4.5649	0.2809	102
454	5.369	0.413	75.31	12.8	448.6	4.6344	0.33255	86
503.3	5.475	0.487	64.51	12.99	497.2	4.7199	0.39179	74

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

552.8	5.578	0.5712	55.53	13.17	546	4.803	0.45913	64
602.7	5.702	0.667	48.1	13.35	595.1	4.903	0.53561	55
652.2	5.829	0.7825	41.47	13.54	643.9	5.0054	0.62772	47
701.9	5.981	0.9191	35.79	13.72	692.7	5.1279	0.73644	41
751.6	6.172	1.099	30.44	13.9	741.6	5.2817	0.87934	35
800.5	6.399	1.31	26.02	14.08	789.7	5.4644	1.04646	30
850.1	6.646	1.533	22.7	14.27	838.4	5.663	1.22253	26
899.5	6.932	1.774	20.06	14.45	886.8	5.8925	1.41211	23
948.9	7.354	2.061	17.81	14.63	935.2	6.23	1.63644	20
998.3	8.075	2.465	15.64	14.82	983.6	6.8041	1.94973	18
1048	8.415	2.484	15.83	15	1032	7.0726	1.96172	18
1097	9.044	2.751	14.83	15.18	1080	7.5702	2.16652	17
994.8	8.462	2.3	17.12	15.45	980.2	7.1081	1.81621	19
896.2	7.846	1.852	20.42	15.71	883.6	6.6181	1.46699	23
796.7	7.228	1.41	25.69	16.03	786	6.1251	1.12072	29
697.6	6.737	1.069	32.68	16.42	688.6	5.7326	0.85224	37
598.4	6.37	0.8225	41.24	16.89	590.9	5.4386	0.65731	47
498.8	6.093	0.6329	52.38	17.5	492.8	5.2163	0.50678	60
399.6	5.867	0.4915	66.16	18.27	395	5.0347	0.39421	76
300.1	5.667	0.4005	79.78	19.28	296.8	4.874	0.32172	92

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2146	MPN-231_Shulman_3_JSC-1A(A).docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
24.48	4.894	0.1805	164.4	0	24.49	3.9978	0.1327	202
53.16	4.947	0.1954	152.7	0.3548	52.82	4.0368	0.14355	187
101.1	5.02	0.2104	142.9	0.6207	100.2	4.0904	0.15442	175
149.1	5.125	0.2286	132.8	0.8953	147.6	4.1675	0.16754	163
196.3	5.215	0.2445	125.3	1.132	194.3	4.2334	0.17899	154
244.1	5.309	0.2641	117.1	1.377	241.4	4.3022	0.19312	144
291.8	5.395	0.2854	109.2	1.627	288.6	4.3651	0.20847	134
339.8	5.516	0.3202	98.43	1.831	335.9	4.4535	0.23356	121
389.4	5.608	0.3615	87.92	2.028	384.9	4.5207	0.2634	108
438.6	5.717	0.4169	76.97	2.222	433.5	4.6003	0.30339	94
486.9	5.814	0.4791	67.57	2.415	481.1	4.671	0.34828	83
536.1	5.924	0.5562	58.75	2.604	529.6	4.7512	0.40383	72
585.7	6.057	0.6505	50.82	2.795	578.5	4.8481	0.47163	62
635.6	6.209	0.7658	43.73	2.986	627.6	4.9588	0.55434	53
686.1	6.415	0.9266	36.76	3.178	677.3	5.1086	0.66934	45
736.7	6.681	1.131	30.77	3.372	727	5.3018	0.81488	38
787	6.968	1.321	26.92	3.567	776.5	5.5096	0.94928	33
835.9	7.209	1.485	24.37	3.824	824.4	5.6838	1.06489	30
886.5	7.388	1.625	22.57	4.096	874.1	5.8131	1.16351	27
936.9	7.579	1.731	21.47	4.379	923.5	5.9506	1.2375	26
987.2	7.712	1.747	21.46	4.662	972.7	6.0456	1.24769	26
1038	7.882	1.834	20.67	4.973	1022	6.1676	1.30814	25
1087	9.424	2.791	14.91	5.926	1070	7.2695	1.97016	18
986.3	9.014	2.332	17.41	6.164	971.9	6.9754	1.65057	21
885.7	8.497	1.887	20.85	6.406	873.3	6.6053	1.34028	25
784	7.833	1.407	26.79	6.654	773.6	6.1291	1.00421	33
682.9	7.365	1.029	35.47	6.937	674.2	5.7922	0.73718	43
582.2	6.978	0.7379	48.08	7.266	575	5.5131	0.53039	59
482.5	6.693	0.5211	66.64	7.657	476.7	5.3072	0.37552	82
385.5	6.454	0.3849	88.58	8.137	381	5.1344	0.278	109
289.3	6.248	0.3118	107.5	8.754	286	4.9853	0.22565	132
193.8	6.094	0.2792	118.7	9.646	191.7	4.8737	0.20237	146
100	5.932	0.2601	125.6	11.36	99.12	4.7561	0.18885	154
25.03	5.82	0.2538	127.5	11.97	24.92	4.6747	0.1845	157

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2147	MPN-231_Shulman_3_JSC-1A (B) .docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
24.62	4.581	0.06101	470.6	0	24.57	3.6195	0.04224	604
53.09	4.609	0.06542	440.2	0.2097	52.75	3.6388	0.04527	565
101.5	4.646	0.07439	388.7	0.4689	100.6	3.6645	0.05144	499
148.4	4.691	0.08749	332	0.7349	146.9	3.6956	0.06046	426
196.2	4.746	0.1025	285.1	0.9732	194.1	3.7336	0.07076	366
243.8	4.808	0.1199	245.3	1.217	241.1	3.7764	0.08269	315
291	4.881	0.1409	210.3	1.463	287.8	3.8267	0.09705	270
339.3	4.968	0.1686	177.3	1.666	335.4	3.8867	0.11597	228
389	5.061	0.2068	146	1.863	384.5	3.9507	0.14203	187
438.3	5.162	0.2517	121.1	2.057	433.2	4.0201	0.17259	155
486.5	5.265	0.3079	100	2.25	480.7	4.0908	0.2108	128
535.7	5.384	0.3797	82.01	2.44	529.1	4.1724	0.25949	105
585.4	5.52	0.4711	66.96	2.631	578.1	4.2657	0.32131	86
635.5	5.681	0.5874	54.5	2.824	627.4	4.3759	0.39972	70
686	5.883	0.7366	44.25	3.019	677.2	4.514	0.49986	57
733.8	6.132	0.914	36.44	3.296	724.1	4.6838	0.61823	47
784.5	6.421	1.111	30.7	3.582	774	4.8804	0.74879	39
835.9	6.69	1.292	26.98	3.844	824.5	5.0628	0.86804	34
886.4	6.912	1.462	24.26	4.116	874	5.2132	0.97979	31
937	7.104	1.559	23.06	4.404	923.6	5.3426	1.04267	29
987.5	7.213	1.54	23.52	4.701	973	5.4151	1.02887	30
1040	7.604	1.821	20.45	4.992	1025	5.6784	1.21182	26
1087	8.597	2.52	15.77	5.302	1070	6.3431	1.66205	20
986.6	7.927	1.927	19.74	5.533	972.2	5.8938	1.27858	25
886	7.508	1.545	23.91	5.77	873.6	5.6117	1.02931	30
784.5	7.041	1.155	30.91	6.013	774.1	5.2968	0.77323	40
683.2	6.587	0.7831	44.04	6.291	674.4	4.9897	0.52693	56
582.5	6.249	0.5173	64.87	6.614	575.3	4.7605	0.34949	83
482.9	5.99	0.3364	97.62	7	477.2	4.5847	0.22802	125
385.7	5.804	0.2357	137.1	7.473	381.3	4.4582	0.16015	176
289.3	5.701	0.1895	169	8.084	286.1	4.3881	0.12894	217
193.9	5.687	0.1746	183.2	8.97	191.8	4.3785	0.11882	236
99.79	5.568	0.1755	180.4	10.68	98.89	4.2975	0.11963	232
24.84	5.461	0.1796	174.5	16.69	24.77	4.2245	0.12261	224

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

CERL0960	CERALINK NYSERDA_10.doc					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
23.93	4.96	0.1178	253.5	0	23.74	4.0246	0.0858	313
109.4	5.007	0.1049	286.1	0.1329	108.6	4.0588	0.07636	353
148.6	5.042	0.1076	279.7	0.2589	147.5	4.0843	0.07829	346
195.3	5.073	0.1138	265.3	0.3803	193.8	4.1069	0.08276	328
238.8	5.117	0.1168	259.6	0.4998	236.9	4.1389	0.08489	321
278.2	5.17	0.1256	242.7	0.6181	275.9	4.1774	0.09123	300
326.1	5.254	0.133	231.1	0.7359	323.3	4.2384	0.0965	286
373.1	5.323	0.1451	213.2	0.8536	369.8	4.2884	0.10519	264
425.1	5.41	0.1617	192.9	0.9714	421.3	4.3515	0.11709	238
475.9	5.492	0.2068	152	1.089	471.4	4.4109	0.1496	188
526.3	5.604	0.262	121.2	1.207	521.2	4.492	0.18928	150
576.1	5.74	0.3297	97.45	1.325	570.4	4.5903	0.23782	120
626.7	5.954	0.4261	76.82	1.443	620.3	4.7448	0.30662	95
678.3	6.331	0.5635	59.92	1.56	670.9	5.016	0.40388	74
730.1	6.778	0.7888	44.32	1.678	721.9	5.3366	0.56291	55
780.8	6.946	1.236	28.69	1.796	771.7	5.4592	0.8805	35
830.8	7.017	1.388	25.71	1.914	820.9	5.5109	0.98806	31
882.2	7.132	1.354	26.56	2.032	871.3	5.5924	0.96294	33
930.7	6.981	1.199	29.66	2.15	918.8	5.4838	0.8539	36
984	7.033	1.208	29.54	2.268	970.5	5.5209	0.85992	36
1032	7.685	1.629	22.94	2.386	1017	5.9866	1.15318	28
1079	9.354	2.564	16.14	2.503	1063	7.1682	1.7939	20
969.2	7.448	1.257	29.21	2.631	944.9	5.8159	0.8917	36
882.2	7.287	1.114	32.57	2.773	871.3	5.7007	0.79136	40
783.4	6.934	0.7967	44.38	2.935	774.4	5.4478	0.56775	55
679.6	6.602	0.5137	67.11	3.125	665.1	5.2097	0.36723	83
575.6	6.351	0.3292	102.7	3.351	570	5.0296	0.23592	127
475.8	6.114	0.2111	157	3.62	471.5	4.8593	0.15165	194
374.6	5.928	0.1498	218	3.951	371.3	4.7254	0.10783	270
273.2	5.768	0.1219	264.1	4.378	271	4.6101	0.0879	327
189.5	5.645	0.1315	242.3	4.909	188	4.5214	0.09496	300
23.93	5.225	0.1627	188.4	6.414	23.87	4.2174	0.11809	233
23.93	5.23	0.1632	187.9	6.466	23.87	4.221	0.11845	232
97	5.53	0.1467	214.9	7.208	96.36	4.4383	0.10608	266
146.8	5.578	0.1303	243	7.344	145.7	4.473	0.09416	301
196.6	5.625	0.1248	254.8	7.468	195.1	4.5069	0.09014	315
239.4	5.679	0.1213	263.4	7.587	237.5	4.5459	0.08756	326

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

279.2	5.734	0.1187	270.4	7.706	276.9	4.5856	0.08563	335
327.7	5.829	0.1226	264.1	7.824	324.9	4.6541	0.08835	327
374.7	5.901	0.1434	227.1	7.941	371.4	4.706	0.10325	281
425.9	5.99	0.166	197.7	8.059	422	4.7701	0.11941	245
476.4	6.08	0.1993	165.9	8.177	472	4.8348	0.14323	205
526.6	6.189	0.2551	130.8	8.295	521.5	4.9132	0.18312	162
576.2	6.3	0.3261	103.2	8.413	570.5	4.993	0.23382	128
626.6	6.439	0.4232	80.43	8.53	620.2	5.0928	0.30302	99
678.2	6.587	0.516	66.74	8.648	670.9	5.199	0.36893	82
730.4	6.755	0.6553	53.24	8.766	722.3	5.3196	0.46777	66
781	6.949	0.7815	45.29	8.884	771.9	5.4585	0.55685	56
830.8	7.072	0.8955	39.89	9.001	820.9	5.5466	0.63736	49
882.4	7.196	1.063	33.92	9.119	871.4	5.6358	0.75572	42
930.8	7.383	1.19	30.72	9.237	918.6	5.7693	0.84465	38
984.1	7.771	1.542	24.35	9.355	970.6	6.0467	1.09095	30
1032	8.394	2.004	19.51	9.473	1017	6.49	1.41109	24
1079	10.26	3.345	13.01	9.59	1063	7.8077	2.32758	16
983.1	8.673	2.415	16.5	9.718	969.6	6.6901	1.69685	20
870.9	7.842	1.41	26.73	9.86	850.6	6.0958	0.99711	33
783.5	7.675	1.041	35.74	10.02	774.5	5.9753	0.73724	44
679.5	7.391	0.7287	50.08	10.21	672.3	5.7725	0.5173	62
575.8	7.067	0.4298	82.95	10.44	564.3	5.5412	0.30597	103
475.9	6.858	0.2871	122.3	10.71	471.5	5.3919	0.20477	152
375	6.627	0.2187	157.8	11.04	371.7	5.2269	0.15631	196
273.7	6.416	0.1753	193.8	11.46	271.4	5.0759	0.12555	240
189.5	6.253	0.1703	196.9	11.99	188	4.959	0.12217	244
23.93	5.713	0.2126	150.7	15.45	23.87	4.5706	0.1534	186

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2179	MPN-241_Shulman_4_Merriam Crater Basalt .docx					Scaled Density 1.75		
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
23.83	4.977	0.113	264.7	0	24.08	4.0156	0.08161	329
191.9	5.241	0.1331	230.6	0.4565	189.9	4.2059	0.09578	287
192.9	5.233	0.1321	232.2	0.8219	190.8	4.2002	0.09507	289
193.5	5.231	0.1338	229.2	1.187	191.5	4.1987	0.09629	285
100.8	5.089	0.1189	254.5	2.431	99.87	4.0964	0.08573	316
23.88	4.975	0.1115	268.3	2.559	24.01	4.0141	0.08052	333
98.29	5.091	0.1188	254.7	2.754	97.4	4.0979	0.08566	316
145.1	5.17	0.1257	242.6	3.061	143.6	4.1548	0.09054	301
197.4	5.254	0.1336	230.1	3.248	195.3	4.2153	0.09612	286
247	5.311	0.145	213.2	3.428	244.3	4.2563	0.10425	265
297.4	5.361	0.1606	193.4	3.609	294.1	4.2923	0.11539	240
346.1	5.435	0.1788	174.9	3.782	342.1	4.3454	0.12834	217
395.4	5.488	0.2063	152.3	3.96	390.8	4.3835	0.14799	189
445	5.541	0.2422	130.4	4.139	439.8	4.4216	0.17363	162
493.4	5.628	0.2845	111.9	4.32	487.4	4.484	0.20373	139
543.2	5.735	0.3489	92.1	4.501	536.6	4.5607	0.24953	114
593.4	5.894	0.4453	73.17	4.683	586	4.6747	0.31789	91
643.4	6.206	0.6198	53.97	4.866	635.2	4.8977	0.44093	67
693.4	6.677	0.856	40.57	5.048	684.4	5.233	0.60604	50
743.6	7.203	1.23	29.37	5.232	733.7	5.6067	0.86651	36
792.6	7.431	1.577	23.31	5.415	781.9	5.7699	1.10857	29
842.6	7.631	1.818	20.52	5.598	831	5.9124	1.2757	25
892.6	7.909	2.089	18.21	5.782	880.1	6.1098	1.46242	22
942.3	8.402	2.417	16.25	5.966	928.8	6.4572	1.68564	20
992.5	8.908	2.653	15.25	6.15	977.8	6.8115	1.84373	19
1042	9.321	2.813	14.72	6.334	1027	7.0993	1.94974	18
1092	10.31	3.22	13.53	6.519	1075	7.7859	2.21897	17
993.5	9.799	2.781	15.25	6.773	978.9	7.4291	1.92232	19
894.4	9.203	2.226	18.41	7.028	881.9	7.0115	1.54464	23
794.2	8.619	1.694	23.36	7.286	783.5	6.6013	1.1803	29
694.6	8.115	1.265	30.29	7.563	685.7	6.2466	0.88473	37
595.2	7.714	0.9376	39.8	7.898	587.8	5.9639	0.65786	49
495.1	7.384	0.6939	52.58	8.307	489.2	5.731	0.48822	65
395.4	7.1	0.5242	68.21	8.821	390.8	5.5304	0.36974	85
296	6.805	0.4138	84.58	9.48	292.7	5.3217	0.29266	105
196.4	6.571	0.3452	99.64	10.42	194.4	5.1559	0.24469	124

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

99.83	6.358	0.3021	112	12.1	98.93	5.0046	0.2146	139
24.37	6.176	0.2901	114.9	12.17	24.39	4.8752	0.20647	143

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

SHUL2127	MPN-218_Shulman_1_NU-LHT-2M.docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
24.16	3.947	0.0216	123.4	0	23.19	3.6335	0.01892	1351
24.24	3.95	0.02149	124.1	0.088	23.88	3.6362	0.01882	1358
24.25	3.947	0.02152	123.9	0.1477	23.89	3.6335	0.01885	1356
73.65	3.968	0.0215	124.3	0.3839	73.03	3.6519	0.01883	1361
113.8	3.991	0.02258	118.7	0.5962	112.7	3.6721	0.01977	1299
168.9	4.023	0.02498	107.7	0.7948	167.1	3.7001	0.02187	1179
226.7	4.056	0.03058	88.34	0.9936	224.2	3.729	0.02677	967
234.7	4.056	0.02928	92.25	1.192	232.1	3.729	0.02563	1010
235	4.058	0.02956	91.41	1.391	232.4	3.7308	0.02587	1001
24.38	3.941	0.0207	128.6	1.593	24.36	3.6283	0.01813	1409
235.6	4.053	0.03003	89.91	1.791	233	3.7264	0.02629	984
280.5	4.085	0.03437	78.88	1.99	277.3	3.7544	0.03008	863
330.6	4.114	0.04045	67.26	2.188	326.8	3.7798	0.03539	736
379.9	4.128	0.04569	59.65	2.387	375.4	3.792	0.03997	653
427.4	4.146	0.05315	51.39	2.586	422.2	3.8078	0.04649	562
474	4.178	0.06239	43.95	2.767	468.2	3.8358	0.05456	481
522.4	4.209	0.07205	38.19	2.933	515.9	3.8629	0.063	418
570.4	4.241	0.08509	32.46	3.098	563.1	3.8909	0.07438	355
617.4	4.264	0.1044	26.54	3.247	609.3	3.911	0.09125	290
664	4.317	0.1315	21.19	3.379	655.1	3.9573	0.11489	232
711.5	4.361	0.1691	16.57	3.51	701.8	3.9958	0.1477	181
759.4	4.488	0.2593	10.96	3.642	748.7	4.1068	0.22628	120
806.7	4.606	0.3689	7.809	3.774	795.1	4.2099	0.32166	85
853.9	4.704	0.4507	6.462	3.906	841.3	4.2955	0.39273	70
901.8	4.989	0.5797	5.177	4.038	888.1	4.544	0.50423	56
950.2	4.918	0.6272	4.752	4.17	935.4	4.4824	0.54577	52
998	13.07	4.775	1.032	4.302	961.8	11.4844	4.04986	11

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

MPN02284	MPN-258_MPN_NU-LHT-4M .docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
23.72	4.501	0.03494	815.4	0	23.05	3.564	0.02422	1045
23.72	4.492	0.03219	884.3	0.1135	23.46	3.5578	0.02232	1133
23.76	4.489	0.03138	906.7	0.1826	23.5	3.5557	0.02176	1162
119.2	4.384	0.02307	1219	0.3945	118	3.4828	0.01603	1561
183.5	4.402	0.02247	1254	0.593	181.6	3.4953	0.01561	1606
239.7	4.446	0.02115	1339	0.7748	237	3.5258	0.01468	1715
292.9	4.482	0.02234	1273	0.9566	289.6	3.5508	0.01549	1631
342.4	4.506	0.02483	1148	1.138	338.5	3.5675	0.01721	1471
390.1	4.524	0.02723	1049	1.32	385.6	3.58	0.01887	1344
436.4	4.546	0.03346	855.9	1.485	431.2	3.5952	0.02318	1097
483.2	4.576	0.03964	724.8	1.651	477.3	3.616	0.02745	929
530.1	4.604	0.05054	570.1	1.816	523.6	3.6354	0.03498	731
576.7	4.619	0.06075	475.1	1.981	569.6	3.6458	0.04203	609
622.8	4.607	0.06884	418.7	2.13	614.9	3.6375	0.04764	536
669.9	4.619	0.08222	351.1	2.278	661.3	3.6458	0.05689	450
717	4.667	0.09855	294.4	2.426	707.6	3.679	0.06813	377
764.5	4.658	0.1122	258.3	2.575	754.3	3.6728	0.07758	331
810.8	4.662	0.1264	229.3	2.707	799.8	3.6756	0.08739	294
858.1	4.651	0.1362	212.7	2.839	846.2	3.668	0.09418	272
906.1	4.642	0.1484	195	2.971	893.2	3.6618	0.10264	250
954.5	4.56	0.1484	193.2	3.102	940.6	3.605	0.10279	247
1003	4.61	0.1652	174.6	3.234	988.1	3.6397	0.11432	223
1051	4.627	0.1702	169.7	3.366	1035	3.6515	0.11775	217
1100	4.753	0.2204	132.9	3.498	1083	3.7386	0.15214	170
1149	5.047	0.3337	90.45	3.63	1130	3.9414	0.22923	116
1197	5.834	0.6359	51.09	3.762	1159	4.4801	0.43183	65
1239	9.137	2.632	15.58	3.894	1201	6.699	1.72888	20
1295	10.42	4.313	10.26	4.027	1244	7.5587	2.80549	13
1344	12.2	7.041	6.914	4.159	1304	8.7518	4.52657	9
1392	16.01	12.23	4.669	4.291	1366	11.2636	7.72137	6
1294	13	5.783	8.568	4.426	1262	9.2403	3.70945	11
1197	10.3	2.76	15.75	4.568	1166	7.4597	1.79904	20
1097	6.901	0.5124	68.9	4.72	1070	5.1993	0.34365	89
1002	7.086	0.4714	75.87	4.885	986.7	5.3231	0.31555	98
903.6	6.984	0.4221	84.12	5.068	890.8	5.2546	0.28285	108
806.4	6.905	0.3618	97.57	5.258	795.4	5.2015	0.24265	126

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

707.3	6.802	0.2748	127.5	5.499	698	5.1322	0.18451	164
610.3	6.7	0.1943	178.9	5.775	602.6	5.0635	0.1306	231
514.4	6.587	0.1404	245.4	6.098	508.1	4.9875	0.09449	316
421.7	6.48	0.1015	336.9	6.481	416.7	4.9154	0.06839	434
329.6	6.363	0.07491	452.3	6.936	325.9	4.8365	0.05054	583
234.8	6.242	0.06089	551	7.568	232.3	4.7547	0.04114	710
126.6	6.003	0.05146	639.5	8.683	125	4.593	0.03487	824
23.91	5.988	0.05139	639.5	8.895	23.62	4.5828	0.03483	824

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

NASA2358	MPN-285_NUW-LHT-5M_Rickman_1mm.docx				Scaled Density 1.75			
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
23.45	4.525	0.01398	2041	0	23.84	3.6513	0.01	2562
23.53	4.496	0.01347	2110	0.07503	23.73	3.6305	0.00964	2650
23.51	4.502	0.01369	2078	0.1347	23.72	3.6348	0.00979	2611
51.7	4.525	0.01201	2374	0.3279	51.37	3.6513	0.00859	2983
99.75	4.555	0.01154	2479	0.6248	98.86	3.6728	0.00825	3115
148.4	4.572	0.01171	2449	0.9488	146.9	3.6849	0.00837	3075
203.3	4.61	0.01291	2231	1.309	201.1	3.7121	0.00922	2802
204.1	4.605	0.01247	2307	1.591	201.9	3.7085	0.00891	2898
204.2	4.609	0.01127	2553	1.873	202.1	3.7114	0.00805	3209
204.6	4.608	0.01153	2497	2.155	202.4	3.7106	0.00823	3139
204.8	4.613	0.01344	2143	2.437	202.6	3.7142	0.0096	2692
153.2	4.577	0.01226	2339	2.984	151.6	3.6885	0.00876	2940
100.7	4.547	0.01206	2371	3.941	99.78	3.667	0.00862	2979
50.7	4.526	0.01203	2370	6.221	50.39	3.652	0.0086	2980
23.68	4.513	0.0134	2125	6.349	23.85	3.6427	0.00958	2671
23.65	4.514	0.0131	2174	6.49	23.82	3.6434	0.00937	2732
46.67	4.527	0.01252	2279	6.619	46.4	3.6527	0.00895	2863
99.45	4.57	0.0127	2257	6.925	98.55	3.6835	0.00907	2837
151.6	4.6	0.01094	2628	7.253	150.1	3.7049	0.00781	3305
200.2	4.626	0.01221	2361	7.586	198.1	3.7235	0.00872	2967
249.9	4.65	0.01295	2232	7.922	247.2	3.7406	0.00924	2807
298.6	4.666	0.01416	2046	8.261	295.2	3.7521	0.0101	2572
348.4	4.687	0.01514	1917	8.548	344.4	3.7671	0.0108	2410
397.8	4.701	0.01498	1941	8.835	393.2	3.777	0.01068	2440
448.1	4.724	0.01727	1687	9.128	442.8	3.7934	0.01231	2121
497.6	4.744	0.01949	1499	9.423	491.6	3.8077	0.01389	1884
547	4.77	0.02179	1344	9.679	540.3	3.8262	0.01552	1690
596.9	4.788	0.02389	1228	9.938	589.5	3.8391	0.01702	1543
646.8	4.814	0.02838	1036	10.2	638.6	3.8576	0.02021	1303
696.6	4.849	0.03365	877.4	10.46	687.6	3.8825	0.02395	1103
746.2	4.887	0.04185	708.2	10.71	736.4	3.9096	0.02977	890
795.7	4.959	0.05582	534.9	10.97	785	3.9607	0.03966	672
845.1	5.026	0.0691	435	11.23	833.5	4.0083	0.04905	547
895.4	4.915	0.06609	449.7	11.5	882.8	3.9295	0.04699	565
949.6	4.832	0.0784	375.9	11.77	935.9	3.8704	0.05581	472
999	4.842	0.0966	305.4	12.03	984.2	3.8776	0.06876	384

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

1024	4.85	0.108	273.5	12.21	1009	3.8833	0.07687	343
1048	4.857	0.1216	243.1	12.39	1032	3.8883	0.08654	305
1072	4.872	0.1419	208.6	12.56	1056	3.899	0.10096	262
1096	4.894	0.1703	174.1	12.74	1079	3.9147	0.12113	219
1048	4.876	0.1596	185.5	12.97	1033	3.9019	0.11355	233
999.2	4.848	0.1441	204.9	13.21	984.5	3.8819	0.10256	257
950.4	4.812	0.1304	225.5	13.45	936.7	3.8563	0.09286	283
900.7	4.787	0.1143	256.7	13.7	888	3.8384	0.08143	322
850.3	4.754	0.09979	293	13.94	838.6	3.8149	0.07113	368
799.9	4.72	0.08577	339.6	14.19	789.2	3.7906	0.06117	426
750.7	4.69	0.07295	398	14.44	740.8	3.7692	0.05205	500
701.5	4.657	0.06096	474.6	14.68	692.4	3.7457	0.04352	596
652	4.632	0.05369	537.5	14.93	643.7	3.7278	0.03834	675
599.5	4.607	0.04662	617.2	15.19	592	3.7099	0.03331	775
549.8	4.578	0.04218	680.2	15.43	543	3.6892	0.03015	854
500.1	4.557	0.03674	779.1	15.69	494.1	3.6742	0.02627	978
450.6	4.532	0.03241	880.7	15.98	445.3	3.6563	0.02318	1106
400.6	4.505	0.02926	972.4	16.29	395.9	3.637	0.02094	1221
350.3	4.485	0.02418	1174	16.64	346.3	3.6227	0.01731	1474
300.7	4.458	0.02239	1265	17.05	297.3	3.6033	0.01603	1588
250.2	4.433	0.01951	1447	17.51	247.4	3.5854	0.01398	1816
201.3	4.408	0.01546	1821	18.06	199.1	3.5675	0.01108	2286
149.2	4.379	0.01478	1898	18.79	147.7	3.5467	0.0106	2382
100.1	4.349	0.0139	2012	19.88	99.24	3.5252	0.00997	2525
24.65	4.303	0.01569	1773	20.29	24.61	3.4922	0.01126	2225

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

NASA2360	MPN-285_NUW-LHT- 5M_Rickman_2m.docx					Scaled Density 1.75		
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
23.37	4.551	0.01492	1917	0	23.79	3.6699	0.01067	2407
23.29	4.55	0.01491	1918	0.07397	23.54	3.6692	0.01066	2409
23.32	4.549	0.01467	1950	0.1333	23.56	3.6685	0.01049	2448
53.2	4.571	0.01388	2066	0.3235	52.86	3.6842	0.00992	2594
102.5	4.605	0.01285	2238	0.6146	101.6	3.7085	0.00918	2813
152.4	4.633	0.01325	2178	0.9321	150.9	3.7285	0.00946	2737
203.9	4.662	0.01409	2055	1.277	201.7	3.7492	0.01005	2583
255	4.688	0.01362	2132	1.615	252.2	3.7678	0.00971	2681
303	4.707	0.01618	1798	1.948	299.6	3.7813	0.01154	2259
353.3	4.732	0.01631	1789	2.23	349.2	3.7992	0.01163	2247
403.3	4.755	0.01827	1600	2.514	398.6	3.8155	0.01302	2012
453.1	4.781	0.0193	1519	2.801	447.8	3.8341	0.01375	1909
502.2	4.804	0.02253	1304	3.088	496.1	3.8505	0.01604	1640
552	4.832	0.02431	1212	3.339	545.2	3.8704	0.0173	1525
601.7	4.861	0.02721	1086	3.593	594.2	3.891	0.01936	1366
651.3	4.881	0.03181	931.2	3.847	643.1	3.9053	0.02263	1171
700.8	4.921	0.03698	804.2	4.101	691.7	3.9337	0.02629	1011
750.3	4.96	0.04426	674.7	4.355	740.4	3.9615	0.03145	848
799.5	5.045	0.05923	508.4	4.609	788.7	4.0218	0.04203	639
823.2	5.069	0.06598	457.5	4.776	812.1	4.0389	0.04681	575
848.3	5.082	0.07307	413.7	4.947	836.6	4.0481	0.05183	520
875.1	4.985	0.06951	430.7	5.124	863	3.9792	0.04937	541
898.2	4.926	0.06807	437.1	5.288	885.6	3.9373	0.04839	549
922.2	4.904	0.07876	377	5.456	909	3.9217	0.05601	474
952.1	4.884	0.09106	325.4	5.643	938.4	3.9075	0.06477	409
974.2	4.89	0.1008	294.2	5.804	960	3.9117	0.0717	369
1001	4.905	0.117	253.7	5.981	986.4	3.9224	0.0832	319
1026	4.931	0.1327	224.4	6.152	1011	3.9409	0.09433	282
1050	4.952	0.1435	208	6.319	1034	3.9559	0.10198	261
1074	4.975	0.1541	194.1	6.486	1058	3.9722	0.10947	244
1099	4.997	0.1701	176.2	6.654	1081	3.9879	0.1208	221
1123	5.033	0.1974	152.4	6.821	1105	4.0135	0.14011	191
1147	5.108	0.192	157.9	6.989	1128	4.0667	0.13613	198
1100	5.069	0.1717	175.9	7.226	1083	4.039	0.12181	221
1050	5.036	0.1583	190.1	7.48	1034	4.0155	0.11235	239
1002	4.998	0.1433	209.1	7.728	987	3.9885	0.10176	263

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

953.8	4.96	0.1216	245.5	7.975	940	3.9615	0.0864	308
904.7	4.906	0.0991	299.7	8.226	892	3.9231	0.07047	376
854.6	4.868	0.08143	363.3	8.48	842.8	3.8961	0.05794	456
804.6	4.836	0.06985	422.1	8.734	793.7	3.8733	0.04972	530
755.5	4.808	0.06052	485.8	8.985	745.5	3.8533	0.0431	610
706.3	4.783	0.05346	548.5	9.235	697.1	3.8355	0.03809	689
656.8	4.76	0.04712	620.8	9.486	648.5	3.8191	0.03358	780
604.3	4.732	0.04204	693.7	9.747	596.7	3.7992	0.02997	872
554.6	4.708	0.03922	741.8	9.998	547.8	3.782	0.02797	932
505.1	4.688	0.03407	852	10.27	499	3.7678	0.02431	1070
455.4	4.662	0.0308	940	10.58	450	3.7492	0.02198	1181
405.5	4.637	0.02668	1082	10.91	400.8	3.7314	0.01905	1359
355.7	4.612	0.0232	1241	11.3	351.7	3.7135	0.01657	1559
305.3	4.588	0.01975	1454	11.73	301.9	3.6964	0.01411	1827
253.8	4.561	0.01795	1595	12.25	251.1	3.677	0.01283	2004
205.4	4.529	0.01479	1929	12.85	203.2	3.6542	0.01058	2423
152.7	4.496	0.01398	2033	13.67	151.2	3.6305	0.01	2555
102.4	4.467	0.0134	2115	14.91	101.4	3.6098	0.00959	2657
23.18	4.416	0.01507	1870	18.59	23.46	3.5732	0.0108	2347

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

NASA2361	MPN-285_NUW-LHT- 5M_Rickman_3m.docx					Scaled Density 1.75		
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
23.62	4.508	0.01494	1905	0	23.95	3.6942	0.01095	2354
23.57	4.509	0.01488	1913	0.07805	23.77	3.695	0.01091	2362
23.56	4.511	0.01482	1921	0.1376	23.75	3.6964	0.01086	2374
102.7	4.509	0.01445	1971	0.2661	101.7	3.695	0.01059	2434
165.7	4.539	0.0127	2250	0.3813	164	3.717	0.0093	2780
227.3	4.572	0.01397	2053	0.4964	224.8	3.7411	0.01023	2535
283.6	4.603	0.01377	2089	0.6115	280.5	3.7638	0.01008	2581
336.5	4.637	0.01492	1935	0.7266	332.7	3.7887	0.01091	2392
385.9	4.663	0.0165	1755	0.8418	381.4	3.8078	0.01207	2168
434.2	4.694	0.01621	1792	0.9569	429.1	3.8304	0.01185	2215
482	4.724	0.0198	1472	1.072	476.2	3.8524	0.01447	1819
529.4	4.753	0.0227	1288	1.187	522.9	3.8736	0.01658	1592
577	4.787	0.02445	1200	1.302	569.9	3.8984	0.01785	1483
624.7	4.822	0.02802	1051	1.417	616.9	3.9239	0.02044	1299
672.5	4.857	0.03434	860.5	1.533	663.8	3.9495	0.02505	1063
720.1	4.897	0.04191	708	1.648	710.7	3.9787	0.03055	875
767.7	4.94	0.05063	588.5	1.763	757.5	4.01	0.03689	728
815.3	5.002	0.06057	495.1	1.878	804.2	4.0552	0.04409	612
839.3	5.026	0.06871	437.5	1.993	827.8	4.0726	0.05	541
862.4	4.992	0.06795	440.9	2.108	850.4	4.0479	0.04947	545
885.8	4.917	0.06325	470	2.223	873.4	3.9932	0.0461	581
909.5	4.898	0.06587	450.5	2.339	896.7	3.9794	0.04802	557
933.6	4.884	0.07323	404.6	2.454	920.2	3.9692	0.05339	500
957.8	4.893	0.0828	358.2	2.569	944	3.9758	0.06036	443
982	4.913	0.09244	321.5	2.684	967.6	3.9904	0.06737	397
1006	4.934	0.1054	282.5	2.799	991.2	4.0057	0.0768	349
1030	4.962	0.118	253.1	2.914	1015	4.0261	0.08595	313
1054	4.997	0.1384	216.7	3.029	1038	4.0516	0.10076	267
1079	5.042	0.172	175.1	3.145	1062	4.0844	0.12514	216
1103	5.096	0.2148	141	3.26	1086	4.1238	0.15617	174
1127	5.172	0.2549	119.7	3.375	1110	4.1791	0.18514	148
1152	5.252	0.2505	122.7	3.49	1133	4.2371	0.18176	151
1176	5.383	0.2189	142.2	3.605	1157	4.332	0.15857	176
1200	5.724	0.2784	115.2	3.72	1180	4.5787	0.20085	142
1224	6.228	0.4101	81.63	3.835	1197	4.9416	0.29426	101
1248	6.919	0.5724	61.67	3.951	1207	5.4362	0.408	76

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

1200	6.632	0.3657	94.46	4.066	1177	5.2307	0.26136	117
1151	6.365	0.1972	171.6	4.182	1133	5.0393	0.1413	213
1102	6.197	0.1305	255.8	4.298	1085	4.9188	0.09367	317
1054	6.148	0.121	274.8	4.414	1038	4.8836	0.08689	341
1005	6.112	0.1075	308.3	4.529	990.2	4.8577	0.07723	382
956.7	6.079	0.09589	344.7	4.646	942.9	4.834	0.06891	427
907.9	6.045	0.08639	381.6	4.767	895.1	4.8096	0.0621	473
858.7	6.012	0.07768	423.2	4.892	846.9	4.7858	0.05586	525
809.8	5.98	0.06928	473.3	5.022	798.9	4.7628	0.04984	587
760.9	5.948	0.06142	532.4	5.158	750.8	4.7398	0.0442	660
711.8	5.915	0.05618	580.5	5.301	702.6	4.716	0.04044	720
663.2	5.884	0.0518	627.9	5.453	654.8	4.6937	0.0373	778
614.2	5.852	0.04653	697.1	5.616	606.4	4.6706	0.03352	864
565.5	5.82	0.04297	752.8	5.79	558.5	4.6476	0.03096	933
518.2	5.784	0.03903	826.2	5.977	512	4.6216	0.02814	1024
470.6	5.747	0.035	918.3	6.181	465	4.5949	0.02524	1138
422.4	5.716	0.0312	1027	6.397	417.4	4.5726	0.02251	1274
377.3	5.667	0.02978	1072	6.642	373	4.5372	0.0215	1328
330	5.631	0.02654	1199	6.908	326.2	4.5112	0.01916	1486
282.9	5.584	0.025	1267	7.214	279.8	4.4772	0.01806	1571
234.6	5.537	0.02325	1357	7.589	232	4.4433	0.01681	1681
180.8	5.489	0.02224	1412	8.045	178.9	4.4086	0.01609	1750
122.6	5.484	0.02304	1363	8.744	121.5	4.4049	0.01667	1688
23.75	5.41	0.0279	1118	11.41	23.9	4.3514	0.0202	1384

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

MPN023101	MPN-292_MPN_Glass for 5M Simulant_Creedon_Washington Mills.docx					Scaled Density 1.75		
	Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled
23.95	4.012	0.02118	1268	0	24.16	3.6699	0.01838	1397
23.91	4.011	0.02069	1298	0.1896	24.04	3.6691	0.01795	1431
23.95	4.01	0.02042	1315	0.2493	24.06	3.6682	0.01772	1449
61.63	4.033	0.01984	1357	0.5084	61.19	3.6882	0.01721	1496
100.6	4.045	0.01949	1383	0.7574	99.64	3.6986	0.01691	1525
150.1	4.064	0.01899	1424	1.078	148.6	3.7151	0.01647	1569
201.5	4.089	0.01919	1413	1.425	199.3	3.7368	0.01664	1558
251.9	4.115	0.01833	1484	1.765	249.2	3.7593	0.01589	1636
300.3	4.139	0.01797	1518	2.102	296.9	3.7801	0.01558	1673
350.6	4.164	0.0183	1495	2.387	346.6	3.8018	0.01586	1648
399.8	4.182	0.01813	1512	2.676	395.2	3.8174	0.01571	1667
449.8	4.197	0.01844	1489	2.967	444.5	3.8304	0.01598	1642
499.5	4.213	0.01865	1476	3.26	493.5	3.8443	0.01616	1627
523.8	4.219	0.01813	1519	3.45	517.5	3.8495	0.0157	1676
548.5	4.225	0.0178	1548	3.622	541.8	3.8547	0.01542	1707
573.9	4.235	0.0193	1429	3.798	566.8	3.8633	0.01672	1576
598.3	4.244	0.01913	1444	3.971	590.8	3.8711	0.01657	1592
623.7	4.255	0.02072	1335	4.147	615.9	3.8806	0.01794	1472
648	4.263	0.02302	1202	4.321	639.8	3.8876	0.01993	1326
672.6	4.275	0.02375	1167	4.494	664	3.898	0.02056	1287
697.8	4.289	0.02864	969.5	4.672	688.7	3.9101	0.0248	1069
722.1	4.304	0.02943	945	4.846	712.7	3.9231	0.02548	1042
747.5	4.323	0.03396	820.7	5.025	737.6	3.9395	0.0294	905
771.7	4.33	0.0377	740	5.2	761.4	3.9456	0.03263	816
796.9	4.359	0.04393	637.3	5.379	786.1	3.9707	0.03802	702
821.1	4.4	0.05069	554.8	5.556	809.9	4.0062	0.04385	612
846.4	4.459	0.05958	475.2	5.736	834.8	4.0572	0.05152	524
873.5	4.422	0.05792	486.8	5.924	861.4	4.0252	0.0501	537
896.7	4.338	0.03704	753.8	6.099	884.1	3.9525	0.03206	831
920.9	4.232	0.02363	1167	6.278	907.8	3.8607	0.02047	1287
951	4.179	0.01642	1669	6.477	937.3	3.8148	0.01423	1840
973.1	4.177	0.01637	1673	6.651	958.9	3.8131	0.01418	1846
1000	4.177	0.01478	1854	6.843	985.4	3.8131	0.01281	2044
955.2	4.161	0.01343	2036	7.059	941.5	3.7992	0.01164	2245
905.1	4.147	0.01306	2090	7.296	892.3	3.787	0.01132	2305
854.5	4.132	0.01277	2134	7.538	842.7	3.774	0.01107	2353

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

803.9	4.121	0.01114	2443	7.782	793.1	3.7645	0.00965	2696
754.3	4.108	0.01173	2317	8.023	744.4	3.7532	0.01017	2554
704.8	4.097	0.01158	2344	8.266	695.7	3.7437	0.01004	2584
655.3	4.083	0.0109	2486	8.51	647	3.7315	0.00945	2741
602.6	4.069	0.0118	2291	8.764	595	3.7194	0.01023	2528
552.8	4.055	0.01034	2611	9.009	546	3.7073	0.00897	2878
502.9	4.047	0.00986	2735	9.274	496.8	3.7003	0.00855	3017
453.3	4.032	0.01067	2523	9.568	448	3.6873	0.00925	2784
403.3	4.016	0.01006	2671	9.892	398.6	3.6734	0.00873	2944
353.2	4.002	0.009923	2703	10.26	349.1	3.6613	0.00861	2980
302.6	3.99	0.01055	2538	10.67	299.3	3.6508	0.00915	2800
251.8	3.975	0.01042	2566	11.16	249	3.6378	0.00904	2829
202.5	3.966	0.01065	2508	11.73	200.4	3.63	0.00924	2765
150.6	3.954	0.01161	2297	12.5	149.1	3.6196	0.01008	2531
101.1	3.946	0.01219	2185	13.64	100.1	3.6126	0.01058	2409
24.16	3.944	0.01806	1475	17.15	24.23	3.6109	0.01568	1625

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

MPN023100	MPN-294_MPN_5M Glass to 1300C_Creedon_Washington Mills .docx					Scaled Density 1.75		
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
24.8	4.438	0.02513	1124	0	24.68	3.8178	0.01988	1318
24.86	4.426	0.02466	1144	0.1491	24.78	3.8083	0.01952	1340
24.89	4.427	0.02422	1165	0.2177	24.81	3.8091	0.01917	1365
51.85	4.443	0.02292	1233	0.4008	51.52	3.8217	0.01813	1446
101.5	4.471	0.02217	1279	0.695	100.5	3.8439	0.01753	1499
150.9	4.485	0.02198	1292	1.013	149.4	3.855	0.01738	1515
202.7	4.518	0.02182	1306	1.36	200.6	3.8811	0.01725	1531
253.6	4.542	0.02231	1281	1.699	250.8	3.9	0.01763	1502
301.7	4.546	0.02115	1352	2.032	298.3	3.9032	0.01671	1585
352.4	4.566	0.02204	1300	2.315	348.4	3.919	0.01741	1524
401.8	4.577	0.01986	1444	2.6	397.1	3.9277	0.01569	1694
451.5	4.581	0.01964	1461	2.888	446.1	3.9309	0.01551	1714
501.1	4.547	0.02014	1420	3.177	495.1	3.904	0.01591	1665
550.4	4.613	0.02149	1340	3.427	543.6	3.9561	0.01697	1571
600.4	4.638	0.02209	1307	3.681	592.9	3.9759	0.01744	1533
650	4.656	0.02445	1183	3.935	641.8	3.9901	0.0193	1388
699.4	4.66	0.02477	1169	4.189	690.4	3.9933	0.01955	1370
749	4.708	0.0266	1094	4.443	739.2	4.0311	0.02098	1283
798.5	4.793	0.03385	867.2	4.697	787.8	4.0982	0.02668	1017
822.2	4.85	0.04174	707.5	4.864	811	4.1431	0.03288	830
847.2	4.94	0.04624	644.5	5.035	835.5	4.214	0.03639	756
875.3	4.953	0.04279	697.3	5.212	859	4.2242	0.03367	818
897.3	4.826	0.02515	1171	5.377	884.7	4.1242	0.01981	1374
921.4	4.724	0.01258	2317	5.544	908.3	4.0438	0.00992	2718
951.3	4.708	0.01044	2786	5.732	937.6	4.0311	0.00823	3271
973.5	4.719	0.01032	2823	5.892	959.3	4.0398	0.00814	3311
1000	4.721	0.01324	2201	6.07	985.7	4.0414	0.01044	2582
1026	4.722	0.01398	2085	6.24	1010	4.0422	0.01102	2446
1050	4.735	0.01503	1941	6.408	1034	4.0524	0.01185	2278
1074	4.751	0.01634	1789	6.575	1057	4.0651	0.01288	2099
1098	4.768	0.01788	1638	6.742	1081	4.0785	0.01409	1922
1122	4.796	0.01894	1550	6.91	1104	4.1005	0.01492	1820
1146	4.84	0.03152	935.7	7.077	1128	4.1352	0.02483	1098
1100	4.802	0.01711	1717	7.315	1083	4.1053	0.01348	2015
1049	4.778	0.01424	2057	7.569	1034	4.0863	0.01122	2416
1001	4.764	0.01338	2188	7.816	986.4	4.0753	0.01055	2566

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

953.1	4.775	0.01282	2286	8.064	939.4	4.084	0.0101	2683
904	4.758	0.01199	2438	8.314	891.3	4.0706	0.00945	2863
854.1	4.754	0.01061	2755	8.568	842.3	4.0674	0.00836	3235
803.9	4.762	0.009556	3062	8.822	793.1	4.0737	0.00753	3594
754.9	4.746	0.00904	3231	9.073	744.9	4.0611	0.00712	3795
705.6	4.72	0.008265	3524	9.324	696.5	4.0406	0.00652	4134
656.1	4.693	0.00845	3437	9.575	647.7	4.0193	0.00666	4037
603.6	4.664	0.008019	3611	9.835	596.1	3.9964	0.00633	4235
554.1	4.696	0.007146	4066	10.09	547.3	4.0217	0.00563	4777
504.5	4.686	0.006004	4834	10.36	498.4	4.0138	0.00473	5680
454.8	4.644	0.005309	5442	10.66	449.4	3.9806	0.00419	6386
404.9	4.648	0.004399	6571	11	400.2	3.9838	0.00347	7714
354.9	4.635	0.005242	5506	11.39	350.9	3.9735	0.00413	6473
304.6	4.606	0.005142	5597	11.83	301.2	3.9506	0.00406	6565
253.6	4.597	0.004173	6889	12.35	250.9	3.9435	0.00329	8095
204.4	4.591	0.004535	6334	12.96	202.2	3.9388	0.00358	7434
152.9	4.547	0.005602	5103	13.8	151.4	3.904	0.00442	5995
102.8	4.53	0.006681	4271	15.06	101.9	3.8906	0.00528	5010
24.96	4.474	0.01159	2448	21.46	24.87	3.8463	0.00916	2871

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

MPN023109 Revised	MPN-294_MPN_5M Glass to 1300C_Creedon_Washington Mills .docx				Scaled Density 1.75			
Index Temp	e'	e''	HPD	LAPST	Temp	e' Scaled	e'' Scaled	Adjusted HPD
23.96	4.373	0.02415	1163	0	23.79	3.6877	0.01849	1392
24.01	4.379	0.02364	1189	0.07261	23.91	3.6923	0.01809	1424
24	4.389	0.02395	1175	0.1317	23.9	3.7	0.01833	1407
110.8	4.352	0.02145	1306	0.2602	110.5	3.6716	0.01642	1565
175.6	4.393	0.02187	1287	0.3754	175.1	3.703	0.01674	1541
238	4.449	0.02095	1352	0.4905	237.2	3.7459	0.01602	1620
295.5	4.482	0.02148	1324	0.6057	294.5	3.7711	0.01642	1586
349.4	4.521	0.02155	1325	0.7209	348.2	3.8009	0.01646	1588
398.9	4.535	0.02286	1251	0.8361	397.4	3.8116	0.01746	1499
446.1	4.544	0.02329	1229	0.9512	444.4	3.8185	0.01779	1473
492.5	4.56	0.02326	1233	1.066	490.5	3.8307	0.01776	1477
538.6	4.56	0.02325	1233	1.182	536.4	3.8307	0.01775	1478
584	4.57	0.02785	1031	1.297	581.6	3.8384	0.02126	1235
629.7	4.567	0.02917	983.7	1.412	626.9	3.8361	0.02227	1179
653.6	4.577	0.03386	848.6	1.527	650.6	3.8437	0.02585	1017
675.4	4.571	0.03527	814	1.642	672.3	3.8391	0.02693	975
697.6	4.575	0.04038	711.3	1.757	694.3	3.8422	0.03083	852
720	4.605	0.04452	647.2	1.873	716.5	3.8651	0.03398	775
743	4.606	0.04859	593.1	1.988	739.4	3.8659	0.03708	711
766.2	4.626	0.05218	553.5	2.103	762.3	3.8811	0.03981	663
789.4	4.645	0.05669	510.5	2.218	785.3	3.8956	0.04324	612
812.4	4.703	0.06062	480.4	2.333	808.1	3.9399	0.04621	576
835.6	4.759	0.06815	429.9	2.448	831	3.9825	0.05191	515
859	4.946	0.07814	382.2	2.564	854.2	4.1248	0.05939	458
882.6	4.956	0.07307	409.1	2.679	877.6	4.1324	0.05553	490
906.4	4.777	0.05135	571.6	2.794	901.1	3.9962	0.0391	685
930.5	4.666	0.03651	794.6	2.909	924.9	3.9116	0.02784	952
954.7	4.595	0.02998	960.2	3.024	948.8	3.8575	0.02288	1151
978.6	4.592	0.02481	1160	3.14	972.4	3.8552	0.01894	1390
1003	4.59	0.02432	1183	3.255	996.5	3.8536	0.01856	1418
1027	4.599	0.02208	1304	3.37	1020	3.8605	0.01685	1563
1051	4.581	0.02033	1414	3.485	1044	3.8468	0.01552	1694
1075	4.587	0.01941	1482	3.6	1068	3.8513	0.01481	1777
1100	4.589	0.02032	1416	3.715	1092	3.8529	0.01551	1697
1124	4.579	0.02067	1391	3.831	1115	3.8452	0.01578	1666
1148	4.654	0.03595	805.8	3.946	1139	3.9025	0.02742	966

Appendix C. Original Differential Scanning Calorimetry (DSC) Values

1172	4.778	0.06637	442.3	4.061	1163	3.997	0.05054	530
1196	5.036	0.1381	218.3	4.176	1187	4.1933	0.10485	261
1220	5.39	0.2781	112.2	4.291	1204	4.4617	0.2103	134
1245	6.012	0.5083	64.84	4.407	1227	4.9312	0.38199	78
1269	7.008	0.9564	37.25	4.523	1250	5.6782	0.71269	44
1293	8.643	2.046	19.42	4.638	1270	6.8962	1.50768	23
1245	7.336	0.7771	46.87	4.754	1228	5.9215	0.57773	56
1196	7.091	0.4449	80.42	4.87	1186	5.7381	0.33138	96
1148	6.92	0.2453	144	4.985	1139	5.6102	0.18295	173
1099	6.739	0.152	229.3	5.1	1091	5.475	0.11352	276
1051	6.616	0.09398	367.5	5.215	1044	5.3831	0.07026	442
1003	6.528	0.07193	477	5.331	996.1	5.3173	0.05381	574
954.4	6.478	0.0589	580.3	5.448	948.5	5.2798	0.04408	699
905.8	6.445	0.05087	670.2	5.57	900.5	5.2551	0.03808	807
856.9	6.423	0.04282	794.9	5.695	852.2	5.2386	0.03206	957
808.6	6.404	0.0379	896.7	5.826	804.3	5.2244	0.02838	1080
760.1	6.389	0.03162	1074	5.962	756.3	5.2132	0.02368	1293
711.5	6.369	0.02669	1270	6.105	708.1	5.1982	0.01999	1529
663.5	6.344	0.0216	1566	6.257	660.4	5.1795	0.01618	1886
615.3	6.344	0.01818	1861	6.419	612.6	5.1795	0.01362	2240
567.5	6.345	0.01529	2212	6.593	565.2	5.1802	0.01145	2665
521.4	6.309	0.01335	2527	6.78	519.3	5.1532	0.01	3044
475.6	6.289	0.009723	3464	6.983	473.8	5.1382	0.00728	4175
428.4	6.304	0.009314	3620	7.201	426.7	5.1495	0.00698	4360
384.7	6.255	0.009837	3414	7.444	383.3	5.1127	0.00737	4114
340	6.217	0.01001	3345	7.708	338.8	5.0842	0.0075	4032
292.6	6.188	0.006376	5239	8.006	291.6	5.0625	0.00478	6312
245.5	6.145	0.007042	4727	8.372	244.7	5.0302	0.00528	5696
192.9	6.097	0.006418	5167	8.825	192.3	4.9942	0.00481	6231
134.6	6.01	0.007806	4217	9.511	134.2	4.9288	0.00586	5080
23.79	5.93	0.01788	1829	12.38	23.67	4.8687	0.01344	2201
23.84	5.927	0.01828	1788	12.45	23.57	4.8664	0.01374	2153

**Appendix D. Differential Scanning Calorimetry (DSC) Values**

Data columns are Temp in °C and Cp in J/gK. Because of the high degree of redundancy in the original DSC data at the precisions of the tables, the values in the following tables are thinned. Features with a total amplitude less than 0.01 Cp have been lost.

## CSM-LHT-1G

Temp Cp	559 1.18	836 1.13	897 1.04	983 1.19	1067 1.51	1105 1.82
51 1.02	570 1.19	837 1.12	898 1.03	985 1.20	1069 1.52	1106 1.83
52 1.01	575 1.20	839 1.11	899 1.02	987 1.21	1070 1.53	1108 1.84
53 1.00	576 1.21	841 1.10	900 1.01	990 1.22	1071 1.54	1109 1.85
55 0.99	580 1.20	843 1.09	901 1.00	995 1.23	1072 1.55	1110 1.86
56 0.98	590 1.21	846 1.08	902 0.99	997 1.24	1073 1.56	1112 1.87
59 0.97	598 1.22	851 1.07	903 0.98	999 1.25	1074 1.57	1113 1.88
64 0.96	605 1.23	854 1.08	904 0.97	1001 1.26	1075 1.58	1114 1.89
94 0.97	610 1.24	858 1.09	913 0.98	1004 1.27	1076 1.59	1115 1.90
105 0.98	618 1.25	860 1.10	918 0.99	1006 1.28	1077 1.60	1116 1.91
117 0.99	626 1.26	862 1.11	927 0.98	1008 1.29	1078 1.61	1118 1.92
131 1.00	637 1.27	864 1.12	942 0.99	1011 1.30	1079 1.62	1119 1.93
145 1.01	652 1.28	865 1.13	945 1.00	1013 1.31	1080 1.63	1120 1.94
180 1.02	669 1.27	867 1.14	948 1.01	1016 1.32	1081 1.64	1121 1.95
195 1.03	688 1.26	868 1.15	951 1.02	1022 1.33	1082 1.65	1122 1.97
212 1.04	698 1.25	870 1.16	953 1.03	1029 1.34	1083 1.66	1123 1.98
236 1.05	744 1.24	871 1.17	956 1.04	1035 1.35	1084 1.67	1124 1.99
261 1.06	786 1.25	873 1.18	959 1.05	1039 1.36	1085 1.68	1126 2.00
288 1.07	796 1.26	876 1.19	960 1.06	1043 1.37	1087 1.69	1127 2.02
305 1.08	810 1.25	882 1.18	962 1.07	1046 1.38	1088 1.70	1128 2.03
323 1.09	815 1.24	885 1.17	964 1.08	1048 1.39	1089 1.71	1129 2.04
340 1.10	819 1.23	887 1.16	966 1.09	1051 1.40	1091 1.72	1130 2.05
363 1.11	821 1.22	888 1.15	967 1.10	1053 1.41	1092 1.73	1131 2.06
396 1.12	822 1.21	889 1.14	969 1.11	1055 1.42	1093 1.74	1132 2.07
397 1.11	824 1.20	890 1.13	970 1.12	1057 1.43	1095 1.75	1133 2.08
398 1.12	826 1.19	891 1.12	972 1.13	1059 1.44	1096 1.76	1134 2.09
424 1.13	827 1.18	892 1.11	974 1.14	1060 1.45	1098 1.77	1135 2.10
456 1.14	829 1.17	893 1.10	976 1.15	1062 1.46	1099 1.78	1136 2.11
478 1.15	831 1.16	894 1.09	978 1.16	1063 1.47	1101 1.79	1137 2.12
501 1.16	832 1.15	895 1.07	980 1.17	1064 1.48	1102 1.80	1138 2.13
543 1.17	834 1.14	896 1.06	981 1.18	1065 1.49	1104 1.81	1139 2.14

Appendix D. Differential Scanning Calorimetry (DSC) Values

1140 2.15	1227 2.52	1303 2.53	1372 2.59	1431 2.28	1482 1.85	1530 1.17
1141 2.16	1228 2.53	1305 2.54	1374 2.58	1432 2.26	1483 1.83	1533 1.16
1142 2.17	1230 2.54	1306 2.56	1375 2.57	1433 2.24	1487 1.82	1538 1.17
1143 2.18	1231 2.55	1307 2.57	1377 2.56	1434 2.22	1489 1.8	1539 1.15
1145 2.19	1232 2.56	1310 2.56	1378 2.55	1435 2.21	1490 1.79	1543 1.16
1146 2.20	1233 2.57	1312 2.57	1381 2.56	1439 2.20	1492 1.78	1547 1.17
1148 2.21	1234 2.58	1317 2.58	1382 2.57	1440 2.19	1493 1.77	1548 1.18
1149 2.22	1235 2.59	1319 2.59	1383 2.58	1441 2.18	1494 1.75	1551 1.19
1152 2.23	1236 2.61	1320 2.61	1384 2.57	1442 2.17	1495 1.73	1553 1.18
1156 2.24	1238 2.62	1321 2.62	1386 2.56	1443 2.16	1497 1.72	1558 1.17
1166 2.25	1241 2.63	1322 2.61	1387 2.55	1445 2.15	1498 1.71	1565 1.16
1170 2.26	1242 2.64	1323 2.62	1389 2.53	1446 2.13	1499 1.69	1566 1.18
1172 2.27	1243 2.65	1324 2.63	1390 2.52	1447 2.12	1501 1.67	1567 1.19
1176 2.28	1250 2.66	1325 2.64	1391 2.50	1448 2.11	1502 1.65	1573 1.18
1178 2.29	1253 2.67	1326 2.65	1392 2.49	1450 2.10	1503 1.63	1576 1.17
1180 2.30	1254 2.66	1327 2.66	1393 2.48	1451 2.08	1504 1.62	1577 1.16
1185 2.31	1256 2.67	1329 2.65	1395 2.47	1452 2.06	1507 1.61	1579 1.17
1189 2.32	1258 2.66	1331 2.64	1396 2.46	1453 2.04	1508 1.59	1585 1.18
1193 2.33	1260 2.65	1333 2.63	1397 2.45	1454 2.03	1509 1.57	1586 1.19
1195 2.34	1262 2.64	1336 2.64	1399 2.46	1455 2.04	1512 1.55	1587 1.20
1197 2.35	1263 2.63	1340 2.65	1401 2.45	1457 2.03	1513 1.54	1588 1.19
1199 2.36	1265 2.61	1342 2.66	1403 2.46	1458 2.02	1514 1.52	1590 1.20
1202 2.37	1266 2.59	1343 2.67	1405 2.45	1460 2.01	1515 1.50	1591 1.19
1206 2.38	1267 2.57	1345 2.68	1407 2.44	1461 2.00	1516 1.49	1595 1.18
1208 2.39	1268 2.56	1347 2.69	1408 2.42	1462 1.99	1517 1.48	1596 1.17
1211 2.4	1269 2.55	1349 2.68	1411 2.41	1463 1.98	1518 1.46	1602 1.16
1212 2.41	1270 2.54	1350 2.67	1412 2.40	1464 1.97	1519 1.45	1603 1.18
1213 2.42	1271 2.53	1351 2.65	1413 2.39	1468 1.96	1520 1.43	1608 1.19
1214 2.43	1272 2.52	1352 2.64	1414 2.37	1469 1.95	1521 1.41	1614 1.18
1215 2.44	1275 2.51	1353 2.63	1415 2.36	1471 1.94	1522 1.40	1615 1.17
1216 2.45	1276 2.50	1359 2.62	1420 2.35	1472 1.92	1523 1.39	1616 1.18
1217 2.46	1278 2.51	1361 2.63	1421 2.34	1474 1.91	1524 1.38	1618 1.19
1219 2.47	1296 2.50	1362 2.65	1422 2.33	1476 1.90	1525 1.37	1622 1.20
1220 2.48	1297 2.51	1363 2.66	1423 2.34	1478 1.89	1526 1.35	1624 1.21
1222 2.49	1298 2.52	1364 2.65	1426 2.32	1479 1.88	1527 1.31	1627 1.22
1223 2.50	1299 2.53	1370 2.62	1427 2.30	1480 1.87	1528 1.28	1628 1.23
1225 2.51	1300 2.54	1371 2.60	1428 2.29	1481 1.86	1529 1.25	1631 1.24

## Appendix D. Differential Scanning Calorimetry (DSC) Values

## NU-LHT-4M

Temp Cp	597 1.31	867 1.22	1087 1.41	1158 1.78	1195 2.25	1232 3.29
23 1.03	602 1.32	871 1.21	1092 1.42	1159 1.79	1196 2.27	1233 3.33
25 1.02	608 1.33	875 1.20	1098 1.43	1160 1.80	1197 2.29	1234 3.36
27 1.01	618 1.32	879 1.19	1102 1.44	1161 1.81	1198 2.31	1235 3.40
31 1.00	628 1.31	882 1.18	1105 1.45	1162 1.83	1199 2.33	1236 3.43
45 1.01	646 1.30	886 1.17	1107 1.46	1163 1.84	1200 2.35	1237 3.47
68 1.02	647 1.31	891 1.16	1109 1.47	1164 1.85	1201 2.37	1238 3.51
78 1.03	673 1.32	895 1.15	1112 1.48	1165 1.86	1202 2.39	1239 3.54
91 1.04	674 1.31	900 1.14	1114 1.49	1166 1.87	1203 2.41	1240 3.57
109 1.05	675 1.32	912 1.15	1116 1.50	1167 1.88	1204 2.43	1241 3.61
125 1.06	693 1.33	920 1.16	1119 1.51	1168 1.90	1205 2.46	1242 3.64
138 1.07	704 1.34	924 1.17	1121 1.52	1169 1.91	1206 2.48	1243 3.68
152 1.08	711 1.35	929 1.18	1123 1.53	1170 1.92	1207 2.51	1244 3.72
168 1.09	718 1.36	932 1.19	1125 1.54	1171 1.93	1208 2.54	1245 3.76
190 1.10	728 1.37	936 1.20	1127 1.55	1172 1.95	1209 2.56	1246 3.79
223 1.11	735 1.38	939 1.21	1129 1.56	1173 1.96	1210 2.59	1247 3.83
250 1.12	743 1.39	942 1.22	1131 1.57	1174 1.97	1211 2.61	1248 3.87
264 1.13	754 1.40	944 1.23	1133 1.58	1175 1.98	1212 2.64	1249 3.90
279 1.14	755 1.39	949 1.24	1135 1.59	1176 2.00	1213 2.67	1250 3.94
302 1.15	756 1.40	953 1.25	1136 1.60	1177 2.01	1214 2.70	1251 3.98
325 1.16	782 1.39	956 1.26	1137 1.61	1178 2.02	1215 2.73	1252 4.01
400 1.17	790 1.38	959 1.27	1139 1.62	1179 2.03	1216 2.77	1253 4.05
438 1.18	795 1.37	964 1.28	1141 1.63	1180 2.05	1217 2.79	1254 4.08
439 1.17	800 1.36	981 1.27	1142 1.64	1181 2.06	1218 2.83	1255 4.12
440 1.18	805 1.35	996 1.28	1144 1.65	1182 2.07	1219 2.86	1256 4.16
484 1.19	809 1.34	1017 1.29	1145 1.66	1183 2.08	1220 2.89	1257 4.19
493 1.20	815 1.33	1031 1.30	1146 1.67	1184 2.09	1221 2.92	1258 4.22
503 1.21	821 1.32	1037 1.31	1147 1.68	1185 2.11	1222 2.95	1259 4.26
512 1.22	826 1.31	1041 1.32	1148 1.69	1186 2.12	1223 2.98	1260 4.29
524 1.23	832 1.30	1051 1.33	1149 1.70	1187 2.14	1224 3.02	1261 4.32
541 1.24	838 1.29	1055 1.34	1151 1.71	1188 2.15	1225 3.05	1262 4.35
553 1.25	843 1.28	1061 1.35	1152 1.72	1189 2.16	1226 3.09	1263 4.36
562 1.26	848 1.27	1065 1.36	1153 1.73	1190 2.18	1227 3.12	1264 4.37
569 1.27	853 1.26	1070 1.37	1154 1.74	1191 2.19	1228 3.15	1265 4.38
578 1.28	857 1.25	1074 1.38	1155 1.75	1192 2.21	1229 3.18	1266 4.37
586 1.29	861 1.24	1078 1.39	1156 1.76	1193 2.22	1230 3.22	1268 4.36
592 1.30	865 1.23	1084 1.40	1157 1.77	1194 2.24	1231 3.25	1269 4.35

Appendix D. Differential Scanning Calorimetry (DSC) Values

1270 4.33	1317 3.71	1358 2.84	1397 2.26	1436 1.73	1491 1.30
1271 4.32	1318 3.69	1359 2.81	1398 2.24	1437 1.71	1493 1.29
1272 4.3	1319 3.66	1360 2.78	1399 2.22	1439 1.69	1496 1.28
1273 4.28	1320 3.63	1361 2.76	1400 2.21	1440 1.68	1500 1.27
1274 4.26	1321 3.61	1362 2.74	1401 2.20	1441 1.67	1502 1.26
1275 4.25	1322 3.58	1363 2.73	1402 2.18	1443 1.66	1505 1.25
1276 4.23	1323 3.56	1364 2.72	1403 2.17	1444 1.65	1511 1.24
1277 4.22	1324 3.53	1365 2.70	1404 2.16	1445 1.63	1518 1.23
1278 4.20	1325 3.51	1366 2.69	1405 2.14	1446 1.62	1519 1.24
1280 4.19	1326 3.49	1367 2.67	1406 2.12	1447 1.61	1522 1.23
1282 4.18	1327 3.46	1368 2.65	1407 2.11	1448 1.60	1539 1.22
1283 4.17	1328 3.44	1369 2.63	1408 2.10	1449 1.59	1555 1.23
1286 4.18	1329 3.42	1370 2.62	1409 2.08	1450 1.58	1560 1.24
1287 4.19	1330 3.40	1371 2.61	1410 2.07	1451 1.57	1562 1.23
1291 4.18	1331 3.38	1372 2.60	1411 2.06	1452 1.56	1581 1.22
1292 4.16	1332 3.36	1373 2.58	1412 2.04	1453 1.55	1582 1.23
1293 4.15	1333 3.34	1374 2.57	1413 2.03	1454 1.54	1583 1.22
1294 4.13	1334 3.32	1375 2.56	1414 2.01	1455 1.52	1591 1.23
1295 4.12	1335 3.30	1376 2.55	1415 1.99	1456 1.51	1593 1.24
1296 4.11	1336 3.28	1377 2.53	1416 1.97	1457 1.50	1596 1.25
1298 4.10	1337 3.27	1378 2.52	1417 1.96	1458 1.49	1597 1.26
1299 4.08	1338 3.26	1379 2.50	1418 1.94	1459 1.48	1610 1.27
1300 4.07	1339 3.25	1380 2.49	1419 1.92	1460 1.47	1616 1.27
1301 4.05	1340 3.24	1381 2.48	1420 1.91	1461 1.46	
1302 4.04	1342 3.22	1382 2.47	1421 1.89	1462 1.45	
1303 4.02	1343 3.21	1383 2.45	1422 1.88	1463 1.44	
1304 4.01	1344 3.19	1384 2.43	1423 1.86	1464 1.43	
1305 3.99	1345 3.18	1385 2.42	1424 1.85	1465 1.42	
1306 3.97	1347 3.16	1386 2.41	1425 1.84	1467 1.41	
1307 3.94	1348 3.14	1387 2.39	1426 1.83	1468 1.40	
1308 3.92	1349 3.12	1388 2.38	1427 1.82	1469 1.39	
1309 3.89	1350 3.10	1389 2.36	1428 1.81	1471 1.38	
1310 3.87	1351 3.07	1390 2.35	1429 1.80	1472 1.37	
1311 3.85	1352 3.04	1391 2.34	1430 1.79	1474 1.36	
1312 3.83	1353 3.01	1392 2.32	1431 1.78	1476 1.35	
1313 3.8	1354 2.97	1393 2.31	1432 1.77	1478 1.34	
1314 3.78	1355 2.94	1394 2.29	1433 1.76	1482 1.33	
1315 3.76	1356 2.90	1395 2.28	1434 1.75	1484 1.32	
1316 3.73	1357 2.86	1396 2.27	1435 1.74	1486 1.31	

## Appendix D. Differential Scanning Calorimetry (DSC) Values

## NUW-LHT-5M Glass

Temp Cp	734 0.94	802 1.32	913 0.96	949 -2.29	986 -0.94	1022 0.44
51 1.01	739 0.95	803 1.34	914 0.90	950 -2.31	987 -0.90	1023 0.47
52 0.99	745 0.96	804 1.35	915 0.84	951 -2.32	988 -0.86	1024 0.50
53 0.96	752 0.97	805 1.36	916 0.77	953 -2.33	989 -0.82	1025 0.52
54 0.95	757 0.98	806 1.37	917 0.70	954 -2.32	990 -0.78	1026 0.55
55 0.93	761 0.99	807 1.38	918 0.61	955 -2.31	991 -0.74	1027 0.57
56 0.92	764 1.00	808 1.39	919 0.52	956 -2.29	992 -0.70	1028 0.59
57 0.91	766 1.01	810 1.40	920 0.43	957 -2.27	993 -0.65	1029 0.61
58 0.90	769 1.02	811 1.41	921 0.32	958 -2.24	994 -0.61	1030 0.63
59 0.89	771 1.03	813 1.42	922 0.22	959 -2.21	995 -0.57	1031 0.65
61 0.88	773 1.04	821 1.41	923 0.10	960 -2.17	996 -0.52	1032 0.66
63 0.87	775 1.05	824 1.40	924 -0.02	961 -2.13	997 -0.48	1033 0.68
65 0.86	776 1.06	828 1.39	925 -0.14	962 -2.09	998 -0.44	1034 0.69
69 0.85	777 1.07	832 1.38	926 -0.27	963 -2.04	999 -0.40	1035 0.71
74 0.84	779 1.08	838 1.37	927 -0.4	964 -1.99	1000 -0.36	1036 0.72
87 0.83	780 1.09	847 1.36	928 -0.53	965 -1.93	1001 -0.32	1037 0.73
95 0.84	782 1.10	863 1.35	929 -0.66	966 -1.88	1002 -0.28	1038 0.74
96 0.83	783 1.11	872 1.34	930 -0.80	967 -1.83	1003 -0.24	1039 0.75
104 0.84	784 1.12	880 1.33	931 -0.94	968 -1.78	1004 -0.20	1041 0.76
107 0.83	785 1.13	887 1.32	932 -1.07	969 -1.72	1005 -0.16	1043 0.77
109 0.84	786 1.14	893 1.31	933 -1.20	970 -1.67	1006 -0.12	1046 0.78
128 0.85	787 1.15	896 1.30	934 -1.32	971 -1.62	1007 -0.08	1054 0.79
143 0.86	788 1.16	898 1.29	935 -1.44	972 -1.57	1008 -0.04	1064 0.80
162 0.87	789 1.17	900 1.28	936 -1.55	973 -1.52	1009 0.00	1077 0.81
192 0.88	790 1.18	901 1.27	937 -1.65	974 -1.47	1010 0.04	1080 0.82
229 0.89	791 1.19	902 1.26	938 -1.74	975 -1.43	1011 0.07	1084 0.83
270 0.90	792 1.20	903 1.25	939 -1.82	976 -1.38	1012 0.11	1088 0.84
311 0.91	793 1.21	904 1.24	940 -1.90	977 -1.33	1013 0.15	1093 0.85
458 0.90	794 1.23	905 1.22	941 -1.97	978 -1.29	1014 0.18	1098 0.86
524 0.91	795 1.24	906 1.20	942 -2.03	979 -1.24	1015 0.22	1104 0.87
551 0.92	796 1.25	907 1.18	943 -2.08	980 -1.20	1016 0.25	1110 0.88
569 0.93	797 1.26	908 1.15	944 -2.13	981 -1.16	1017 0.29	1112 0.89
594 0.94	798 1.28	909 1.12	945 -2.17	982 -1.11	1018 0.32	1115 0.90
635 0.95	799 1.29	910 1.09	946 -2.21	983 -1.07	1019 0.35	1119 0.91
661 0.96	800 1.30	911 1.05	947 -2.24	984 -1.03	1020 0.38	1123 0.92
710 0.95	801 1.31	912 1.01	948 -2.27	985 -0.98	1021 0.41	1127 0.93

Appendix D. Differential Scanning Calorimetry (DSC) Values

1130 0.94	1180 1.41	1218 2.30	1257 3.19	1302 1.88	1351 2.37	1392 3.14
1133 0.95	1181 1.43	1219 2.32	1258 3.22	1304 1.89	1352 2.38	1393 3.18
1137 0.96	1182 1.45	1220 2.33	1259 3.26	1305 1.90	1353 2.40	1394 3.21
1141 0.97	1183 1.47	1221 2.34	1260 3.29	1306 1.89	1354 2.43	1395 3.24
1144 0.98	1184 1.49	1222 2.36	1261 3.33	1307 1.88	1355 2.45	1396 3.27
1146 0.99	1185 1.52	1223 2.37	1262 3.35	1310 1.89	1356 2.47	1397 3.29
1148 1.00	1186 1.54	1224 2.38	1263 3.38	1312 1.90	1357 2.49	1398 3.32
1149 1.01	1187 1.56	1226 2.39	1264 3.40	1314 1.91	1358 2.51	1399 3.36
1150 1.02	1188 1.58	1227 2.40	1265 3.41	1315 1.92	1359 2.53	1400 3.38
1151 1.03	1189 1.61	1228 2.42	1266 3.43	1316 1.93	1360 2.54	1401 3.39
1152 1.04	1190 1.63	1229 2.43	1268 3.40	1317 1.94	1361 2.56	1403 3.40
1153 1.05	1191 1.65	1230 2.44	1269 3.38	1318 1.95	1362 2.58	1404 3.41
1154 1.06	1192 1.67	1231 2.45	1270 3.34	1319 1.97	1364 2.57	1405 3.44
1155 1.07	1193 1.70	1232 2.46	1271 3.3	1321 1.98	1366 2.59	1406 3.46
1156 1.08	1194 1.72	1233 2.48	1272 3.25	1322 2.00	1367 2.61	1407 3.48
1157 1.09	1195 1.75	1234 2.50	1273 3.18	1323 2.01	1368 2.62	1408 3.50
1158 1.10	1196 1.77	1235 2.52	1274 3.10	1324 2.02	1369 2.64	1409 3.51
1159 1.11	1197 1.80	1236 2.54	1275 3.01	1327 2.03	1370 2.66	1410 3.53
1160 1.12	1198 1.83	1237 2.56	1276 2.91	1328 2.04	1371 2.67	1411 3.58
1161 1.13	1199 1.85	1238 2.59	1277 2.80	1329 2.05	1372 2.70	1412 3.6
1162 1.14	1200 1.90	1239 2.62	1278 2.69	1330 2.06	1373 2.73	1413 3.62
1163 1.16	1201 1.93	1240 2.65	1279 2.58	1331 2.08	1374 2.77	1414 3.64
1164 1.17	1202 1.96	1241 2.67	1280 2.47	1332 2.10	1375 2.79	1420 3.61
1165 1.18	1203 1.99	1242 2.70	1281 2.37	1333 2.11	1376 2.82	1421 3.57
1166 1.19	1204 2.02	1243 2.73	1282 2.27	1334 2.13	1377 2.84	1422 3.54
1167 1.21	1205 2.05	1244 2.76	1283 2.18	1335 2.16	1378 2.86	1423 3.52
1168 1.22	1206 2.07	1245 2.79	1284 2.11	1336 2.18	1379 2.88	1424 3.51
1169 1.24	1207 2.10	1246 2.83	1285 2.05	1337 2.20	1380 2.91	1425 3.49
1170 1.25	1208 2.12	1247 2.86	1286 2.00	1338 2.22	1381 2.94	1426 3.46
1171 1.27	1209 2.15	1248 2.89	1287 1.95	1339 2.24	1384 2.95	1427 3.42
1172 1.28	1210 2.16	1249 2.92	1288 1.91	1340 2.26	1385 2.96	1428 3.36
1173 1.29	1211 2.18	1250 2.94	1289 1.88	1341 2.28	1386 2.98	1429 3.32
1174 1.31	1212 2.20	1251 2.97	1290 1.86	1342 2.30	1387 3.00	1430 3.27
1175 1.32	1213 2.21	1252 3.01	1291 1.85	1343 2.31	1388 3.03	1431 3.20
1176 1.34	1214 2.23	1253 3.04	1292 1.84	1347 2.32	1389 3.05	1432 3.08
1177 1.36	1215 2.25	1254 3.07	1297 1.85	1348 2.33	1390 3.07	1433 2.96
1178 1.37	1216 2.27	1255 3.11	1298 1.86	1349 2.35	1391 3.10	1434 2.82
1179 1.39	1217 2.28	1256 3.14	1300 1.87	1350 2.36		1435 2.67

Appendix D. Differential Scanning Calorimetry (DSC) Values

1436	2.51	1498	1.11	1592	0.99
1437	2.36	1500	1.10	1595	1.00
1438	2.21	1502	1.09	1596	0.99
1439	2.04	1504	1.08	1598	0.98
1440	1.88	1506	1.09	1599	0.99
1441	1.75	1507	1.10	1600	1.00
1442	1.64	1508	1.11	1602	1.01
1443	1.54	1510	1.10	1605	1.00
1444	1.46	1513	1.11	1609	0.99
1445	1.39	1515	1.10	1611	0.98
1446	1.35	1516	1.09	1614	0.99
1447	1.31	1517	1.08	1618	1.00
1448	1.29	1523	1.07	1619	1.01
1449	1.28	1524	1.08	1620	1.02
1450	1.27	1525	1.09	1622	1.03
1451	1.26	1531	1.10	1626	1.04
1452	1.25	1532	1.09	1630	1.03
1454	1.24	1534	1.08	1631	1.02
1458	1.23	1535	1.06		
1459	1.20	1541	1.05		
1460	1.18	1544	1.06		
1463	1.17	1545	1.07		
1464	1.16	1547	1.06		
1467	1.17	1553	1.05		
1468	1.18	1554	1.03		
1469	1.19	1558	1.04		
1470	1.18	1560	1.03		
1477	1.17	1562	1.04		
1478	1.16	1564	1.05		
1479	1.15	1567	1.04		
1481	1.16	1568	1.05		
1485	1.15	1572	1.04		
1487	1.16	1573	1.03		
1488	1.17	1582	1.04		
1490	1.16	1585	1.03		
1491	1.15	1587	1.02		
1496	1.14	1590	1.01		
1497	1.12	1591	1.00		

Appendix D. Differential Scanning Calorimetry (DSC) Values

JSC-1A

JSC-1A	493 1.03	765 1.01	825 0.41	866 0.47	908 1.01	1057 1.33
Temp Cp	494 1.02	769 1.00	826 0.38	867 0.50	912 1.02	1058 1.35
52 0.79	495 1.03	777 0.99	827 0.35	868 0.52	917 1.03	1059 1.37
61 0.80	496 1.02	783 0.98	828 0.32	869 0.54	922 1.04	1060 1.38
68 0.81	522 1.01	787 0.97	829 0.30	870 0.57	928 1.05	1061 1.40
75 0.82	538 1.00	790 0.96	830 0.27	871 0.59	938 1.06	1062 1.43
83 0.83	571 1.01	792 0.95	831 0.25	872 0.61	939 1.05	1063 1.45
91 0.84	581 1.02	794 0.94	832 0.22	873 0.63	950 1.06	1064 1.47
97 0.85	593 1.03	796 0.93	833 0.20	874 0.66	951 1.05	1065 1.50
101 0.86	607 1.04	797 0.92	834 0.18	875 0.68	957 1.06	1066 1.52
111 0.87	621 1.05	798 0.91	835 0.16	876 0.70	959 1.05	1067 1.55
122 0.88	627 1.06	799 0.90	836 0.15	877 0.71	962 1.06	1068 1.58
132 0.89	630 1.07	800 0.89	837 0.13	878 0.73	963 1.05	1069 1.6
141 0.90	634 1.08	802 0.87	838 0.12	879 0.75	969 1.06	1070 1.63
155 0.91	636 1.09	803 0.86	839 0.11	880 0.77	1021 1.07	1071 1.66
165 0.92	639 1.10	804 0.85	840 0.10	881 0.78	1026 1.08	1072 1.70
180 0.93	641 1.11	805 0.84	842 0.09	882 0.80	1030 1.09	1073 1.73
195 0.94	644 1.12	806 0.82	845 0.10	883 0.81	1033 1.10	1074 1.76
214 0.95	647 1.13	807 0.81	847 0.11	884 0.83	1035 1.11	1075 1.80
238 0.96	650 1.14	808 0.79	849 0.12	885 0.84	1037 1.12	1076 1.84
265 0.97	655 1.15	809 0.78	850 0.14	886 0.85	1039 1.13	1077 1.87
313 0.98	668 1.14	810 0.76	851 0.15	887 0.86	1040 1.14	1078 1.91
362 0.99	675 1.13	811 0.74	852 0.16	888 0.87	1042 1.15	1079 1.95
384 1.00	683 1.12	812 0.72	853 0.18	889 0.88	1043 1.16	1080 1.99
406 1.01	689 1.11	813 0.70	854 0.20	890 0.89	1044 1.17	1081 2.04
417 1.02	699 1.10	814 0.68	855 0.22	891 0.90	1046 1.18	1082 2.08
425 1.03	710 1.09	815 0.66	856 0.24	892 0.91	1047 1.20	1083 2.12
470 1.02	715 1.10	816 0.64	857 0.26	893 0.92	1048 1.21	1084 2.16
473 1.03	716 1.09	817 0.61	858 0.28	894 0.93	1049 1.22	1085 2.20
474 1.02	724 1.08	818 0.59	859 0.30	895 0.94	1050 1.23	1086 2.24
476 1.03	731 1.07	819 0.56	860 0.33	897 0.95	1051 1.24	1087 2.29
477 1.02	736 1.06	820 0.54	861 0.35	899 0.96	1052 1.26	1088 2.33
480 1.03	743 1.05	821 0.51	862 0.38	900 0.97	1053 1.27	1089 2.37
483 1.02	748 1.04	822 0.49	863 0.4	902 0.98	1054 1.28	1090 2.41
484 1.03	753 1.03	823 0.46	864 0.42	904 0.99	1055 1.30	1091 2.45
492 1.02	758 1.02	824 0.43	865 0.45	906 1.00	1056 1.31	1092 2.50

Appendix D. Differential Scanning Calorimetry (DSC) Values

1093 2.53	1131 3.56	1174 2.88	1234 2.47	1272 2.02	1324 1.62	1488 1.31
1094 2.57	1132 3.58	1175 2.86	1235 2.46	1273 2.00	1326 1.61	
1095 2.61	1133 3.61	1176 2.84	1236 2.45	1274 1.99	1328 1.60	
1096 2.65	1134 3.62	1177 2.82	1237 2.44	1275 1.98	1330 1.59	
1097 2.69	1135 3.64	1178 2.80	1238 2.43	1276 1.96	1332 1.58	
1098 2.73	1136 3.66	1179 2.78	1239 2.42	1277 1.95	1335 1.57	
1099 2.76	1137 3.68	1180 2.77	1240 2.41	1278 1.94	1337 1.56	
1100 2.80	1138 3.70	1181 2.75	1241 2.40	1279 1.93	1340 1.55	
1101 2.83	1139 3.71	1182 2.74	1242 2.39	1280 1.92	1343 1.54	
1102 2.87	1140 3.73	1183 2.73	1243 2.38	1281 1.91	1347 1.53	
1103 2.91	1141 3.74	1184 2.72	1244 2.37	1282 1.90	1349 1.52	
1104 2.94	1142 3.75	1185 2.71	1245 2.36	1283 1.89	1351 1.51	
1105 2.97	1143 3.76	1187 2.70	1246 2.35	1284 1.88	1355 1.50	
1106 3.00	1144 3.77	1190 2.69	1247 2.34	1286 1.87	1356 1.49	
1107 3.02	1149 3.76	1195 2.70	1248 2.33	1287 1.86	1359 1.48	
1108 3.05	1151 3.74	1199 2.71	1249 2.32	1288 1.85	1365 1.47	
1109 3.07	1152 3.72	1200 2.70	1250 2.31	1289 1.84	1367 1.46	
1110 3.10	1153 3.70	1204 2.69	1251 2.30	1290 1.83	1370 1.45	
1111 3.12	1154 3.68	1207 2.68	1252 2.28	1291 1.82	1375 1.44	
1112 3.14	1155 3.65	1208 2.67	1253 2.27	1292 1.81	1378 1.43	
1113 3.17	1156 3.62	1210 2.66	1254 2.26	1294 1.80	1381 1.42	
1114 3.19	1157 3.59	1213 2.65	1255 2.25	1295 1.79	1384 1.41	
1115 3.21	1158 3.55	1215 2.64	1256 2.23	1296 1.78	1392 1.40	
1116 3.24	1159 3.50	1216 2.63	1257 2.22	1297 1.77	1393 1.39	
1117 3.26	1160 3.45	1217 2.62	1258 2.21	1299 1.76	1398 1.38	
1118 3.28	1161 3.40	1218 2.61	1259 2.20	1300 1.75	1402 1.37	
1119 3.30	1162 3.35	1219 2.60	1260 2.18	1302 1.74	1408 1.36	
1120 3.32	1163 3.30	1220 2.59	1261 2.17	1304 1.73	1412 1.35	
1121 3.34	1164 3.25	1221 2.58	1262 2.16	1305 1.72	1417 1.34	
1122 3.36	1165 3.20	1222 2.57	1263 2.14	1307 1.71	1427 1.33	
1123 3.38	1166 3.15	1224 2.55	1264 2.12	1308 1.70	1439 1.32	
1124 3.4	1167 3.11	1226 2.54	1265 2.11	1311 1.69	1447 1.33	
1125 3.42	1168 3.07	1227 2.53	1266 2.10	1312 1.68	1448 1.32	
1126 3.45	1169 3.03	1228 2.52	1267 2.08	1314 1.67	1450 1.33	
1127 3.47	1170 3.00	1230 2.51	1268 2.07	1316 1.66	1459 1.32	
1128 3.49	1171 2.96	1231 2.50	1269 2.06	1318 1.65	1466 1.31	
1129 3.51	1172 2.93	1232 2.49	1270 2.04	1320 1.64	1487 1.30	
1130 3.54	1173 2.91	1233 2.48	1271 2.03	1323 1.63		

## Appendix E. Reports from Microwave Properties North

MPN reports for each run are provided below, ordered following the master measurement table, Table 1. Here the reports are reproduced verbatim, and each is 13 to 26 pages long. A report starts with a line giving the report's file name and the date, and ends after the  $\epsilon''$  data table. The reports contain much more information than is the focus of this paper. All reports include both the  $\epsilon'$  and the  $\epsilon''$  two data tables for all frequencies measured, and tables and graphs of multiple variables needed to understand the data. Many of the reports also have photos of the pellets before and after processing.

Note the report "MPN-292\_MPN\_Glass for 5M Simulant\_Creedon\_Washington Mills.docx" is a double report; it contains the information for both the 1000 °C and the 1150 °C runs on NUW-LHT-5M Glass.

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102 – 115	Anorthite (Synthetic)	MPN-231_Shulman_3_Anorthite A-006
116 – 132	CSM-LHT-1G 1000 C	MPN-257_Shulman_CSM-LHT-1G_1
133 – 149	CSM-LHT-1G 1100 C	MPN-257_Shulman_CSM-LHT-1G_2
150 – 167	CSM-LHT-1G 1400 C	MPN-258_CSM-LHT-1G_heat-treated
168 – 184	Diopside Synthetic	MPN-231_Shulman_3_Diopside D-009
185 – 198	Diopside w/ Actinolite	MPN-242_MPN_Diopside with Actinolite
199 – 212	Enstatite	MPN-242_MPN_Enstatite_Mirabel Springs, Mt St Helena CA
213 – 133	JSC-1A	MPN-218_Shulman_1_JSC-1A
234 – 148	JSC-1A	MPN-218_Shulman_2_JSC-1A
249 – 166	JSC-1A	MPN-231_Shulman_3_JSC-1A(A)
267 – 183	JSC-1A	MPN-231_Shulman_3_JSC-1A (B)
284 – 199	JSC-1AC	CERALINK_NYSERDA_10
300 – 313	Merriam Crater	MPN-241_Shulman_4_Merriam Crater Basalt
314 – 331	NU-LHT-2M	MPN-218_Shulman_1_NU-LHT-2M
332 – 350	NU-LHT-4M	MPN-258_MPN_NU-LHT-4M
351 – 366	NUW-LHT-5M	MPN-285_NUW-LHT-5M_Rickman_1mm
367 – 381	NUW-LHT-5M	MPN-285_NUW-LHT-5M_Rickman_2m
382 – 299	NUW-LHT-5M	MPN-285_NUW-LHT-5M_Rickman_3m
400 – 421	NUW-LHT-5M Glass	MPN-292_MPN_Glass for 5M Simulant_Creedon_ Washington Mills
422 – 444	NUW-LHT-5M Glass	MPN-292_MPN_Glass for Corrected 5M Simulant_ Creedon_Washington Mills
445 – 472	NUW-LHT-5M Glass	MPN-294_MPN_5M Glass to 1300C_Creedon_ Washington Mills

MPN-231\_Shulman\_3\_Anorthite A-006

August 13, 2021

Anorthite (Synthetic) A-006 Plagioclase Feldspar  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in < 1 milli Torr Vacuum

Dr. Holly Shulman ( Shulman LLC) again requested that Microwave Properties North measure the complex dielectric properties of lab-manufactured synthetic anorthite powder, up to 1100C with a direct, uninterrupted, temperature cycle, in as good a vacuum as we could produce in the MPN system. The powder sample material arrived at MPN on July 21/ 2021.

MPN pressed pellets of the powder material in a uniaxial press. The press pressure of ~ 18,000 psi was sufficient to produce pellets that could be handled. This produced pellets of a density of ~ 1.57 g/cc . The pellets were not baked to ensure dryness.

MPN was requested to cycle the sample directly up to 1100C and then return to room temperature (RT) , ) in as good a vacuum as we could produce in the MPN system.

The initial sample parameters were:

- a) diameter 3.63 +- 0.05 mm
- b) length 13.40 +- 0.10 mm
- c) mass 0.218 +- 0.002 gm
- d) room temperature density  $1.57 \pm 0.06$  gm/cc.
- e) appearance - three (stacked) white pellets .

The dielectric properties measurements were performed at RT and then the temperature was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps. The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was then run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.65 \pm 0.05$  mm
- b) length  $13.53 \pm 0.1$  mm
- c) mass  $0.217 \pm 0.002$  gm
- d) room temperature density  $1.53 \pm 0.06$  gm/cc.
- e) appearance - three white pellets ( see photo)

Note: The percent mass loss was zero ( +- 0.7 % ) .

The frequency coding is :

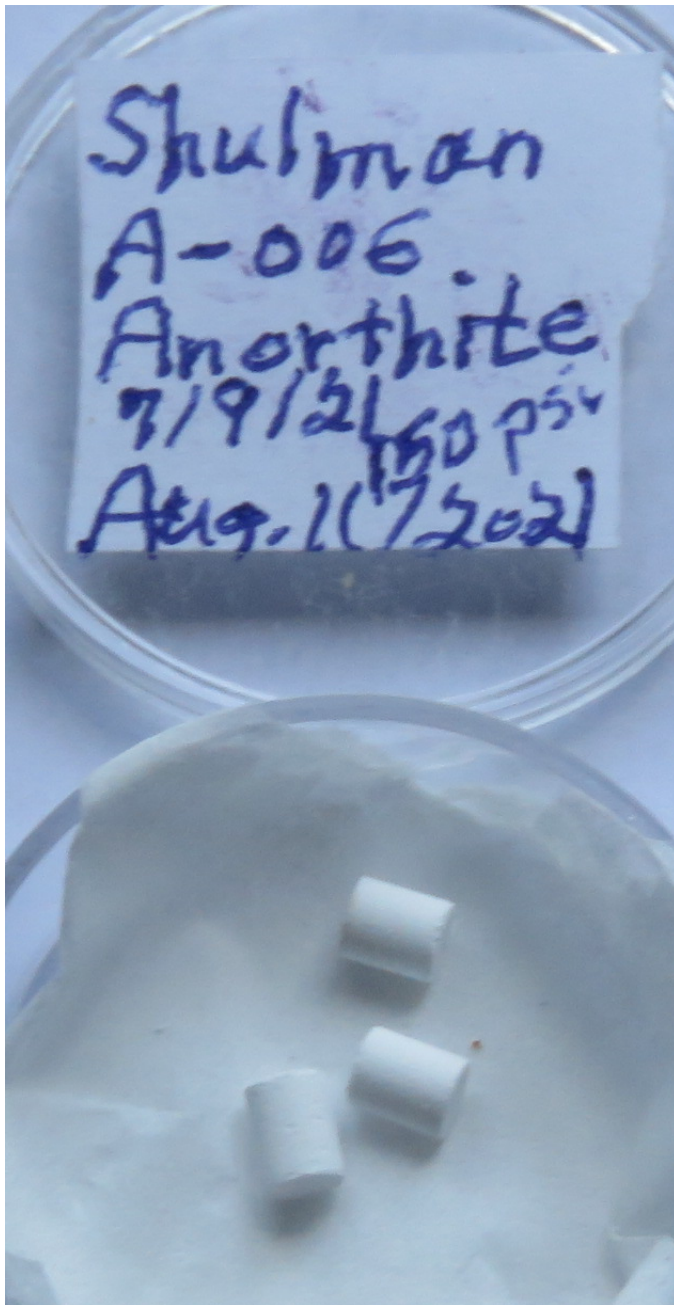
Legend for Data Plots :

#	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line
6	2986	black diamond, dotted line

Comments on the data analysis:

A thermal expansion coefficient (CTE) of  $0.0 \times 10^{-6}/\text{C}$  was used.

The data for the ramp up to 1100C shows a peak slightly above  $\sim 700\text{C}$  which is gone at the return down in temperature. Some irreversible change has occurred.



Final 3 Pellets

Values for the Temperature Cycle (to 1100 C and back to RT) :

Test = 2021081101

SHUL2149\_LowCal.mcd

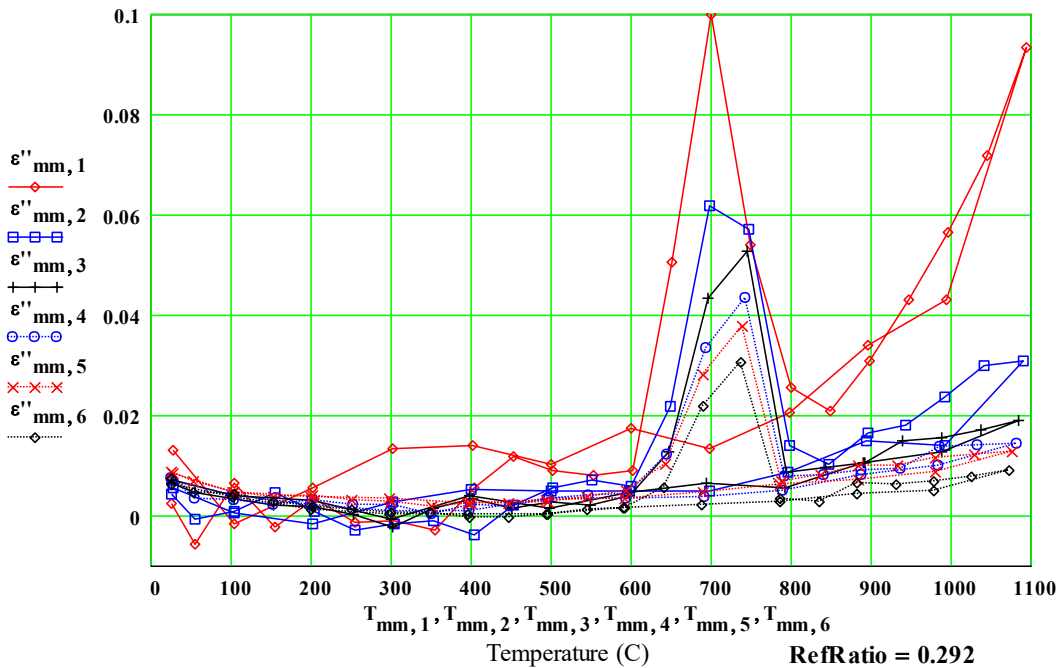
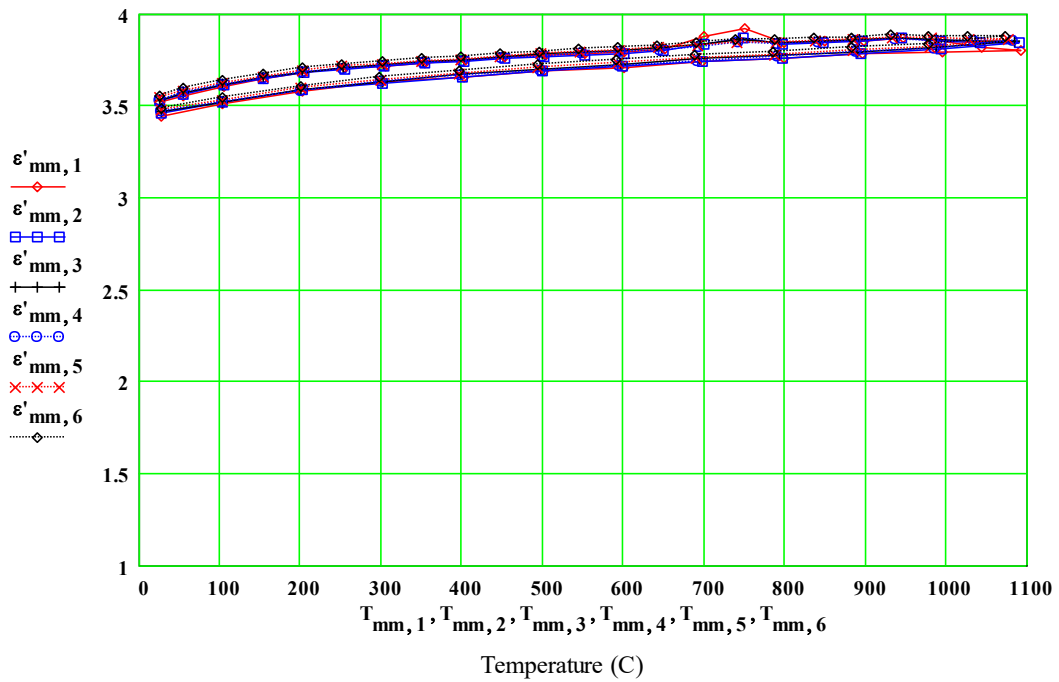
AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.57 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.53 \text{ gm/cc}$

Final\_over\_Initial\_mass = 0.995



RefRatio = 0.292

# Appendix E. MPN Reports

Test = 2021081101

SHUL2149\_LowCal.mcd

AnDat = 20210813

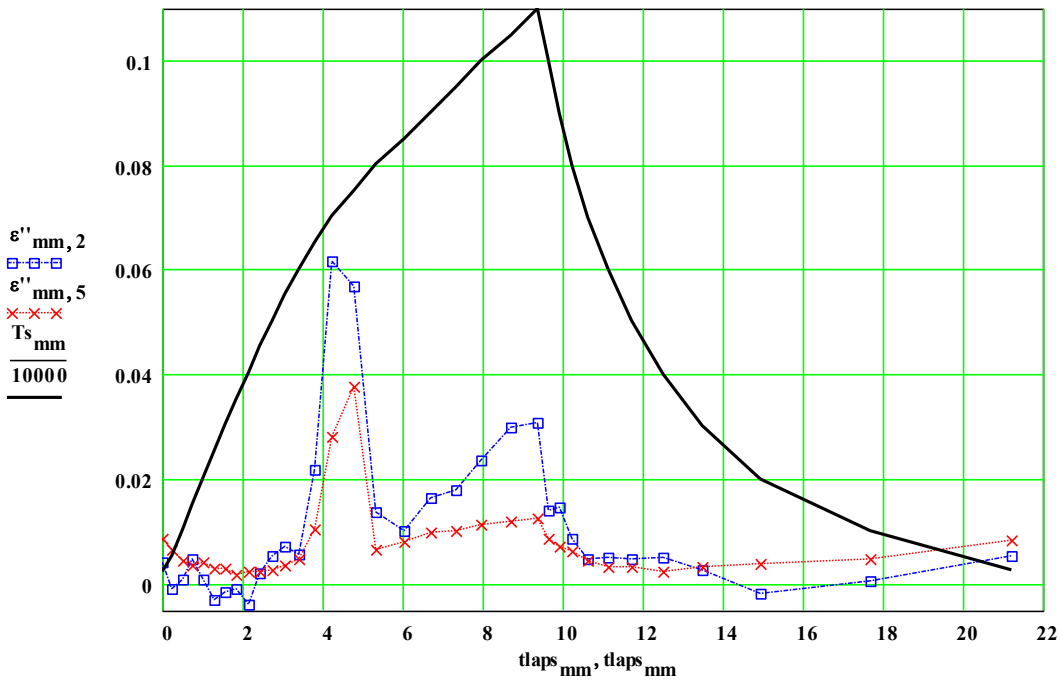
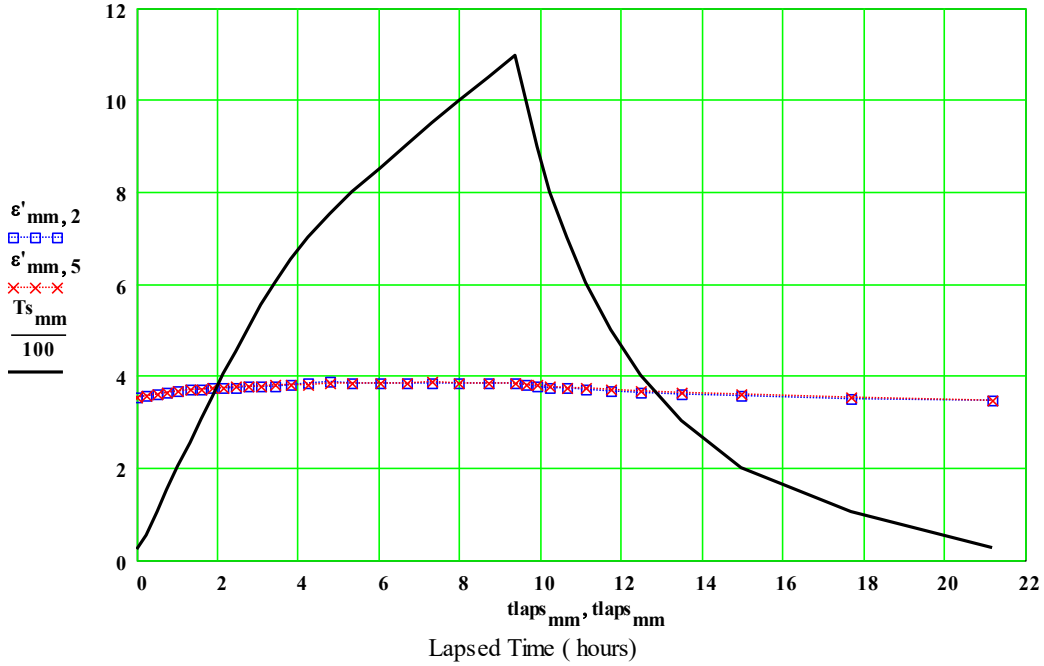
Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.57 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 1.53 \text{ gm/cc}$        $\text{FracMassChange} = 1$

$\alpha_1 = 0$



# Appendix E. MPN Reports

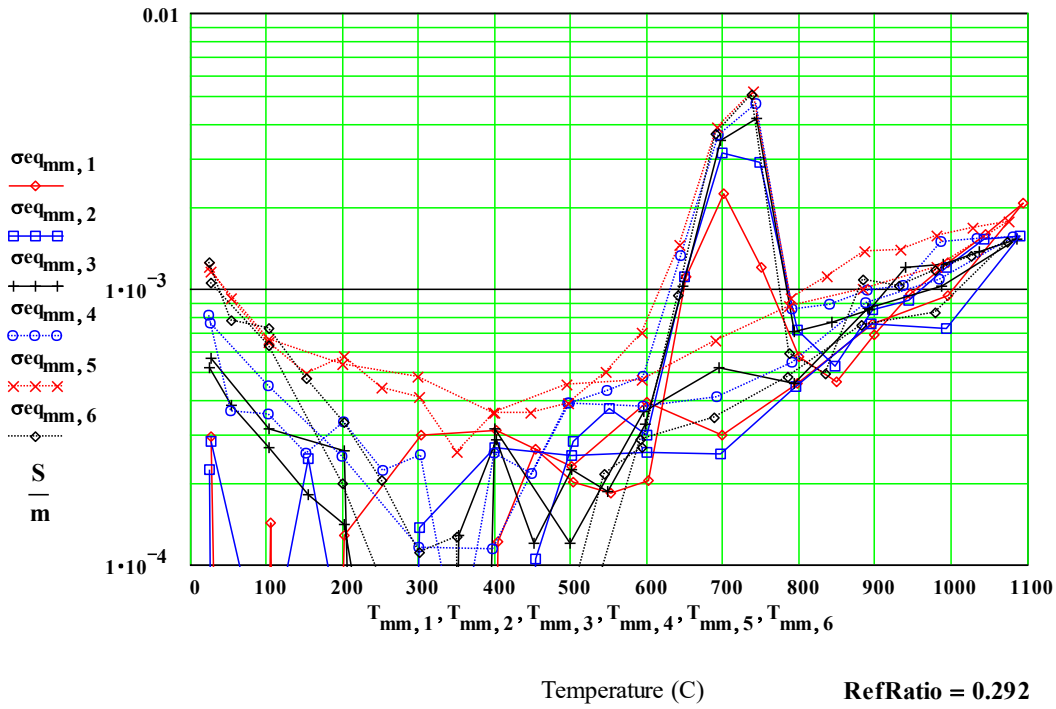
Test = 2021081101

SHUL2149\_LowCaL.mcd

AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



Appendix E. MPN Reports

Test = 2021081101

SHUL2149\_LowCal.mcd

AnDat = 20210813

T

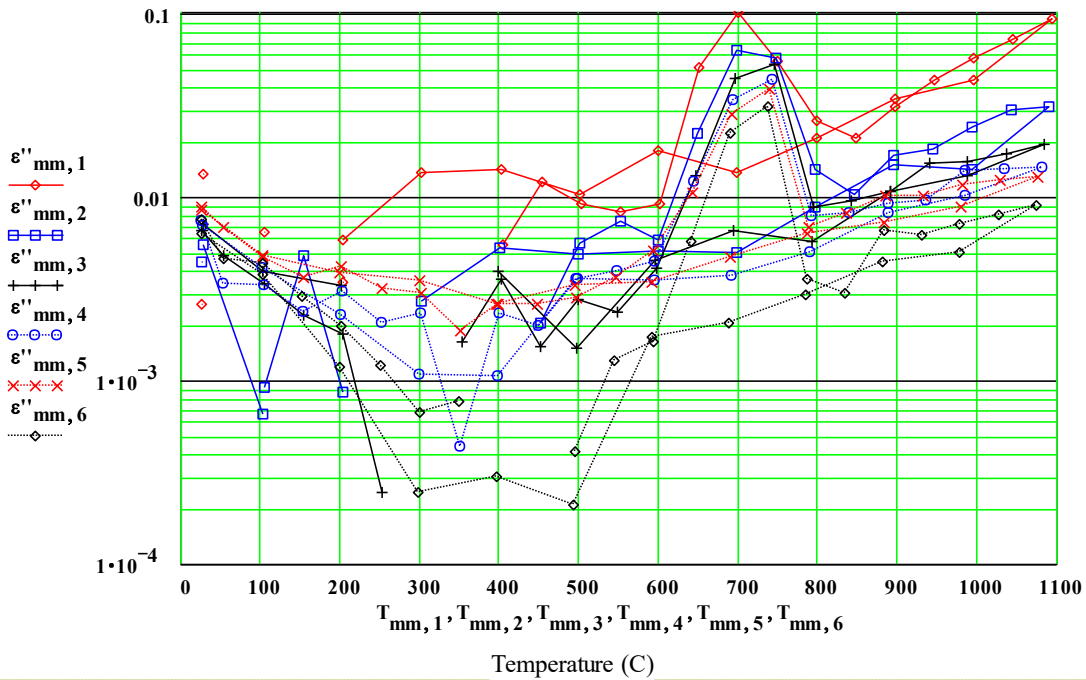
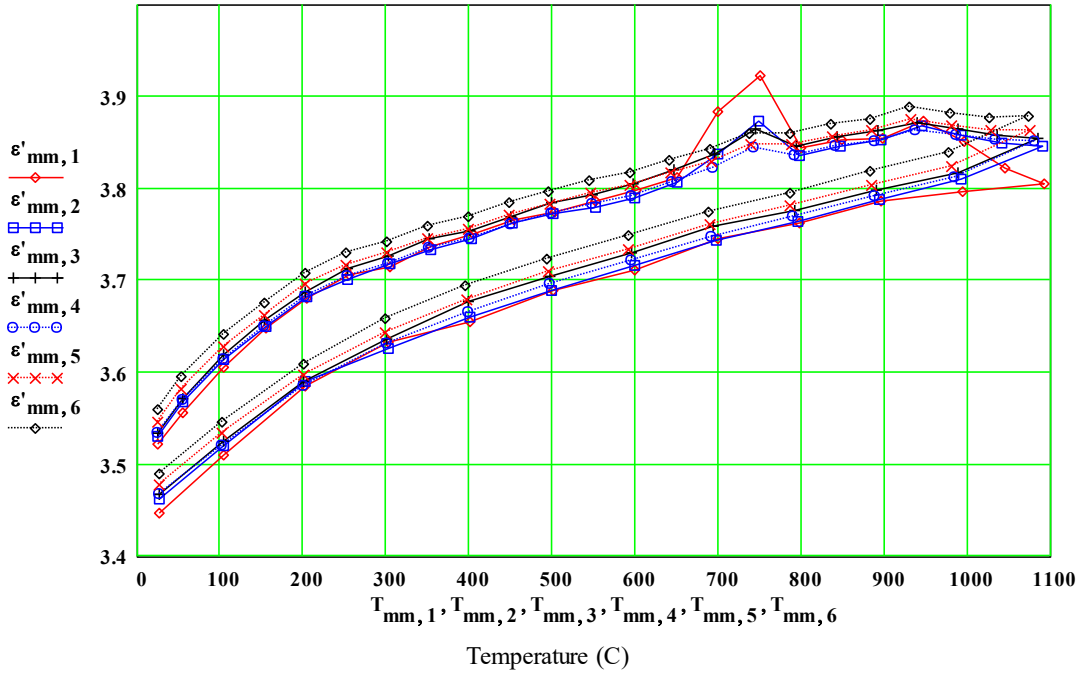
Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.57 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.53 \text{ gm/cc}$

Ir

FracMassChange = 1  $\alpha_1 = 0$  /C  $\alpha_2 = 0$  /C

F



# Appendix E. MPN Reports

Test = 2021081101

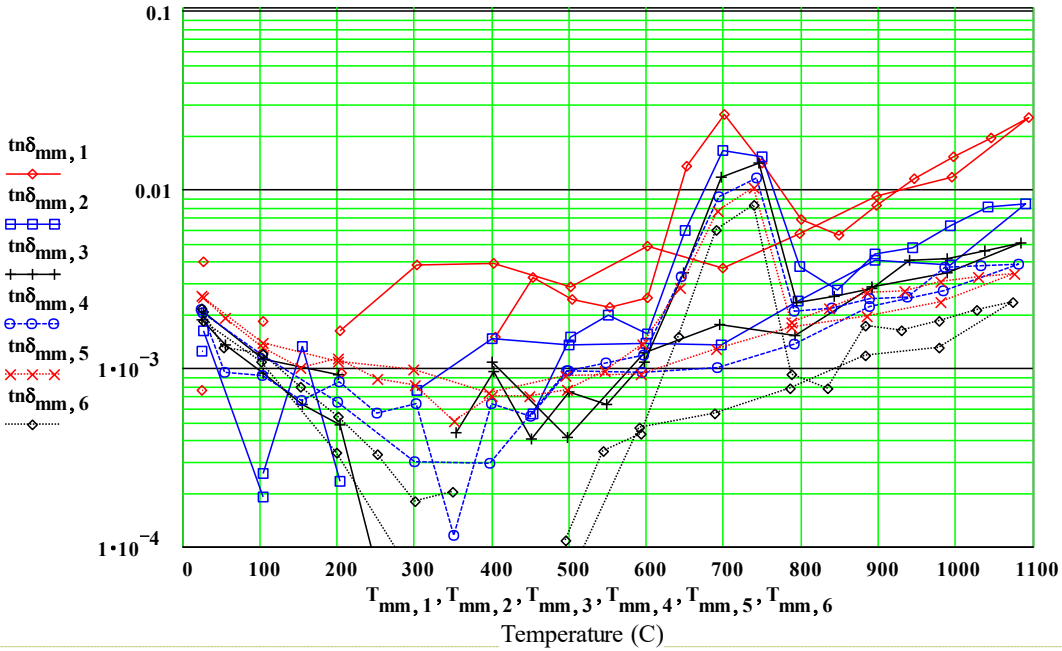
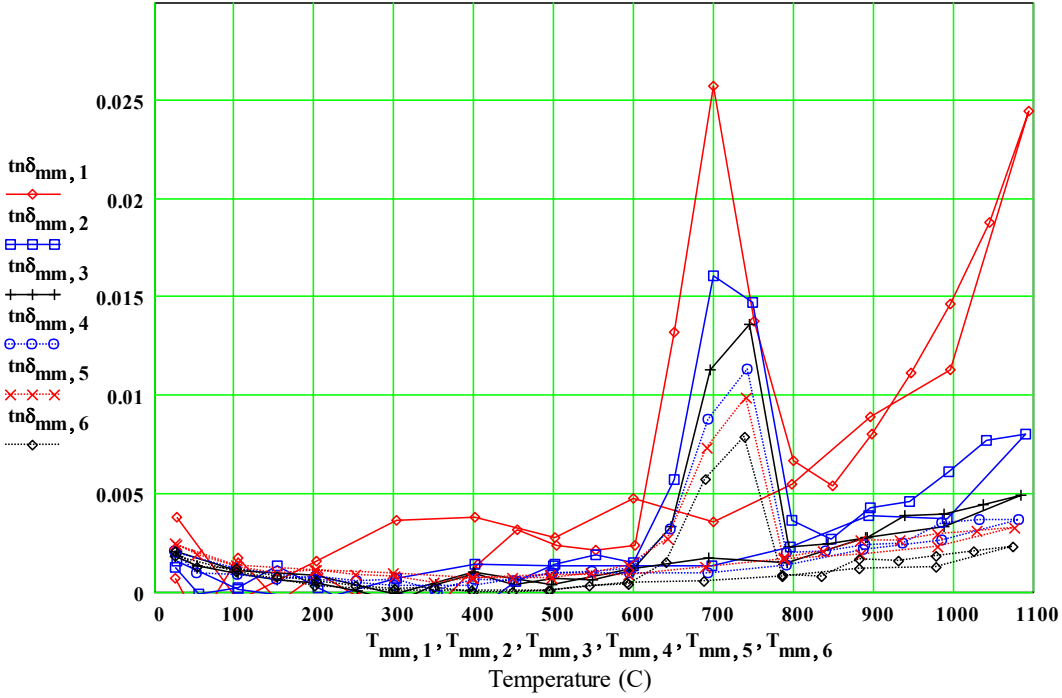
SHUL2149\_LowCal.mcd

AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.57 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.53 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2021081101

SHUL2149\_LowCal.mcd

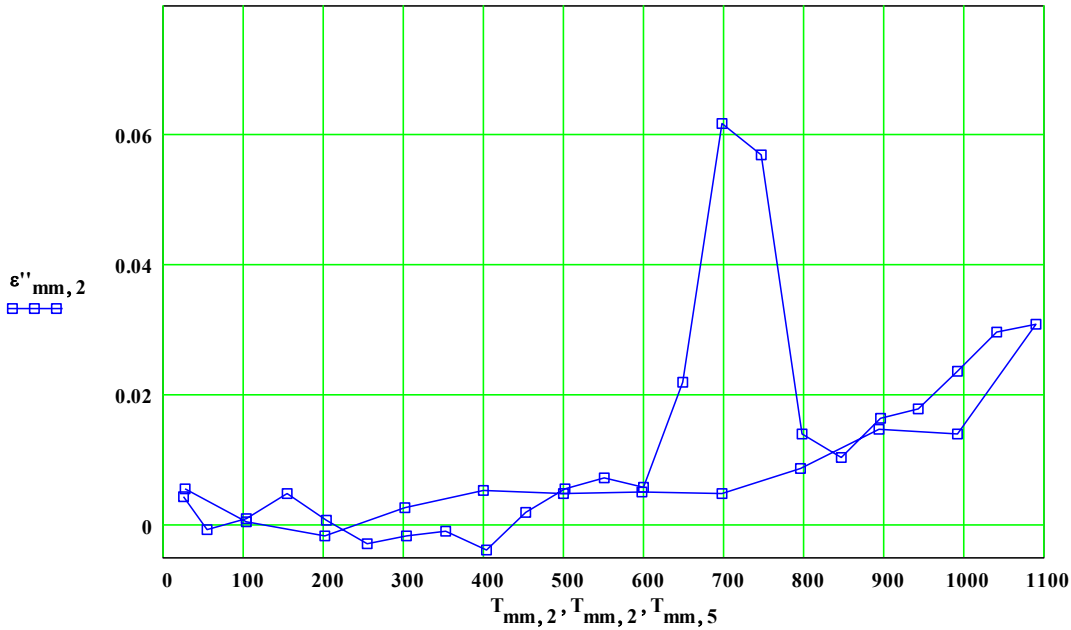
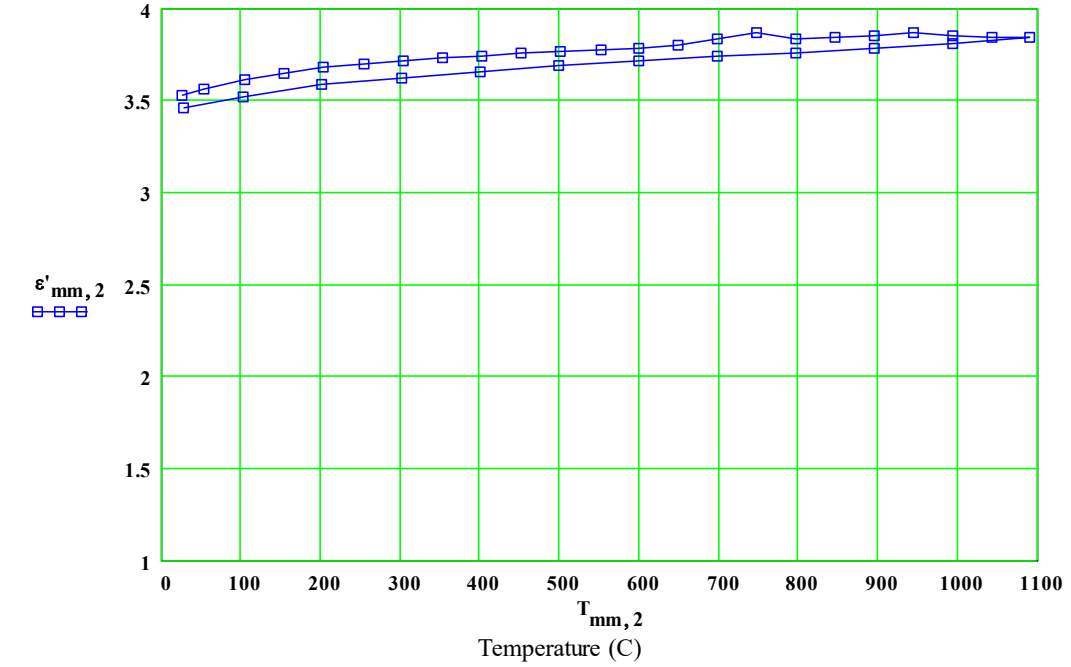
AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.57 \text{ gm/cc}$ , Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 1.53 \text{ gm/cc}$

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021081101

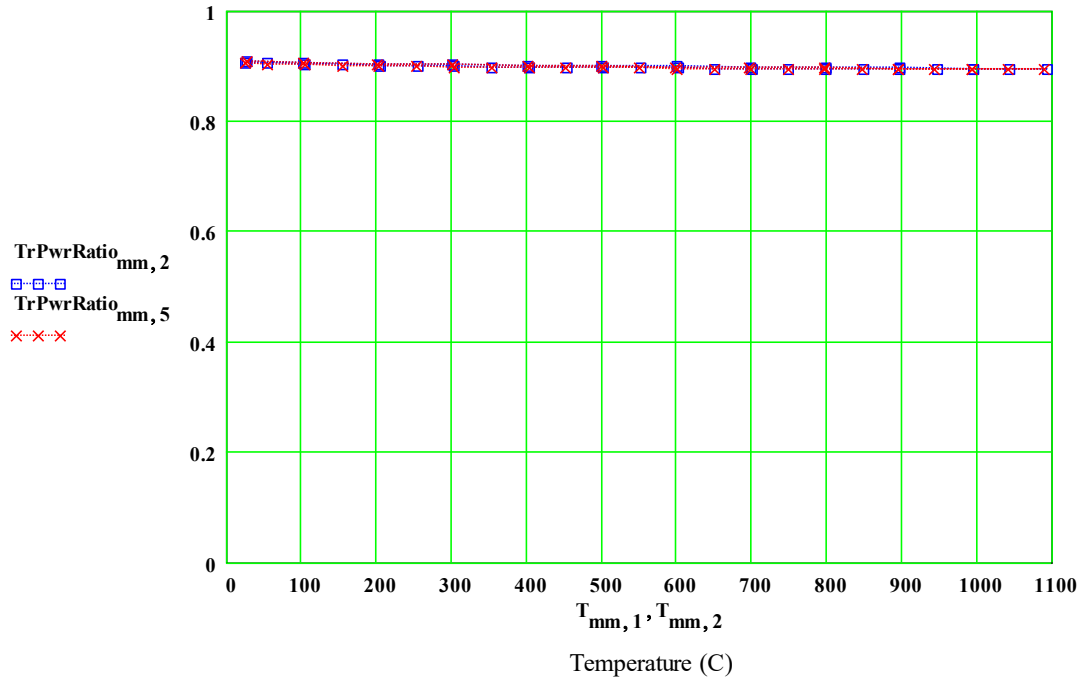
SHUL2149\_LowCal.mcd

AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.57 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.53 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



# Appendix E. MPN Reports

Half-power Depth (millimeters)

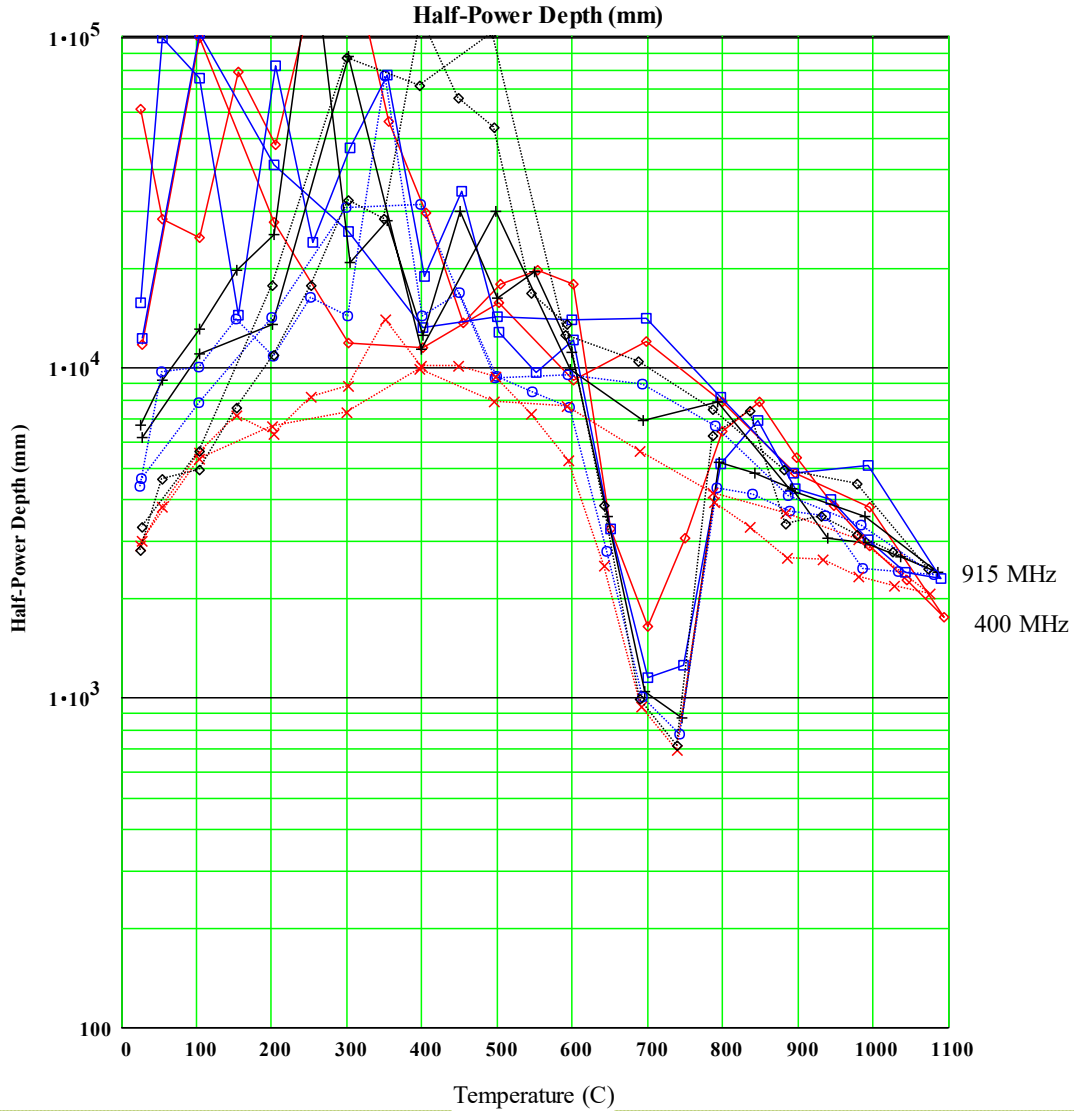
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021081101

SHUL2149\_LowCal.mcd

AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC



Use the Jonscher Formalism to fit the Frequency and Thermal Dependence of  $\epsilon_{pp}$  and Conductivity

Fit to 'Disordered' Structure which Exists after the Highest Temperature was Attained (1100C),  
formulation without sine and cosine

Fit to 'Intrinsic' Values - High Temperature

$$E_{an} := 0.73 \text{ eV}$$

$$\sigma_{intn} := 7.0 \cdot 10^{-1} \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.01$$

$$\epsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{f_n}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \epsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6} \quad \epsilon_{ppth(16,2)} = 71.958$$

$$H_{activ} := E_{an} \cdot 96.5 \text{ Kjoule/mol}$$

$$H_{activ} = 70 \text{ Kjoule/mol}$$

$$E_{gn} := 2 \cdot E_{an} \text{ Conduction Gap Energy}$$

$$\frac{E_{gn}}{2} = 0.73 \text{ eV}$$

Fit to 'Extrinsic' Values - Low Temperature, Impurity Dependent :

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{am} := 0.0025 \quad \sigma_{intm} := 0.0000055 \quad m_J := 1.05$$

$$\epsilon_{ppthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{(2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6})} \cdot \exp \left[ \frac{-E_{am}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{f_n}{400} \right)^{m_J} + \left[ \frac{\sigma_{infin}}{(2 \cdot \pi \cdot f_n \cdot 10^6) \cdot 8.85 \cdot 10^{-12}} \right]$$

$$\sigma_{thJm_{mn,n}} := \epsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6}$$

$$\epsilon_{ppthTotal_{mn,n}} := \epsilon_{ppthJn_{mn,n}} + \epsilon_{ppthJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

Test = 2021081101

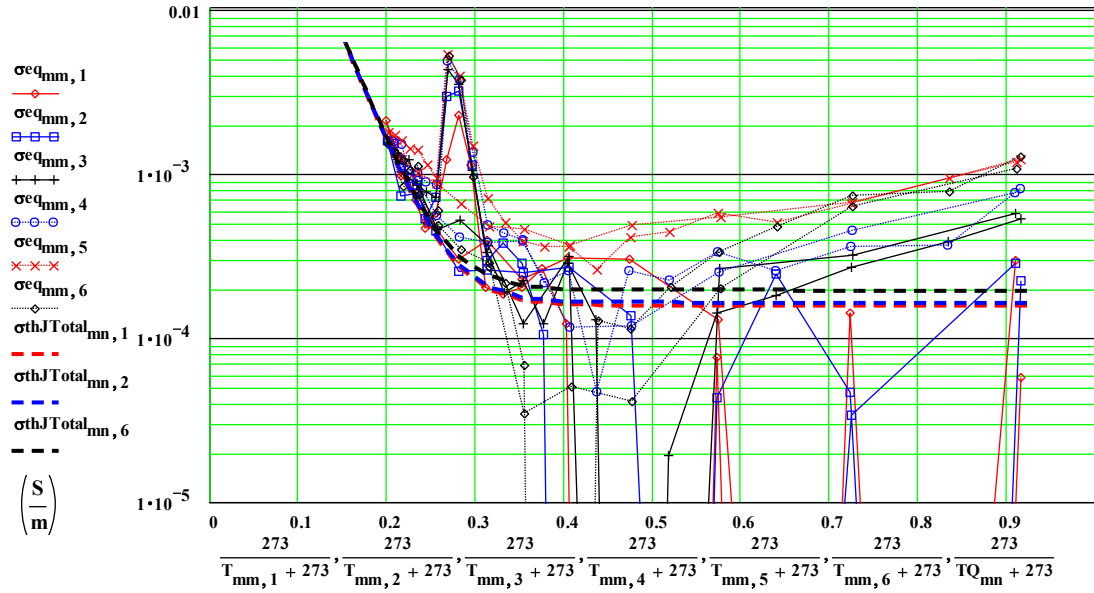
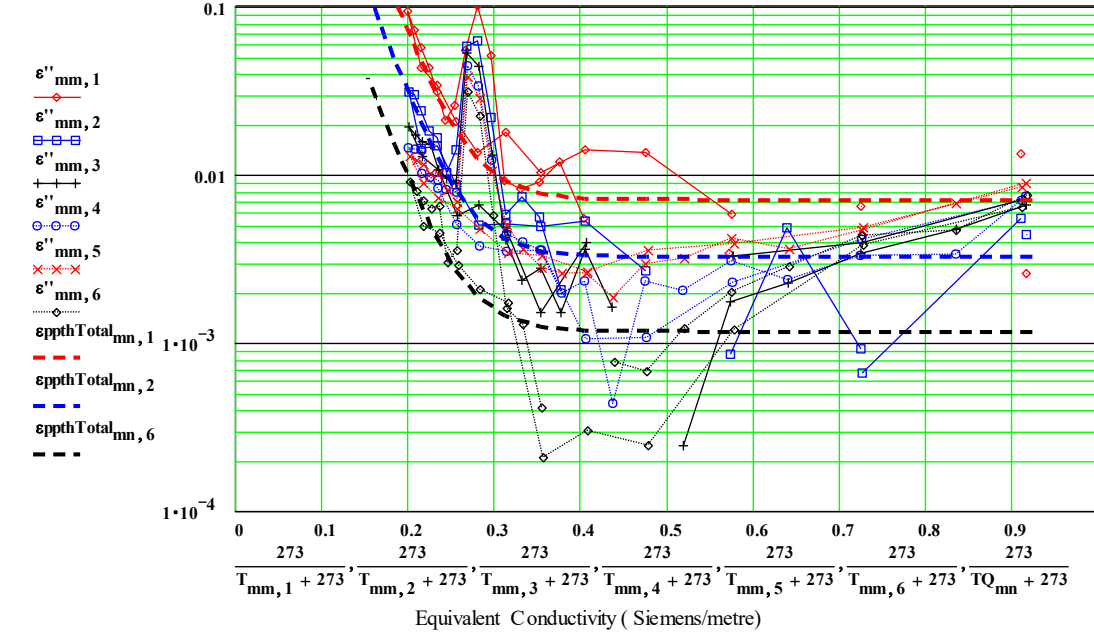
SHUL2149\_LowCal.mcd

AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_0 = 0.87 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.53 \text{ gm/cc}$

Egn = 1.46 eV       $\sigma_{\text{intn}} = 0.7$  Siemens/metre      nJ = 0.01



## Appendix E. MPN Reports

**Test = 2021081101**

**SHUL2149\_LowCal.mcd**

**AnDat = 20210813**

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LL

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ^^^

Initial density = **samdns<sub>NCal + 1</sub> = 1.572** gm/cc      Final density(25C) = **dnsfinal = 1.533** gm/cc  
 Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz 2466MHz 2986MHz  
 Time (hours)

samdns <sub>rmm</sub>	T <sub>mm,1</sub>	$\epsilon'_{mm,1}$	$\epsilon'_{mm,2}$	$\epsilon'_{mm,3}$	$\epsilon'_{mm,4}$	$\epsilon'_{mm,5}$	$\epsilon'_{mm,6}$	tlaps <sub>mm</sub>	sammass <sub>mm</sub>	
1.572	10	25	3.52	3.53	3.54	3.54	3.55	3.56	0	0.218
1.572	11	54	3.56	3.57	3.57	3.57	3.58	3.6	0.24	0.218
1.572	12	104	3.61	3.61	3.62	3.62	3.63	3.64	0.49	0.218
1.572	13	154	3.65	3.65	3.66	3.65	3.66	3.68	0.76	0.218
1.572	14	204	3.68	3.68	3.69	3.68	3.7	3.71	1.03	0.218
1.572	15	254	3.71	3.7	3.71	3.71	3.72	3.73	1.3	0.218
1.572	16	304	3.72	3.72	3.73	3.72	3.73	3.74	1.58	0.218
1.572	17	354	3.74	3.73	3.75	3.74	3.75	3.76	1.86	0.218
1.572	18	404	3.75	3.75	3.75	3.75	3.76	3.77	2.15	0.218
1.572	19	453	3.77	3.76	3.77	3.76	3.77	3.79	2.44	0.218
1.572	20	503	3.78	3.77	3.79	3.77	3.78	3.8	2.74	0.218
1.572	21	552	3.79	3.78	3.79	3.78	3.79	3.81	3.07	0.218
1.572	22	601	3.8	3.79	3.81	3.79	3.8	3.82	3.43	0.218
1.572	23	651	3.81	3.81	3.82	3.81	3.82	3.83	3.81	0.218
1.572	24	700	3.88	3.84	3.84	3.82	3.83	3.84	4.25	0.218
1.572	25	750	3.92	3.87	3.87	3.84	3.85	3.86	4.77	0.218
1.572	26	799	3.84	3.84	3.85	3.84	3.85	3.86	5.34	0.218
1.572	27	848	3.85	3.85	3.86	3.85	3.86	3.87	6.02	0.218
1.572	28	898	3.86	3.85	3.86	3.85	3.86	3.88	6.69	0.218
1.572	29	946	3.87	3.87	3.87	3.86	3.87	3.89	7.32	0.218
1.557	30	996	3.85	3.86	3.87	3.86	3.87	3.88	7.97	0.217
1.549	31	1045	3.82	3.85	3.86	3.85	3.86	3.88	8.7	0.217
1.541	32	1093	3.8	3.85	3.85	3.85	3.86	3.88	9.38	0.217
1.533	33	995	3.8	3.81	3.82	3.81	3.82	3.84	9.63	0.217
1.533	34	897	3.79	3.79	3.8	3.79	3.8	3.82	9.91	0.217
1.533	35	798	3.76	3.76	3.78	3.77	3.78	3.8	10.24	0.217
1.533	36	699	3.75	3.74	3.76	3.75	3.76	3.78	10.64	0.217
1.533	37	600	3.71	3.72	3.73	3.72	3.73	3.75	11.13	0.217
1.533	38	501	3.69	3.69	3.71	3.7	3.71	3.72	11.73	0.217
1.533	39	401	3.66	3.66	3.68	3.67	3.68	3.69	12.5	0.217
1.533	40	302	3.63	3.63	3.64	3.63	3.64	3.66	13.5	0.217
1.533	41	202	3.59	3.59	3.59	3.59	3.6	3.61	14.95	0.217
1.533	42	104	3.51	3.52	3.53	3.52	3.53	3.55	17.68	0.217
1.533	43	27	3.45	3.46	3.47	3.47	3.48	3.49	21.2	0.217

Appendix E. MPN Reports

Test = 2021081101

SHUL2149\_LowCal.mcd

AnDat = 20210813

Anorthite (synthetic) A-006, 1300 Sh, 7/9/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.572$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 1.533$  gm/cc

Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz

Time

(hours)

samdns <sub>mmmm</sub>	T <sub>mm,1</sub>	$\epsilon''_{\text{mm},1}$	$\epsilon''_{\text{mm},2}$	$\epsilon''_{\text{mm},3}$	$\epsilon''_{\text{mm},4}$	$\epsilon''_{\text{mm},5}$	$\epsilon''_{\text{mm},6}$	tlaps <sub>mm</sub>	sammas <sub>mm</sub>	
1.572	10	25	0.003	0.004	0.007	0.007	0.009	0.007	0	0.218
1.572	11	54	-0.006	-0.001	0.005	0.003	0.007	0.005	0.24	0.218
1.572	12	104	0.006	0.001	0.003	0.003	0.005	0.004	0.49	0.218
1.572	13	154	-0.002	0.005	0.002	0.002	0.004	0.003	0.76	0.218
1.572	14	204	0.003	0.001	0.002	0.003	0.004	0.002	1.03	0.218
1.572	15	254	-0.001	-0.003	0	0.002	0.003	0.001	1.3	0.218
1.572	16	304	-0.001	-0.002	-0.002	0.002	0.003	0.001	1.58	0.218
1.572	17	354	-0.003	-0.001	0.002	0	0.002	0.001	1.86	0.218
1.572	18	404	0.006	-0.004	0.004	0.002	0.003	-0	2.15	0.218
1.572	19	453	0.012	0.002	0.002	0.002	0.003	-0	2.44	0.218
1.572	20	503	0.009	0.006	0.003	0.004	0.003	0	2.74	0.218
1.572	21	552	0.008	0.007	0.002	0.004	0.004	0.001	3.07	0.218
1.572	22	601	0.009	0.006	0.004	0.004	0.005	0.002	3.43	0.218
1.572	23	651	0.051	0.022	0.013	0.012	0.01	0.006	3.81	0.218
1.572	24	700	0.1	0.062	0.043	0.033	0.028	0.022	4.25	0.218
1.572	25	750	0.054	0.057	0.053	0.043	0.038	0.031	4.77	0.218
1.572	26	799	0.026	0.014	0.009	0.008	0.007	0.004	5.34	0.218
1.572	27	848	0.021	0.01	0.01	0.008	0.008	0.003	6.02	0.218
1.572	28	898	0.031	0.017	0.011	0.009	0.01	0.007	6.69	0.218
1.572	29	946	0.043	0.018	0.015	0.009	0.01	0.006	7.32	0.218
1.557	30	996	0.057	0.024	0.016	0.014	0.011	0.007	7.97	0.217
1.549	31	1045	0.072	0.03	0.017	0.014	0.012	0.008	8.7	0.217
1.541	32	1093	0.093	0.031	0.019	0.014	0.013	0.009	9.38	0.217
1.533	33	995	0.043	0.014	0.013	0.01	0.009	0.005	9.63	0.217
1.533	34	897	0.034	0.015	0.011	0.008	0.007	0.004	9.91	0.217
1.533	35	798	0.021	0.009	0.006	0.005	0.006	0.003	10.24	0.217
1.533	36	699	0.013	0.005	0.007	0.004	0.005	0.002	10.64	0.217
1.533	37	600	0.018	0.005	0.005	0.003	0.003	0.002	11.13	0.217
1.533	38	501	0.01	0.005	0.002	0.004	0.003	0	11.73	0.217
1.533	39	401	0.014	0.005	0.004	0.001	0.003	0	12.5	0.217
1.533	40	302	0.013	0.003	-0.001	0.001	0.004	0	13.5	0.217
1.533	41	202	0.006	-0.002	0.003	0.002	0.004	0.001	14.95	0.217
1.533	42	104	-0.002	0.001	0.004	0.004	0.005	0.004	17.68	0.217
1.533	43	27	0.013	0.006	0.007	0.007	0.008	0.006	21.2	0.217

MPN-257\_Shulman\_CSM-LHT-1G\_1

June 30, 2022

Lunar Simulant CMS-LHT-1G  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in < 1 milliTorr Vacuum

Dr. Holly Shulman ( Shulman LLC) requested that Microwave Properties North measure the complex dielectric properties of CMS-LHT-1G lunar regolith simulant up to 1100C with a direct, uninterrupted, temperature cycle, in vacuum. Choosing a maximum temperature of 1100 C allowed us to run in vacuum, with a base pressure of less than 1 milliTorr ( using a Varian 810 readout with a Varian 531 TC gauge head).

The powder sample material arrived at MPN on June 23/ 2022. Dr. Shulman had already baked the powder at 250C for 1 hour in air to dry it.

For this measurement, MPN pressed pellets of the powder material in a uniaxial press. The pellets were not initially baked by MPN to ensure dryness.

The initial sample parameters were:

- a) diameter 3.63 +- 0.05 mm
- b) length 12.85 +- 0.05 mm
- c) mass 0.284 +- 0.002 gm
- f) room temperature density  $2.14 \pm 0.09$  gm/cc.
- g) appearance - three (stacked) light grey pellets with black flecks in them .
- h) magnetic response - The black “particles” are attracted to a strong magnet

The dielectric properties measurements were performed at RT and then the temperature was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus and it and the final sample was weighed. The pellets were easily removed, and the empty holder was run up to 1100C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) diameter  $3.68 \pm 0.05$  mm
- b) length  $12.82 \pm 0.05$  mm
- c) mass  $0.282 \pm 0.002$  gm
- f) room temperature density  $2.07 \pm 0.09$  gm/cc.
- g) appearance - three grey pellets with black specs or particles evident
- h) magnetic response - the pellets were attracted to a permanent magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

#	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line

6

2986

black diamond, dotted line

Comments on the data analysis:

A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

Some slight diametrical expansion of the pellet occurred.

The final pellets were slightly darker.

The data for the ramp up to 1100C is close to that for the ramp down. Some slight change occurred between 750C and 1000 C.



Final pellets after the cycle to 1100 C in vacuum ( at a pressure of less than 1 milliTorr ).

# Appendix E. MPN Reports

Code Calculates Estimated Sample Dimensions & Volume and Plots Density As a Function of Temperature  
 ~~~~~

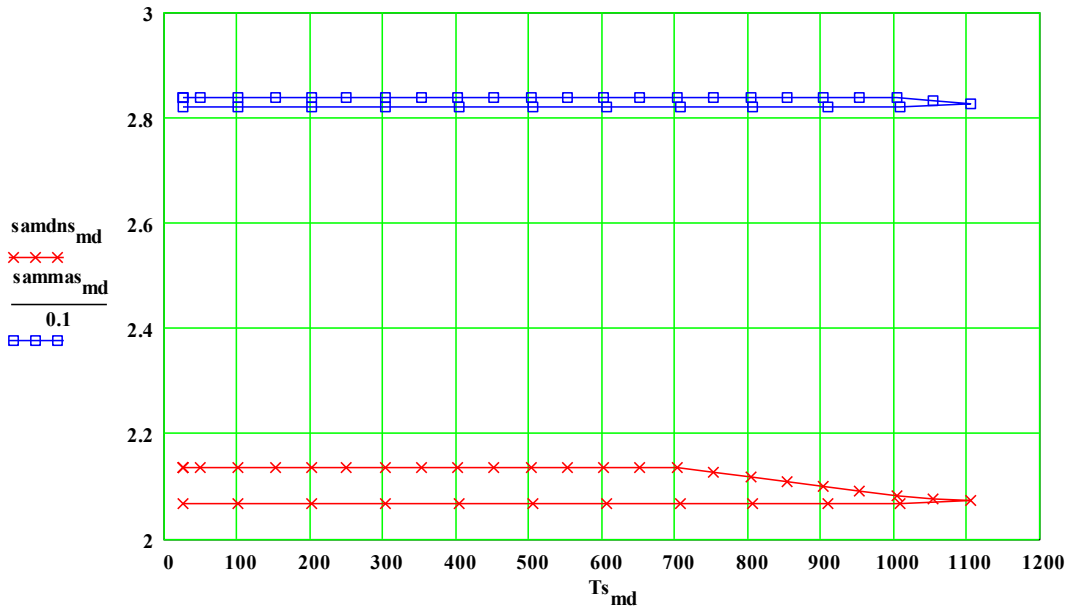
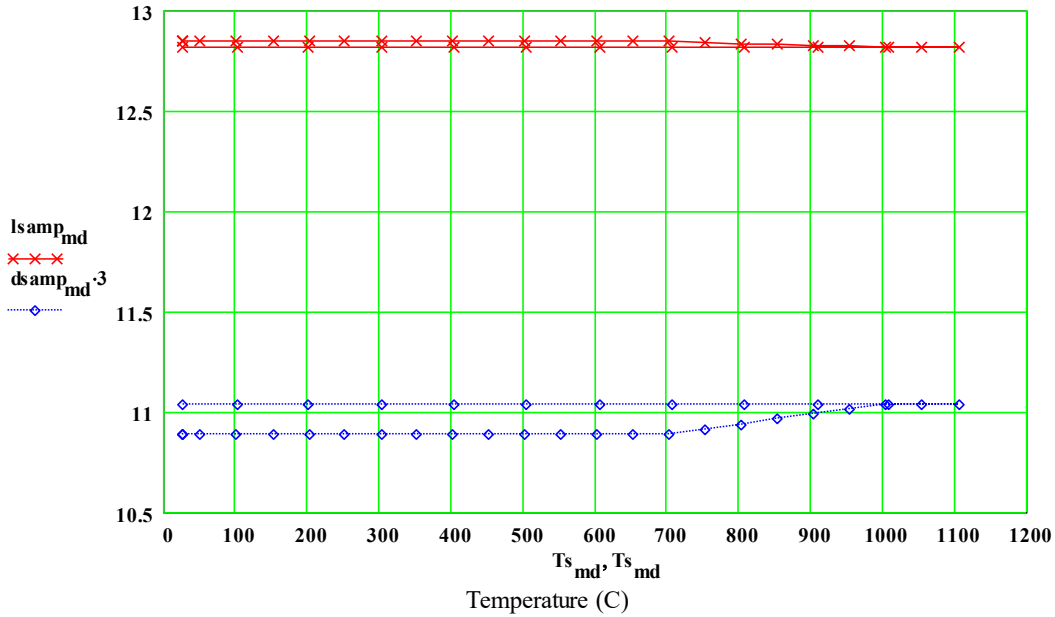
**Test = 2022062801**

SHUL2281.mcd

**AnDat = 20220629**

Lunar Simulant CSM-LHT-1G , RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Assumed Effective Dimensions (mm) and Density (gm/cc) as a Function of Temperature for Solid



# Appendix E. MPN Reports

Test = 2022062801

SHUL2281.mcd

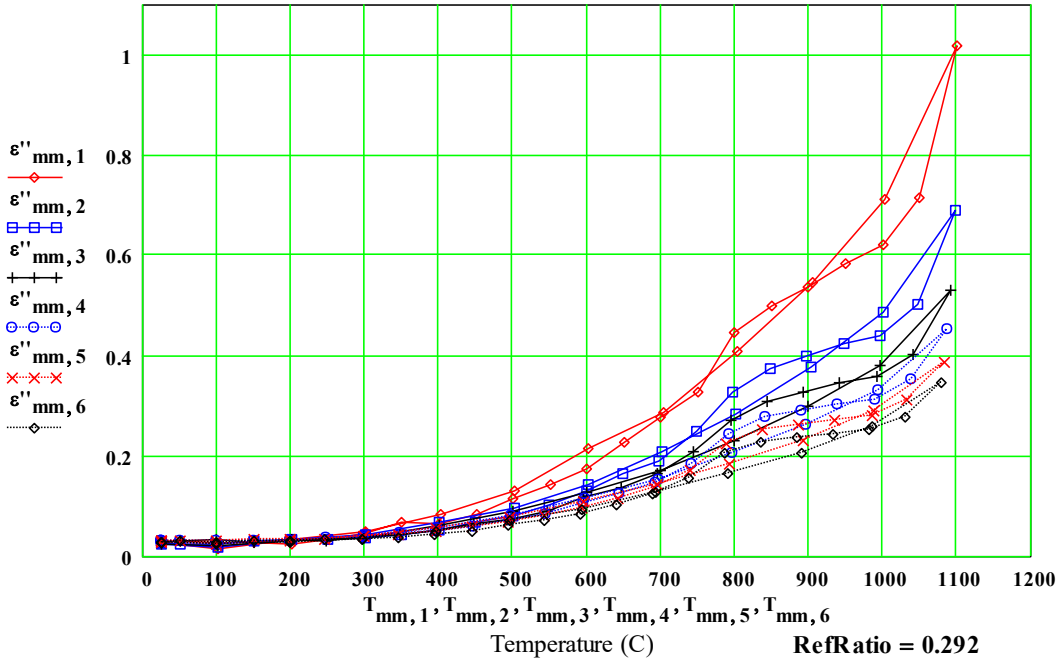
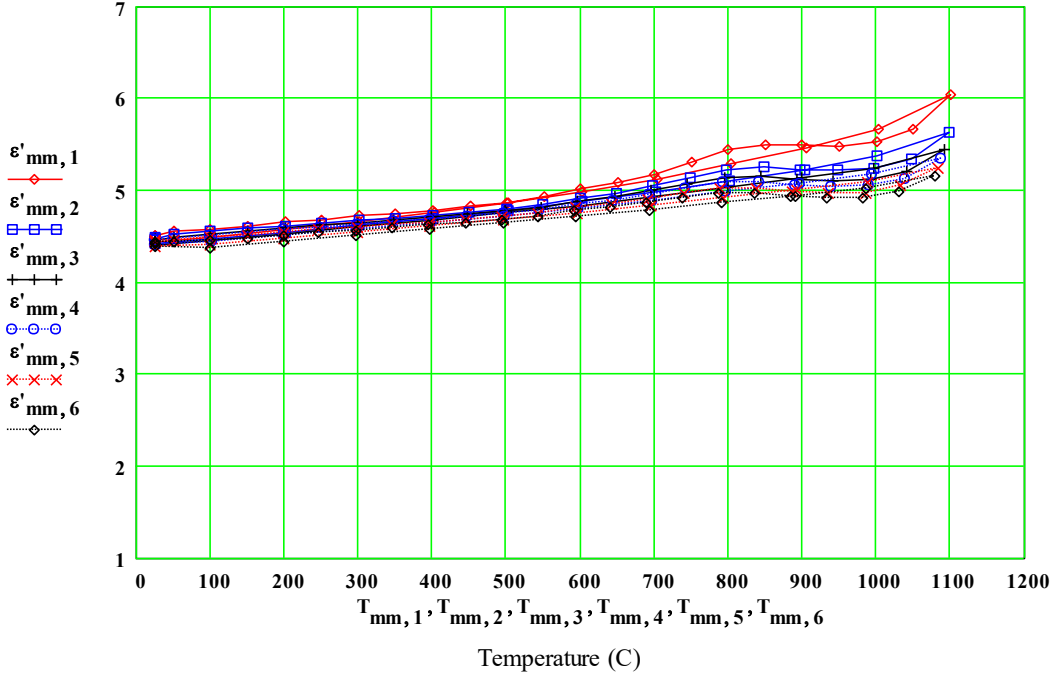
AnDat = 20220629

Lunar Simulant CSM-LHT-1G , RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.14 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.07 \text{ gm/cc}$

**Final\_over\_Initial\_mass = 0.993**



# Appendix E. MPN Reports

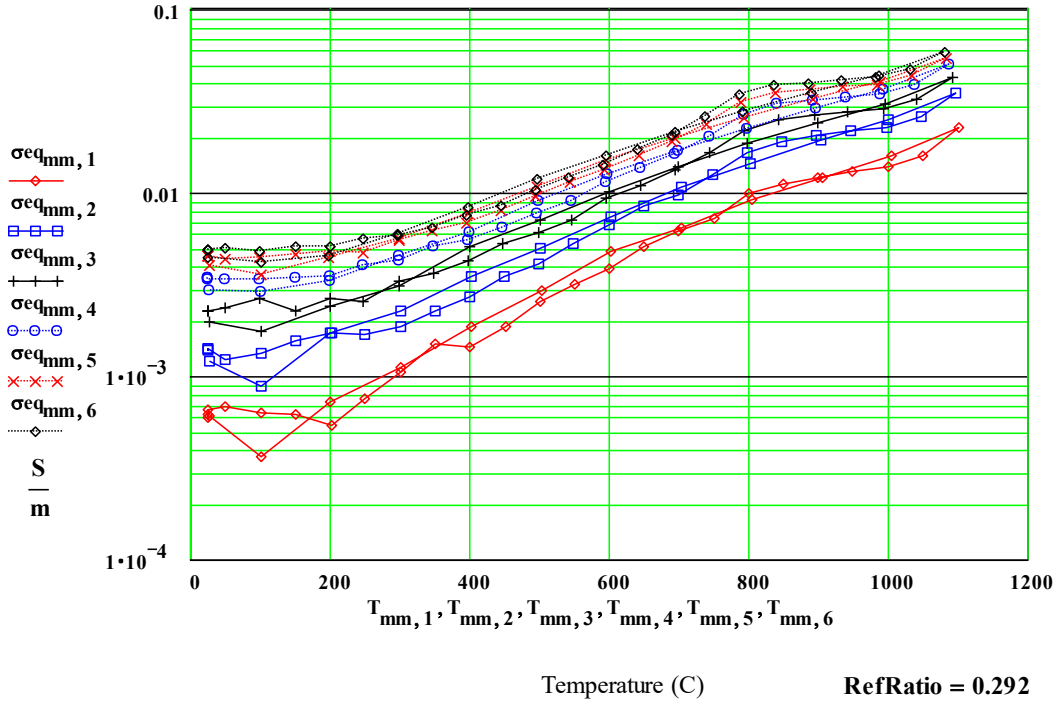
Test = 2022062801

SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G , RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2022062801

SHUL2281.mcd

AnDat = 20220629

T

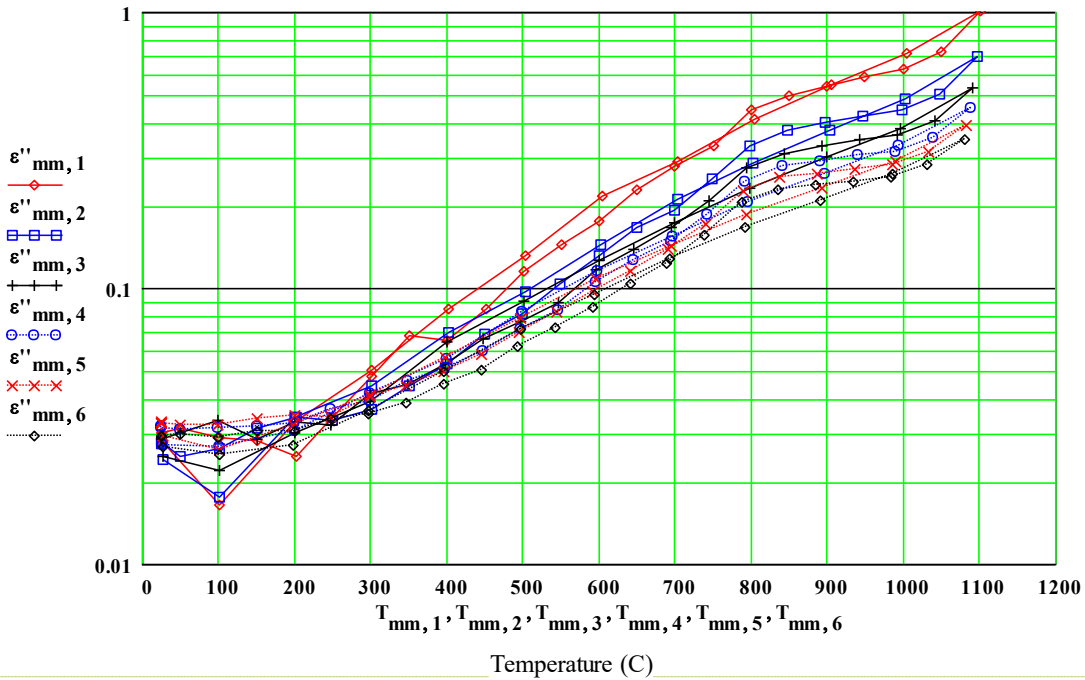
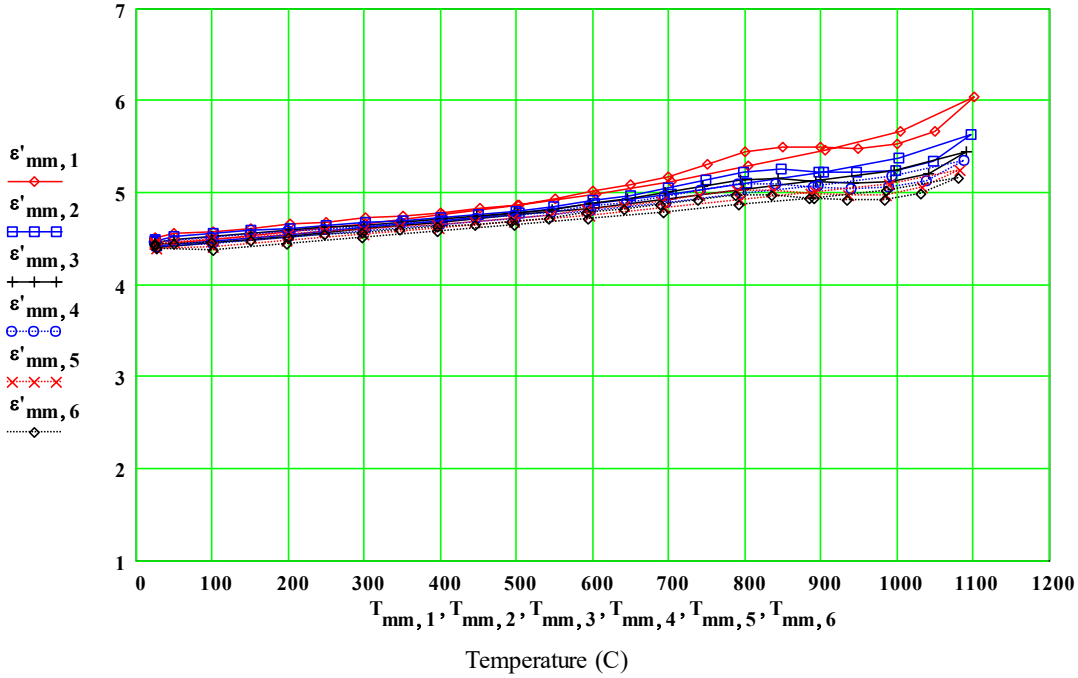
Lunar Simulant CSM-LHT-1G, RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.14 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.07 \text{ gm/cc}$

Ir

FracMassChange = 0.99      $\alpha_1 = 0$  /C      $\alpha_2 = 0$  /C

F



# Appendix E. MPN Reports

Test = 2022062801

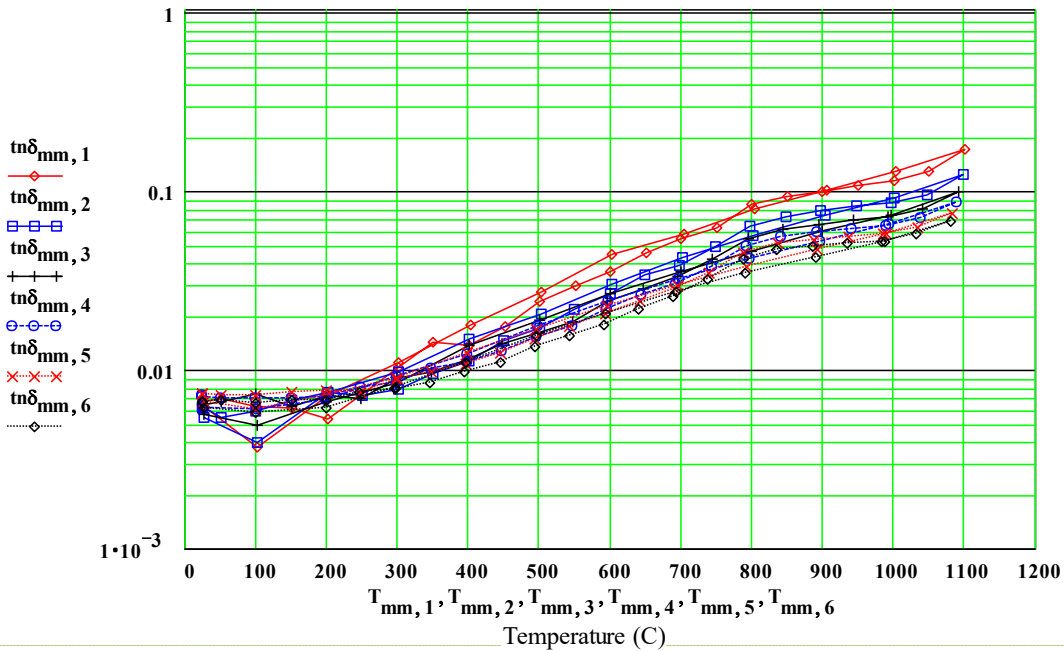
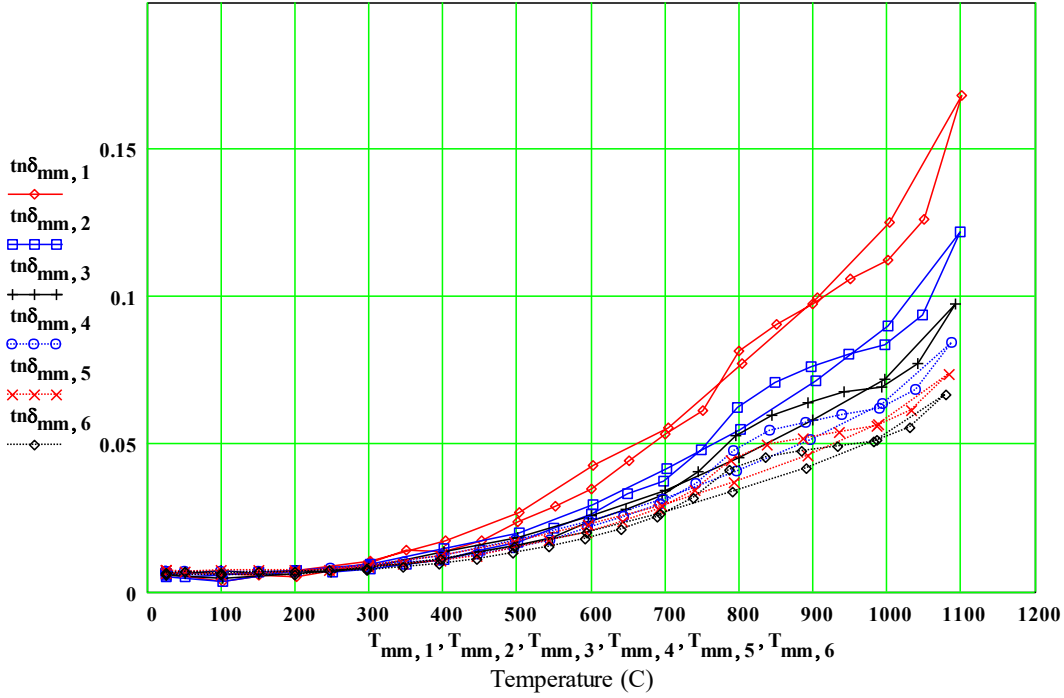
SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G, RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.14 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.07 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2022062801

SHUL2281.mcd

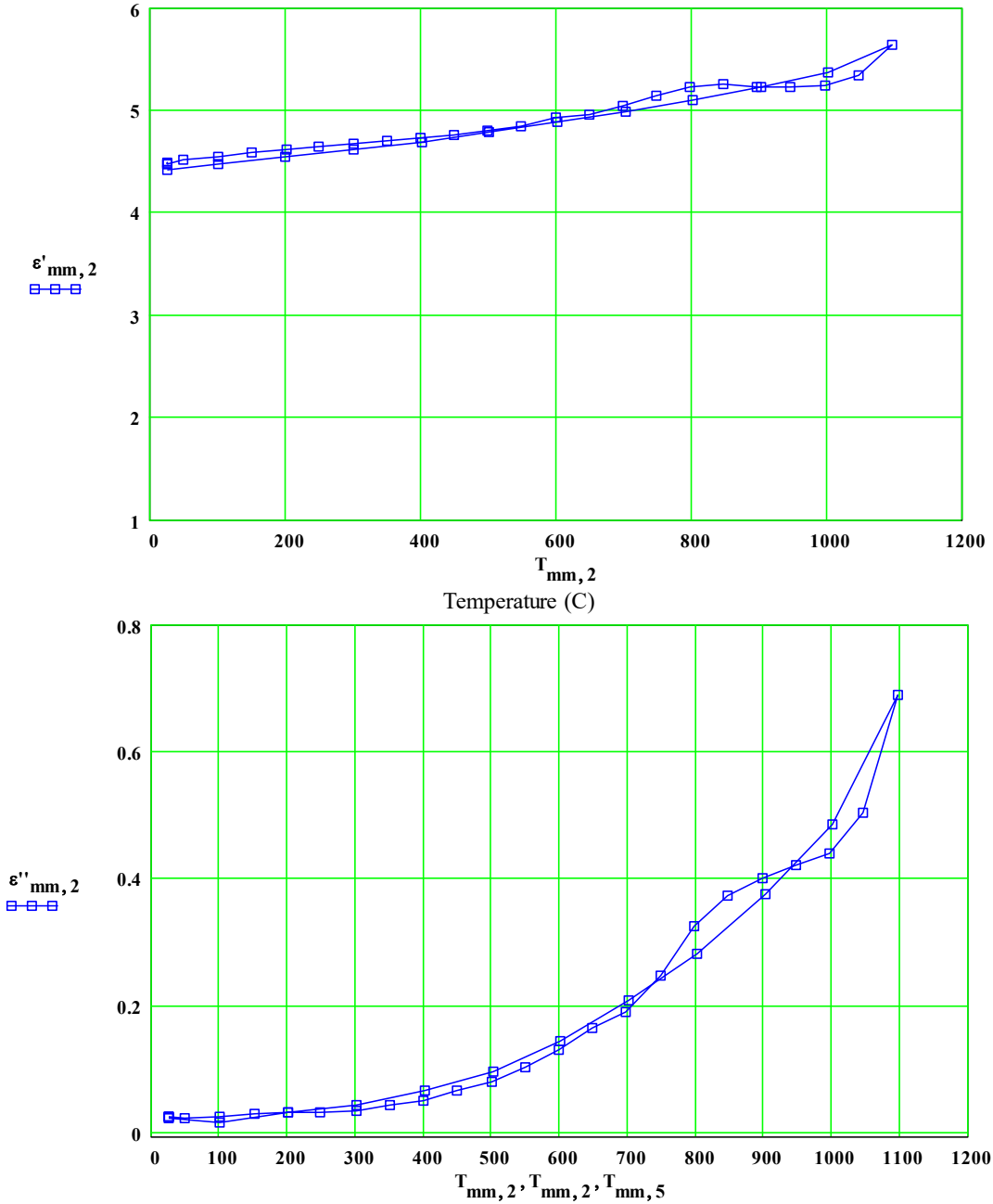
AnDat = 20220629

Lunar Simulant CSM-LHT-1G , RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Initial density =  $\text{sam dns}_{\text{NCal} + 1} = 2.14$  gm/cc, Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dns final} = 2.07$  gm/cc

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2022062801

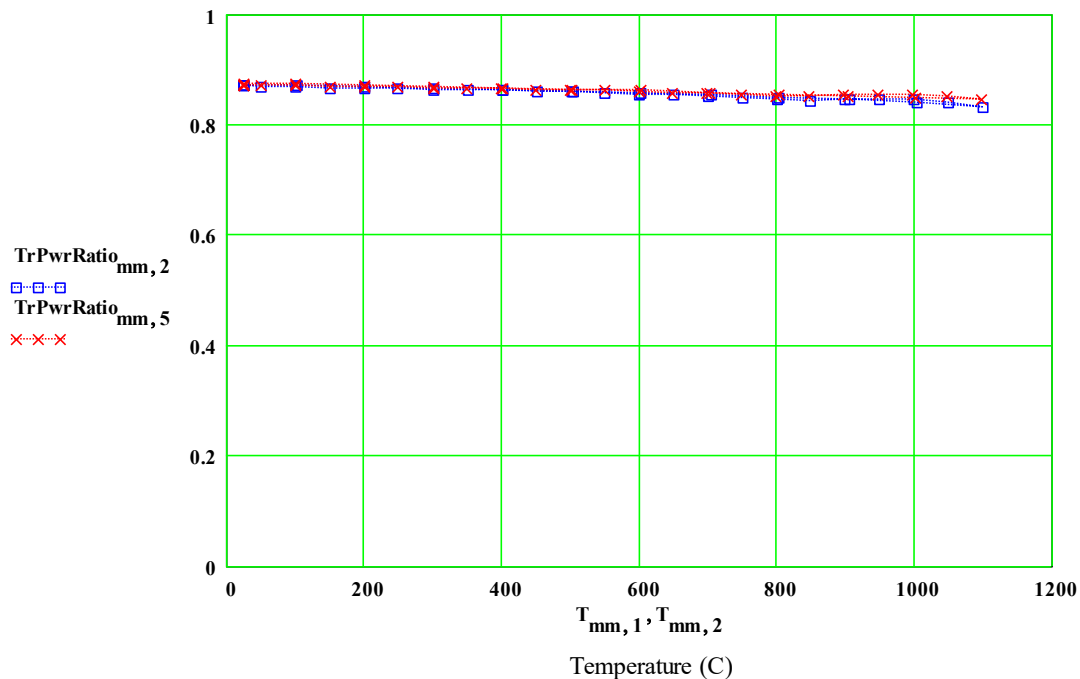
SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G , RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.14 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.07 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



# Appendix E. MPN Reports

Half-power Depth (millimeters)

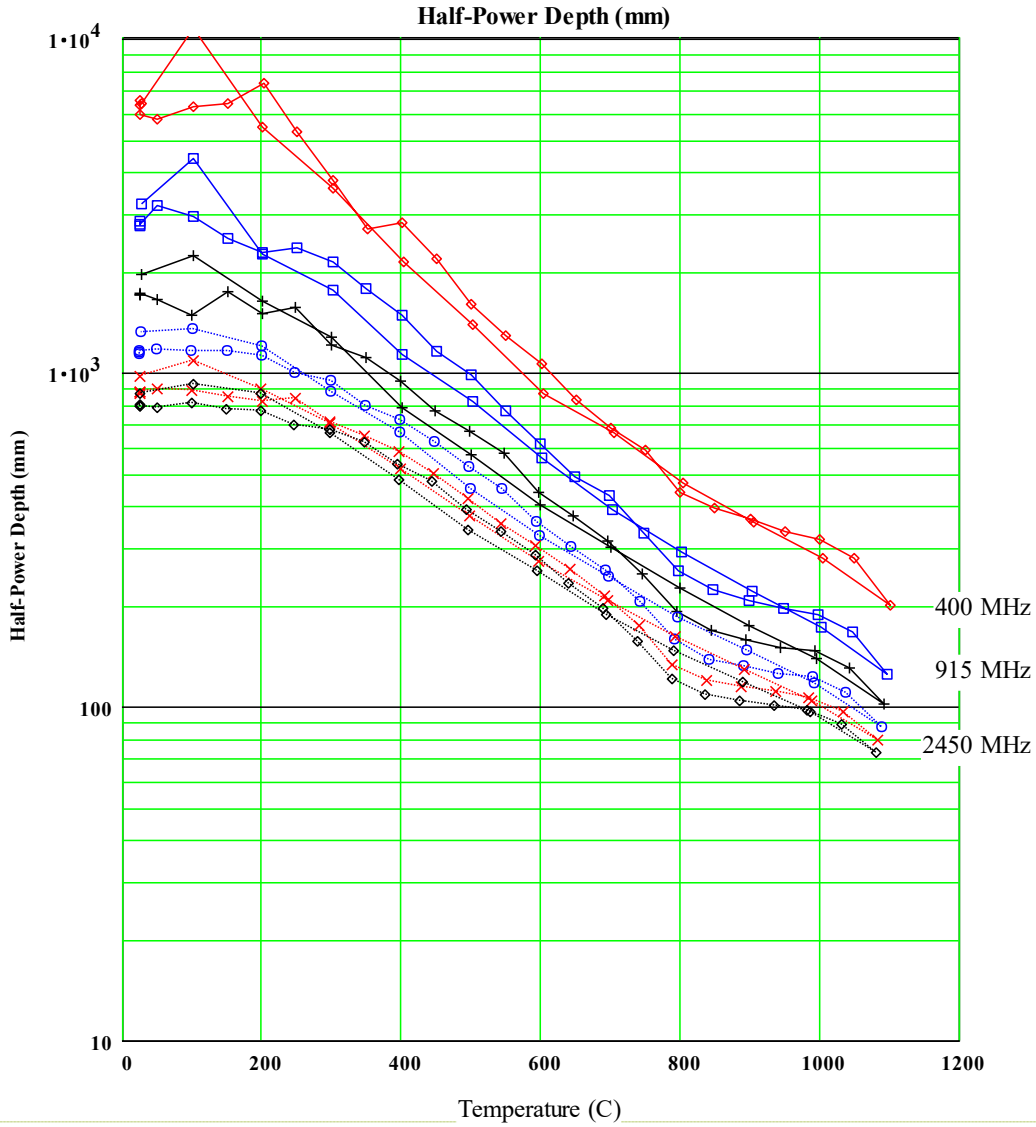
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2022062801

SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G, RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC



Use the Jonscher Formalism to fit the Frequency and Thermal Dependence of  $\epsilon_p$ ,  $\epsilon_{pp}$  and Conductivity

Fit to 'Disordered' Structure which Exists after the Highest Temperature was Attained (1100C)

Fit to 'Intrinsic' Values - High Temperature

$$E_{an} := 0.37 \text{ eV}$$

$$\sigma_{intn} := 0.65 \cdot 10^0 \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.55$$

$$\epsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \cos \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \overrightarrow{\epsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}}$$

$$\epsilon_{infin_{mn}} := 4.50 + 0.16 \cdot \frac{TQ_{mn}}{400}$$

$$\epsilon_{pthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{n_J}$$

$$\epsilon_{pthTotal_{mn,n}} := \epsilon_{pthJn_{mn,n}} + \epsilon_{infin_{mn}}$$

$$H_{activ} := E_{an} \cdot 96.5 \text{ Kjoule/mol}$$

$$H_{activ} = 36 \text{ Kjoule/mol}$$

$$E_{gn} := 2 \cdot E_{an} \text{ Conduction Gap Energy}$$

$$\frac{E_{gn}}{2} = 0.37 \text{ eV}$$

**Fit to 'Extrinsic' Values - Low Temperature, Impurity Dependent :**

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{am} := 0.005 \quad \sigma_{intm} := 0.0007 \quad mJ := 1.0$$

$$\varepsilon_{ppthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{(2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6})} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

$$\sigma_{thJm_{mn,n}} := \overbrace{\varepsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}}$$

$$\varepsilon_{pthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( mJ \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

**Sum up Extrinsic and Intrinsic Contributions :**

$$\varepsilon_{pthTotal_{mn,n}} := \varepsilon_{pthJn_{mn,n}} + \varepsilon_{pthJm_{mn,n}} + \varepsilon_{infin_{mn}}$$

$$\varepsilon_{ppthTotal_{mn,n}} := \varepsilon_{ppthJn_{mn,n}} + \varepsilon_{ppthJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

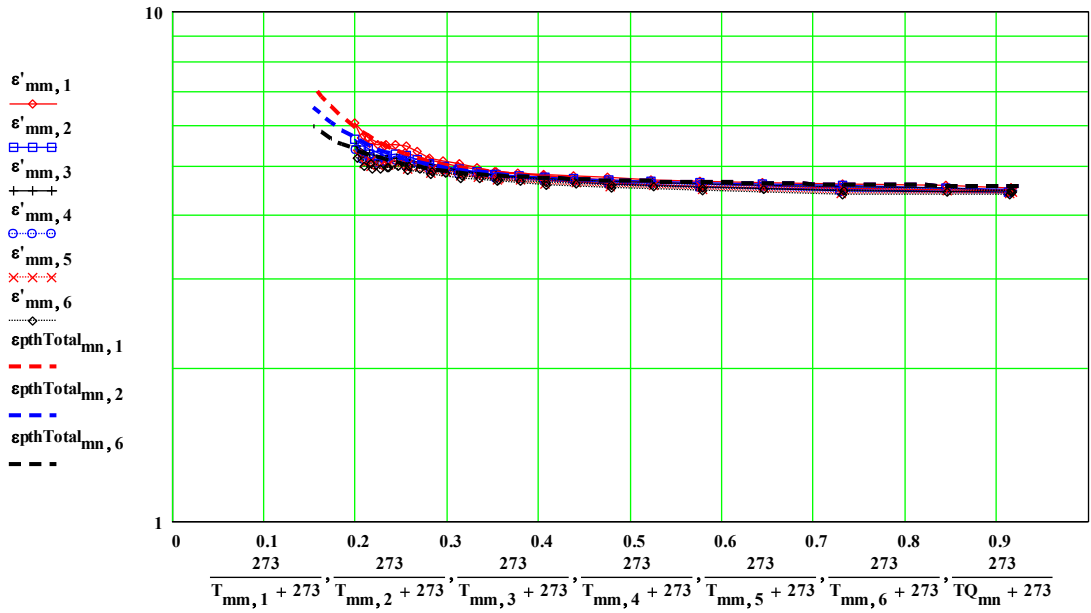
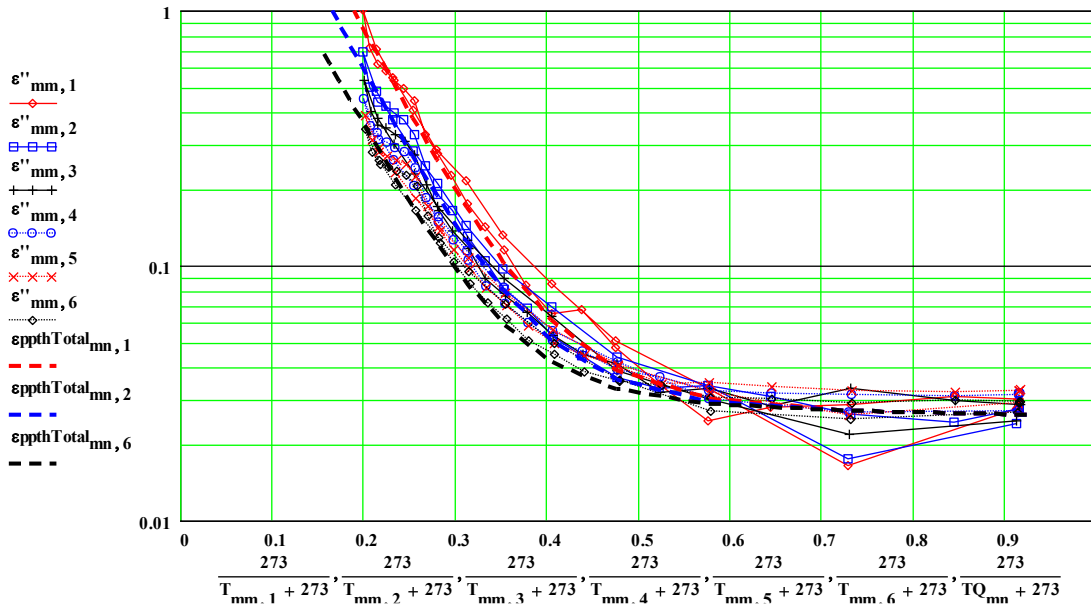
Test = 2022062801

SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G, RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.14 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.07 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2022062801

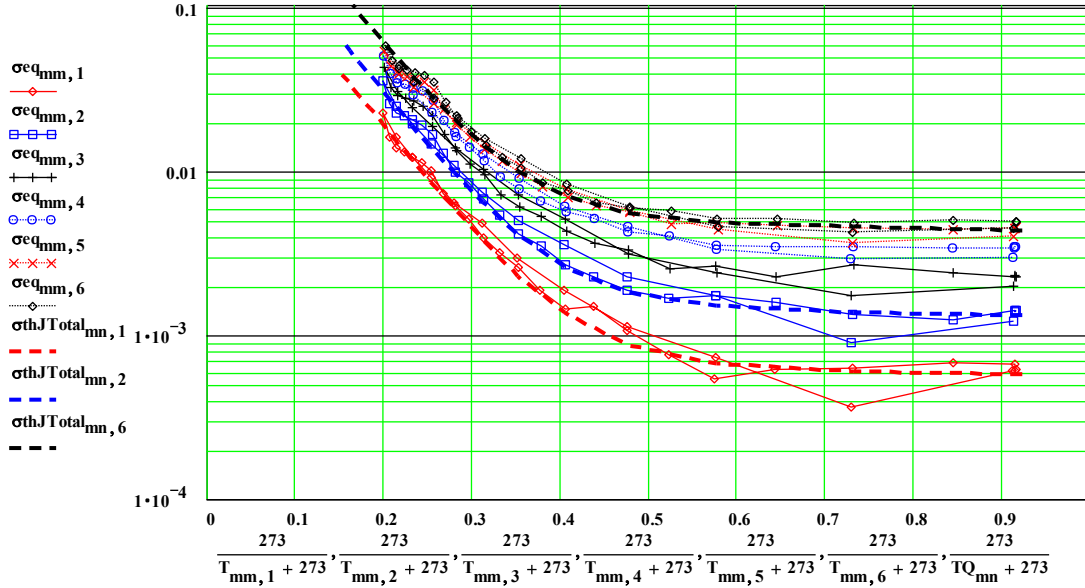
SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G, RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Final density(25C) = **dnsfinal = 2.07** gm/cc

Equivalent Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2022062801

SHUL2281.mcd

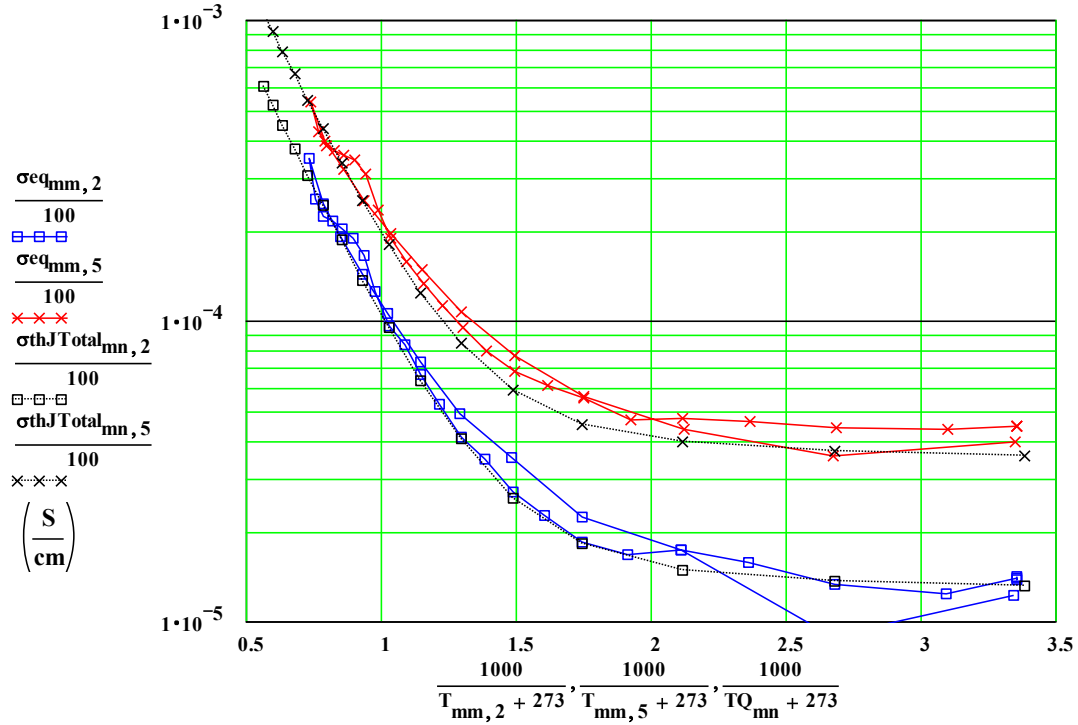
AnDat = 20220629

Lunar Simulant CSM-LHT-1G, RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

Initial density =  $\text{samdns}_0 = 2.14 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.07 \text{ gm/cc}$

$E_{an} = 0.37 \text{ eV}$        $\sigma_{intn} = 0.65 \text{ Siemens/metre}$        $nJ = 0.55$

Equivalent AC Conductivity ( Siemens/centimetre)



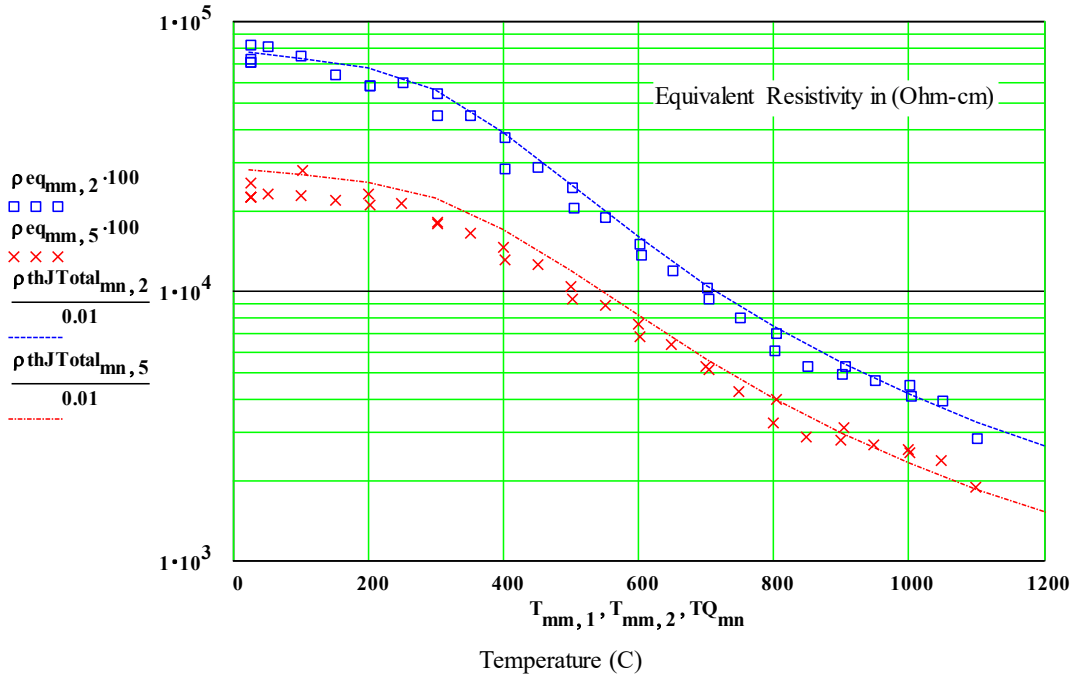
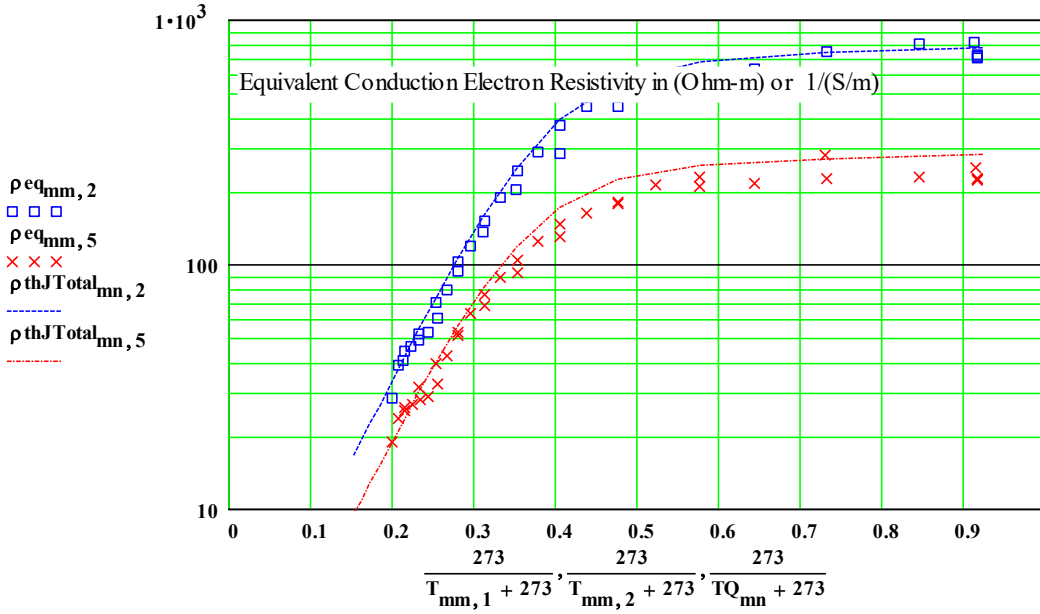
# Appendix E. MPN Reports

Test = 2022062801

SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G, RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC



# Appendix E. MPN Reports

Test = 2022062801

SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G , RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.136$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.068$  gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz 2466MHz 2986MHz      Lapsed Time (hours)

$\text{samdns}_{\text{mm}}$      $T_{\text{mm},1}$      $\epsilon'_{\text{mm},1}$      $\epsilon'_{\text{mm},2}$      $\epsilon'_{\text{mm},3}$      $\epsilon'_{\text{mm},4}$      $\epsilon'_{\text{mm},5}$      $\epsilon'_{\text{mm},6}$      $\text{tlaps}_{\text{mm}}$      $\text{sammass}_{\text{mm}}$

|       |    |      |      |      |      |      |      |      |       |       |
|-------|----|------|------|------|------|------|------|------|-------|-------|
| 2.136 | 9  | 25   | 4.51 | 4.48 | 4.47 | 4.46 | 4.44 | 4.43 | 0     | 0.284 |
| 2.136 | 10 | 25   | 4.52 | 4.49 | 4.47 | 4.46 | 4.45 | 4.43 | 0.08  | 0.284 |
| 2.136 | 11 | 25   | 4.51 | 4.48 | 4.47 | 4.47 | 4.46 | 4.45 | 0.15  | 0.284 |
| 2.136 | 12 | 50   | 4.55 | 4.52 | 4.5  | 4.49 | 4.46 | 4.44 | 0.33  | 0.284 |
| 2.136 | 13 | 100  | 4.59 | 4.56 | 4.54 | 4.52 | 4.49 | 4.46 | 0.54  | 0.284 |
| 2.136 | 14 | 151  | 4.62 | 4.59 | 4.57 | 4.54 | 4.52 | 4.49 | 0.78  | 0.284 |
| 2.136 | 15 | 202  | 4.66 | 4.62 | 4.6  | 4.57 | 4.54 | 4.51 | 0.99  | 0.284 |
| 2.136 | 16 | 250  | 4.69 | 4.65 | 4.63 | 4.6  | 4.57 | 4.54 | 1.17  | 0.284 |
| 2.136 | 17 | 301  | 4.73 | 4.67 | 4.65 | 4.63 | 4.6  | 4.57 | 1.35  | 0.284 |
| 2.136 | 18 | 351  | 4.75 | 4.71 | 4.68 | 4.66 | 4.63 | 4.6  | 1.53  | 0.284 |
| 2.136 | 19 | 401  | 4.79 | 4.74 | 4.71 | 4.69 | 4.65 | 4.62 | 1.71  | 0.284 |
| 2.136 | 20 | 451  | 4.84 | 4.77 | 4.75 | 4.72 | 4.68 | 4.65 | 1.89  | 0.284 |
| 2.136 | 21 | 501  | 4.87 | 4.81 | 4.78 | 4.75 | 4.71 | 4.68 | 2.07  | 0.284 |
| 2.136 | 22 | 550  | 4.93 | 4.84 | 4.82 | 4.78 | 4.75 | 4.71 | 2.25  | 0.284 |
| 2.136 | 23 | 600  | 5.03 | 4.93 | 4.89 | 4.85 | 4.81 | 4.78 | 2.44  | 0.284 |
| 2.136 | 24 | 650  | 5.08 | 4.97 | 4.93 | 4.89 | 4.85 | 4.81 | 2.63  | 0.284 |
| 2.136 | 25 | 700  | 5.18 | 5.05 | 5    | 4.96 | 4.91 | 4.87 | 2.81  | 0.284 |
| 2.127 | 26 | 750  | 5.32 | 5.14 | 5.08 | 5.03 | 4.98 | 4.93 | 3     | 0.284 |
| 2.118 | 27 | 800  | 5.45 | 5.23 | 5.14 | 5.09 | 5.02 | 4.97 | 3.19  | 0.284 |
| 2.109 | 28 | 849  | 5.5  | 5.26 | 5.16 | 5.09 | 5.03 | 4.97 | 3.38  | 0.284 |
| 2.1   | 29 | 900  | 5.49 | 5.23 | 5.13 | 5.06 | 4.99 | 4.93 | 3.57  | 0.284 |
| 2.091 | 30 | 949  | 5.48 | 5.23 | 5.11 | 5.04 | 4.97 | 4.91 | 3.75  | 0.284 |
| 2.083 | 31 | 1000 | 5.53 | 5.24 | 5.12 | 5.05 | 4.98 | 4.92 | 3.94  | 0.284 |
| 2.078 | 32 | 1049 | 5.66 | 5.35 | 5.21 | 5.13 | 5.05 | 4.98 | 4.13  | 0.283 |
| 2.073 | 33 | 1100 | 6.04 | 5.64 | 5.45 | 5.35 | 5.24 | 5.16 | 4.32  | 0.283 |
| 2.068 | 34 | 1004 | 5.67 | 5.37 | 5.25 | 5.17 | 5.09 | 5.02 | 4.57  | 0.282 |
| 2.068 | 35 | 905  | 5.46 | 5.23 | 5.14 | 5.07 | 5    | 4.94 | 4.82  | 0.282 |
| 2.068 | 36 | 804  | 5.29 | 5.11 | 5.04 | 4.98 | 4.92 | 4.87 | 5.08  | 0.282 |
| 2.068 | 37 | 704  | 5.13 | 5    | 4.94 | 4.89 | 4.84 | 4.79 | 5.36  | 0.282 |
| 2.068 | 38 | 603  | 4.99 | 4.89 | 4.84 | 4.8  | 4.75 | 4.71 | 5.7   | 0.282 |
| 2.068 | 39 | 503  | 4.87 | 4.79 | 4.76 | 4.72 | 4.68 | 4.64 | 6.11  | 0.282 |
| 2.068 | 40 | 402  | 4.76 | 4.7  | 4.68 | 4.64 | 4.61 | 4.57 | 6.63  | 0.282 |
| 2.068 | 41 | 301  | 4.67 | 4.62 | 4.61 | 4.58 | 4.54 | 4.51 | 7.31  | 0.282 |
| 2.068 | 42 | 201  | 4.58 | 4.55 | 4.53 | 4.5  | 4.47 | 4.44 | 8.29  | 0.282 |
| 2.068 | 43 | 102  | 4.5  | 4.48 | 4.46 | 4.44 | 4.41 | 4.38 | 10.12 | 0.282 |
| 2.068 | 44 | 26   | 4.45 | 4.43 | 4.42 | 4.41 | 4.4  | 4.38 | 10.46 | 0.282 |

Appendix E. MPN Reports

Test = 2022062801

SHUL2281.mcd

AnDat = 20220629

Lunar Simulant CSM-LHT-1G , RT to 1100C, in vacuum (< 1 millitorr), Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.136$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.068$  gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz  
 Lapsed Time (hours)

| samdns <sub>mmmm</sub> | T <sub>mm,1</sub> | $\epsilon''_{\text{mm},1}$ | $\epsilon''_{\text{mm},2}$ | $\epsilon''_{\text{mm},3}$ | $\epsilon''_{\text{mm},4}$ | $\epsilon''_{\text{mm},5}$ | $\epsilon''_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |       |
|------------------------|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|-------|
| 2.136                  | 9                 | 25                         | 0.028                      | 0.028                      | 0.029                      | 0.032                      | 0.033                      | 0.029               | 0                    | 0.284 |
| 2.136                  | 10                | 25                         | 0.027                      | 0.027                      | 0.029                      | 0.032                      | 0.033                      | 0.029               | 0.08                 | 0.284 |
| 2.136                  | 11                | 25                         | 0.03                       | 0.028                      | 0.029                      | 0.031                      | 0.033                      | 0.029               | 0.15                 | 0.284 |
| 2.136                  | 12                | 50                         | 0.031                      | 0.025                      | 0.03                       | 0.031                      | 0.032                      | 0.03                | 0.33                 | 0.284 |
| 2.136                  | 13                | 100                        | 0.029                      | 0.026                      | 0.033                      | 0.031                      | 0.032                      | 0.029               | 0.54                 | 0.284 |
| 2.136                  | 14                | 151                        | 0.028                      | 0.031                      | 0.028                      | 0.032                      | 0.034                      | 0.03                | 0.78                 | 0.284 |
| 2.136                  | 15                | 202                        | 0.025                      | 0.034                      | 0.033                      | 0.032                      | 0.035                      | 0.031               | 0.99                 | 0.284 |
| 2.136                  | 16                | 250                        | 0.034                      | 0.033                      | 0.032                      | 0.037                      | 0.034                      | 0.034               | 1.17                 | 0.284 |
| 2.136                  | 17                | 301                        | 0.048                      | 0.037                      | 0.041                      | 0.039                      | 0.04                       | 0.035               | 1.35                 | 0.284 |
| 2.136                  | 18                | 351                        | 0.068                      | 0.044                      | 0.045                      | 0.046                      | 0.045                      | 0.038               | 1.53                 | 0.284 |
| 2.136                  | 19                | 401                        | 0.065                      | 0.053                      | 0.053                      | 0.051                      | 0.05                       | 0.045               | 1.71                 | 0.284 |
| 2.136                  | 20                | 451                        | 0.084                      | 0.068                      | 0.066                      | 0.06                       | 0.058                      | 0.051               | 1.89                 | 0.284 |
| 2.136                  | 21                | 501                        | 0.116                      | 0.081                      | 0.076                      | 0.071                      | 0.07                       | 0.062               | 2.07                 | 0.284 |
| 2.136                  | 22                | 550                        | 0.143                      | 0.105                      | 0.089                      | 0.083                      | 0.083                      | 0.072               | 2.25                 | 0.284 |
| 2.136                  | 23                | 600                        | 0.176                      | 0.131                      | 0.117                      | 0.105                      | 0.097                      | 0.085               | 2.44                 | 0.284 |
| 2.136                  | 24                | 650                        | 0.228                      | 0.166                      | 0.138                      | 0.126                      | 0.115                      | 0.104               | 2.63                 | 0.284 |
| 2.136                  | 25                | 700                        | 0.278                      | 0.191                      | 0.166                      | 0.148                      | 0.138                      | 0.124               | 2.81                 | 0.284 |
| 2.127                  | 26                | 750                        | 0.328                      | 0.249                      | 0.209                      | 0.185                      | 0.171                      | 0.156               | 3                    | 0.284 |
| 2.118                  | 27                | 800                        | 0.447                      | 0.327                      | 0.273                      | 0.243                      | 0.225                      | 0.205               | 3.19                 | 0.284 |
| 2.109                  | 28                | 849                        | 0.5                        | 0.374                      | 0.31                       | 0.278                      | 0.252                      | 0.228               | 3.38                 | 0.284 |
| 2.1                    | 29                | 900                        | 0.539                      | 0.401                      | 0.33                       | 0.29                       | 0.261                      | 0.236               | 3.57                 | 0.284 |
| 2.091                  | 30                | 949                        | 0.583                      | 0.424                      | 0.347                      | 0.304                      | 0.271                      | 0.244               | 3.75                 | 0.284 |
| 2.083                  | 31                | 1000                       | 0.623                      | 0.442                      | 0.358                      | 0.314                      | 0.281                      | 0.252               | 3.94                 | 0.284 |
| 2.078                  | 32                | 1049                       | 0.716                      | 0.505                      | 0.403                      | 0.352                      | 0.312                      | 0.279               | 4.13                 | 0.283 |
| 2.073                  | 33                | 1100                       | 1.018                      | 0.69                       | 0.533                      | 0.453                      | 0.389                      | 0.346               | 4.32                 | 0.283 |
| 2.068                  | 34                | 1004                       | 0.713                      | 0.486                      | 0.381                      | 0.331                      | 0.29                       | 0.259               | 4.57                 | 0.282 |
| 2.068                  | 35                | 905                        | 0.547                      | 0.377                      | 0.3                        | 0.261                      | 0.232                      | 0.207               | 4.82                 | 0.282 |
| 2.068                  | 36                | 804                        | 0.41                       | 0.283                      | 0.231                      | 0.205                      | 0.184                      | 0.166               | 5.08                 | 0.282 |
| 2.068                  | 37                | 704                        | 0.288                      | 0.21                       | 0.172                      | 0.155                      | 0.142                      | 0.129               | 5.36                 | 0.282 |
| 2.068                  | 38                | 603                        | 0.216                      | 0.145                      | 0.127                      | 0.115                      | 0.108                      | 0.095               | 5.7                  | 0.282 |
| 2.068                  | 39                | 503                        | 0.132                      | 0.098                      | 0.09                       | 0.083                      | 0.078                      | 0.071               | 6.11                 | 0.282 |
| 2.068                  | 40                | 402                        | 0.085                      | 0.069                      | 0.064                      | 0.056                      | 0.056                      | 0.05                | 6.63                 | 0.282 |
| 2.068                  | 41                | 301                        | 0.051                      | 0.044                      | 0.039                      | 0.042                      | 0.041                      | 0.036               | 7.31                 | 0.282 |
| 2.068                  | 42                | 201                        | 0.033                      | 0.034                      | 0.03                       | 0.03                       | 0.032                      | 0.027               | 8.29                 | 0.282 |
| 2.068                  | 43                | 102                        | 0.017                      | 0.018                      | 0.022                      | 0.027                      | 0.026                      | 0.025               | 10.12                | 0.282 |
| 2.068                  | 44                | 26                         | 0.028                      | 0.024                      | 0.025                      | 0.027                      | 0.029                      | 0.027               | 10.46                | 0.282 |

MPN-257\_Shulman\_CSM-LHT-1G\_2

July 5, 2022

Lunar Simulant CMS-LHT-1G, Heat Treated in Ar/4%H<sub>2</sub>  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in < 1 milliTorr Vacuum

Dr. Holly Shulman ( Shulman LLC) requested that Microwave Properties North measure the complex dielectric properties of a specially heat-treated CMS-LHT-1G lunar regolith simulant up to 1100C with a direct, uninterrupted, temperature cycle, in vacuum.

The powder sample material arrived at MPN on June 23/ 2022. Dr. Shulman had already heat-treated the powder at 750C in argon, and then at 750 C in a 4% hydrogen/argon mixture.

For this measurement, MPN pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness.

The initial sample parameters were:

- a) diameter 3.68 +- 0.05 mm
- b) length 13.19 +- 0.05 mm
- c) mass 0.289 +- 0.002 gm
- i) room temperature density  $2.06 \pm 0.09$  gm/cc.
- j) appearance - three (stacked) light grey pellets
- k) magnetic response - the small black particles that were attracted to a magnet in the previous, untreated, sample were not seen in this powder sample !

The dielectric properties measurements were performed at RT and then the temperature was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus and it and the final sample was weighed. The pellets were easily removed, and the empty holder was run up to 1100C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) diameter  $3.68 \pm 0.05$  mm
- b) length  $13.21 \pm 0.05$  mm
- c) mass  $0.287 \pm 0.002$  gm
- i) room temperature density  $2.04 \pm 0.09$  gm/cc.
- j) appearance - three grey pellets
- k) magnetic response - The black particles were apparent, and the pellets were attracted to a magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

| # | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|---|-----------------------|----------------------------------------------------------|
| 1 | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912                   | blue square, solid line                                  |
| 3 | 1429                  | black cross, solid line                                  |
| 4 | 1948                  | blue circle, dotted line                                 |
| 5 | 2466                  | red cross, dotted line                                   |
| 6 | 2986                  | black diamond, dotted line                               |

Comments on the data analysis:

A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

The final pellets appeared unchanged.

The data for the ramp up to 1100C is close to that for the ramp down. Some slight change in the material occurred between 900C and 1100 C that probably persisted in the return down to RT .



Final pellets after the cycle to 1100 C in vacuum ( at a pressure of less than 1 milliTorr ).



# Appendix E. MPN Reports

Test = 2022070101

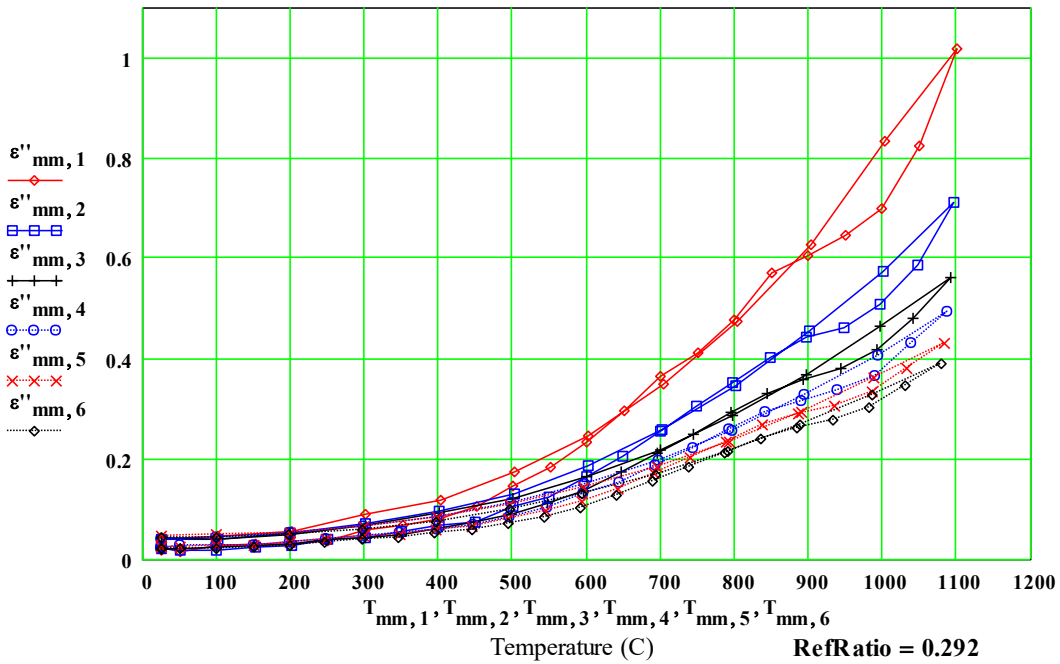
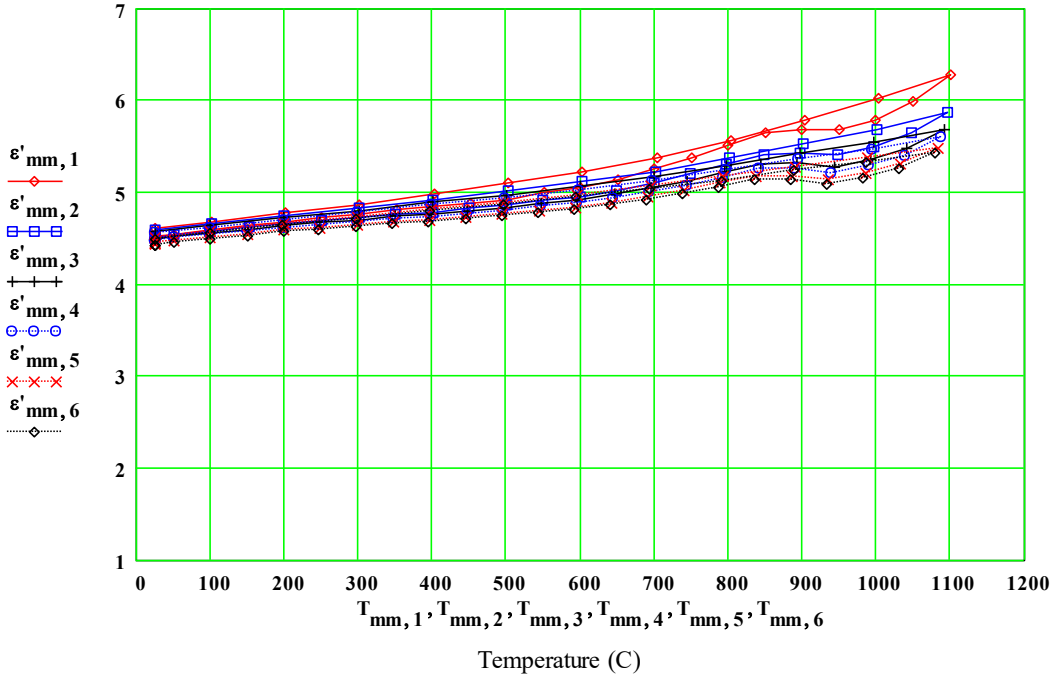
SHUL2282.mcd

AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/H2, to 1100C, in vacuum (< 1 millitorr), Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.06 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.04 \text{ gm/cc}$

**Final\_over\_Initial\_mass = 0.993**



# Appendix E. MPN Reports

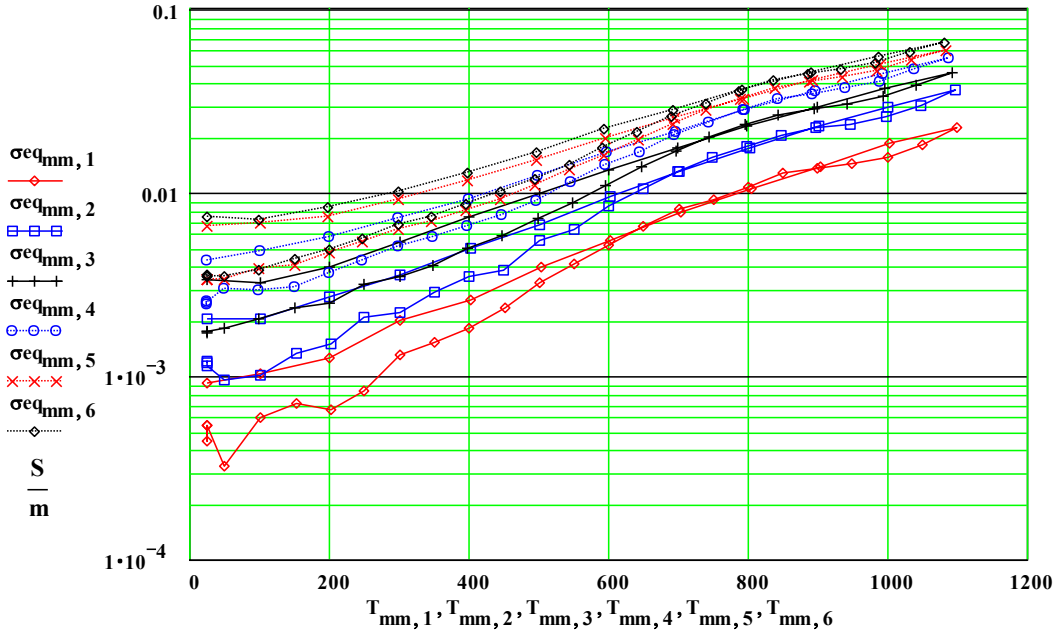
Test = 2022070101

SHUL2282.mcd

AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LL

Equivalent Free Electron Conductivity ( Siemens/metre)



Temperature (C)

RefRatio = 0.292

# Appendix E. MPN Reports

Test = 2022070101

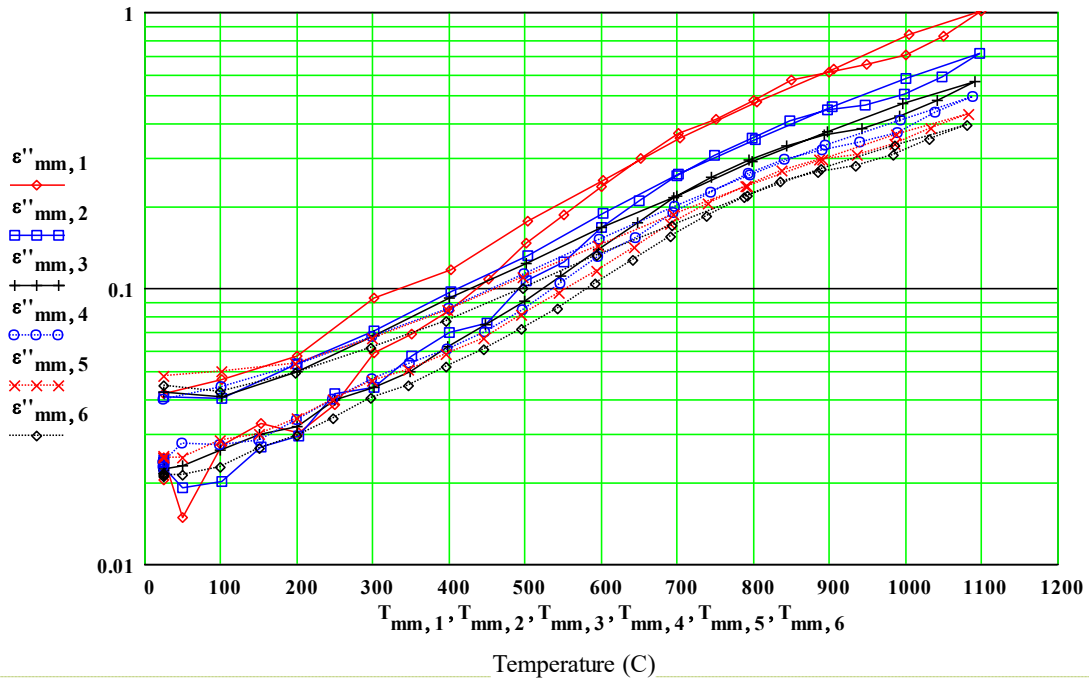
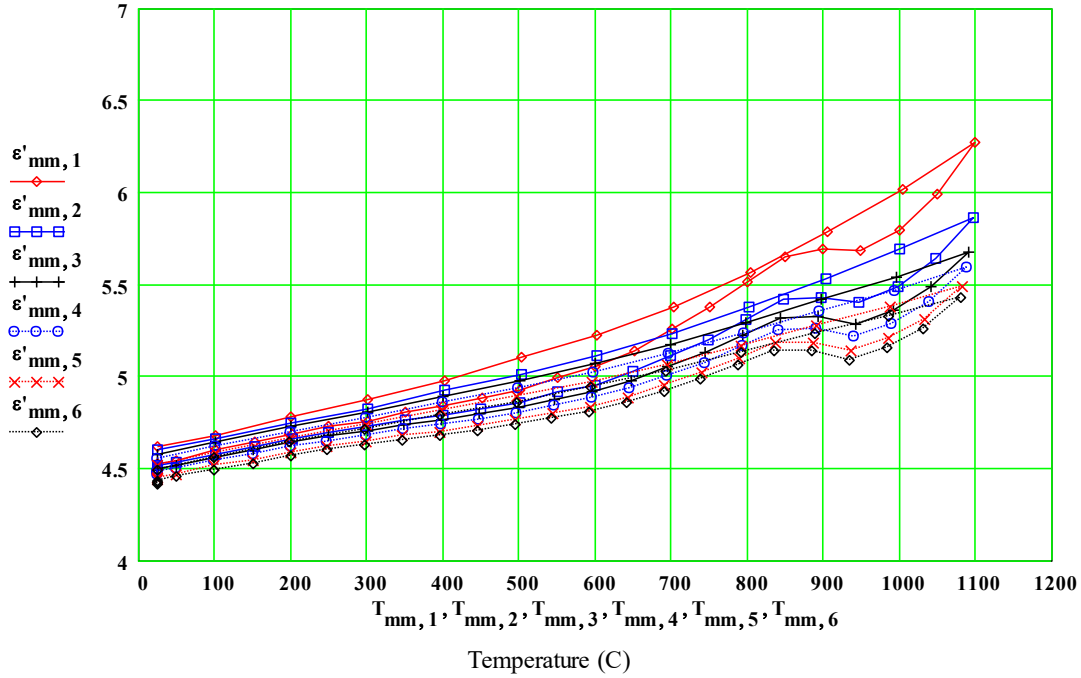
SHUL2282.mcd

AnDat = 20220703 T

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.06 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.04 \text{ gm/cc}$  I

FracMassChange = 0.99     $\alpha_1 = 0$  /C     $\alpha_2 = 0$  /C



# Appendix E. MPN Reports

Test = 2022070101

SHUL2282.mcd

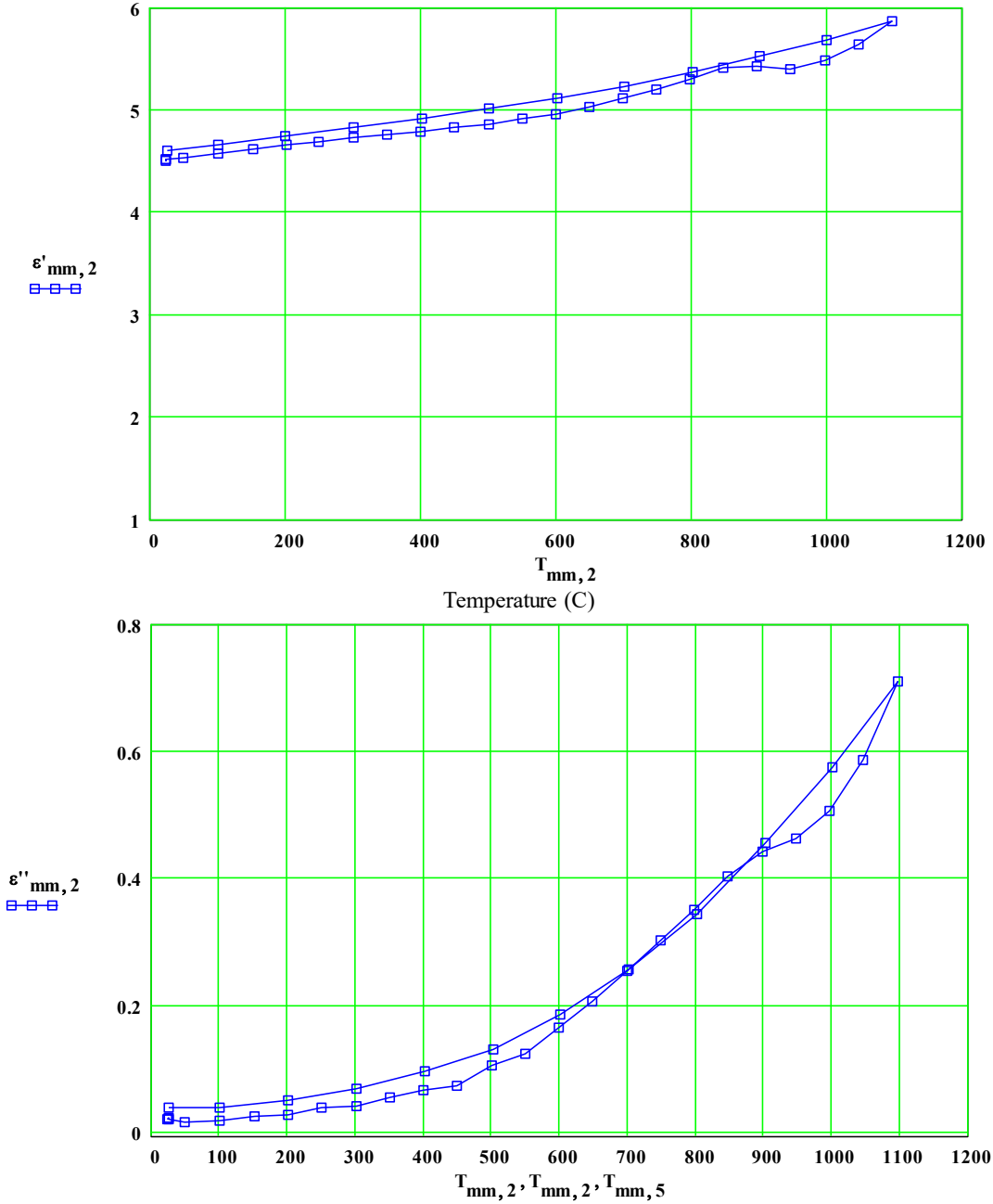
AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.06$  gm/cc, Thermal exp. coeff.  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 2.04$  gm/cc

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2022070101

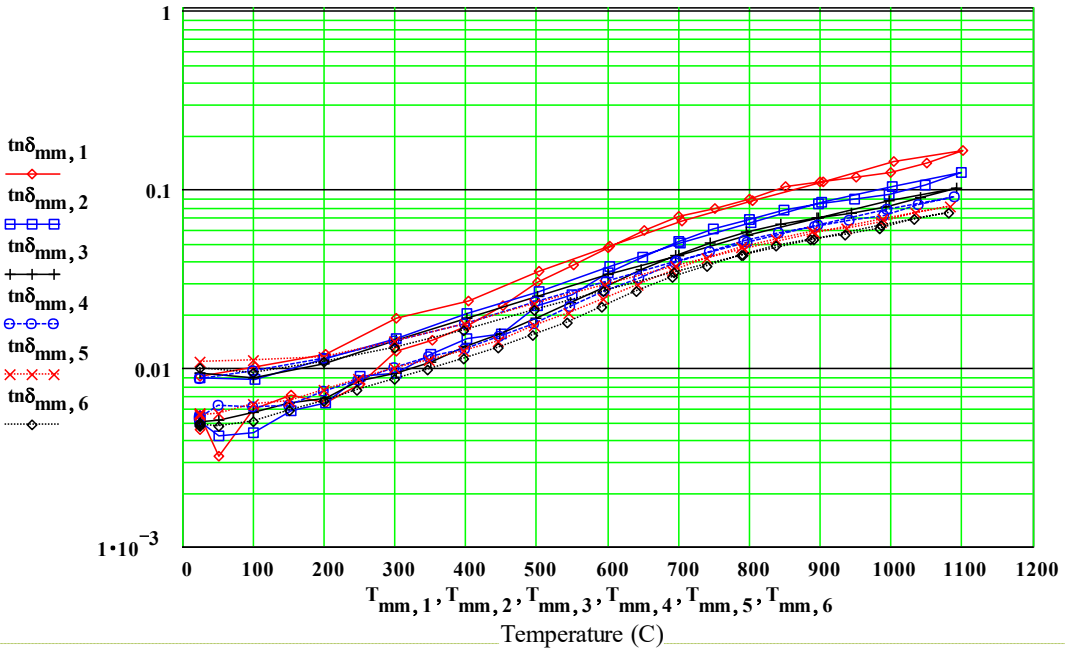
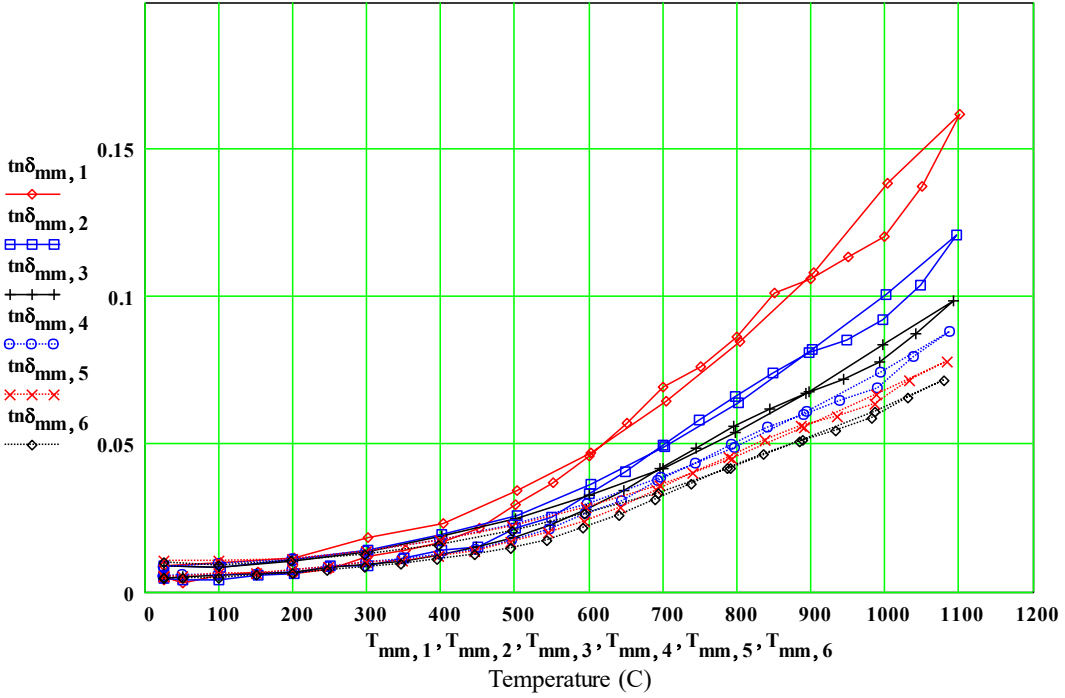
SHUL2282.mcd

AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.06 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.04 \text{ gm/cc}$



# Appendix E. MPN Reports

**Test = 2022070101**

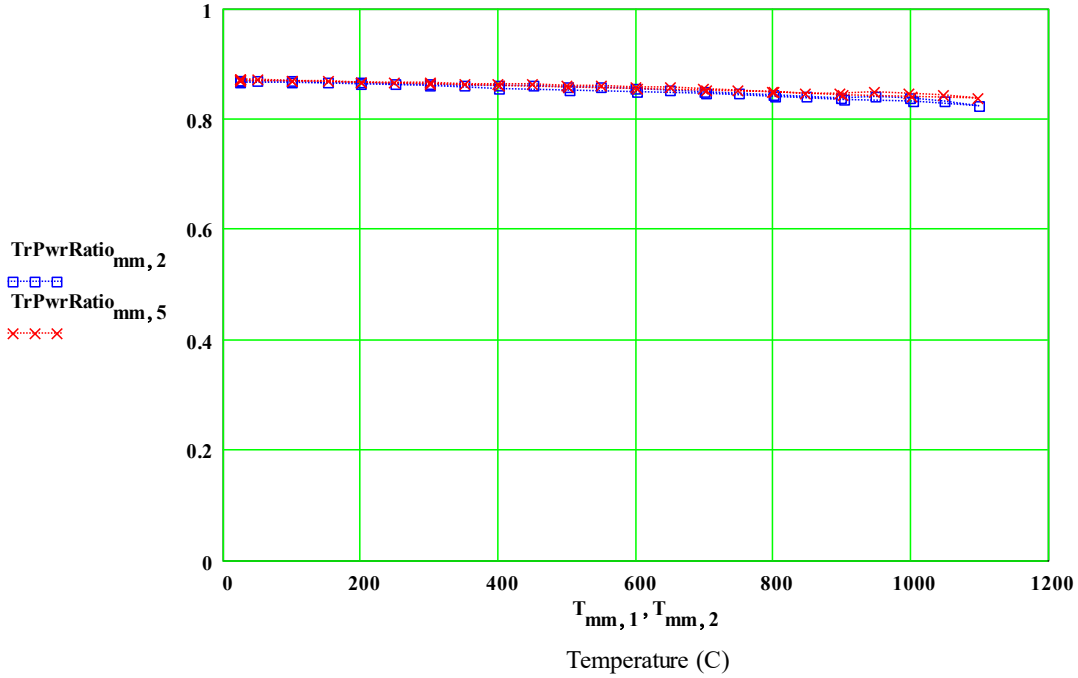
SHUL2282.mcd

**AnDat = 20220703**

Lunar Simulant CSM-LHT-1 G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.06 \text{ gm/cc}$ ,      Final density(25C) =  $\text{dnsfinal} = 2.04 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



Half-power Depth (millimeters)

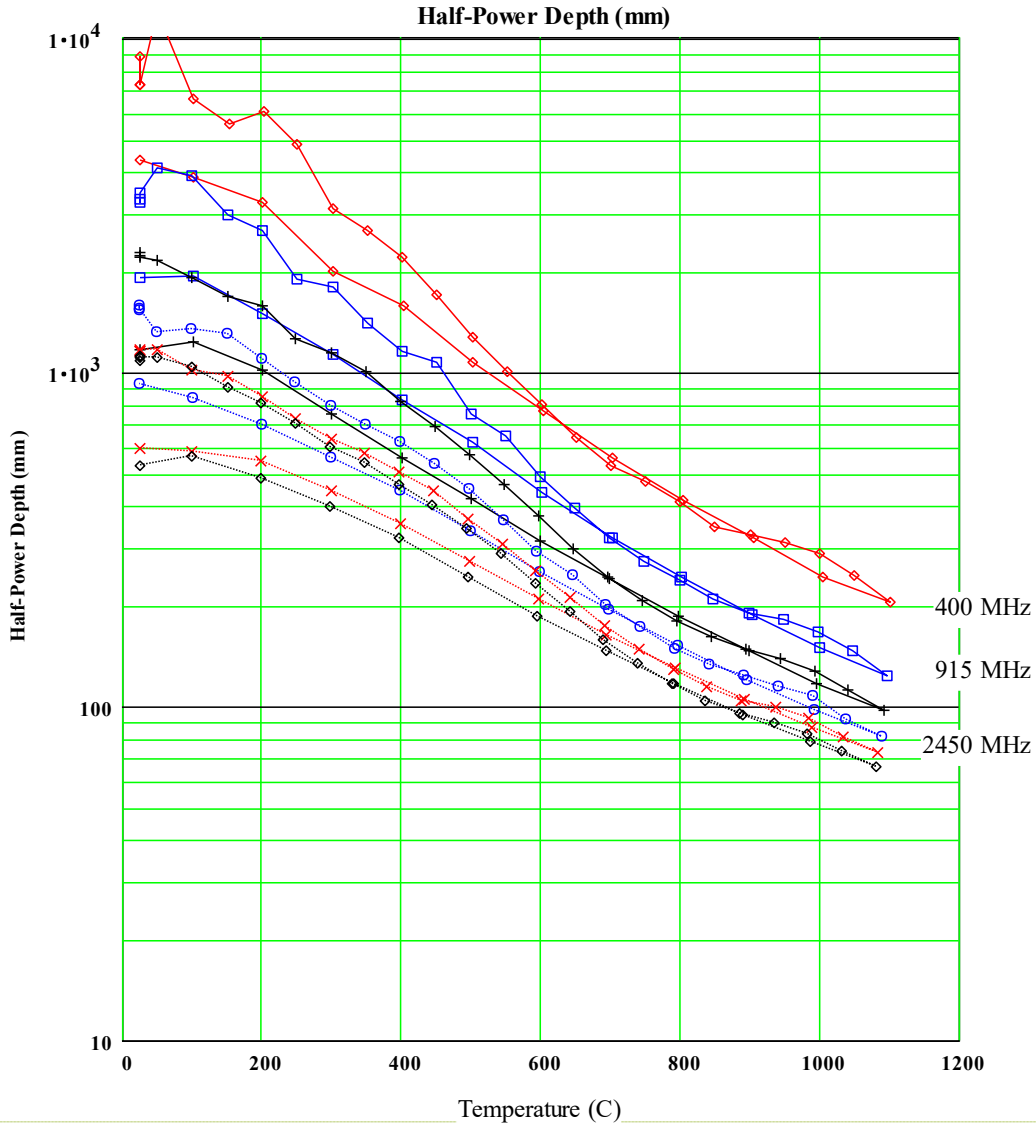
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2022070101

SHUL2282.mcd

AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LL



Use the Jonscher Formalism to fit the Frequency and Thermal Dependence of  $\epsilon_p$ ,  $\epsilon_{pp}$  and Conductivity

Fit to 'Disordered' Structure which Exists after the Highest Temperature was Attained (1100C)

Fit to 'Intrinsic' Values - High Temperature

$$E_{an} := 0.34 \text{ eV}$$

$$\sigma_{intn} := 0.6 \cdot 10^0 \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.55$$

$$\epsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \cos \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \overrightarrow{\epsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}}$$

$$\epsilon_{infin_{mn}} := 4.50 + 0.16 \cdot \frac{TQ_{mn}}{400}$$

$$\epsilon_{pthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{n_J}$$

$$\epsilon_{pthTotal_{mn,n}} := \epsilon_{pthJn_{mn,n}} + \epsilon_{infin_{mn}}$$

$$H_{activ} := E_{an} \cdot 96.5 \text{ Kjoule/mol}$$

$$H_{activ} = 33 \text{ Kjoule/mol}$$

$$E_{gn} := 2 \cdot E_{an} \text{ Conduction Gap Energy}$$

$$\frac{E_{gn}}{2} = 0.34 \text{ eV}$$

**Fit to 'Extrinsic' Values - Low Temperature, Impurity Dependent :**

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{am} := 0.009 \quad \sigma_{intm} := 0.0008 \quad mJ := 1.0$$

$$\varepsilon_{ppthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{(2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6})} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

$$\sigma_{thJm_{mn,n}} := \overbrace{\varepsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}}$$

$$\varepsilon_{pthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( mJ \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

**Sum up Extrinsic and Intrinsic Contributions :**

$$\varepsilon_{pthTotal_{mn,n}} := \varepsilon_{pthJn_{mn,n}} + \varepsilon_{pthJm_{mn,n}} + \varepsilon_{infin_{mn}}$$

$$\varepsilon_{ppthTotal_{mn,n}} := \varepsilon_{ppthJn_{mn,n}} + \varepsilon_{ppthJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

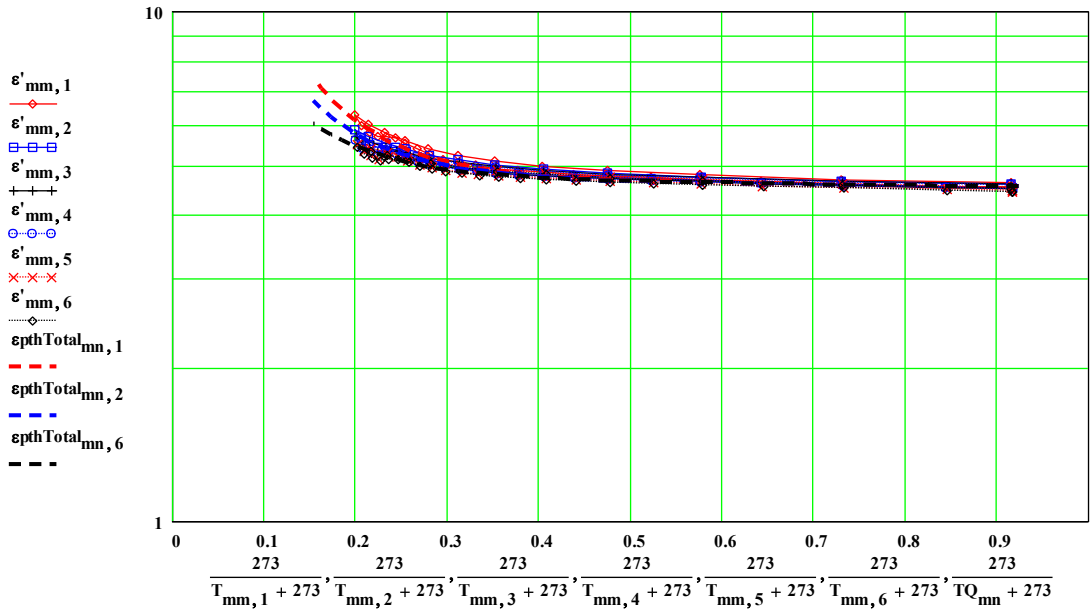
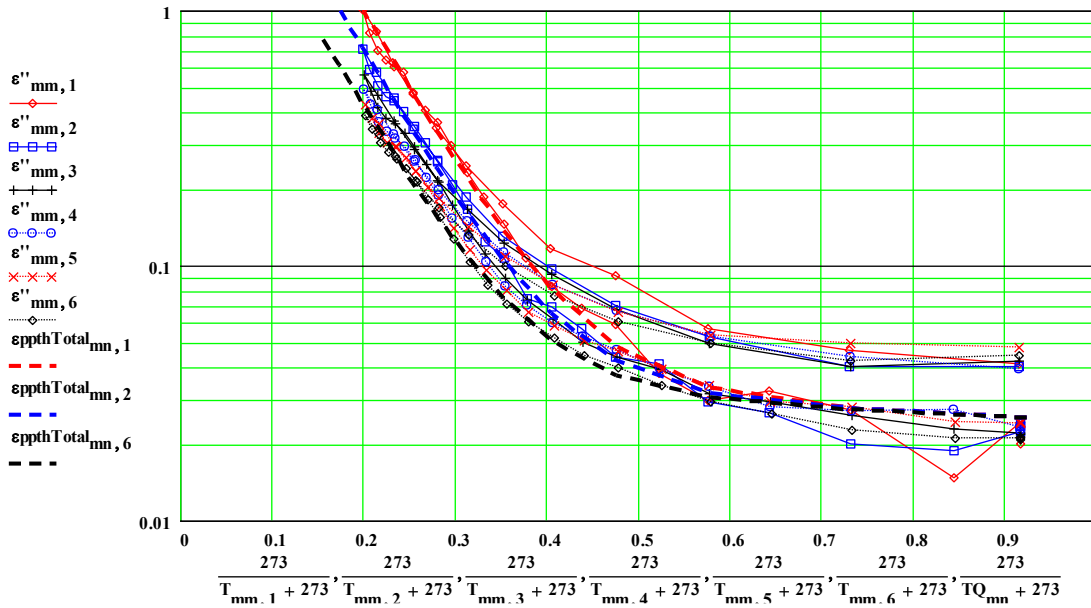
Test = 2022070101

SHUL2282.mcd

AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.06 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.04 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2022070101

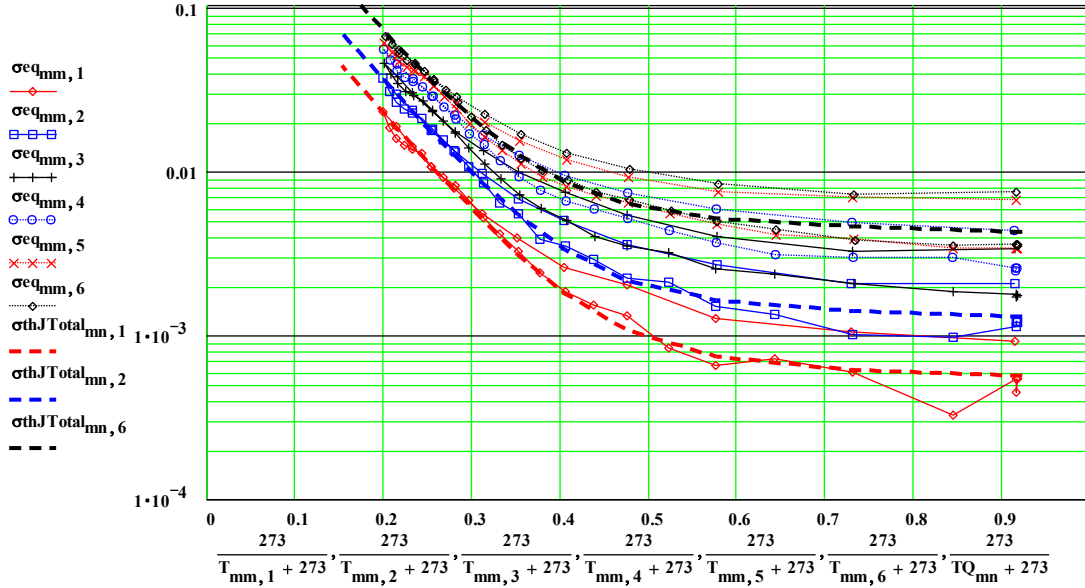
SHUL2282.mcd

AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LLC

Final density(25C) = **dnsfinal = 2.04** gm/cc

Equivalent Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2022070101

SHUL2282.mcd

AnDat = 20220703

Lunar Simulant CSM-LHT-1G, Pre-baked at 750C in Ar/4% H2, to 1100C, in vacuum (< 1 millitorr), Shulman LL

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density = **samdns**<sub>N<sub>Cal</sub> + 1</sub> = 2.06 gm/cc      Final density(25C) = **dnsfinal** = 2.043 gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz      Lapsed Time (hours)

| samdns <sub>mm</sub> | T <sub>mm, 1</sub> | $\epsilon'_{mm, 1}$ | $\epsilon'_{mm, 2}$ | $\epsilon'_{mm, 3}$ | $\epsilon'_{mm, 4}$ | $\epsilon'_{mm, 5}$ | $\epsilon'_{mm, 6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |       |
|----------------------|--------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------------|-------|
| 2.06                 | 9                  | 25                  | 4.53                | 4.52                | 4.51                | 4.48                | 4.45                | 4.42                | 0                    | 0.289 |
| 2.06                 | 10                 | 25                  | 4.52                | 4.51                | 4.49                | 4.47                | 4.44                | 4.42                | 0.15                 | 0.289 |
| 2.06                 | 11                 | 25                  | 4.53                | 4.52                | 4.5                 | 4.48                | 4.45                | 4.43                | 0.23                 | 0.289 |
| 2.06                 | 12                 | 50                  | 4.55                | 4.54                | 4.52                | 4.51                | 4.47                | 4.46                | 0.4                  | 0.289 |
| 2.06                 | 13                 | 100                 | 4.6                 | 4.58                | 4.56                | 4.54                | 4.52                | 4.5                 | 0.62                 | 0.289 |
| 2.06                 | 14                 | 152                 | 4.64                | 4.62                | 4.6                 | 4.58                | 4.55                | 4.53                | 0.85                 | 0.289 |
| 2.06                 | 15                 | 202                 | 4.69                | 4.67                | 4.64                | 4.62                | 4.59                | 4.57                | 1.06                 | 0.289 |
| 2.06                 | 16                 | 250                 | 4.73                | 4.7                 | 4.68                | 4.65                | 4.62                | 4.6                 | 1.24                 | 0.289 |
| 2.06                 | 17                 | 302                 | 4.76                | 4.73                | 4.71                | 4.68                | 4.65                | 4.63                | 1.42                 | 0.289 |
| 2.06                 | 18                 | 351                 | 4.81                | 4.76                | 4.74                | 4.71                | 4.68                | 4.66                | 1.59                 | 0.289 |
| 2.06                 | 19                 | 401                 | 4.84                | 4.79                | 4.77                | 4.74                | 4.7                 | 4.68                | 1.77                 | 0.289 |
| 2.06                 | 20                 | 451                 | 4.88                | 4.83                | 4.8                 | 4.77                | 4.73                | 4.71                | 1.95                 | 0.289 |
| 2.06                 | 21                 | 501                 | 4.93                | 4.86                | 4.84                | 4.8                 | 4.76                | 4.74                | 2.13                 | 0.289 |
| 2.06                 | 22                 | 551                 | 5                   | 4.92                | 4.88                | 4.85                | 4.8                 | 4.78                | 2.32                 | 0.289 |
| 2.06                 | 23                 | 600                 | 5.06                | 4.96                | 4.92                | 4.89                | 4.84                | 4.81                | 2.5                  | 0.289 |
| 2.06                 | 24                 | 651                 | 5.14                | 5.03                | 4.98                | 4.94                | 4.89                | 4.86                | 2.69                 | 0.289 |
| 2.06                 | 25                 | 700                 | 5.26                | 5.11                | 5.06                | 5.01                | 4.95                | 4.92                | 2.87                 | 0.289 |
| 2.059                | 26                 | 750                 | 5.38                | 5.21                | 5.13                | 5.08                | 5.02                | 4.99                | 3.06                 | 0.289 |
| 2.059                | 27                 | 800                 | 5.51                | 5.31                | 5.22                | 5.17                | 5.1                 | 5.06                | 3.25                 | 0.289 |
| 2.058                | 28                 | 849                 | 5.65                | 5.42                | 5.32                | 5.26                | 5.18                | 5.14                | 3.44                 | 0.289 |
| 2.058                | 29                 | 900                 | 5.7                 | 5.44                | 5.33                | 5.26                | 5.18                | 5.14                | 3.62                 | 0.289 |
| 2.057                | 30                 | 949                 | 5.68                | 5.41                | 5.29                | 5.22                | 5.14                | 5.09                | 3.81                 | 0.289 |
| 2.057                | 31                 | 1000                | 5.8                 | 5.5                 | 5.36                | 5.29                | 5.21                | 5.16                | 4                    | 0.289 |
| 2.052                | 32                 | 1049                | 5.99                | 5.65                | 5.49                | 5.4                 | 5.32                | 5.26                | 4.19                 | 0.288 |
| 2.047                | 33                 | 1100                | 6.28                | 5.87                | 5.68                | 5.6                 | 5.49                | 5.43                | 4.38                 | 0.288 |
| 2.043                | 34                 | 1003                | 6.02                | 5.69                | 5.55                | 5.47                | 5.38                | 5.33                | 4.62                 | 0.287 |
| 2.043                | 35                 | 904                 | 5.79                | 5.54                | 5.42                | 5.36                | 5.28                | 5.24                | 4.88                 | 0.287 |
| 2.043                | 36                 | 803                 | 5.57                | 5.38                | 5.29                | 5.24                | 5.17                | 5.13                | 5.14                 | 0.287 |
| 2.043                | 37                 | 703                 | 5.38                | 5.23                | 5.18                | 5.12                | 5.07                | 5.03                | 5.41                 | 0.287 |
| 2.043                | 38                 | 603                 | 5.23                | 5.12                | 5.07                | 5.03                | 4.98                | 4.95                | 5.75                 | 0.287 |
| 2.043                | 39                 | 503                 | 5.11                | 5.02                | 4.98                | 4.94                | 4.89                | 4.86                | 6.16                 | 0.287 |
| 2.043                | 40                 | 402                 | 4.98                | 4.93                | 4.9                 | 4.86                | 4.82                | 4.8                 | 6.69                 | 0.287 |
| 2.043                | 41                 | 302                 | 4.87                | 4.83                | 4.81                | 4.78                | 4.74                | 4.71                | 7.38                 | 0.287 |
| 2.043                | 42                 | 201                 | 4.78                | 4.75                | 4.73                | 4.7                 | 4.67                | 4.64                | 8.35                 | 0.287 |
| 2.043                | 43                 | 101                 | 4.69                | 4.66                | 4.64                | 4.62                | 4.58                | 4.56                | 10.17                | 0.287 |
| 2.043                | 44                 | 25                  | 4.62                | 4.6                 | 4.58                | 4.55                | 4.52                | 4.49                | 14.83                | 0.287 |



MPN-258\_CSM-LHT-1G\_heat-treated

July 24, 2022

Lunar Simulant CSM-LHT-1G  
Initially Heat Treated to 750C in Argon/ Argon/Hydrogen,  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1400°C, in Flowing UHP Argon

Microwave Properties North decided to measure the complex dielectric properties of initially heat treated CSM-LHT-1G lunar simulant powder pellets. The powder sample material had been supplied by Dr. Holly Shulman for previous measurements requested by her up to 1200C in UHP argon.

This measurement was done using a modification of our usual perturbation system – a larger diameter fused silica holder was used ( 8 mm OD, 6 mm ID ), and the three test pellets were placed inside a high purity alumina crucible (5.71 mm OD , 4.03 mm ID mm, 15.09 mm high), which itself was placed in the 6 mm ID fused silica ( GE-214 ) holder.

For this measurement, MPN pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness.

The initial sample parameters were:

- a) pellet diameter 3.67 +- 0.05 mm
- b) length of stack 13.18 +- 0.10 mm
- c) mass 0.295 +- 0.002 gm
- l) room temperature density  $2.12 \pm 0.09$  gm/cc.
- m) appearance - three (stacked) light grey pellets
- n) magnetic response - no response to strong magnet

The initial background measurements and calibrations were done on the holder containing the empty alumina crucible up to 1400C ( see photo). Then the pellets were loaded into the crucible, and the dielectric properties measurements were performed at RT and then the temperature was ramped up to 1400C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus, the crucible was removed from the holder, and the final sample was weighed. The crucible was easily removed, but the sample had “melted” and adhered to the crucible. The crucible, with sample) was sectioned with a thin diamond saw to reveal a large, almost spherical, void at the top of final sample ( melting had occurred – see photo).

The final sample properties, at room temperature were :

- a) diameter  $4.13 \pm 0.05$  mm ( The ID of the crucible)
- b) length ~  $11 \pm 0.5$  mm to top of meniscus,  $9.1 \pm 0.4$  mm average height of sample
- c) mass  $0.294 \pm 0.002$  gm
- l) room temperature bulk density (excluding the large void, small pores included)  $2.38 \pm 0.15$  gm/cc.
- m) appearance - dark brown/grey glassy solid with void and small pores , with meniscus indicating melting, large void and small pores ( see photo)
- n) magnetic response - No response to strong magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

| <u>#</u> | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|----------|-----------------------|----------------------------------------------------------|
| 1        | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2        | 912                   | blue square, solid line                                  |
| 3        | 1429                  | black cross, solid line                                  |
| 4        | 1948                  | blue circle, dotted line                                 |
| 5        | 2466                  | red cross, dotted line                                   |
| 6        | 2986                  | black diamond, dotted line                               |

Comments on the data analysis:

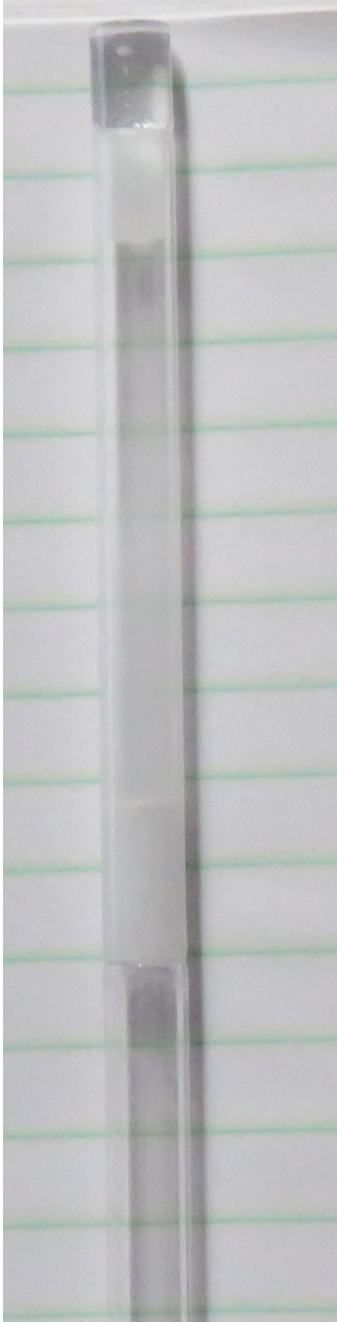
A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6} /C$  was used.

The initial and final sample dimensions, the internal staining of the alumina crucible, and the high temperature dielectric constant behaviour were used to estimate the dimensions of the sample as a function of temperature.

The large void presented problems with sample dimension interpretation. The void was assumed to have formed during the high temperature part of the temperature increase, and to indicate a higher viscosity than the behavior of the NU-LHT-4M at the same temperatures. It may also have been produced by the top surface of the sample being slightly hotter than the lower portion. The final sample height was approximated by estimating what the average height of the final sample would have been without the void !

The lack of exact, detailed, knowledge of the sample dimensions as a function of temperature does introduce some uncertainty in the high temperature values. If it is important, I can show estimates of the possible dielectric constant variation induced by reasonable uncertainties !

The fitting of the dielectric loss and the “equivalent conductivity” to an Arrhenius dependence ( pages 16 and 17 of this report) suggest some form of glass melting occurred above 1100 C.

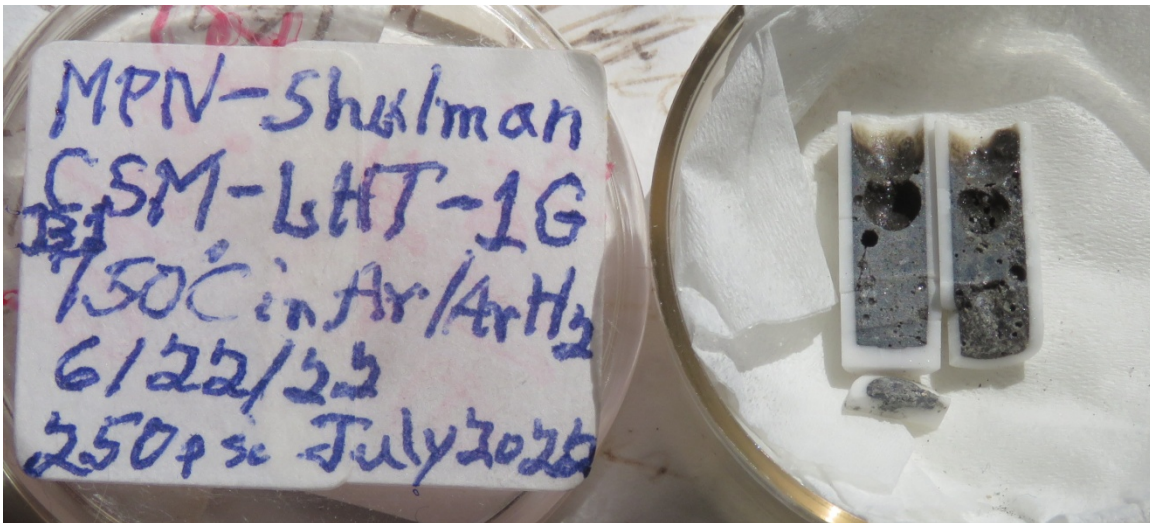


Holder with crucible and fused silica “plug” at top , before insertion of test pellets .

Note: The gas flows up the interior of the holder, past the outside wall of the crucible and past the plug.



Crucible with test sample after run



After sectioning with thin diamond saw.



Details of final CSM-LHT-1G heat treated sample after run to 1400C in argon. There is no indication of the original three-stacked-pellet structure, or of the discontinuities between the pellets, indicating the achievement of melting/mixing.

The one very large void suggests gas formation and high viscosity at high temperatures during the temperature ramp-up.

The small pores suggest gas entrainment and/or incomplete “sintering”.

The final density was ~ 9% higher than the initial density.



# Appendix E. MPN Reports

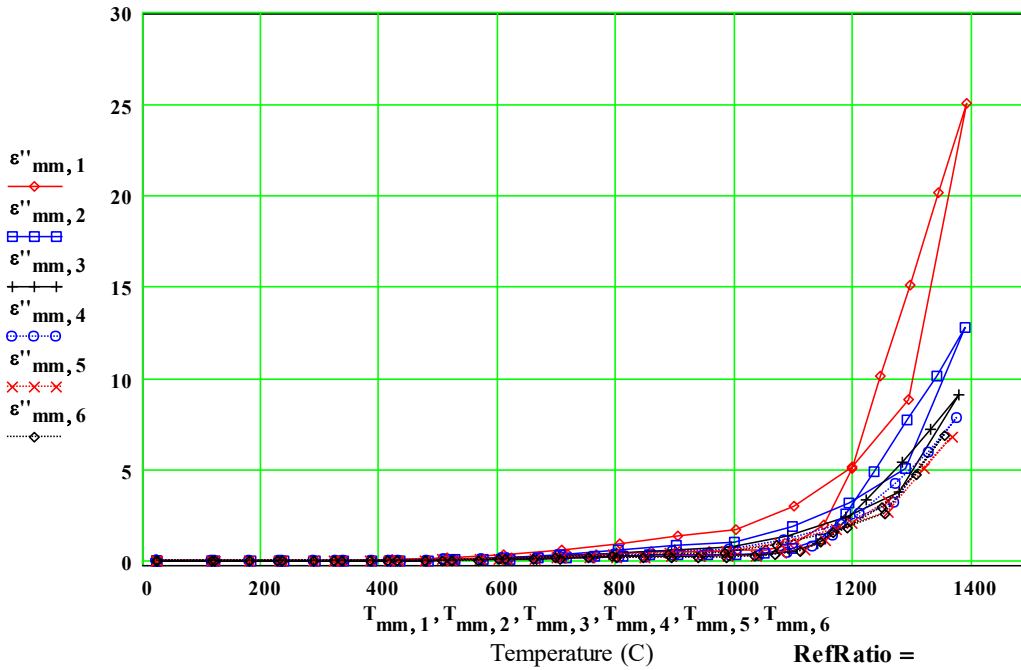
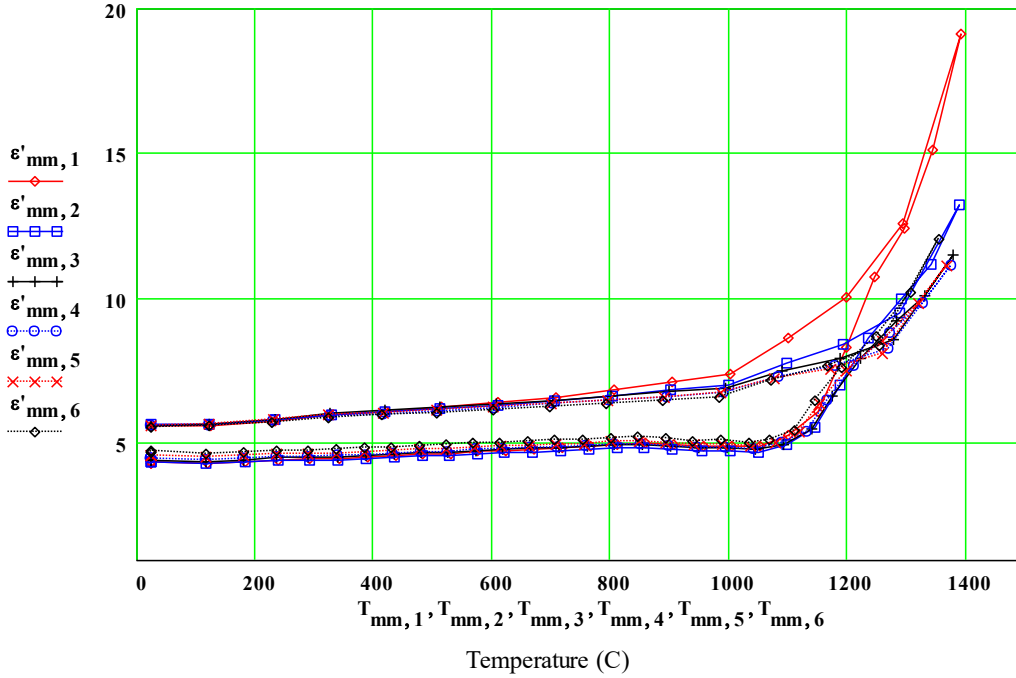
Test = 2022072101

MPN02286.mcd

AnDat = 20191023

CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN - Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.39 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2022072101

MPN02286.mcd

AnDat = 20191023

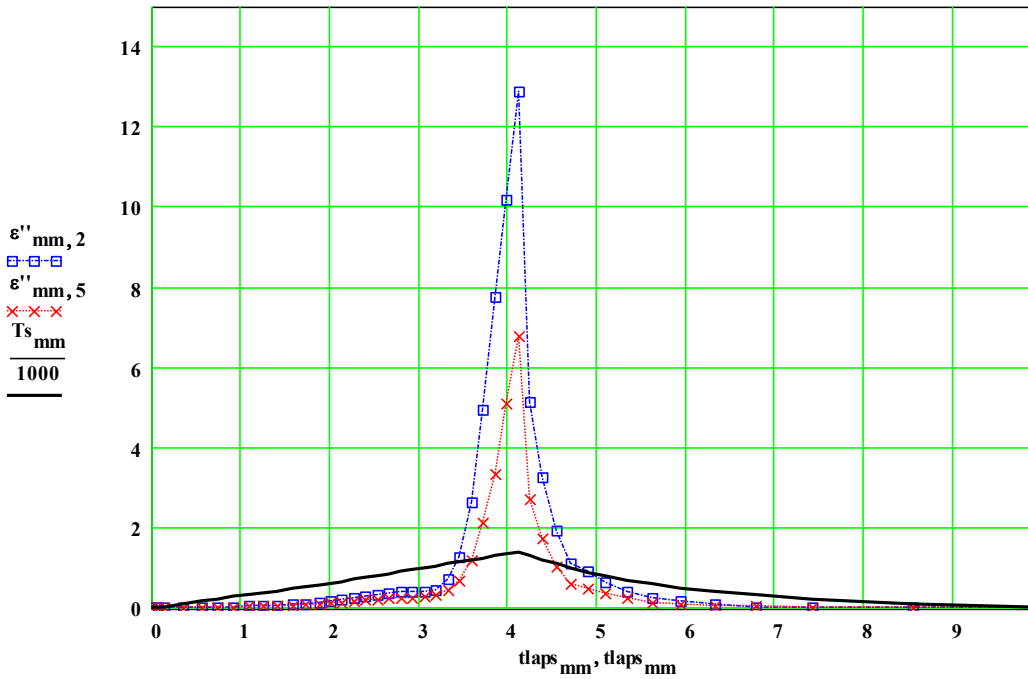
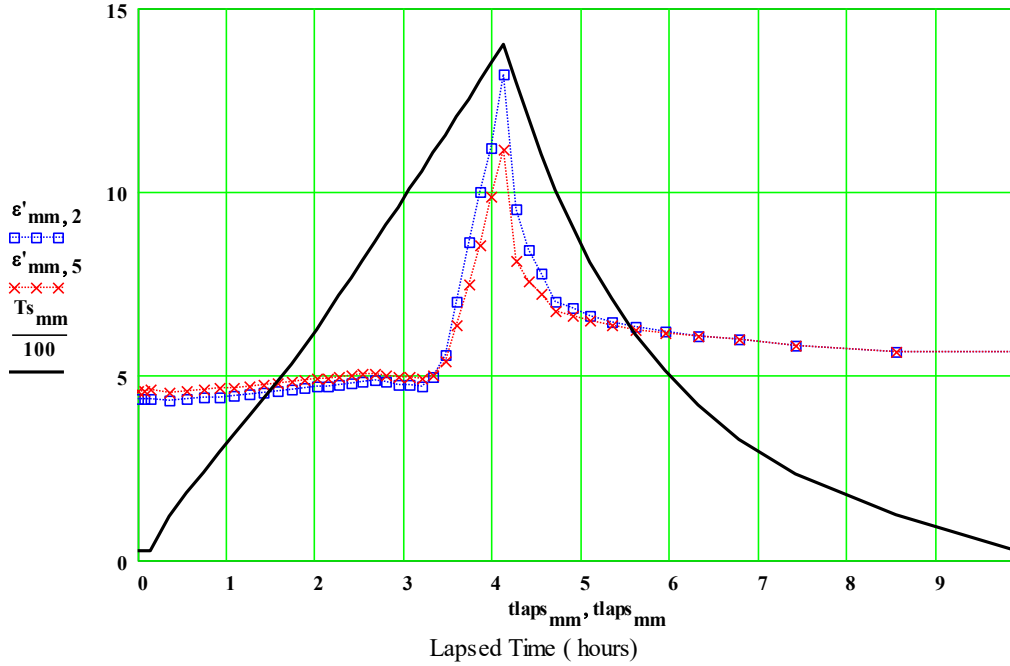
CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN - Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.39 \text{ gm/cc}$       **FracMassChange = 1**

$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2022072101

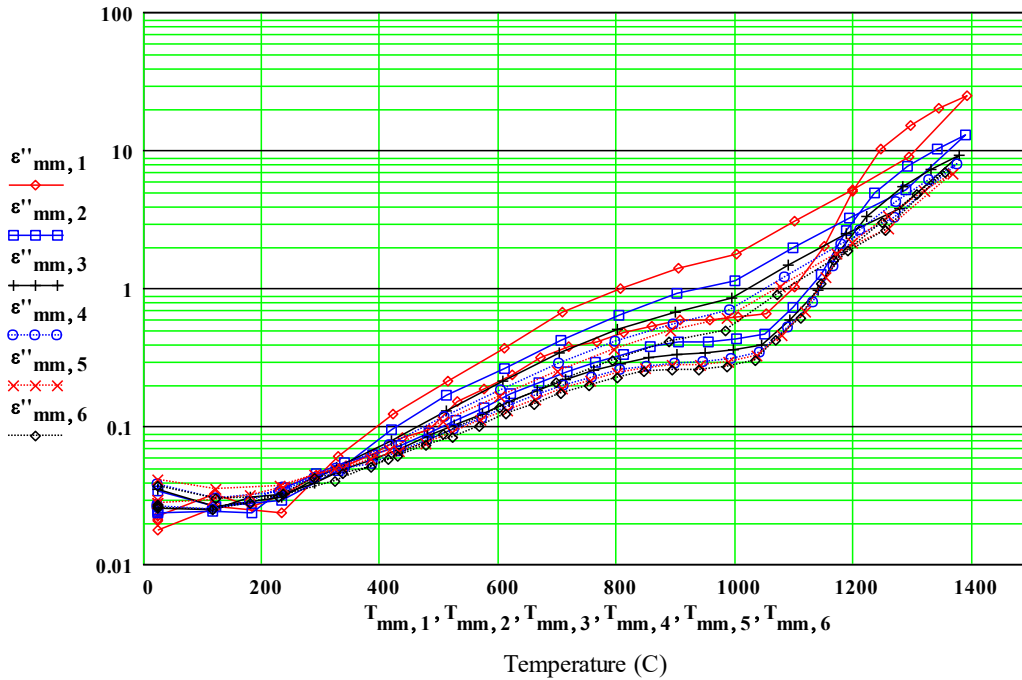
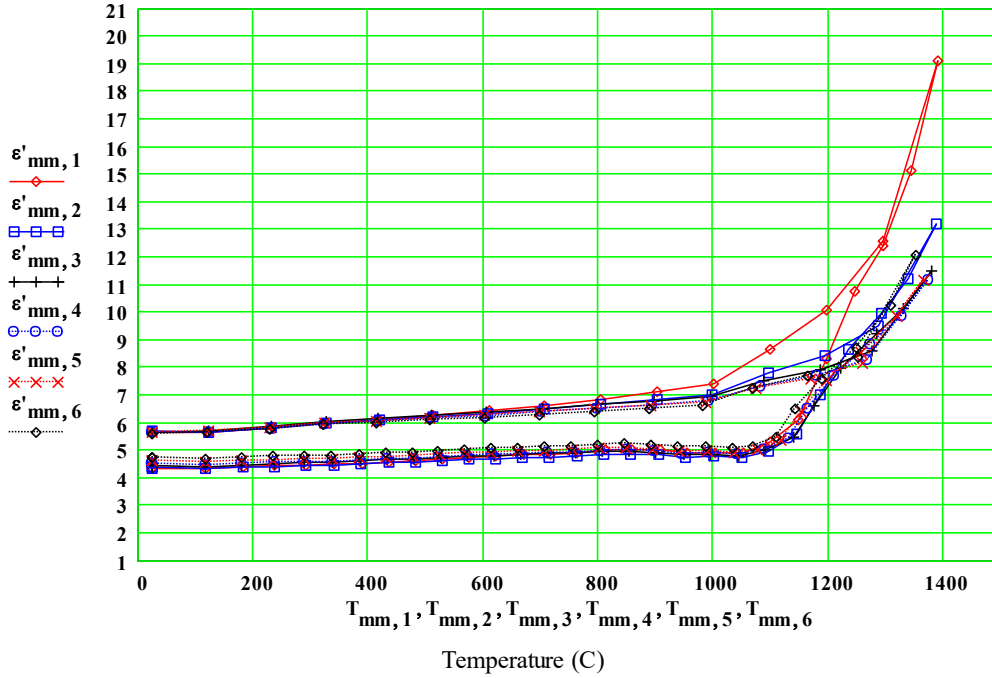
MPN02286.mcd

AnDat = 20191023

CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN -Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.39 \text{ gm/cc}$

FracMassChange = 1       $\alpha_1 = 0$  /C       $\alpha_2 = 0$  /C



# Appendix E. MPN Reports

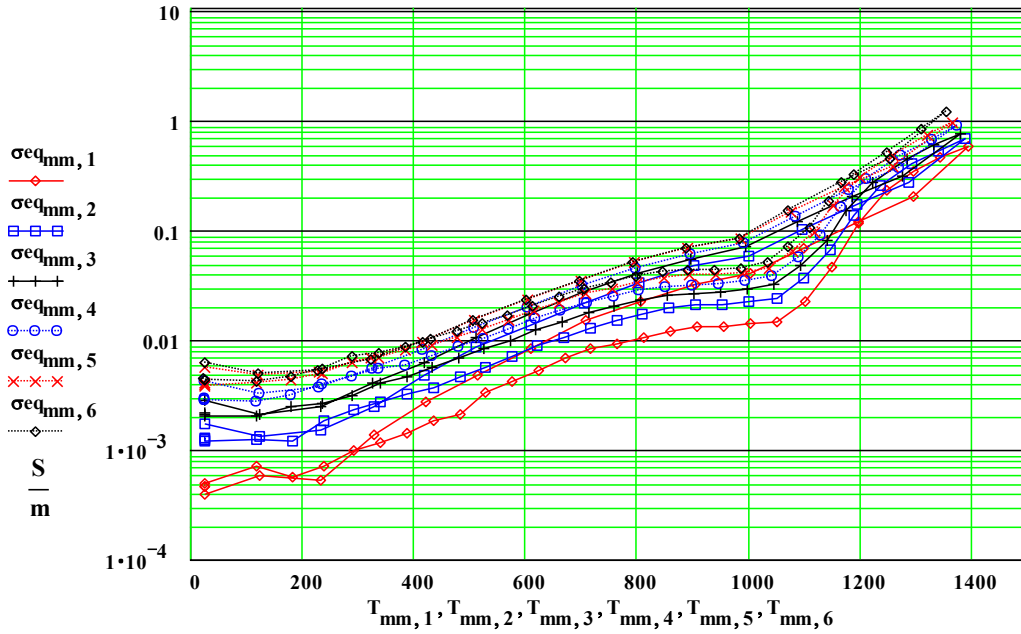
Test = 2022072101

MPN02286.mcd

AnDat = 20191023

CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN -Shulmar

Equivalent Free Electron Conductivity ( Siemens/metre)



Temperature (C)

RefRatio = 0.292

# Appendix E. MPN Reports

Test = 2022072101

MPN02286.mcd

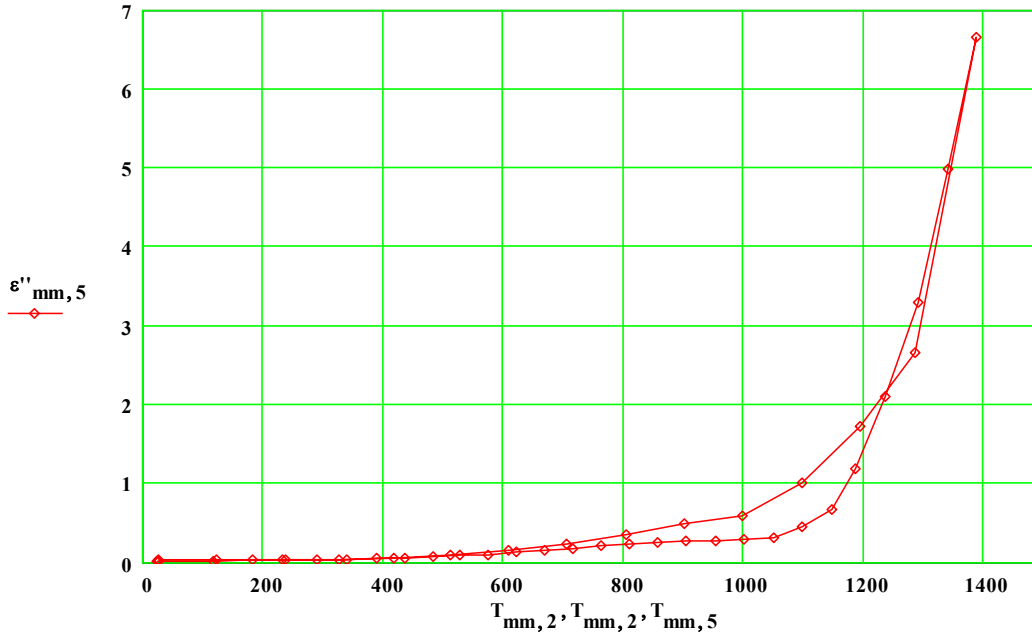
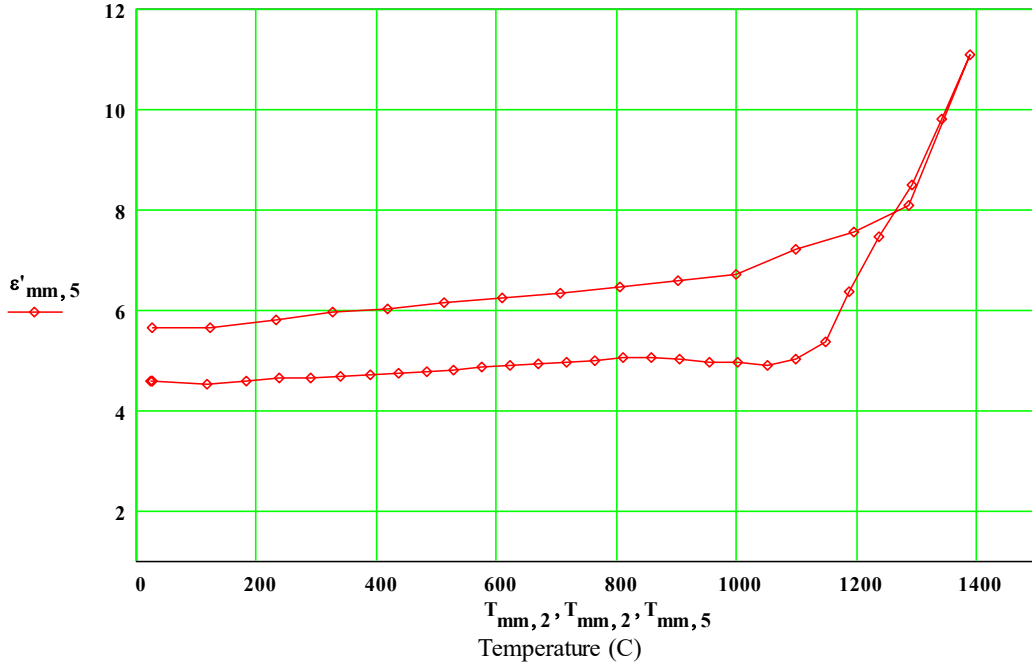
AnDat = 20191023

CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN -Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ , Thermal exp. coeff  $\alpha_1 = 0$   $\alpha_2 = 0 \cdot 10^{-6}$

Final density(25C) =  $\text{dnsfinal} = 2.39 \text{ gm/cc}$

## Values for 2450 MHz



# Appendix E. MPN Reports

Test = 2022072101

MPN02286.mcd

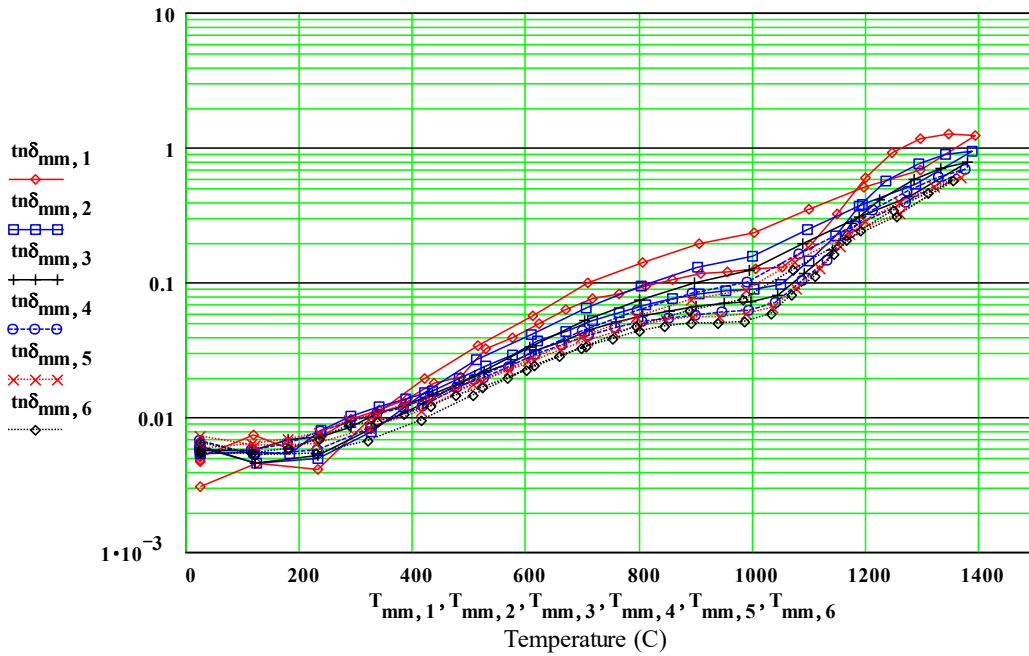
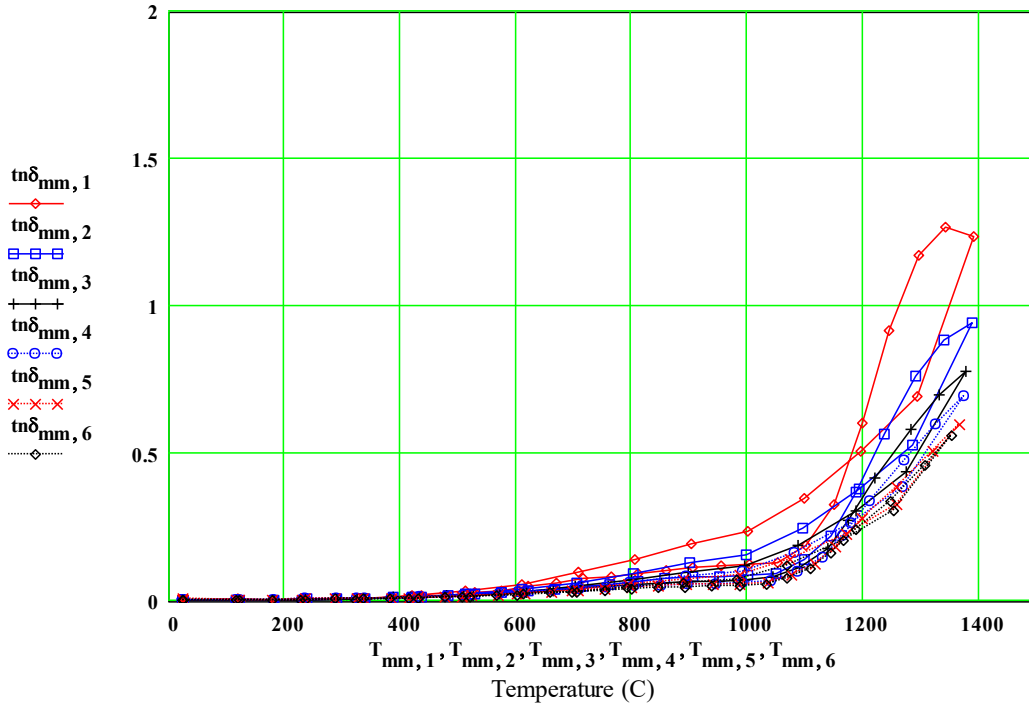
AnDat = 20191023

CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN -Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

FracMassChange = 0.997

Final density(25C) =  $\text{dnsfinal} = 2.39 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2022072101

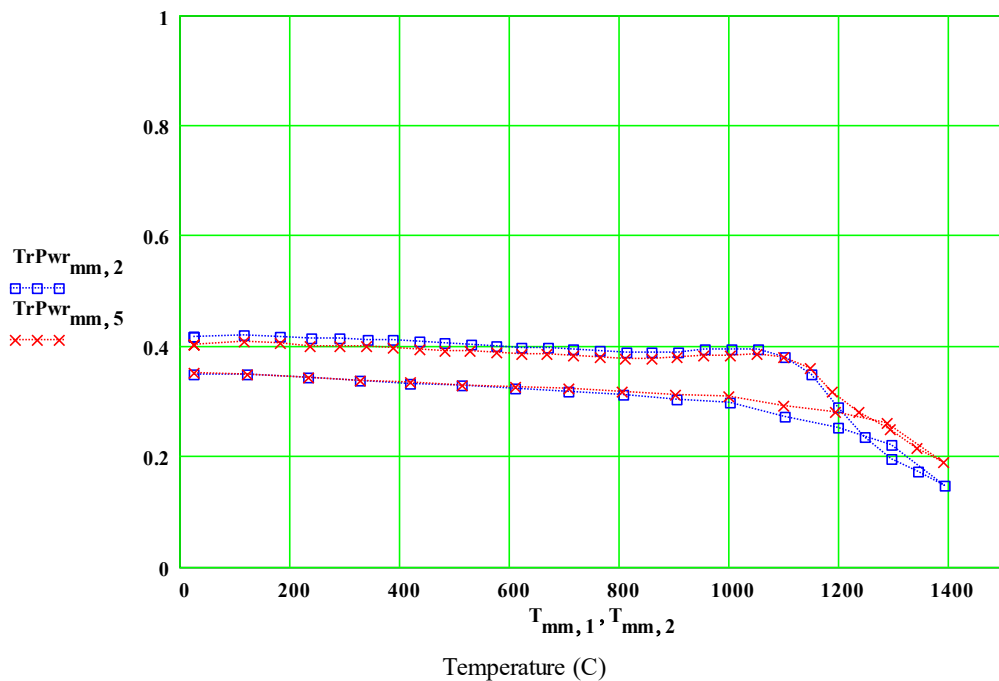
MPN02286.mcd

AnDat = 20191023

CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN -Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.39 \text{ gm/cc}$

Ratio of the Power Transmitted through an interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material



Half-power Depth (millimeters)

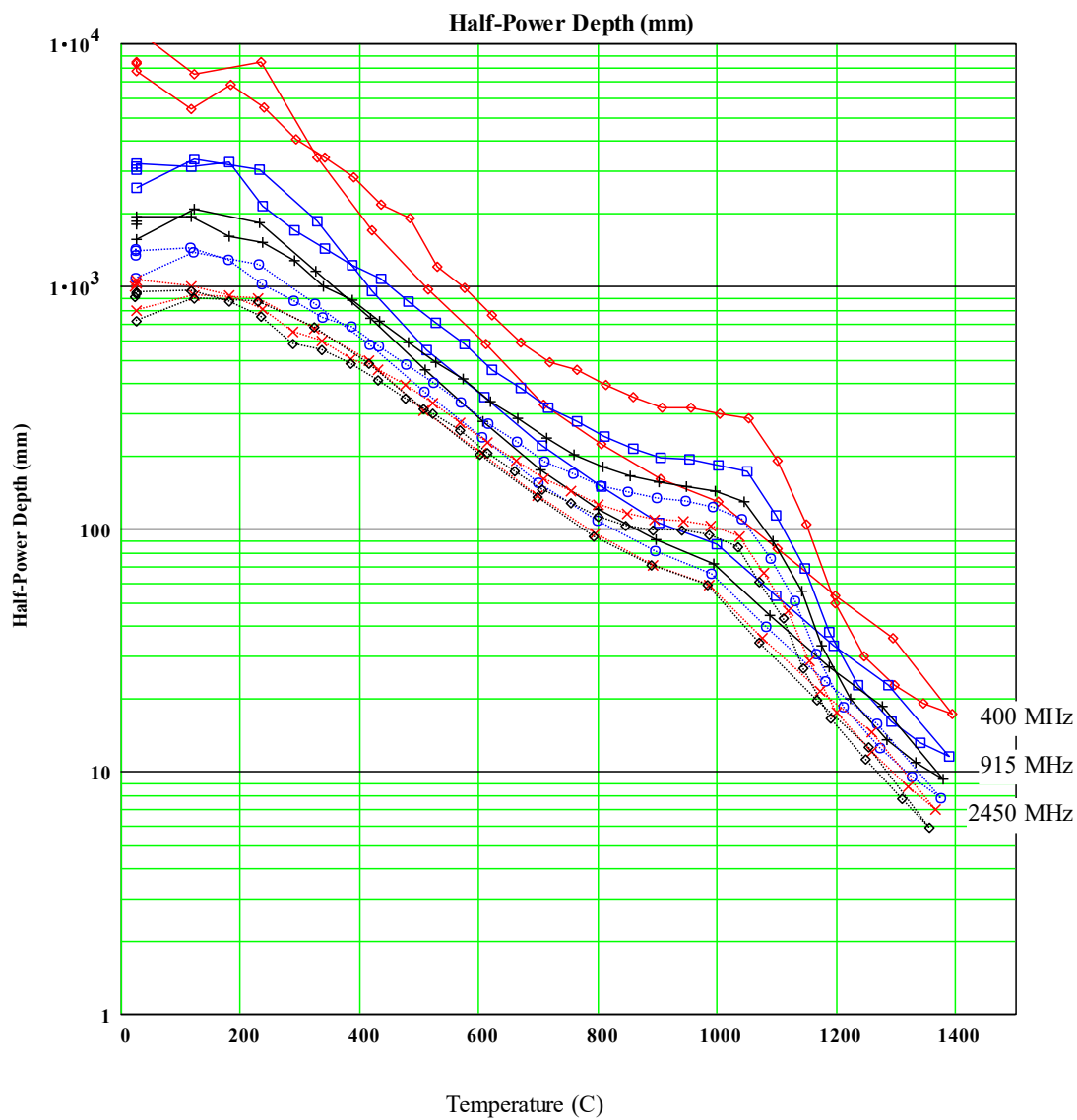
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2022072101

MPN02286.mcd

AnDat = 20191023

CSM-LHT-1G (Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN -Shulman



This fit to the conductivity ( see below) suggests an activation energy (  $E_a = E_g/2$  ) of 2.5 eV above 1100C ---- which is patently ridiculous in a crystalline material --- and is the prime indicator of softening and melting of a glass ( in my experience) !

Calculate a theoretical  $e''$  , with two possible Arrhenius dependences, with activation energy , $E_g$

Operator: Chose the Functional Dependence, Input the Chosen Values for  $E_g$  and the Intrinsic Conductivity  $\sigma_{int}$

$$E_g := 5.00 \quad \text{eV}$$

$$\sigma_{int} := 4 \cdot 10^7 \quad \text{Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \quad \text{eV/K}$$

$$\varepsilon_{ppth_{mn,n}} := \left[ \frac{\sigma_{int}}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_g}{2 \cdot k_B \cdot (T_{Q_{mn}} + 273.)} \right] \right]$$

$$\sigma_{th_{mn,n}} := \varepsilon_{ppth_{mn,n}} \cdot 2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}$$

# Appendix E. MPN Reports

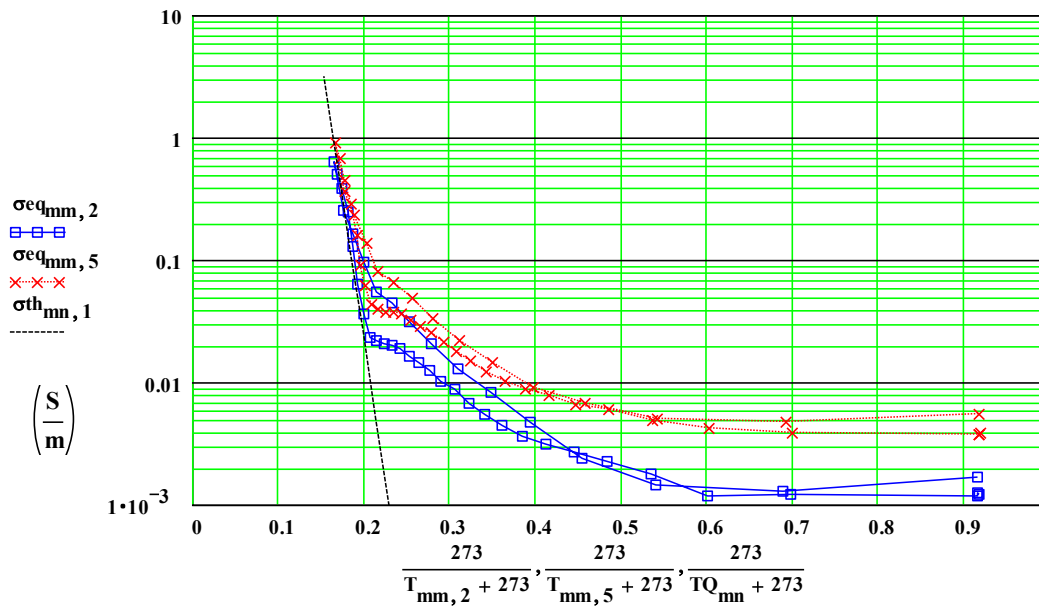
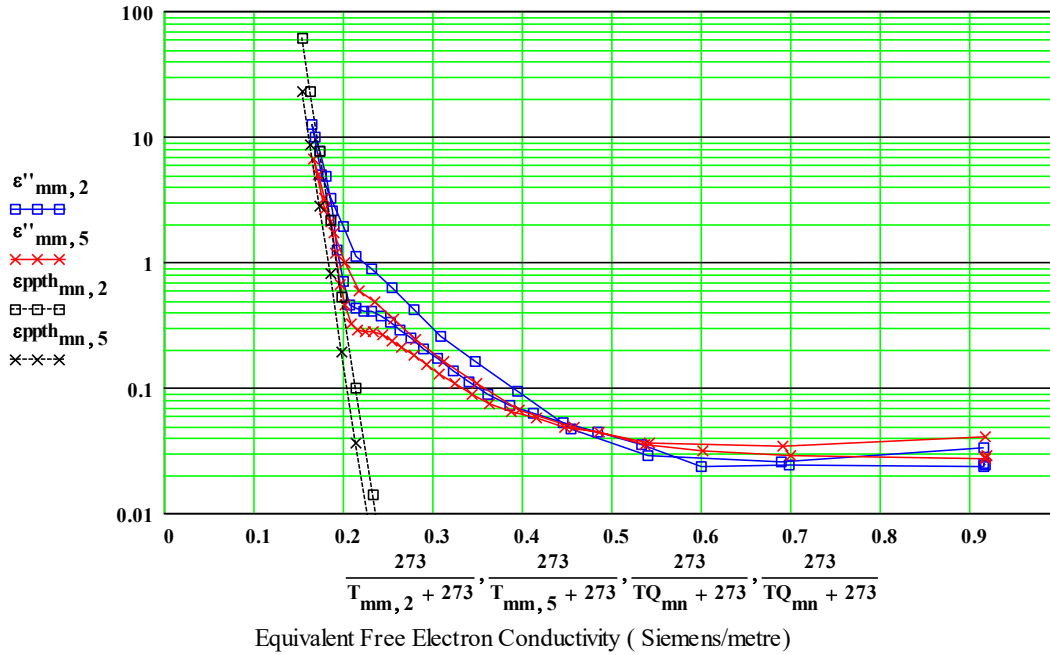
Test = 2022072101

MPN02286.med

AnDat = 20191023

CSM-LHT-1G ( Heat treated in Ar & Ar/H2 to 750C), RT - 1400C, in flowing UHP argon, for MPN - Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.39 \text{ gm/cc}$   
 $E_g = 5 \text{ eV}$ ,  $\sigma_{\text{int}} = 4 \cdot 10^7 \text{ Siemens/metre}$







MPN-231\_Shulman\_3\_Diopside D-009

August 20, 2021

Diopside (Synthetic) D-009 ( MgCa Si<sub>2</sub>O<sub>6</sub> -Monoclimic Pyroxene)  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in < 1 milli Torr Vacuum

Dr. Holly Shulman ( Shulman LLC) again requested that Microwave Properties North measure the complex dielectric properties of lab-manufactured synthetic diopside powder, up to 1100C with a direct, uninterrupted, temperature cycle, in as good a vacuum as we could produce in the MPN system. The powder sample material arrived at MPN on July 21/ 2021.

MPN pressed pellets of the powder material in a uniaxial press. The press pressure of ~ 18,000 psi was sufficient to produce pellets that could be handled. This produced pellets of a density of ~ 1.65 g/cc . The pellets were not baked to ensure dryness.

MPN was requested to cycle the sample directly up to 1100C and then return to room temperature (RT) , ) in as good a vacuum as we could produce in the MPN system.

The initial sample parameters were:

- a) diameter 3.63 +- 0.05 mm
- b) length 12.3 +- 0.1 mm
- c) mass 0.210+- 0.002 gm
- o) room temperature density  $1.65 \pm 0.07$  gm/cc.
- p) appearance - three (stacked) white pellets ( see photo).

The dielectric properties measurements were performed at RT and then the temperature was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps. The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was then run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.63 \pm 0.05$  mm
- b) length  $12.3 \pm 0.1$  mm
- c) mass  $0.209 \pm 0.002$  gm
- o) room temperature density  $1.64 \pm 0.07$  gm/cc.
- p) appearance - three white pellets

Note: The percent mass loss was zero ( +- 0.7 % ) .

The frequency coding is :

Legend for Data Plots :

| # | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|---|-----------------------|----------------------------------------------------------|
| 1 | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912                   | blue square, solid line                                  |
| 3 | 1429                  | black cross, solid line                                  |
| 4 | 1948                  | blue circle, dotted line                                 |
| 5 | 2466                  | red cross, dotted line                                   |
| 6 | 2986                  | black diamond, dotted line                               |

Comments on the data analysis:

A thermal expansion coefficient (CTE) of  $0.0 \times 10^{-6}/\text{C}$  was used.

The data for the ramp up to 1100C shows no phase transitions. No irreversible change has occurred.



Initial 3 Pellets in Holder

Values for the Temperature Cycle (to 1100 C and back to RT) :

# Appendix E. MPN Reports

Test = 2021081801

SHUL2152\_LowCal.mcd

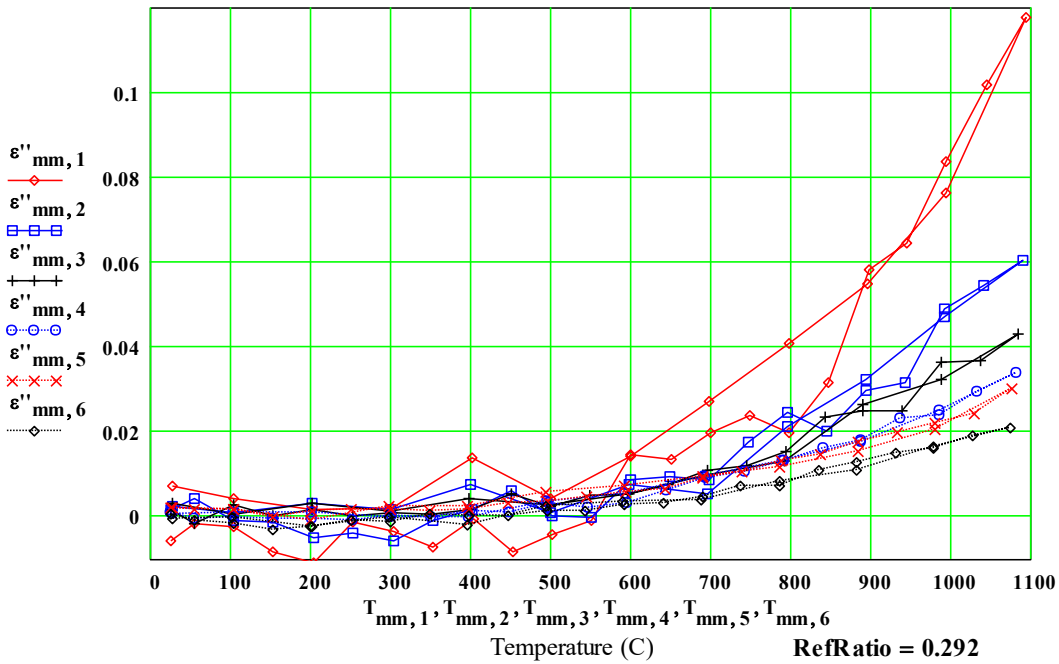
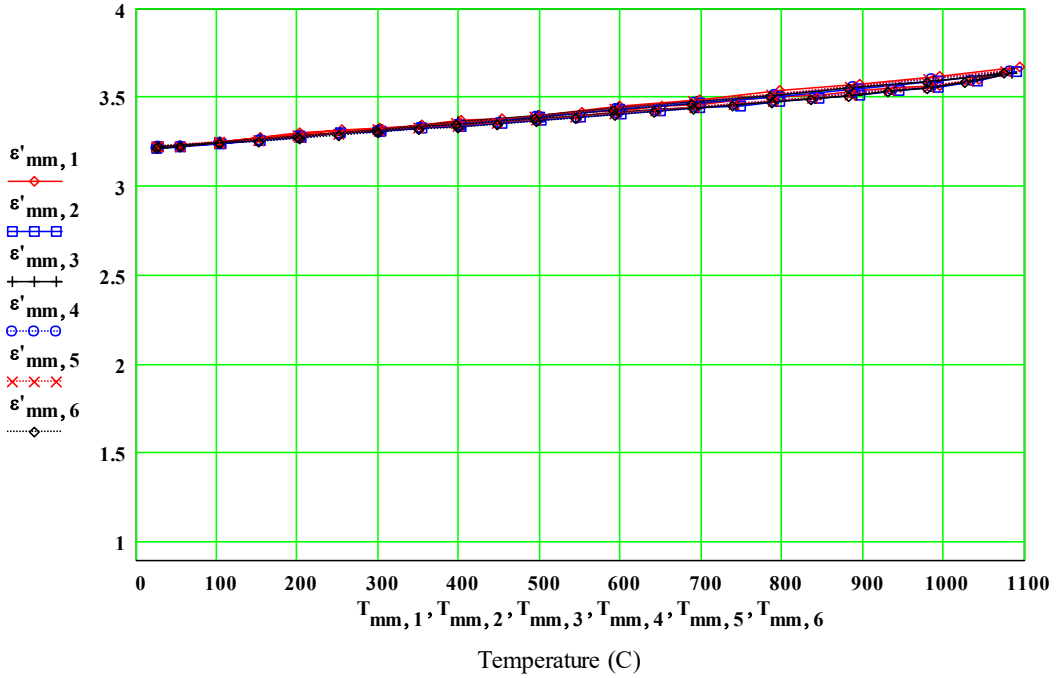
AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.65 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.64 \text{ gm/cc}$

Final\_over\_Initial\_mass = 0.995



# Appendix E. MPN Reports

Test = 2021081801

SHUL2152\_LowCal.mcd

AnDat = 20210820

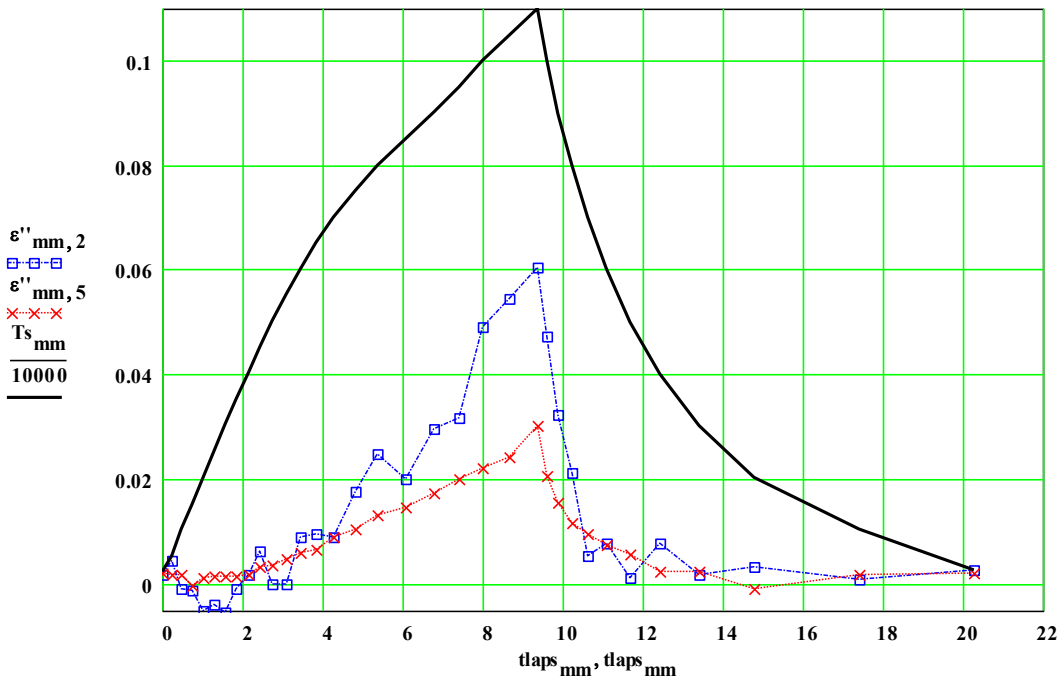
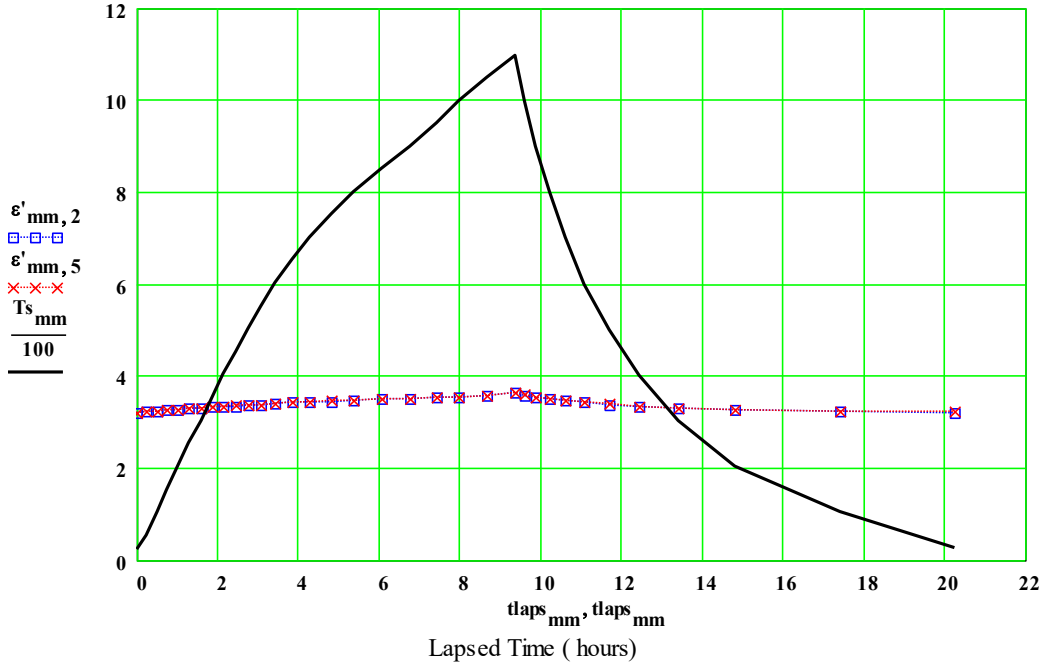
Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.65 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 1.64 \text{ gm/cc}$        $\text{FracMassChange} = 1$

$\alpha_1 = 0$





# Appendix E. MPN Reports

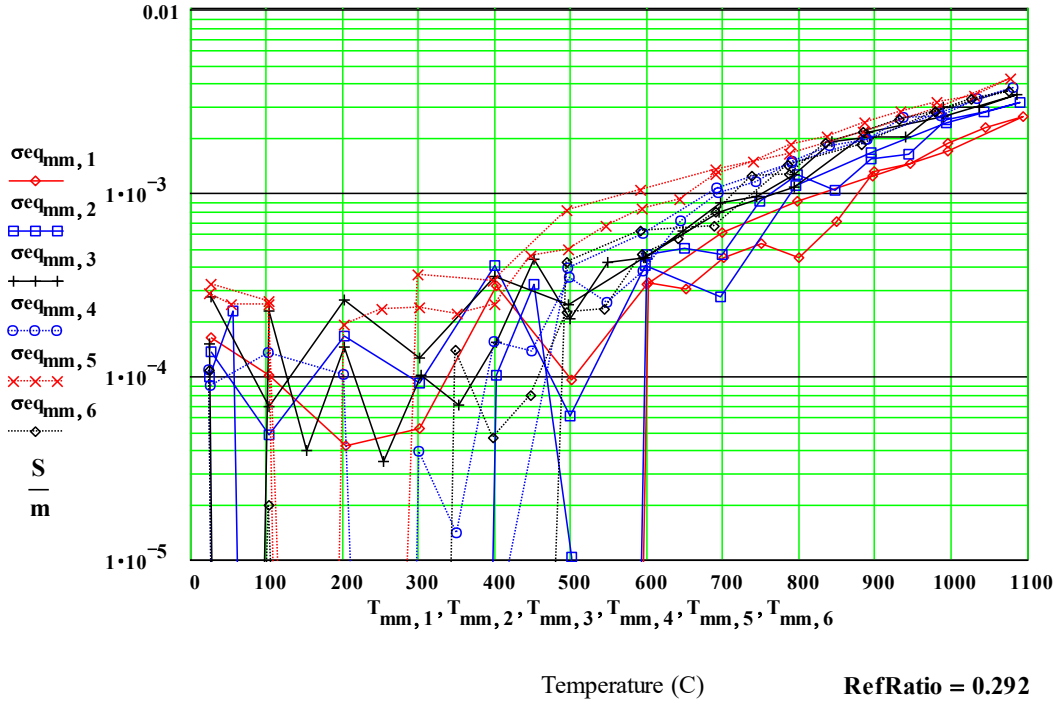
Test = 2021081801

SHUL2152\_LowCaLmed

AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2021081801

SHUL2152\_LowCal.mcd

AnDat = 20210820

T

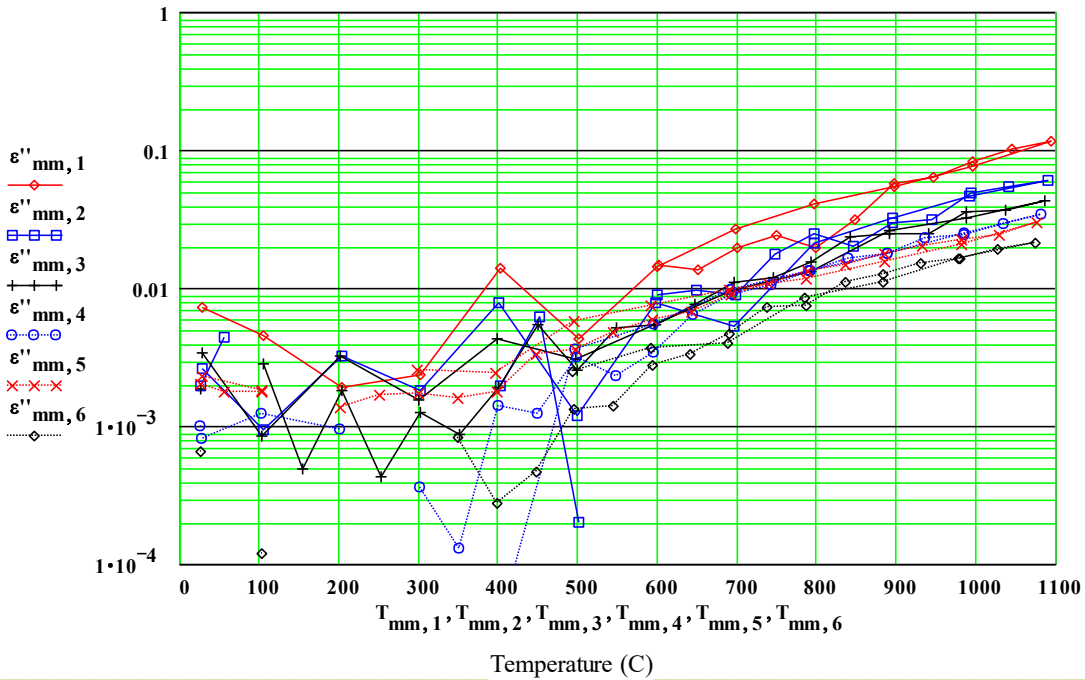
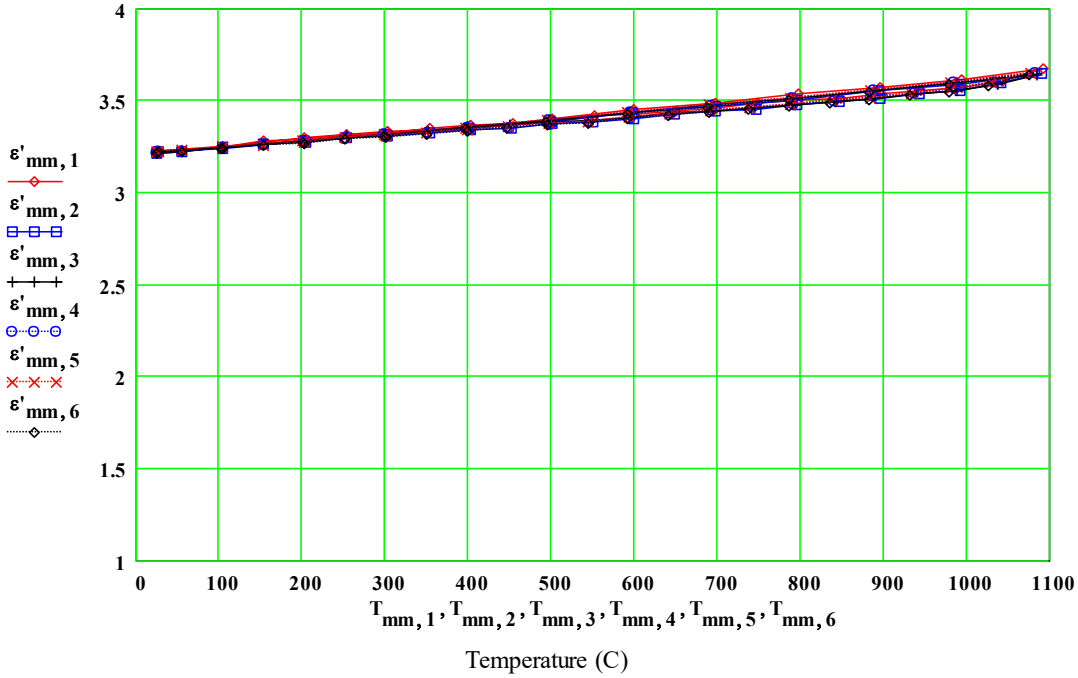
Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.65 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.64 \text{ gm/cc}$

Ir

FracMassChange = 1       $\alpha_1 = 0$  /C       $\alpha_2 = 0$  /C

F



# Appendix E. MPN Reports

Test = 2021081801

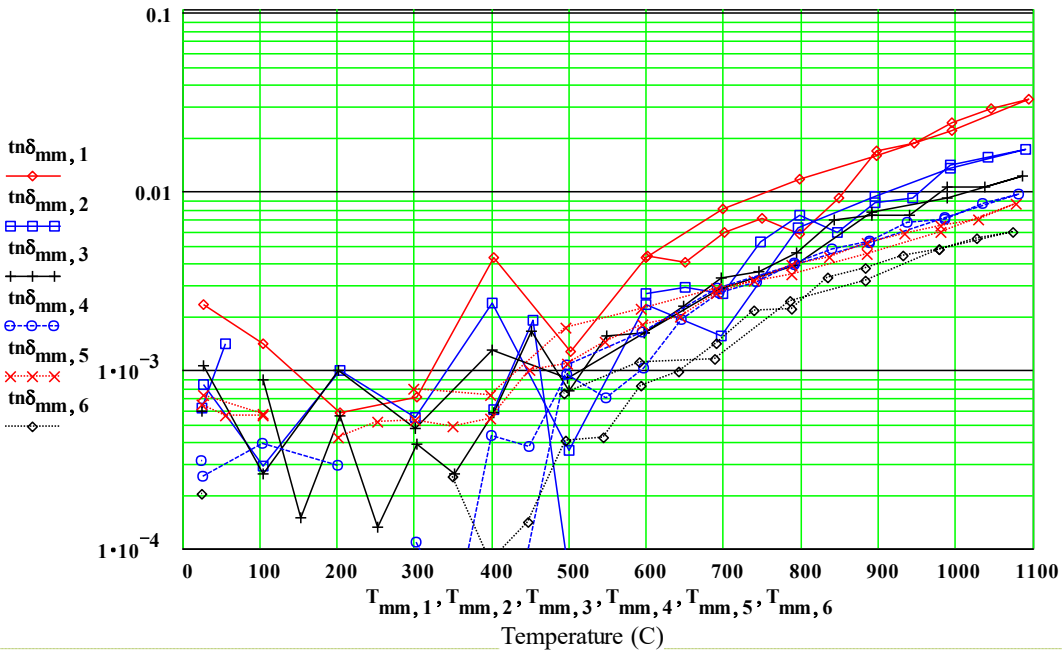
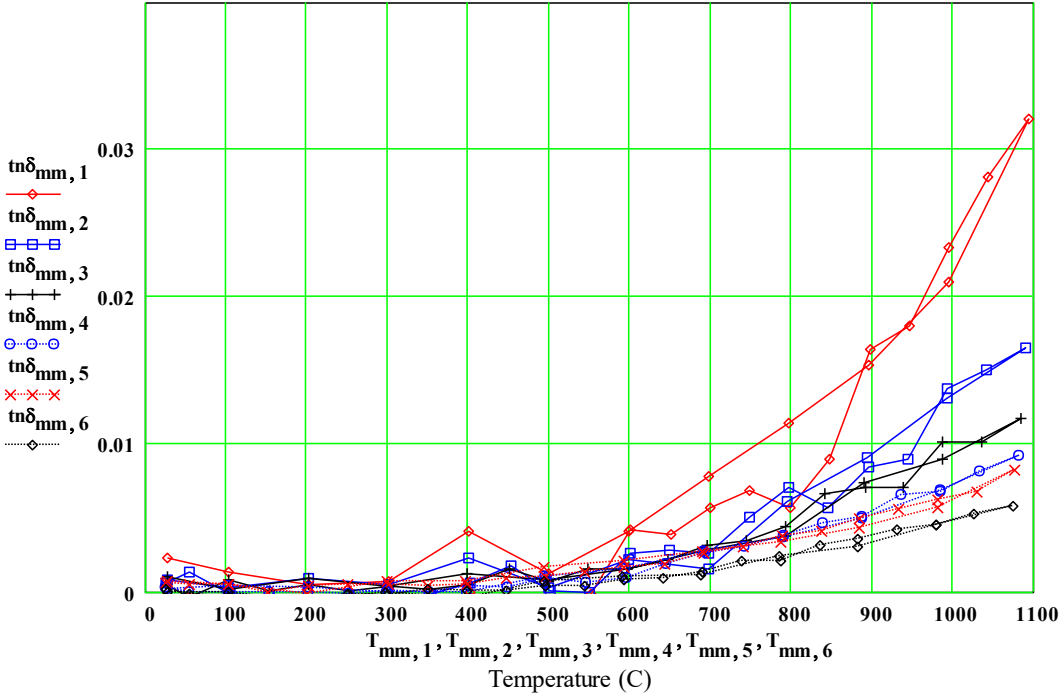
SHUL2152\_LowCal.mcd

AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.65 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.64 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2021081801

SHUL2152\_LowCal.mcd

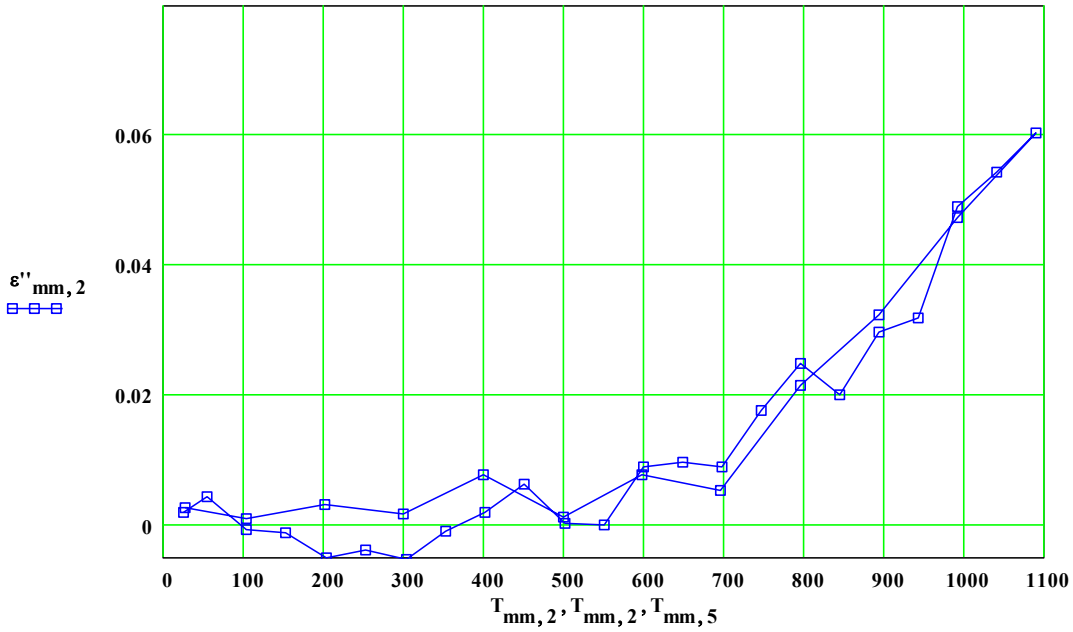
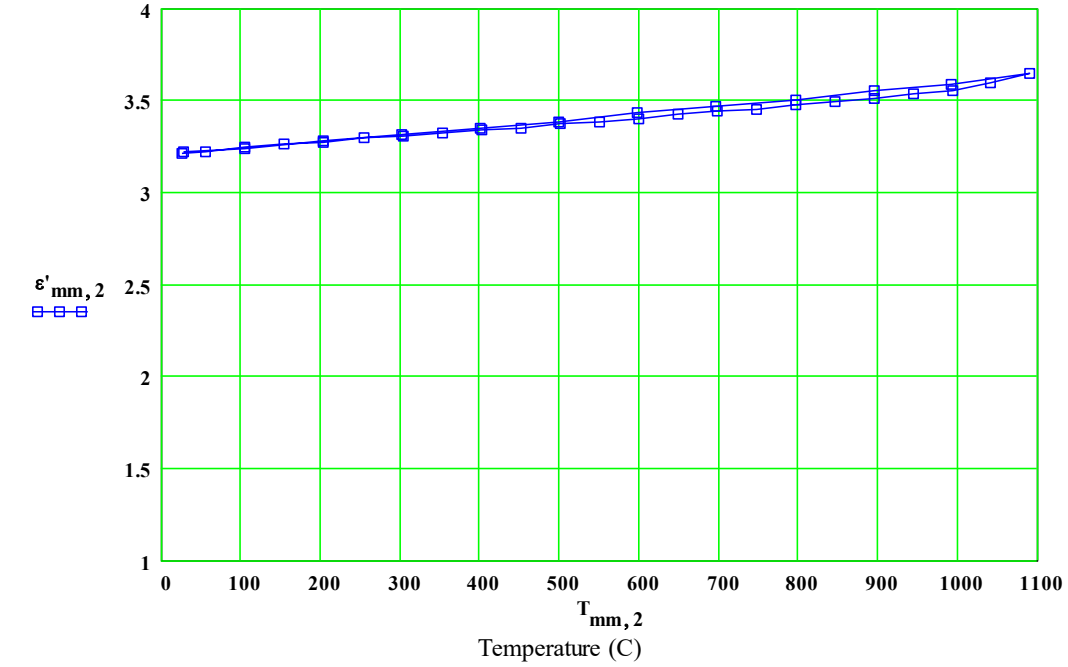
AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.65 \text{ gm/cc}$ , Thermal exp. coeff.  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 1.64 \text{ gm/cc}$

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021081801

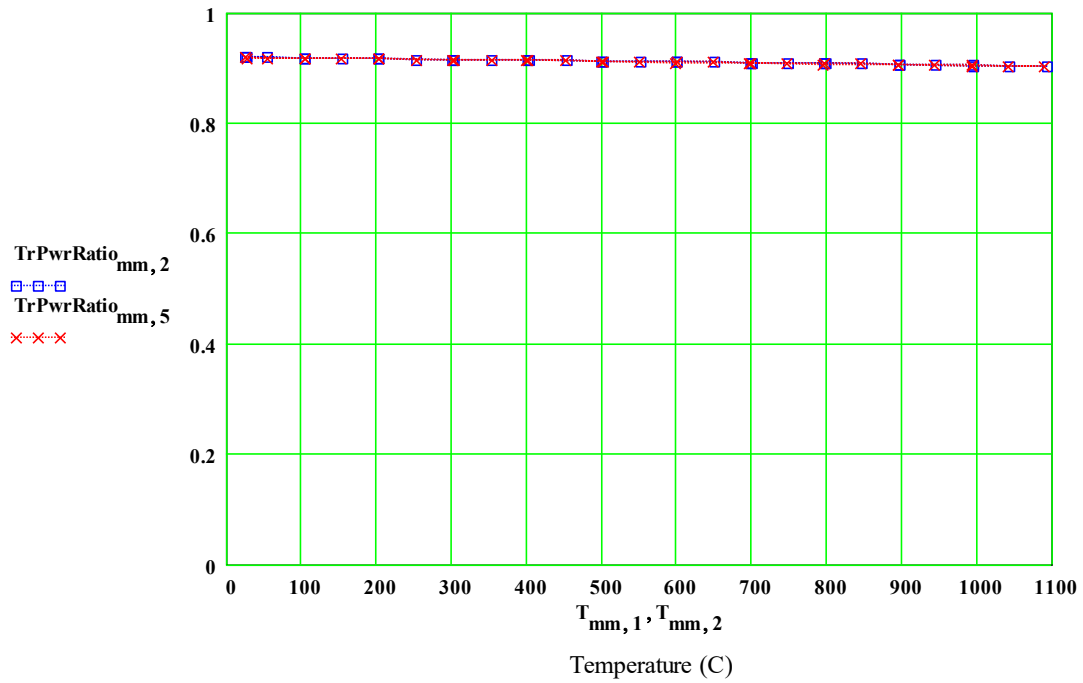
SHUL2152\_LowCal.mcd

AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.65 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.64 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



# Appendix E. MPN Reports

Half-power Depth (millimeters)

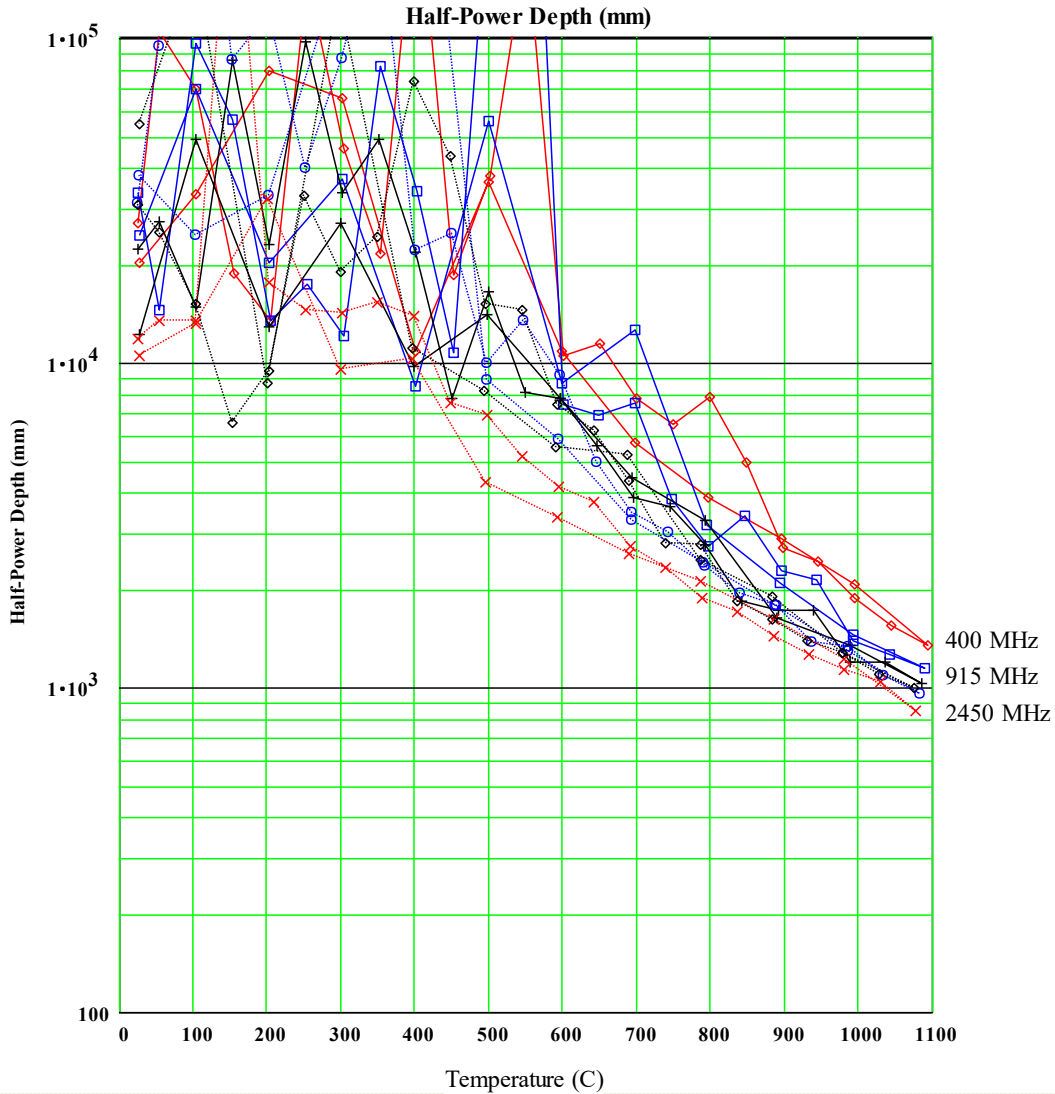
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021081801

SHUL2152\_LowCal.mcd

AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC



Fit to 'Disordered' Structure which Exists after the Highest Temperature was Attained ( 1100CFit to 'Intrinsic' Values - High Temperature

$$E_{an} := 0.57 \text{ eV}$$

$$\sigma_{intn} := 4.0 \cdot 10^{-1} \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.17$$

$$\varepsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \cos \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \varepsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}$$

$$\varepsilon_{infin_{mn}} := 3.22 + 0.15 \cdot \frac{TQ_{mn}}{400}$$

$$\varepsilon_{pthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{n_J}$$

$$\varepsilon_{pthTotal_{mn,n}} := \varepsilon_{pthJn_{mn,n}} + \varepsilon_{infin_{mn}}$$

$$H_{activ} := E_{an} \cdot 96.5 \text{ Kjoule/mol}$$

$$H_{activ} = 55 \text{ Kjoule/mol}$$

$$E_{gn} := 2 \cdot E_{an} \text{ Conduction Gap Energy}$$

$$\frac{E_{gn}}{2} = 0.57 \text{ eV}$$

**Fit to 'Extrinsic' Values - Low Temperature, Impurity Dependent :**

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$\epsilon_{ppthJm_m}$

$E_{am} := 0.0025$        $\sigma_{intm} := 0.000033$        $mJ := 0.8$

$\sigma_{infin} := 0.000099$

$$\epsilon_{ppthJm_{mn,n}} := \left[ \left[ \frac{\sigma_{intm}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \cos \left( mJ \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{mJ} \right] + \frac{\sigma_{infin}}{\left[ (2 \cdot \pi \cdot fh_n \cdot 10^6) \cdot 8.85 \cdot 10^{-12} \right]}$$

$$\sigma_{thJm_{mn,n}} := \epsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}$$

$$\epsilon_{pthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( mJ \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

$\sin \left( mJ \cdot \frac{\pi}{2} \right)$

**Sum up Extrinsic and Intrinsic Contributions :**

$\epsilon_{pthTotal_{mn,n}} := \epsilon_{pthJn_{mn,n}} + \epsilon_{pthJm_{mn,n}} + \epsilon_{infin_{mn}}$

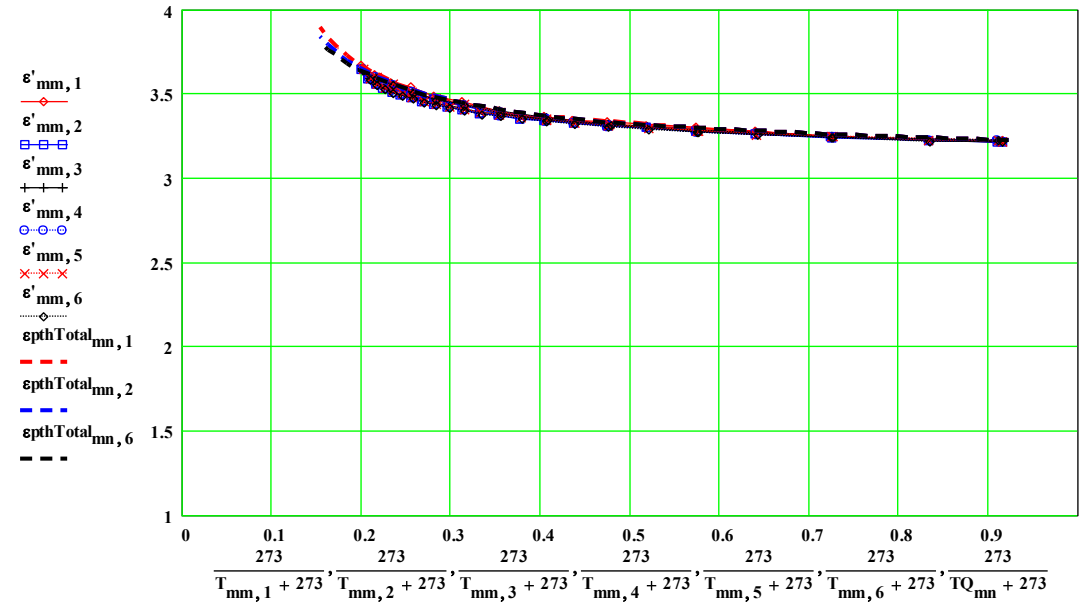
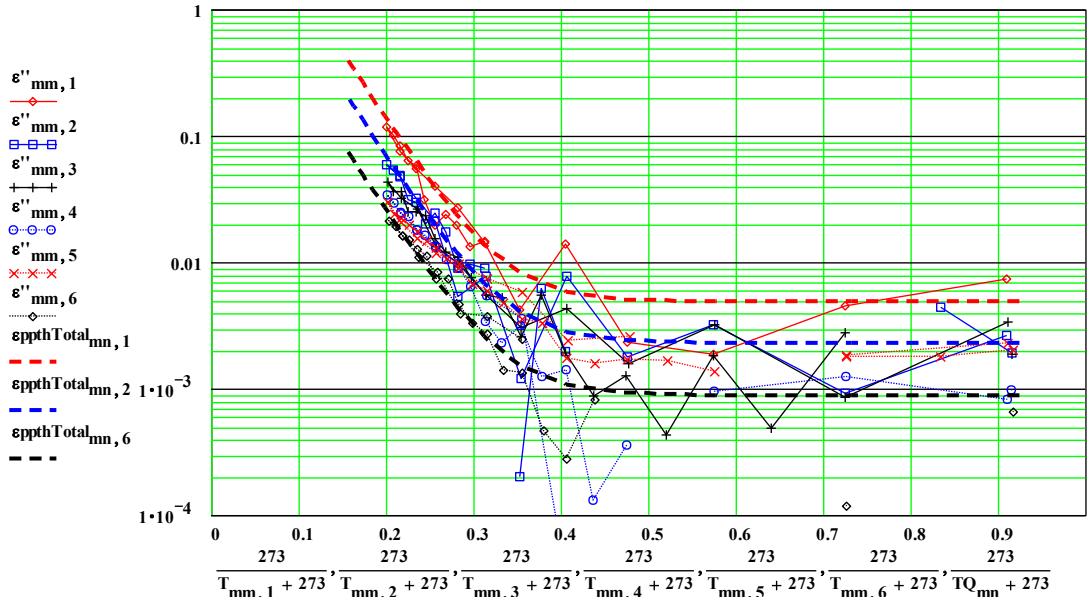
$\epsilon_{ppthTotal_{mn,n}} := \epsilon_{ppthJn_{mn,n}} + \epsilon_{ppthJm_{mn,n}}$

$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$

$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$

# Appendix E. MPN Reports

**Test = 2021081801**                      SHUL2152\_LowCal.mcd                      **AnDat = 20210820**  
 Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC  
 Final density(25C) = **dnsfinal = 1.64 gm/cc**



## Appendix E. MPN Reports

Test = 2021081801

SHUL2152\_LowCal.mcd

AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density = **samdns**<sub>NCal + 1</sub> = 1.65 gm/cc      Final density(25C) = **dnsfinal** = 1.642 gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz 2466MHz 2986MHz  
 Lapsed Time (hours)  
**samdns**<sub>mm</sub>    **T**<sub>mm,1</sub>     $\epsilon'$ <sub>mm,1</sub>     $\epsilon'$ <sub>mm,2</sub>     $\epsilon'$ <sub>mm,3</sub>     $\epsilon'$ <sub>mm,4</sub>     $\epsilon'$ <sub>mm,5</sub>     $\epsilon'$ <sub>mm,6</sub>    **tlaps**<sub>mm</sub>    **sammass**<sub>mm</sub>

|       |    |      |      |      |      |      |      |      |       |       |
|-------|----|------|------|------|------|------|------|------|-------|-------|
| 1.65  | 10 | 25   | 3.22 | 3.22 | 3.22 | 3.22 | 3.22 | 3.21 | 0     | 0.21  |
| 1.65  | 11 | 55   | 3.23 | 3.22 | 3.23 | 3.22 | 3.23 | 3.22 | 0.24  | 0.21  |
| 1.65  | 12 | 104  | 3.25 | 3.25 | 3.25 | 3.24 | 3.25 | 3.24 | 0.49  | 0.21  |
| 1.65  | 13 | 154  | 3.28 | 3.26 | 3.27 | 3.26 | 3.26 | 3.25 | 0.76  | 0.21  |
| 1.65  | 14 | 204  | 3.3  | 3.28 | 3.28 | 3.27 | 3.28 | 3.27 | 1.02  | 0.21  |
| 1.65  | 15 | 254  | 3.32 | 3.3  | 3.31 | 3.29 | 3.3  | 3.29 | 1.3   | 0.21  |
| 1.65  | 16 | 304  | 3.33 | 3.31 | 3.32 | 3.31 | 3.31 | 3.3  | 1.58  | 0.21  |
| 1.65  | 17 | 353  | 3.35 | 3.33 | 3.34 | 3.33 | 3.33 | 3.32 | 1.86  | 0.21  |
| 1.65  | 18 | 403  | 3.37 | 3.34 | 3.35 | 3.34 | 3.34 | 3.33 | 2.14  | 0.21  |
| 1.65  | 19 | 453  | 3.38 | 3.36 | 3.37 | 3.36 | 3.36 | 3.35 | 2.44  | 0.21  |
| 1.65  | 20 | 502  | 3.39 | 3.37 | 3.39 | 3.37 | 3.38 | 3.37 | 2.75  | 0.21  |
| 1.65  | 21 | 551  | 3.42 | 3.39 | 3.4  | 3.39 | 3.39 | 3.38 | 3.08  | 0.21  |
| 1.65  | 22 | 601  | 3.43 | 3.41 | 3.42 | 3.41 | 3.41 | 3.4  | 3.44  | 0.21  |
| 1.65  | 23 | 650  | 3.45 | 3.43 | 3.43 | 3.43 | 3.43 | 3.42 | 3.83  | 0.21  |
| 1.65  | 24 | 700  | 3.47 | 3.44 | 3.45 | 3.44 | 3.44 | 3.43 | 4.27  | 0.21  |
| 1.65  | 25 | 749  | 3.49 | 3.46 | 3.46 | 3.46 | 3.46 | 3.45 | 4.81  | 0.21  |
| 1.65  | 26 | 798  | 3.51 | 3.48 | 3.48 | 3.48 | 3.48 | 3.47 | 5.38  | 0.21  |
| 1.65  | 27 | 848  | 3.52 | 3.5  | 3.5  | 3.5  | 3.5  | 3.49 | 6.07  | 0.21  |
| 1.65  | 28 | 897  | 3.54 | 3.52 | 3.52 | 3.52 | 3.52 | 3.51 | 6.77  | 0.21  |
| 1.65  | 29 | 946  | 3.56 | 3.54 | 3.54 | 3.54 | 3.54 | 3.53 | 7.42  | 0.21  |
| 1.642 | 30 | 995  | 3.57 | 3.56 | 3.56 | 3.56 | 3.56 | 3.55 | 7.98  | 0.209 |
| 1.642 | 31 | 1044 | 3.61 | 3.6  | 3.59 | 3.6  | 3.6  | 3.59 | 8.68  | 0.209 |
| 1.642 | 32 | 1093 | 3.67 | 3.65 | 3.64 | 3.65 | 3.65 | 3.64 | 9.37  | 0.209 |
| 1.642 | 33 | 995  | 3.62 | 3.59 | 3.6  | 3.6  | 3.6  | 3.59 | 9.62  | 0.209 |
| 1.642 | 34 | 896  | 3.57 | 3.55 | 3.56 | 3.56 | 3.56 | 3.55 | 9.89  | 0.209 |
| 1.642 | 35 | 797  | 3.54 | 3.51 | 3.51 | 3.51 | 3.52 | 3.51 | 10.22 | 0.209 |
| 1.642 | 36 | 698  | 3.49 | 3.47 | 3.48 | 3.47 | 3.48 | 3.47 | 10.62 | 0.209 |
| 1.642 | 37 | 599  | 3.46 | 3.43 | 3.44 | 3.43 | 3.44 | 3.43 | 11.1  | 0.209 |
| 1.642 | 38 | 500  | 3.4  | 3.39 | 3.4  | 3.39 | 3.39 | 3.39 | 11.69 | 0.209 |
| 1.642 | 39 | 401  | 3.36 | 3.35 | 3.36 | 3.35 | 3.36 | 3.35 | 12.43 | 0.209 |
| 1.642 | 40 | 302  | 3.33 | 3.31 | 3.32 | 3.31 | 3.32 | 3.31 | 13.4  | 0.209 |
| 1.642 | 41 | 203  | 3.3  | 3.28 | 3.29 | 3.28 | 3.29 | 3.28 | 14.8  | 0.209 |
| 1.642 | 42 | 104  | 3.25 | 3.24 | 3.25 | 3.24 | 3.25 | 3.24 | 17.43 | 0.209 |
| 1.642 | 43 | 27   | 3.22 | 3.22 | 3.23 | 3.22 | 3.23 | 3.22 | 20.26 | 0.209 |

Appendix E. MPN Reports

Test = 2021081801

SHUL2152\_LowCal.mcd

AnDat = 20210820

Diopside (synthetic) D-009, 1250 cs, 7/6/21, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.65$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 1.642$  gm/cc

Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz

Time

(hours)

| samdns <sub>mm</sub> | T <sub>mm,1</sub> | $\epsilon''_{\text{mm},1}$ | $\epsilon''_{\text{mm},2}$ | $\epsilon''_{\text{mm},3}$ | $\epsilon''_{\text{mm},4}$ | $\epsilon''_{\text{mm},5}$ | $\epsilon''_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |       |
|----------------------|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|-------|
| 1.65                 | 10                | 25                         | -0.006                     | 0.002                      | 0.002                      | 0.001                      | 0.002                      | 0.001               | 0                    | 0.21  |
| 1.65                 | 11                | 55                         | -0.001                     | 0.004                      | -0.002                     | -0                         | 0.002                      | -0.001              | 0.24                 | 0.21  |
| 1.65                 | 12                | 104                        | -0.002                     | -0.001                     | 0.003                      | -0                         | 0.002                      | -0.001              | 0.49                 | 0.21  |
| 1.65                 | 13                | 154                        | -0.008                     | -0.001                     | 0                          | -0                         | -0                         | -0.003              | 0.76                 | 0.21  |
| 1.65                 | 14                | 204                        | -0.011                     | -0.005                     | 0.002                      | -0                         | 0.001                      | -0.002              | 1.02                 | 0.21  |
| 1.65                 | 15                | 254                        | -0.001                     | -0.004                     | 0                          | -0.001                     | 0.002                      | -0.001              | 1.3                  | 0.21  |
| 1.65                 | 16                | 304                        | -0.003                     | -0.005                     | 0.001                      | 0                          | 0.002                      | -0.001              | 1.58                 | 0.21  |
| 1.65                 | 17                | 353                        | -0.007                     | -0.001                     | 0.001                      | 0                          | 0.002                      | 0.001               | 1.86                 | 0.21  |
| 1.65                 | 18                | 403                        | -0.001                     | 0.002                      | 0.002                      | 0.001                      | 0.002                      | 0                   | 2.14                 | 0.21  |
| 1.65                 | 19                | 453                        | -0.008                     | 0.006                      | 0.005                      | 0.001                      | 0.003                      | 0                   | 2.44                 | 0.21  |
| 1.65                 | 20                | 502                        | -0.004                     | 0                          | 0.003                      | 0.003                      | 0.004                      | 0.001               | 2.75                 | 0.21  |
| 1.65                 | 21                | 551                        | -0.001                     | -0                         | 0.005                      | 0.002                      | 0.005                      | 0.001               | 3.08                 | 0.21  |
| 1.65                 | 22                | 601                        | 0.015                      | 0.009                      | 0.006                      | 0.003                      | 0.006                      | 0.003               | 3.44                 | 0.21  |
| 1.65                 | 23                | 650                        | 0.014                      | 0.01                       | 0.008                      | 0.006                      | 0.007                      | 0.003               | 3.83                 | 0.21  |
| 1.65                 | 24                | 700                        | 0.02                       | 0.009                      | 0.011                      | 0.009                      | 0.009                      | 0.005               | 4.27                 | 0.21  |
| 1.65                 | 25                | 749                        | 0.024                      | 0.018                      | 0.012                      | 0.011                      | 0.011                      | 0.007               | 4.81                 | 0.21  |
| 1.65                 | 26                | 798                        | 0.02                       | 0.025                      | 0.016                      | 0.013                      | 0.013                      | 0.007               | 5.38                 | 0.21  |
| 1.65                 | 27                | 848                        | 0.032                      | 0.02                       | 0.024                      | 0.016                      | 0.015                      | 0.011               | 6.07                 | 0.21  |
| 1.65                 | 28                | 897                        | 0.058                      | 0.03                       | 0.025                      | 0.018                      | 0.018                      | 0.013               | 6.77                 | 0.21  |
| 1.65                 | 29                | 946                        | 0.065                      | 0.032                      | 0.025                      | 0.023                      | 0.02                       | 0.015               | 7.42                 | 0.21  |
| 1.642                | 30                | 995                        | 0.084                      | 0.049                      | 0.036                      | 0.024                      | 0.022                      | 0.016               | 7.98                 | 0.209 |
| 1.642                | 31                | 1044                       | 0.102                      | 0.054                      | 0.037                      | 0.03                       | 0.024                      | 0.019               | 8.68                 | 0.209 |
| 1.642                | 32                | 1093                       | 0.118                      | 0.06                       | 0.043                      | 0.034                      | 0.03                       | 0.021               | 9.37                 | 0.209 |
| 1.642                | 33                | 995                        | 0.076                      | 0.047                      | 0.033                      | 0.025                      | 0.021                      | 0.016               | 9.62                 | 0.209 |
| 1.642                | 34                | 896                        | 0.055                      | 0.033                      | 0.027                      | 0.018                      | 0.016                      | 0.011               | 9.89                 | 0.209 |
| 1.642                | 35                | 797                        | 0.041                      | 0.021                      | 0.013                      | 0.013                      | 0.012                      | 0.008               | 10.22                | 0.209 |
| 1.642                | 36                | 698                        | 0.027                      | 0.005                      | 0.01                       | 0.01                       | 0.01                       | 0.004               | 10.62                | 0.209 |
| 1.642                | 37                | 599                        | 0.014                      | 0.008                      | 0.006                      | 0.005                      | 0.007                      | 0.004               | 11.1                 | 0.209 |
| 1.642                | 38                | 500                        | 0.004                      | 0.001                      | 0.003                      | 0.004                      | 0.006                      | 0.002               | 11.69                | 0.209 |
| 1.642                | 39                | 401                        | 0.014                      | 0.008                      | 0.004                      | 0                          | 0.002                      | -0.002              | 12.43                | 0.209 |
| 1.642                | 40                | 302                        | 0.002                      | 0.002                      | 0.002                      | -0                         | 0.003                      | -0                  | 13.4                 | 0.209 |
| 1.642                | 41                | 203                        | 0.002                      | 0.003                      | 0.003                      | 0.001                      | -0.001                     | -0.002              | 14.8                 | 0.209 |
| 1.642                | 42                | 104                        | 0.005                      | 0.001                      | 0.001                      | 0.001                      | 0.002                      | 0                   | 17.43                | 0.209 |
| 1.642                | 43                | 27                         | 0.007                      | 0.003                      | 0.003                      | 0.001                      | 0.002                      | -0                  | 20.26                | 0.209 |

MPN-242\_MPN\_Diopside with Actinolite

Nov. 30, 2021

Diopside (a Pyroxene) with Actinolite  
Measurements of Complex Dielectric Constant Between 400 and 2985 MHz  
from Room Temperature to 1100°C to RT, in < 1 milliTorr Vacuum

Jozef Mouris and Ronald Hutcheon

MPN purchased a sample of “massive” Diopside, a calcium-magnesium- silicate ( $\text{CaMgSi}_2\text{O}_6$ ) from Minerals Unlimited ( see photo).

Diamond core-drilling produced a solid, cylindrical, measurement test sample. This sample was baked at 140C in air for two hours to ensure dryness after the core-drilling.

MPN used a measurement cycle up to 1100C and then returning to room temperature (RT), in as good a vacuum as we could produce in the MPN system – which currently is < 1 milliTorr .

The initial sample parameters were:

- a) diameter 3.77 +- 0.05 mm
- b) length 12.17 +- 0.20 mm
- c) mass 0.420+- 0.002 gm
- q) room temperature density  $3.09 \pm 0.15$  gm/cc.
- r) appearance - light grey rod ( see photo) .

The dielectric properties measurements were performed at RT, 50C, and then was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was then run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.78 \pm 0.03$  mm
- b) length  $12.29 \pm 0.1$  mm
- c) mass  $0.417 \pm 0.002$  gm
- q) room temperature density  $3.02 \pm 0.15$  gm/cc.
- r) appearance - grey rod ( see photo)

Note: The percent mass loss was  $0.7 \pm 1$  % .

The frequency coding is :

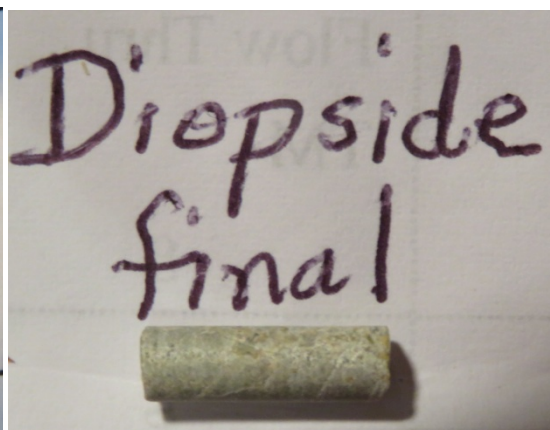
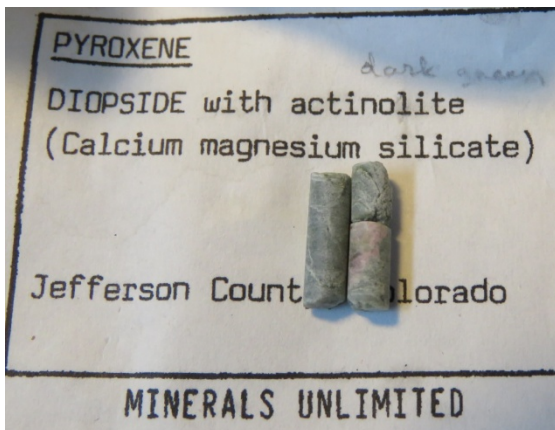
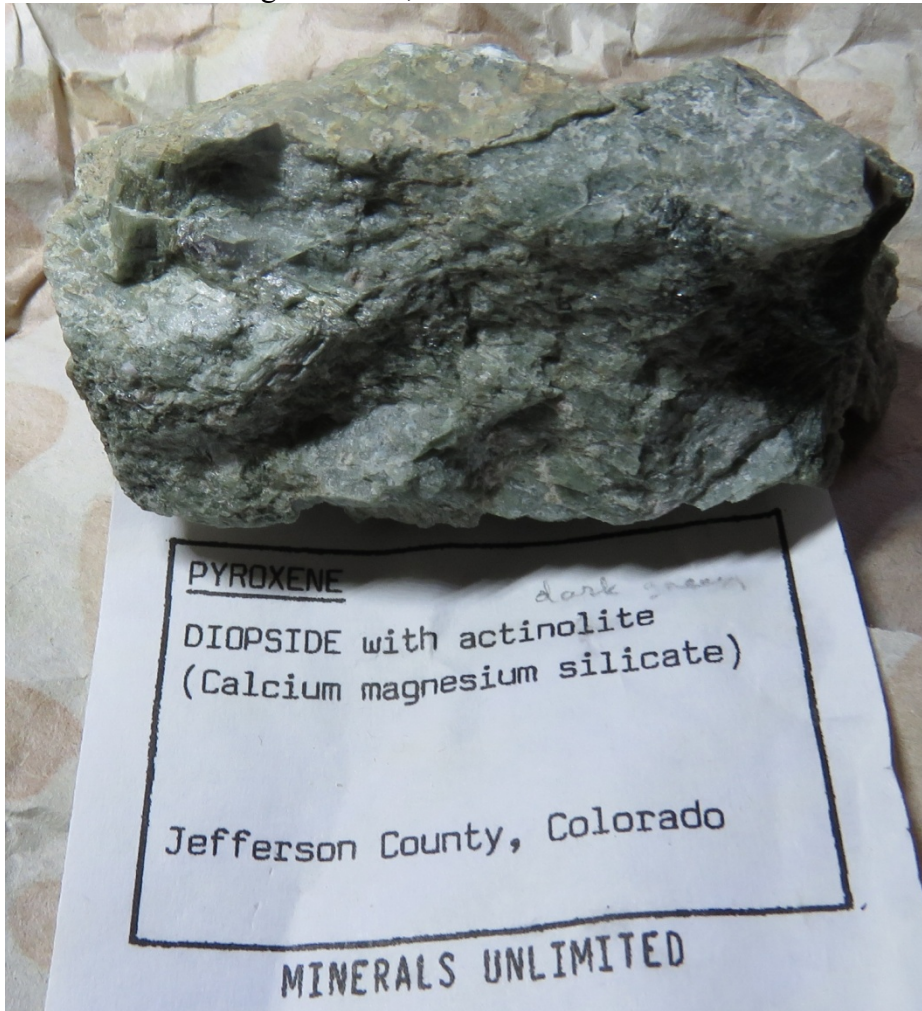
Legend for Data Plots :

| # | Frequency(MHz) | Symbol                                                   |
|---|----------------|----------------------------------------------------------|
| 1 | 397            | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912            | blue square, solid line                                  |
| 3 | 1429           | black cross, solid line                                  |
| 4 | 1948           | blue circle, dotted line                                 |
| 5 | 2466           | red cross, dotted line                                   |
| 6 | 2986           | black diamond, dotted line                               |

Comments on the data analysis:

A linear thermal expansion coefficient ( CTE) of  $10.0 * 10^{-6}/\text{C}$  was used.

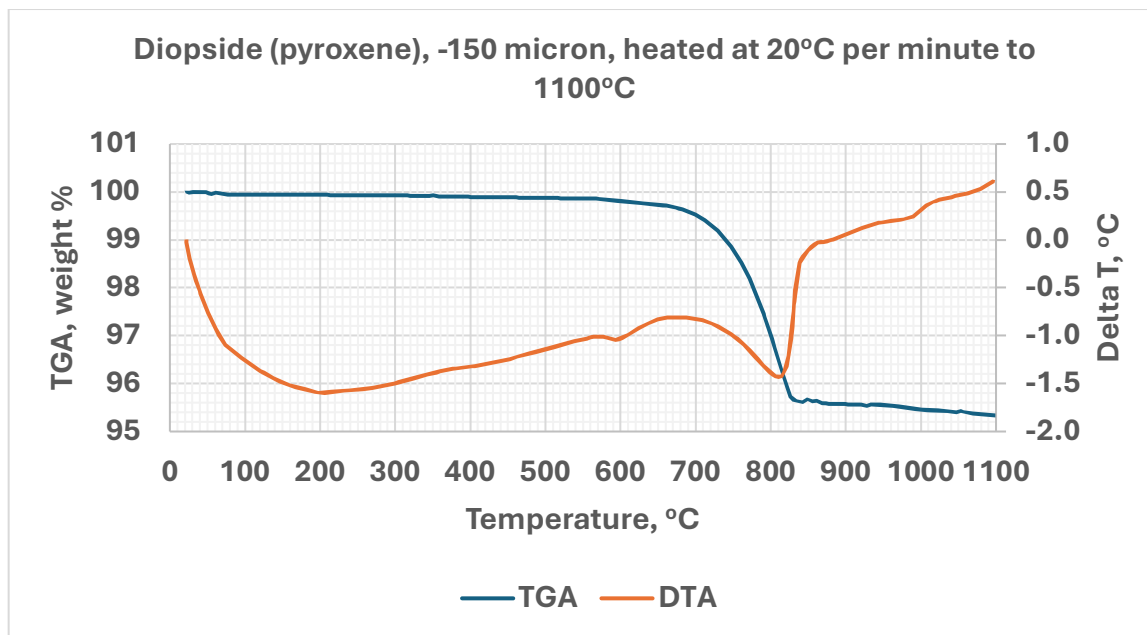
Reference is Finger & Ohashi, "Thermal Expansion of Diopside to 800C",  
American Mineralogist Vol. 61, 1976



Two initial samples, one broken .  
vacuum.

Final sample after run to 1100C in

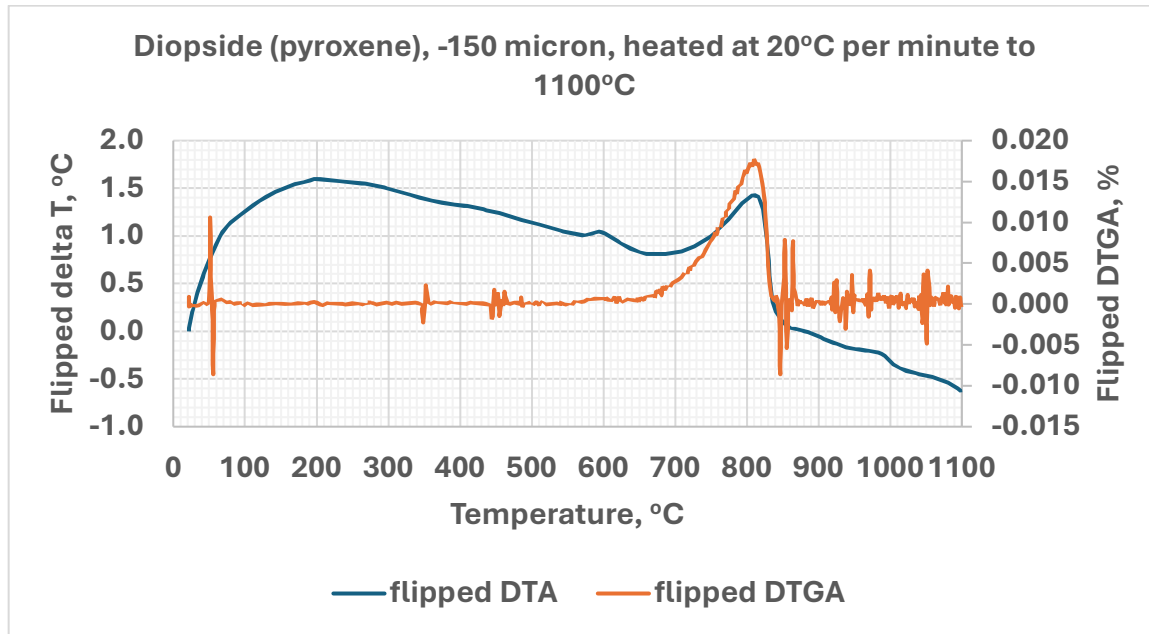
DTA/TGA in Air, by Dr.Peter Hayward, Eutechnics Consulting Inc.,  
Box 718, 3 Monck Place, Pinawa, Manitoba, Canada R0E 1L0 .



Weight loss at 1100C from TGA data = 4.67%

Final weight loss after cooling (from an external balance) = 4,85%, i.e., pretty good agreement

Final sample was a pale brown powder. Note that the original sample was a very pale green powder



Inverted DTA/DTGA plots which often show peaks where the density of diffusing ions is maximum. This may indicate locations of peaks in the plot of  $\epsilon''$  versus temperature.

Values for the Temperature Cycle (to 1100 C and back to RT) :

# Appendix E. MPN Reports

Test = 2021112801

MPN02181\_CalModLowCa.mcd

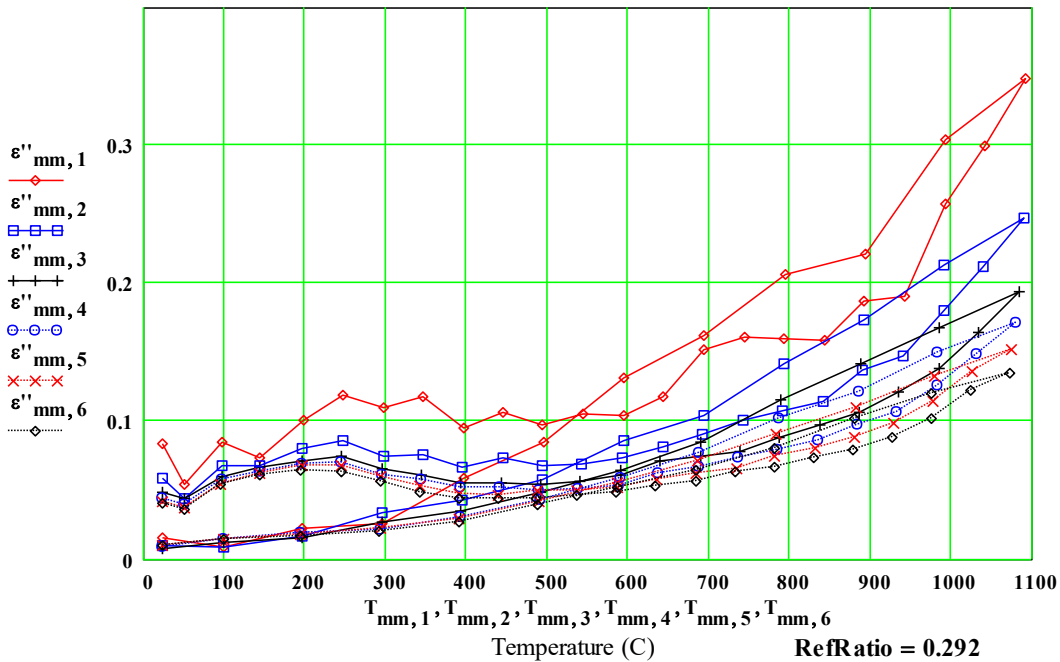
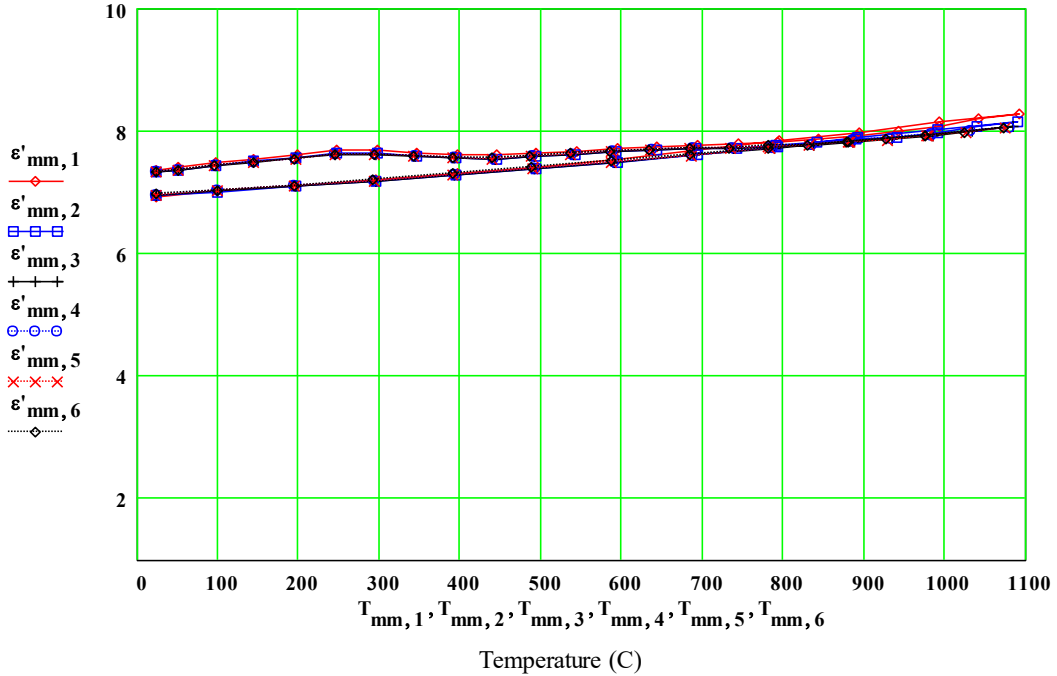
AnDat = 20211128

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 3.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 3.02 \text{ gm/cc}$

Final\_over\_Initial\_mass = 0.993



The data for the ramp up to 1100C shows weak evidence of an extended phase transition starting at ~ 250C and ending at 700 C. There also appeared to be an irreversible change in the material which occurred between 950C and 1100C. However, there was no significant mass loss!

# Appendix E. MPN Reports

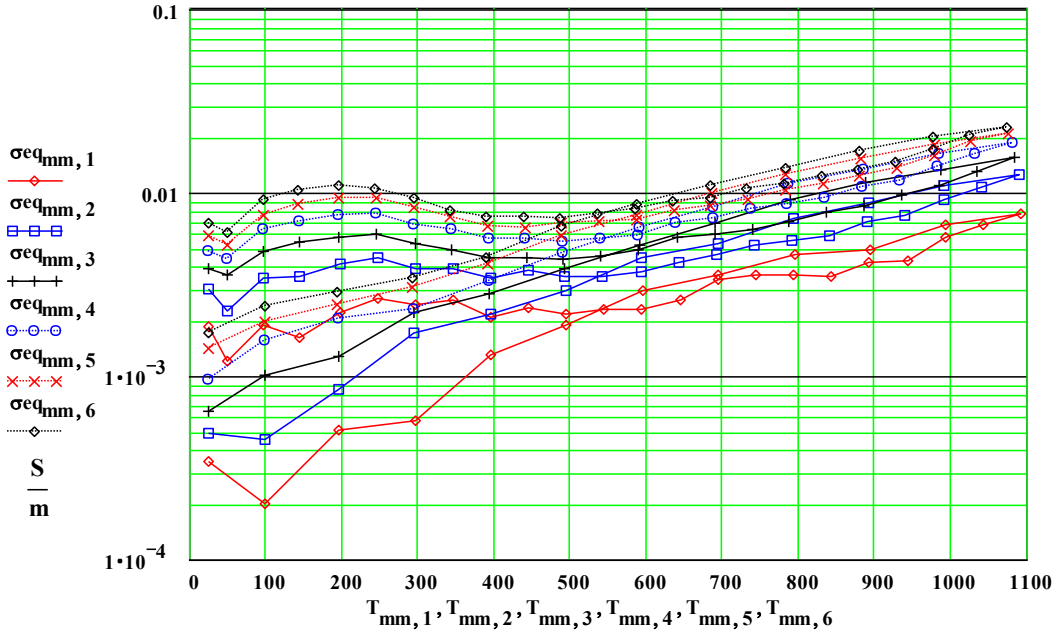
Test = 2021112801

MPN02181\_CaModLowCa.mcd

AnDat = 20211130

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MP

Equivalent Free Electron Conductivity ( Siemens/metre)



Temperature (C)

RefRatio = 0.292

# Appendix E. MPN Reports

Test = 2021112801

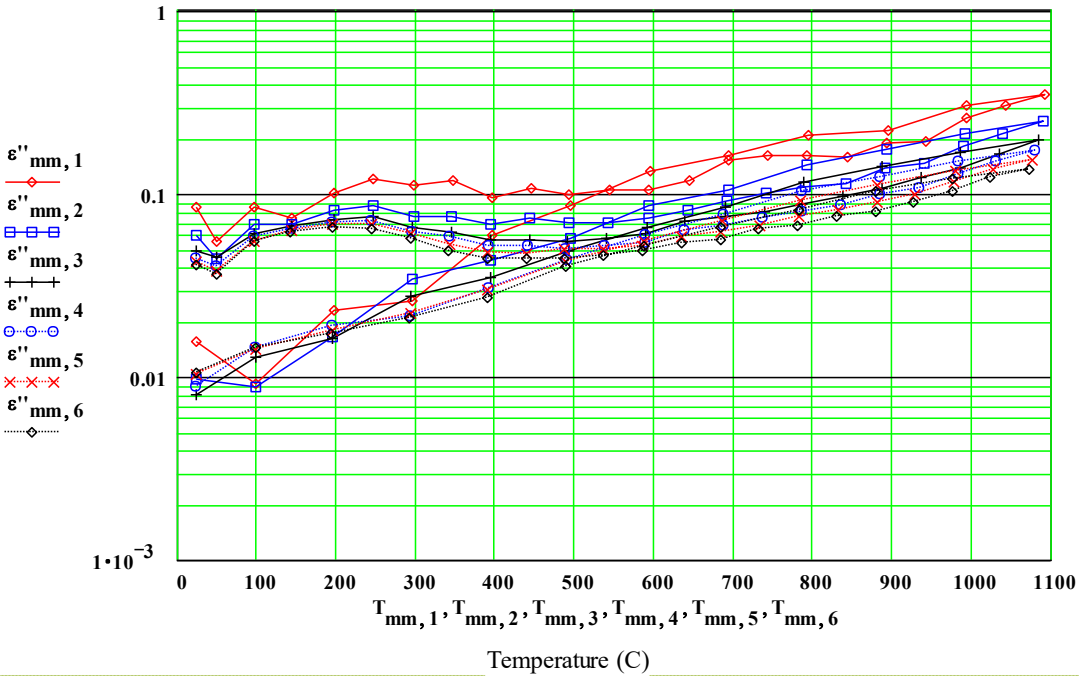
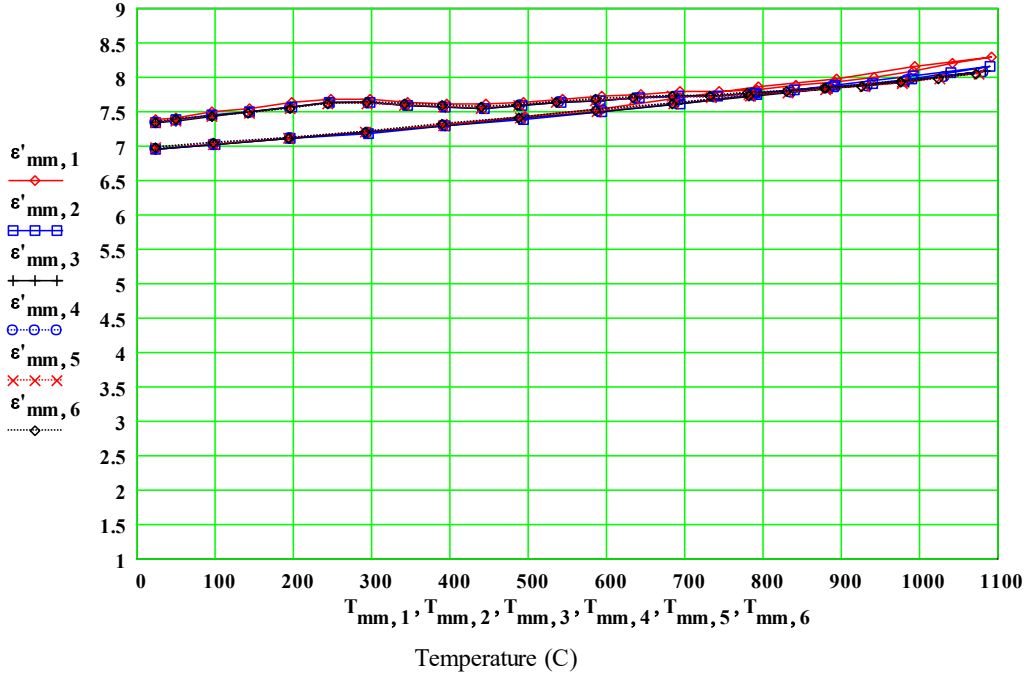
MPN02181\_CalModLowCal.mcd

AnDat = 20211130 T

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 3.09 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 3.02 \text{ gm/cc}$  Ii

FracMassChange = 0.99  $\alpha_1 = 9.9 \cdot 10^{-6} /C$   $\alpha_2 = 0 /C$  F



# Appendix E. MPN Reports

Test = 2021112801

MPN02181\_CalModLowCaLmed

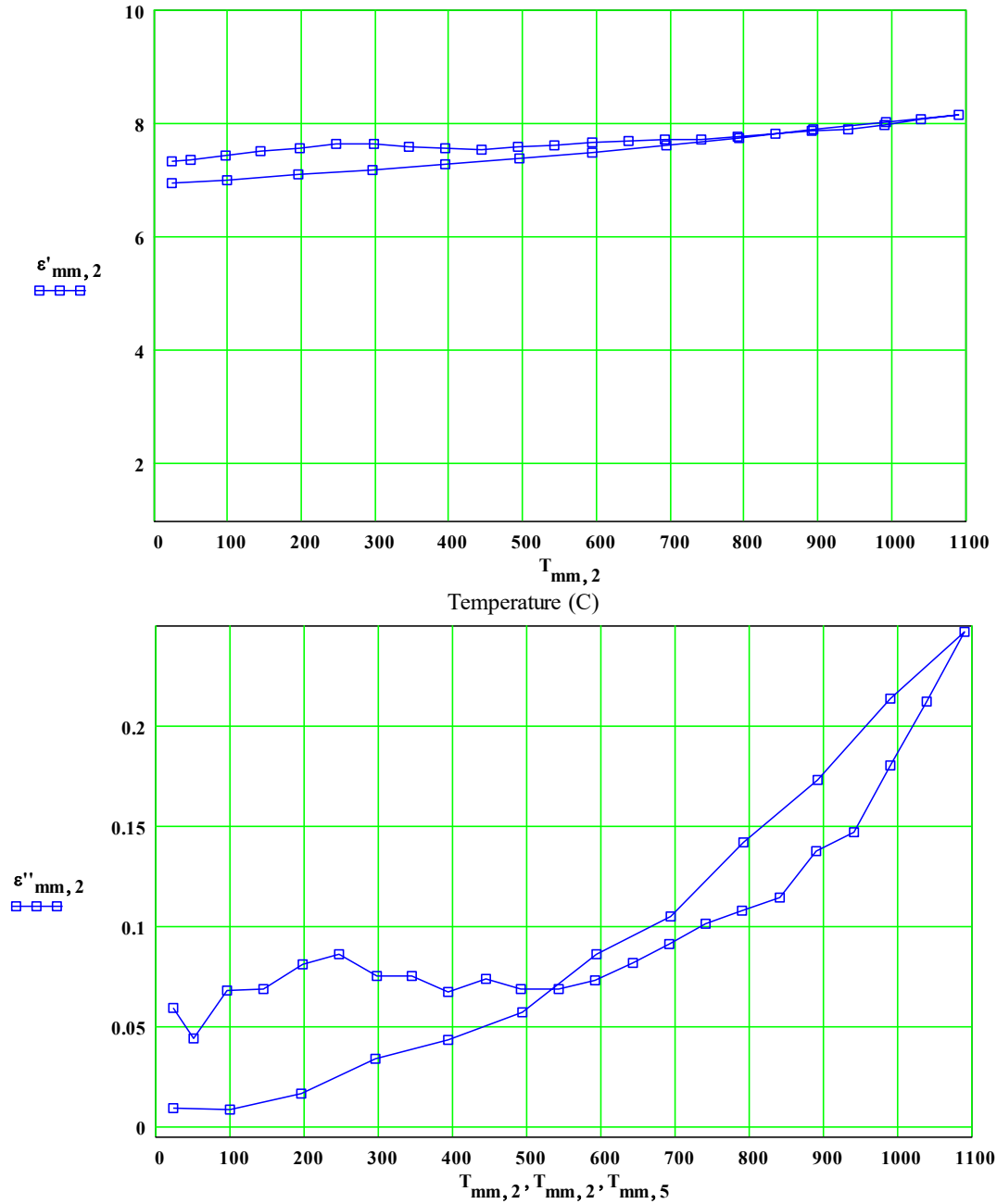
AnDat = 20211130

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6. solid .RT to 1100C, in vacuum,for MPI

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 3.09 \text{ gm/cc}$ , Thermal exp. coeff  $\alpha_1 = 9.9 \cdot 10^{-6}$

Final density(25C) =  $\text{dnsfinal} = 3.02 \text{ gm/cc}$

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021112801

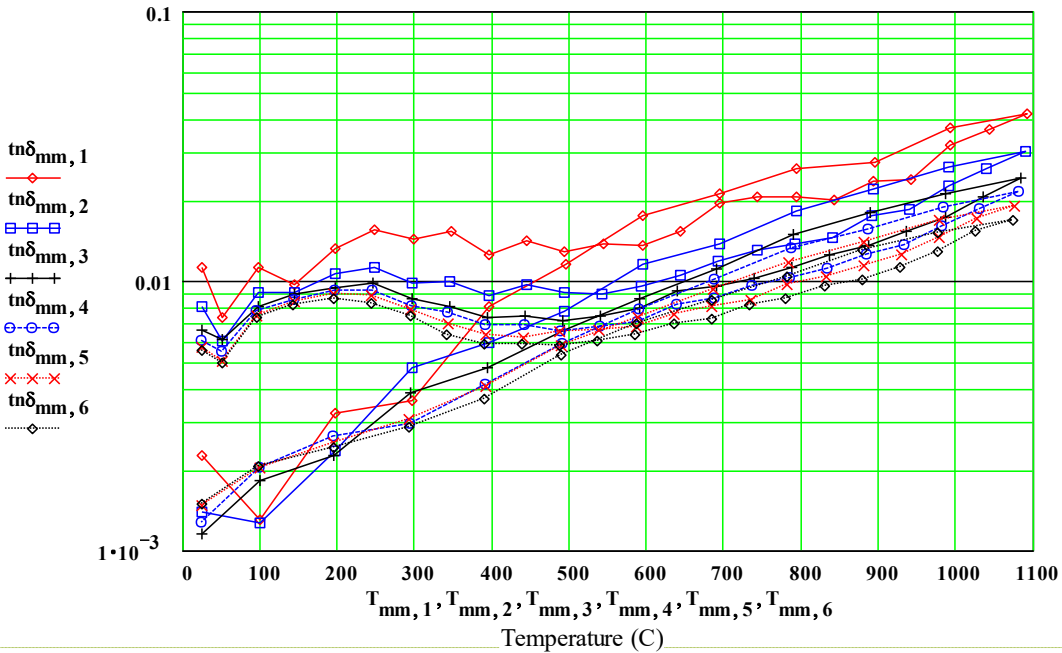
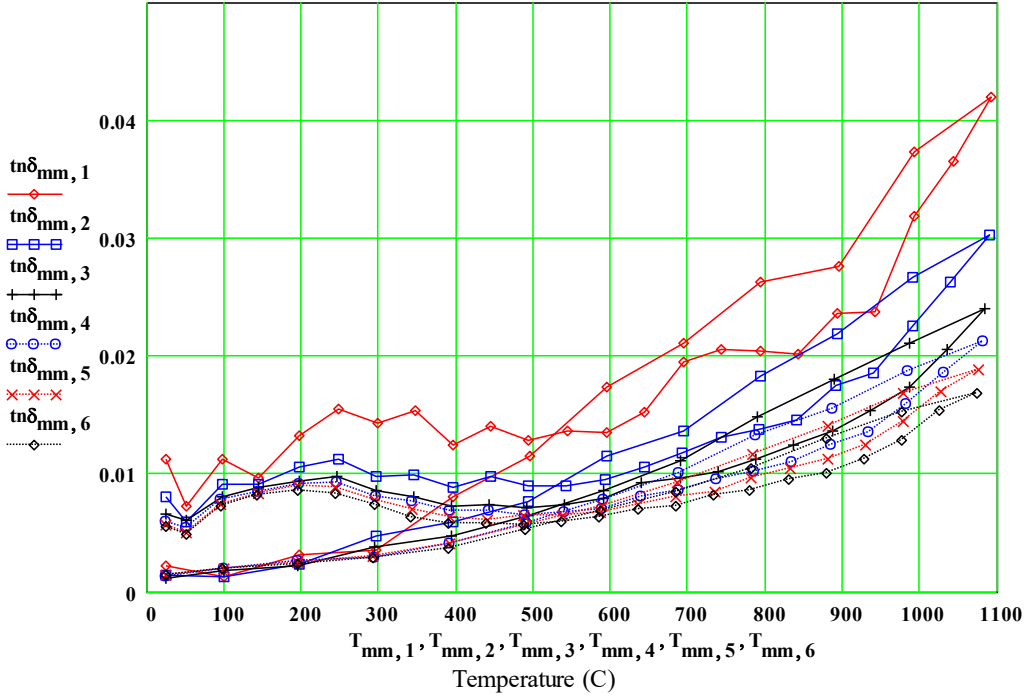
MPN02181\_CalModLowCal.mcd

AnDat = 20211130

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MP

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 3.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 3.02 \text{ gm/cc}$



# Appendix E. MPN Reports

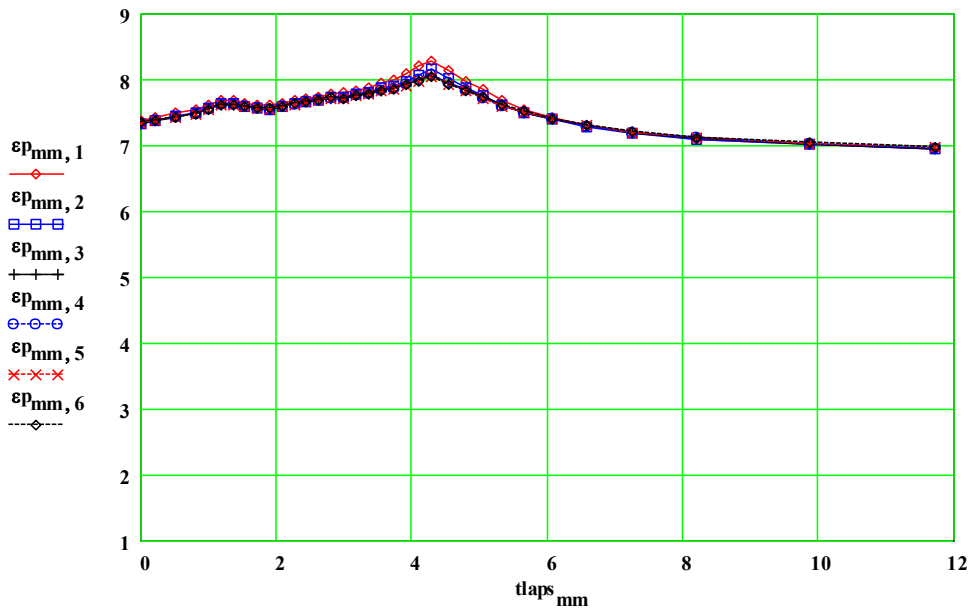
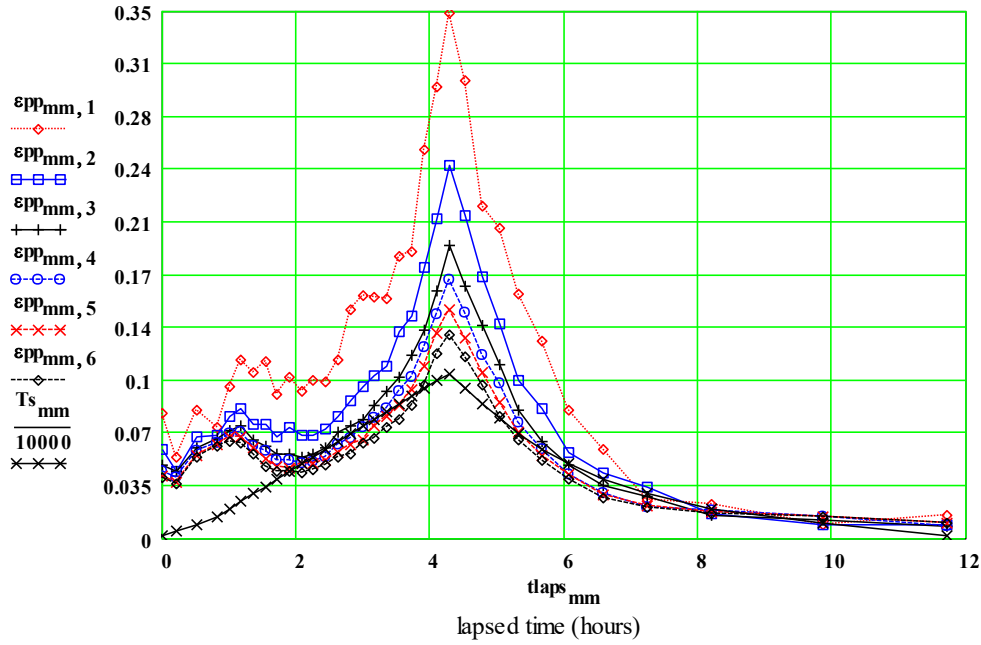
Test = 2021112801

MPN02181\_CalModLowCal.med

AnDat = 20211130

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MP

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 3.09 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 3.02 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

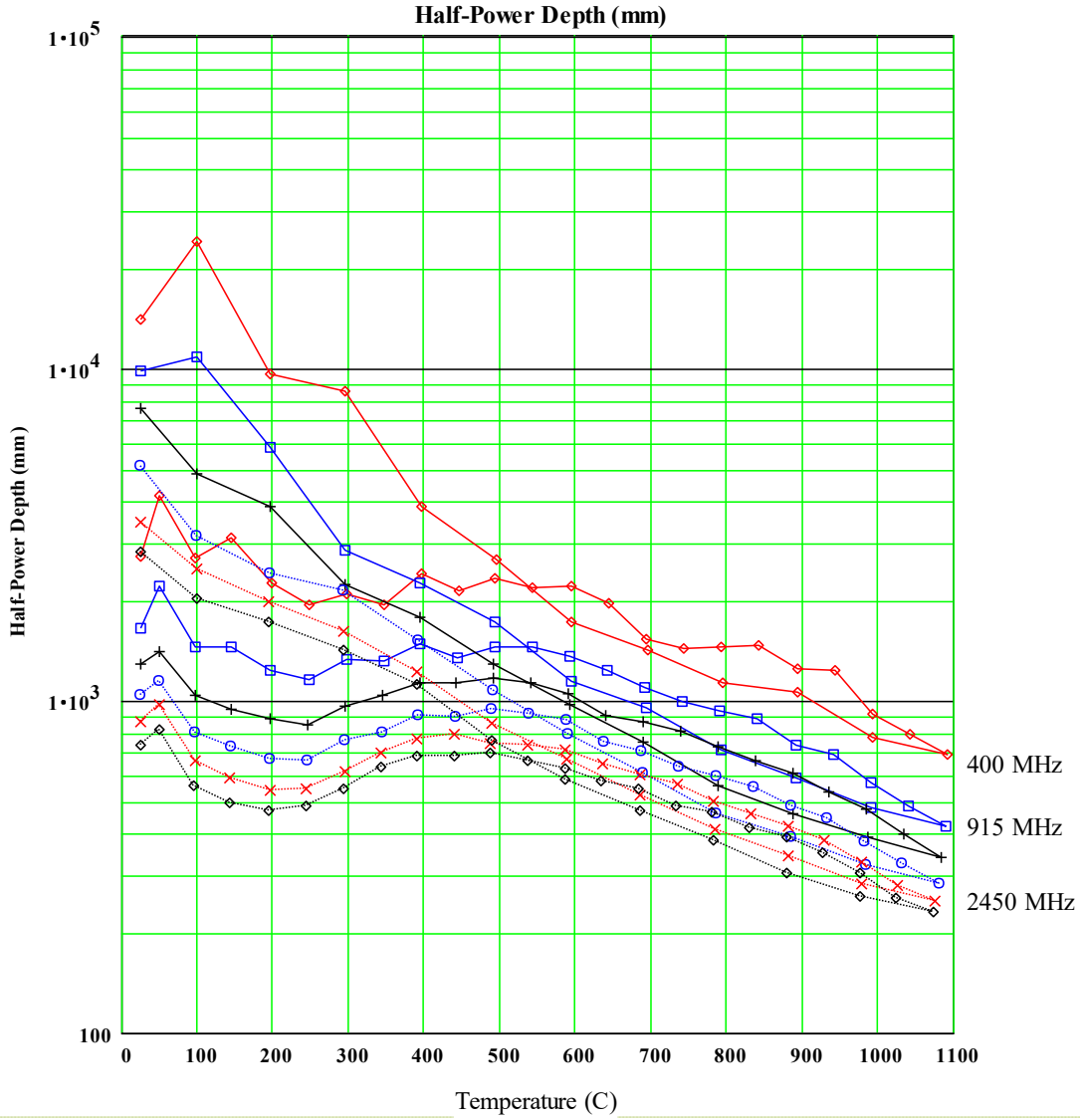
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021112801

MPN02181\_CalModLowCal.mcd

AnDat = 20211130

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MPN



# Appendix E. MPN Reports

**Test = 2021112801**

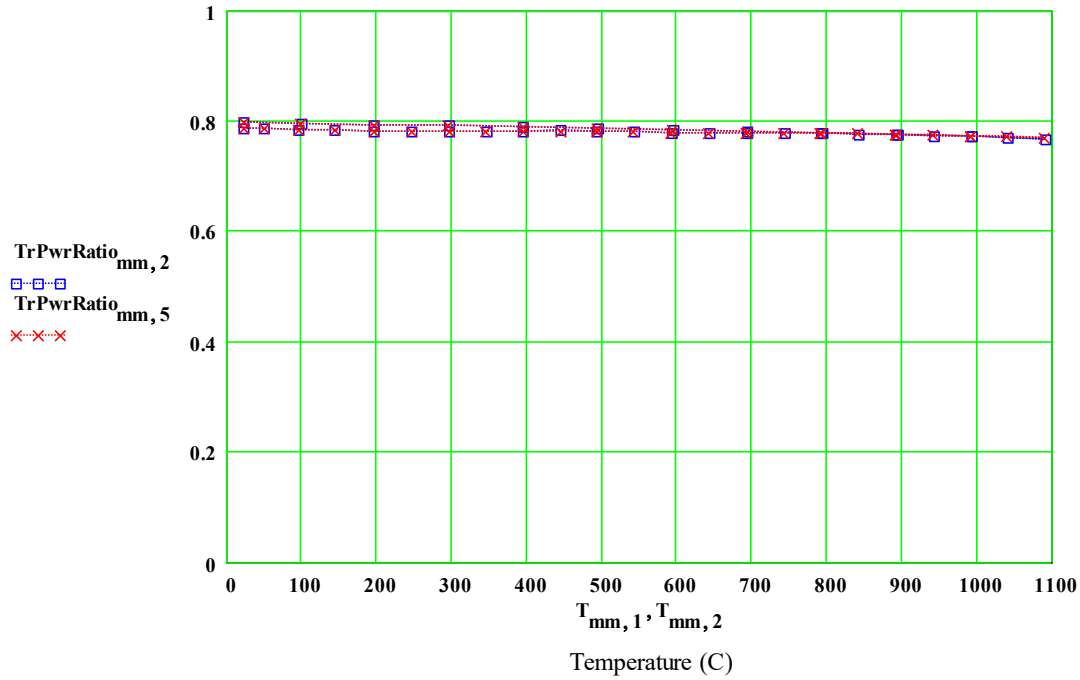
MPN02181\_CalModLowCal.mcd

**AnDat = 20211130**

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 3.09 \text{ gm/cc}$ ,      Final density(25C) =  $\text{dnsfinal} = 3.02 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



Appendix E. MPN Reports

Test = 2021112801

MPN02181\_CaModLowCaI.mcd

AnDat = 20211130

Diopside ( a pyroxene) with Actinolite, Jefferson County,Col.,MgCaSi2O6, solid ,RT to 1100C, in vacuum,for MP

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 3.092$  gm/cc Final density(25C) =  $\text{dnsfinal} = 3.024$  gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MH2466MHz 2986MHz Lapsed Time (hours)

| samdns <sub>mm</sub> | T <sub>mm, 1</sub> | $\epsilon'_{\text{mm}, 1}$ | $\epsilon'_{\text{mm}, 2}$ | $\epsilon'_{\text{mm}, 3}$ | $\epsilon'_{\text{mm}, 4}$ | $\epsilon'_{\text{mm}, 5}$ | $\epsilon'_{\text{mm}, 6}$ | tlaps <sub>mm</sub> | sammass <sub>mm</sub> |
|----------------------|--------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|-----------------------|
| 3.092                | 9                  | 24                         | 7.38                       | 7.35                       | 7.34                       | 7.34                       | 7.35                       | 0                   | 0.42                  |
| 3.089                | 10                 | 50                         | 7.42                       | 7.38                       | 7.37                       | 7.37                       | 7.38                       | 0.21                | 0.42                  |
| 3.085                | 11                 | 97                         | 7.5                        | 7.45                       | 7.44                       | 7.43                       | 7.44                       | 0.51                | 0.42                  |
| 3.081                | 12                 | 145                        | 7.55                       | 7.51                       | 7.49                       | 7.49                       | 7.49                       | 0.81                | 0.42                  |
| 3.076                | 13                 | 197                        | 7.63                       | 7.57                       | 7.56                       | 7.55                       | 7.55                       | 1                   | 0.42                  |
| 3.071                | 14                 | 247                        | 7.69                       | 7.64                       | 7.63                       | 7.62                       | 7.61                       | 1.18                | 0.42                  |
| 3.067                | 15                 | 298                        | 7.69                       | 7.64                       | 7.63                       | 7.62                       | 7.62                       | 1.36                | 0.42                  |
| 3.047                | 16                 | 346                        | 7.64                       | 7.6                        | 7.6                        | 7.59                       | 7.59                       | 1.54                | 0.42                  |
| 3.027                | 17                 | 396                        | 7.62                       | 7.58                       | 7.58                       | 7.57                       | 7.57                       | 1.72                | 0.42                  |
| 3.008                | 18                 | 445                        | 7.61                       | 7.54                       | 7.55                       | 7.54                       | 7.55                       | 1.9                 | 0.42                  |
| 3.003                | 19                 | 494                        | 7.64                       | 7.59                       | 7.59                       | 7.59                       | 7.59                       | 2.08                | 0.42                  |
| 2.999                | 20                 | 544                        | 7.68                       | 7.63                       | 7.63                       | 7.63                       | 7.63                       | 2.26                | 0.42                  |
| 2.994                | 21                 | 594                        | 7.72                       | 7.67                       | 7.66                       | 7.66                       | 7.66                       | 2.44                | 0.42                  |
| 2.99                 | 22                 | 644                        | 7.75                       | 7.7                        | 7.69                       | 7.69                       | 7.69                       | 2.63                | 0.42                  |
| 2.986                | 23                 | 694                        | 7.79                       | 7.73                       | 7.72                       | 7.71                       | 7.72                       | 2.81                | 0.42                  |
| 2.981                | 24                 | 744                        | 7.8                        | 7.73                       | 7.72                       | 7.71                       | 7.71                       | 2.99                | 0.42                  |
| 2.977                | 25                 | 793                        | 7.83                       | 7.78                       | 7.76                       | 7.76                       | 7.76                       | 3.17                | 0.42                  |
| 2.972                | 26                 | 843                        | 7.89                       | 7.81                       | 7.79                       | 7.78                       | 7.78                       | 3.36                | 0.42                  |
| 2.968                | 27                 | 893                        | 7.94                       | 7.87                       | 7.84                       | 7.84                       | 7.83                       | 3.54                | 0.42                  |
| 2.964                | 28                 | 943                        | 8.01                       | 7.91                       | 7.88                       | 7.87                       | 7.86                       | 3.73                | 0.42                  |
| 2.959                | 29                 | 993                        | 8.09                       | 7.99                       | 7.94                       | 7.93                       | 7.92                       | 3.91                | 0.42                  |
| 2.934                | 30                 | 1042                       | 8.2                        | 8.08                       | 8.01                       | 8                          | 7.98                       | 4.09                | 0.417                 |
| 2.93                 | 31                 | 1093                       | 8.29                       | 8.16                       | 8.08                       | 8.07                       | 8.05                       | 4.28                | 0.417                 |
| 2.938                | 32                 | 993                        | 8.15                       | 8.02                       | 7.96                       | 7.95                       | 7.94                       | 4.53                | 0.417                 |
| 2.947                | 33                 | 894                        | 7.98                       | 7.89                       | 7.85                       | 7.84                       | 7.83                       | 4.79                | 0.417                 |
| 2.955                | 34                 | 794                        | 7.86                       | 7.76                       | 7.73                       | 7.72                       | 7.72                       | 5.05                | 0.417                 |
| 2.964                | 35                 | 695                        | 7.7                        | 7.62                       | 7.61                       | 7.61                       | 7.61                       | 5.32                | 0.417                 |
| 2.973                | 36                 | 595                        | 7.55                       | 7.5                        | 7.5                        | 7.5                        | 7.5                        | 5.66                | 0.417                 |
| 2.982                | 37                 | 495                        | 7.42                       | 7.39                       | 7.4                        | 7.4                        | 7.4                        | 6.07                | 0.417                 |
| 2.99                 | 38                 | 396                        | 7.32                       | 7.29                       | 7.3                        | 7.3                        | 7.3                        | 6.59                | 0.417                 |
| 2.999                | 39                 | 296                        | 7.21                       | 7.18                       | 7.2                        | 7.19                       | 7.2                        | 7.25                | 0.417                 |
| 3.008                | 40                 | 196                        | 7.11                       | 7.11                       | 7.11                       | 7.11                       | 7.11                       | 8.19                | 0.417                 |
| 3.017                | 41                 | 99                         | 7.03                       | 7.02                       | 7.02                       | 7.03                       | 7.03                       | 9.86                | 0.417                 |
| 3.024                | 42                 | 24                         | 6.94                       | 6.95                       | 6.95                       | 6.96                       | 6.97                       | 11.73               | 0.417                 |



MPN-242\_MPN\_Enstatite\_Mirabel Springs, Mt St Helena CA

Nov. 28, 2021

Enstatite, Mirabel Springs, Mt. St. Helena, CA  
Measurements of Complex Dielectric Constant Between 400 and 2985 MHz  
from Room Temperature to 1100°C to RT, in < 1 milli Torr Vacuum  
 Jozef Mouris and Ronald Hutcheon

MPN purchased a sample of “massive” Enstatite, a magnesium-iron silicate from Minerals Unlimited ( see photo).

Diamond core-drilling was done to produce a solid, cylindrical, measurement test sample. This sample was baked at 140C in air for two hours to ensure dryness after the core-drilling.

MPN decided on a measurement cycle up to 1100C and then returning to room temperature (RT) in as good a vacuum as we could produce in the MPN system – which currently is < 1 milli Torr .

The initial sample parameters were:

- a) diameter 3.79 +- 0.05 mm
- b) length 12.03 +- 0.20 mm
- c) mass 0.402+- 0.002 gm
- s) room temperature density  $2.96 \pm 0.15$  gm/cc.
- t) appearance - grey rod with 30° angled ends ( see photo) .

The dielectric properties measurements were performed at RT, 50C, and then was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was then run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.83 \pm 0.03$  mm
- b) length  $11.95 \pm 0.1$  mm
- c) mass  $0.398 \pm 0.002$  gm
- s) room temperature density  $2.89 \pm 0.15$  gm/cc.
- t) appearance - grey/brown rod with 30° angled ends ( see photo)

Note: The percent mass loss was 1 +- 1 % .

The frequency coding is :

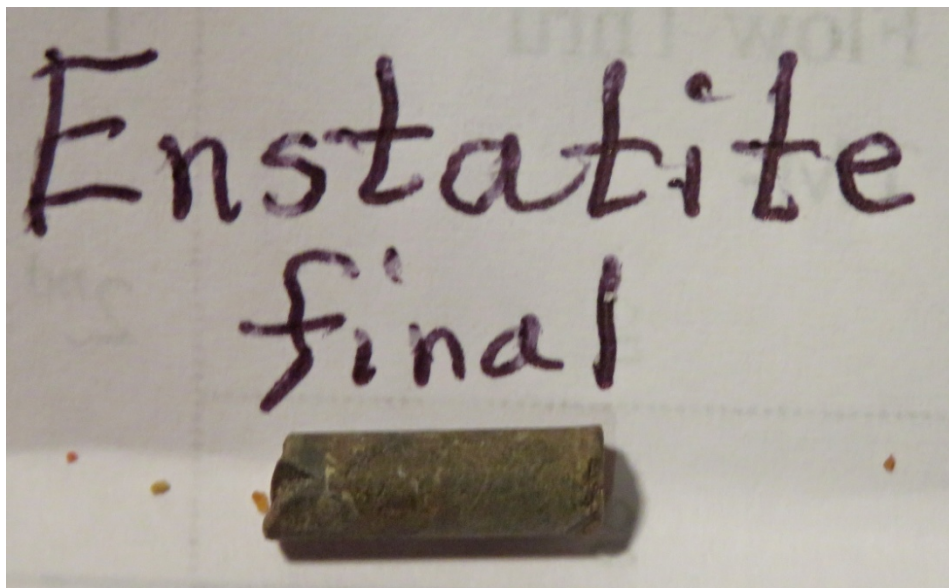
Legend for Data Plots :

| # | Frequency(MHz) | Symbol                                                   |
|---|----------------|----------------------------------------------------------|
| 1 | 397            | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912            | blue square, solid line                                  |
| 3 | 1429           | black cross, solid line                                  |
| 4 | 1948           | blue circle, dotted line                                 |
| 5 | 2466           | red cross, dotted line                                   |
| 6 | 2986           | black diamond, dotted line                               |

Comments on the data analysis:

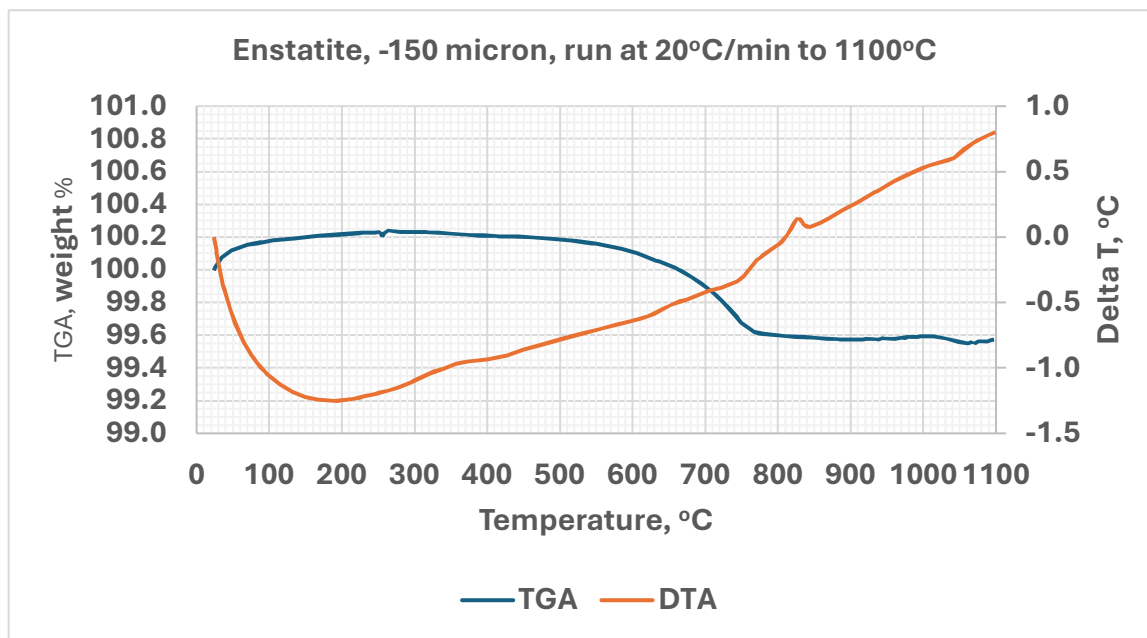
A linear thermal expansion coefficient ( CTE) of  $11.0 * 10^{-6}/C$  was used.

Reference is Jackson et al, Eur. J. Minerals, 2003, "Thermal Expansion Coefficient of Orthoenstatite ( $Mg Si O_3$ ).



Final sample after run to 1100C in Vacuum.

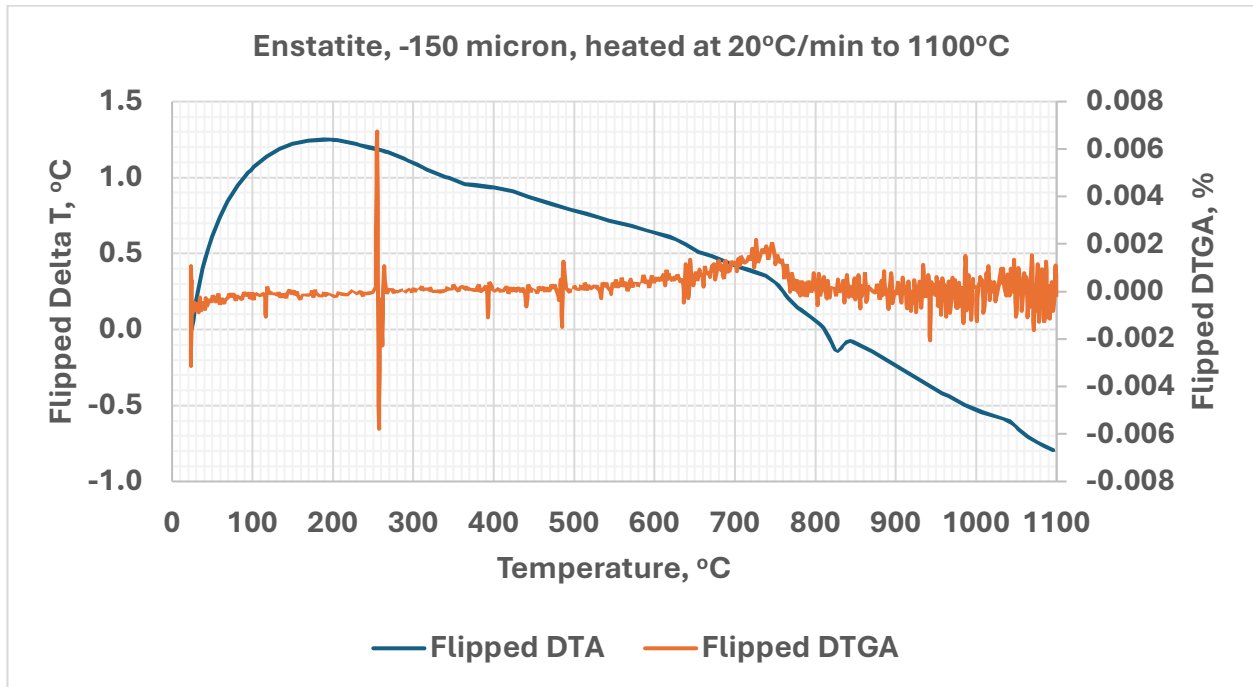
DTA/TGA by Dr. Peter Hayward, Eutechnics Consulting Inc.,  
Box 718, 3 Monck Place, Pinawa, Manitoba, Canada R0E 1L0 .



Weight loss at 1100C from TGA data = 0.43%

Final weight loss after cooling (external balance) = 0.78%, i.e., reasonable agreement.

Final sample was a light brown powder, significantly darker than the initial sample before heating, which was a very pale brown.



Inverted DTA/DTGA plots which often show peaks where the density of diffusing ions is maximum. This may indicate locations of peaks in the plot of  $\epsilon''$  versus temperature.

Values for the Temperature Cycle (to 1100 C and back to RT) :

# Appendix E. MPN Reports

Test = 2021112601

MPN02180\_CaModLowCa.mcd

AnDat = 20211129

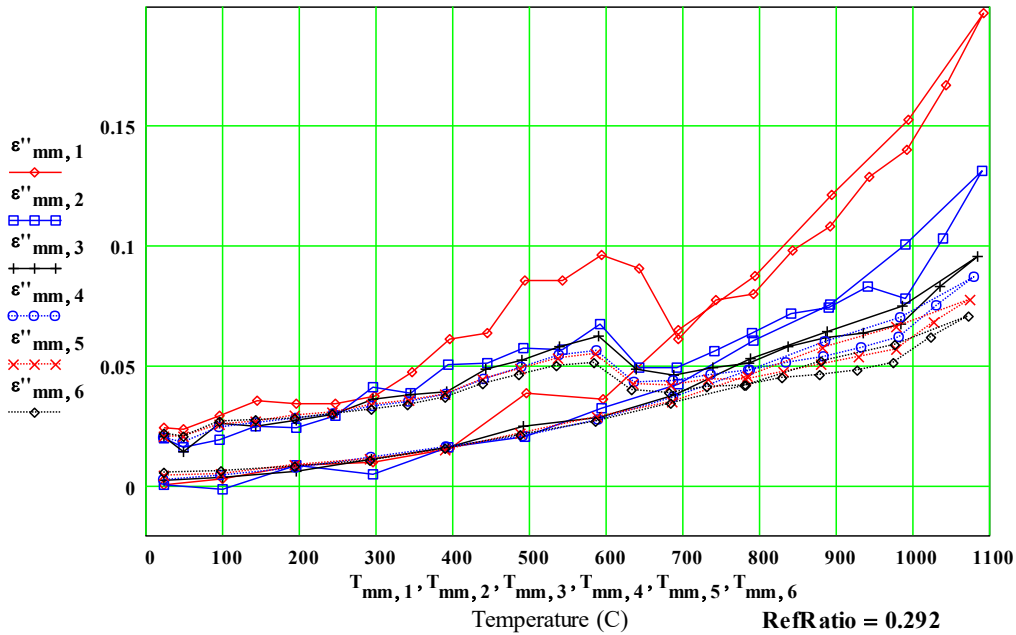
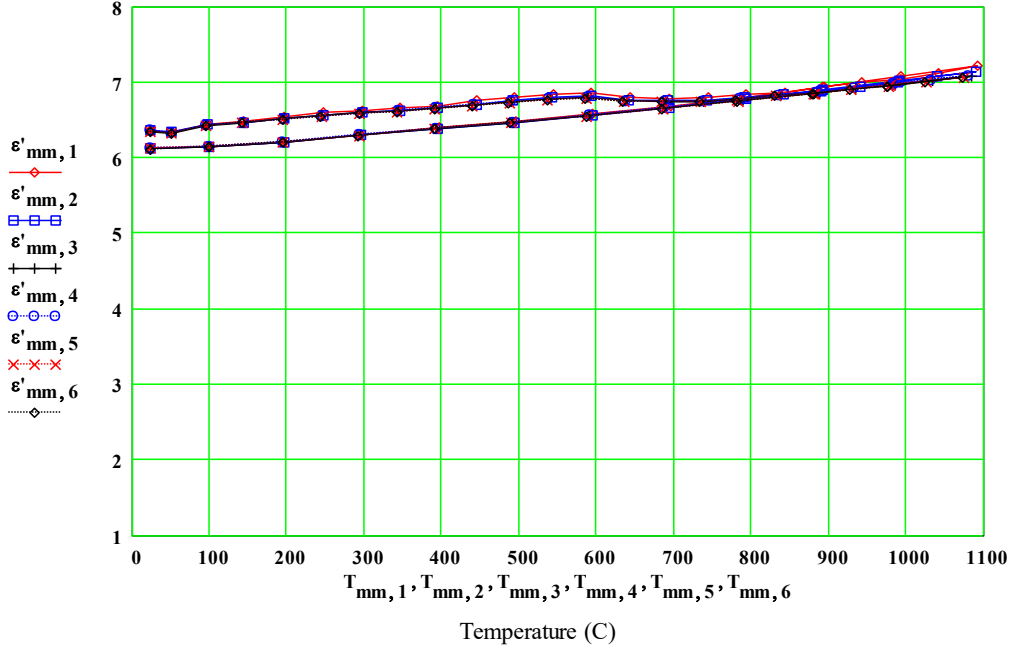
Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA, RT to 1100C, in < 1 milliTorr vacuum, for MF

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.96 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.89 \text{ gm/cc}$

Final\_over\_Initial\_mass = 0.99

$\alpha_1 = 11 \cdot 10^{-6}$  thermal expansion coef/deg C



The data for the ramp up to 1100C shows evidence of a broad phase transition which was complete by ~ 675C. This produced an irreversible change in the material, although there was only very slight mass loss!

# Appendix E. MPN Reports

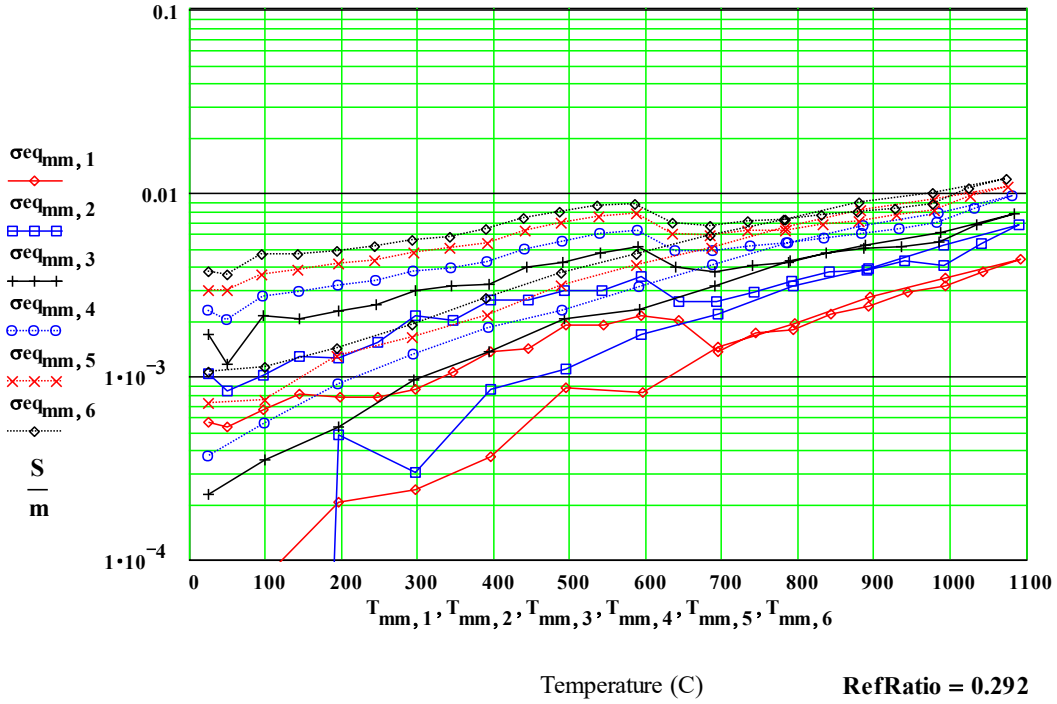
Test = 2021112601

MPN02180\_CalModLowCal.mcd

AnDat = 20211129

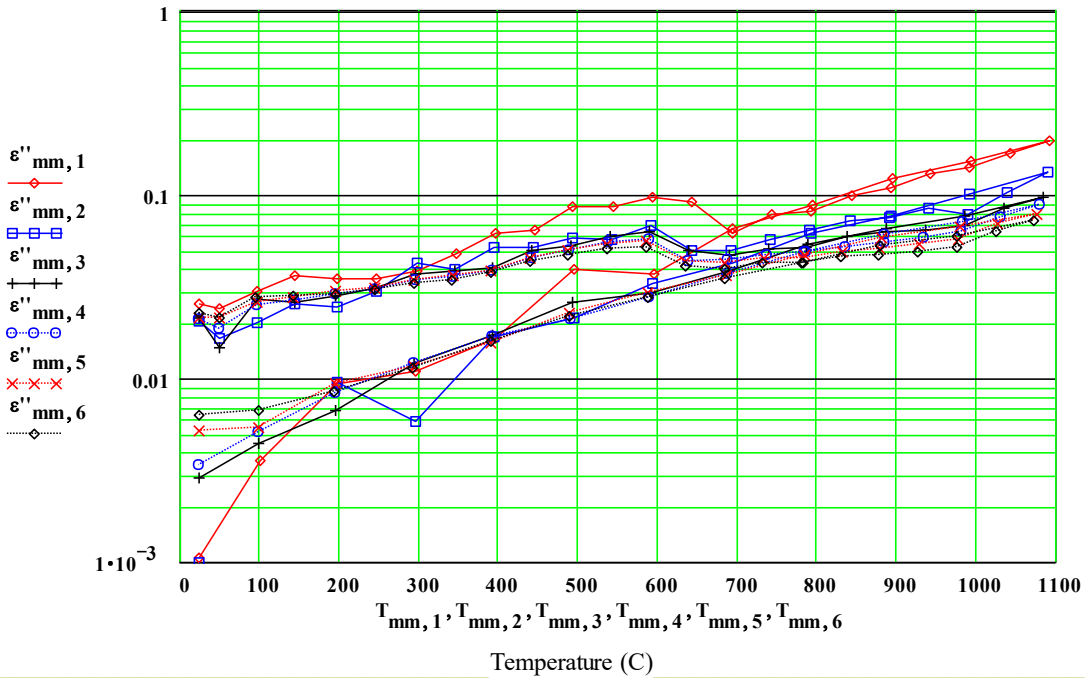
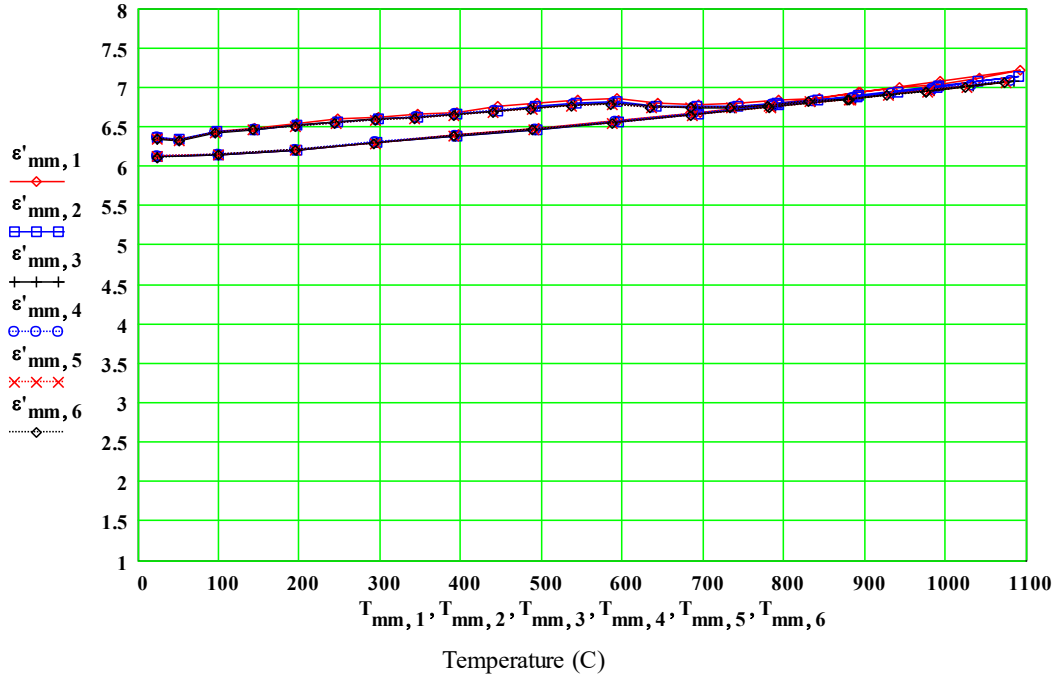
Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA , RT to 1100C, in < 1 milliTorr vacuum, for MPN

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

**Test = 2021112601**                      **MPN02180\_CaModLowCal.mcd**                      **AnDat = 20211128**                      **T**  
 Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA , RT to 1100C, in < 1 milliTorr vacuum, for MPN  
 Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.96 \text{ gm/cc}$ ,                      Final density(25C) =  $\text{dnsfinal} = 2.89 \text{ gm/cc}$                       **Ir**  
**FracMassChange = 0.99**                       $\alpha_1 = 1.1 \cdot 10^{-5} / \text{C}$                        $\alpha_2 = 0 / \text{C}$                       **F**



# Appendix E. MPN Reports

Test = 2021112601

MPN02180\_CalModLowCal.mcd

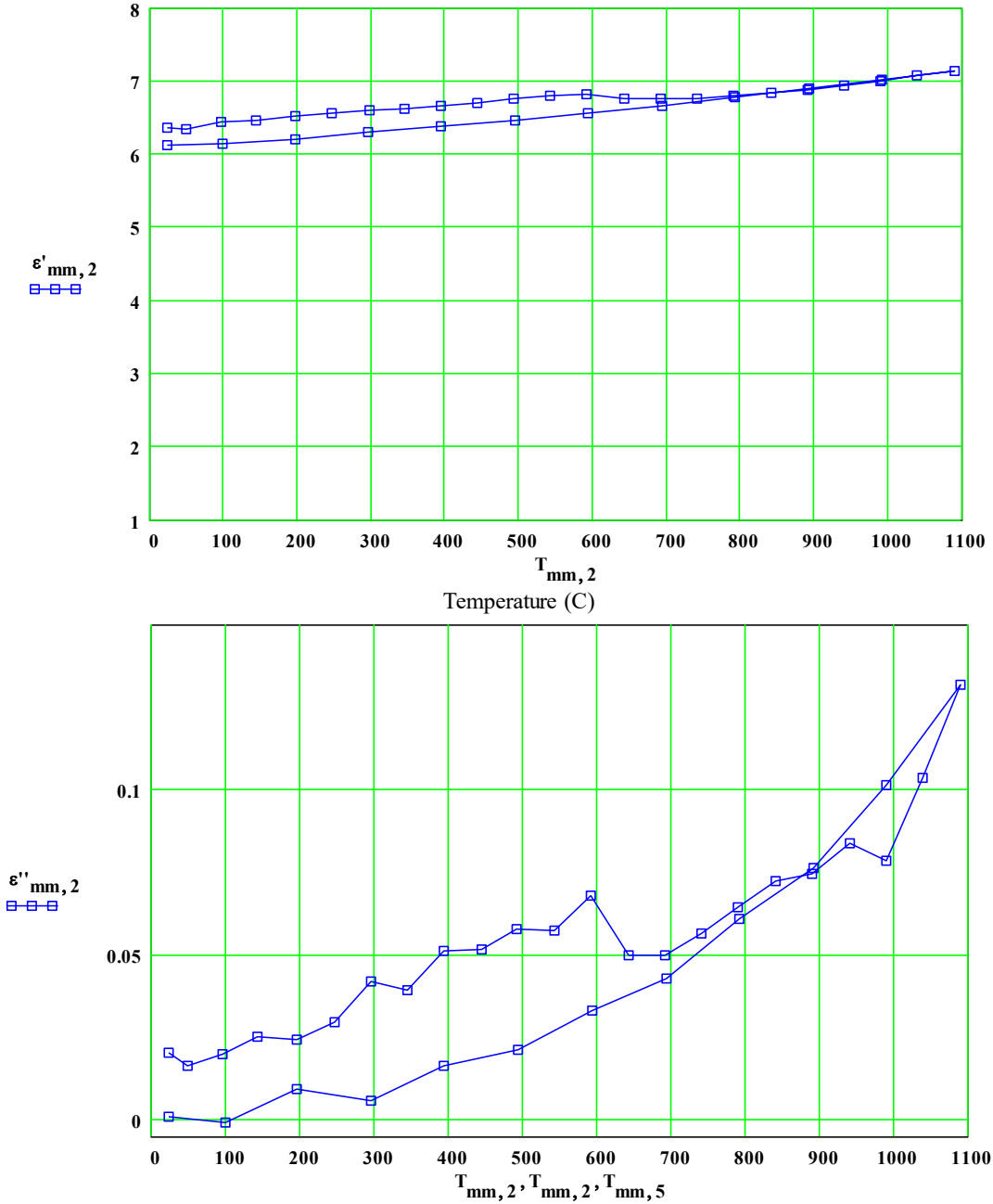
AnDat = 20211128

Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St. Helena CA, RT to 1100C. in < 1 milli Torr vacuum, for MPN

Initial density =  $\text{sam dns}_{\text{NCal} + 1} = 2.96 \text{ gm/cc}$ , Thermal exp. coeff  $\alpha_1 = 1.1 \cdot 10^{-5}$

Final density(25C) =  $\text{dns final} = 2.89 \text{ gm/cc}$

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021112601

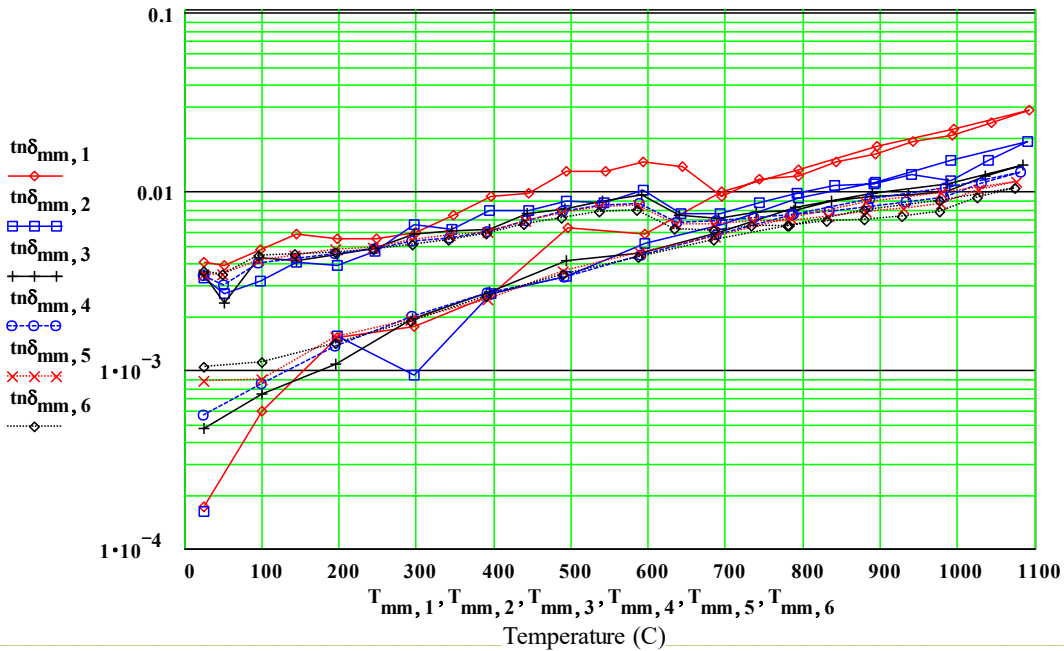
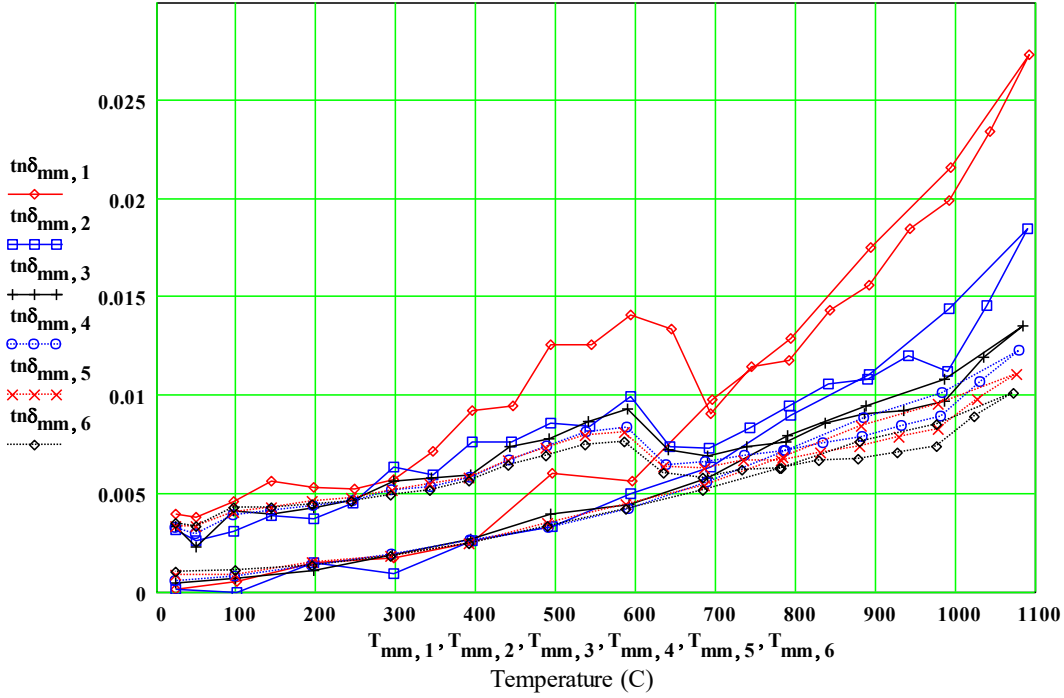
MPN02180\_CalModLowCal.mcd

AnDat = 20211129

Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA , RT to 1100C, in < 1 milliTorr vacuum, for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.96 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.89 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2021112601

MPN02180\_CalModLowCa.lmcd

AnDat = 20211129

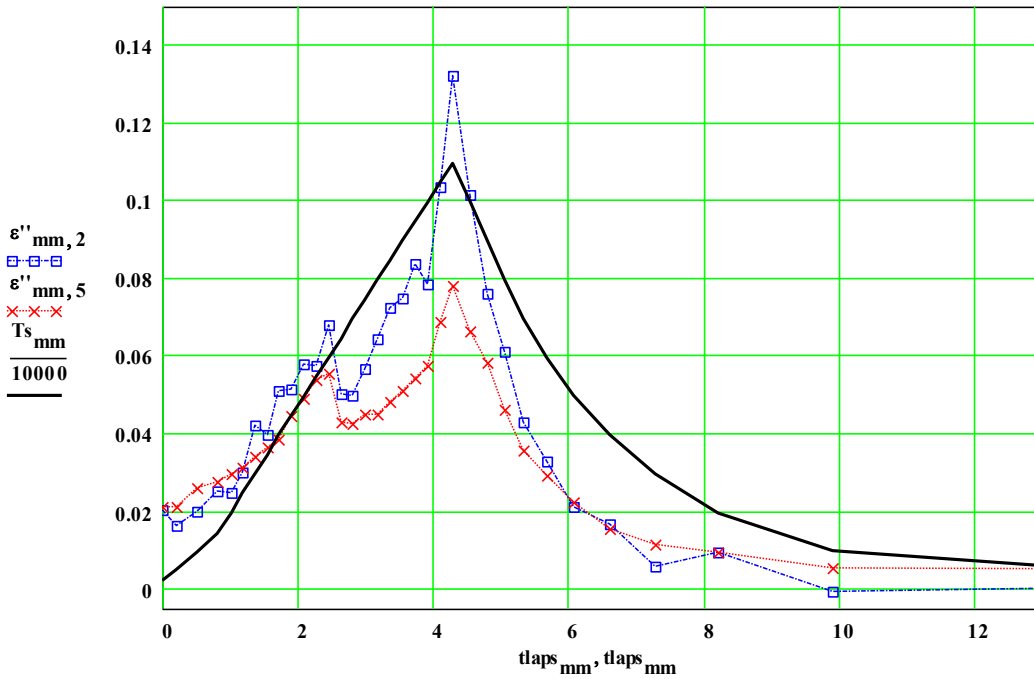
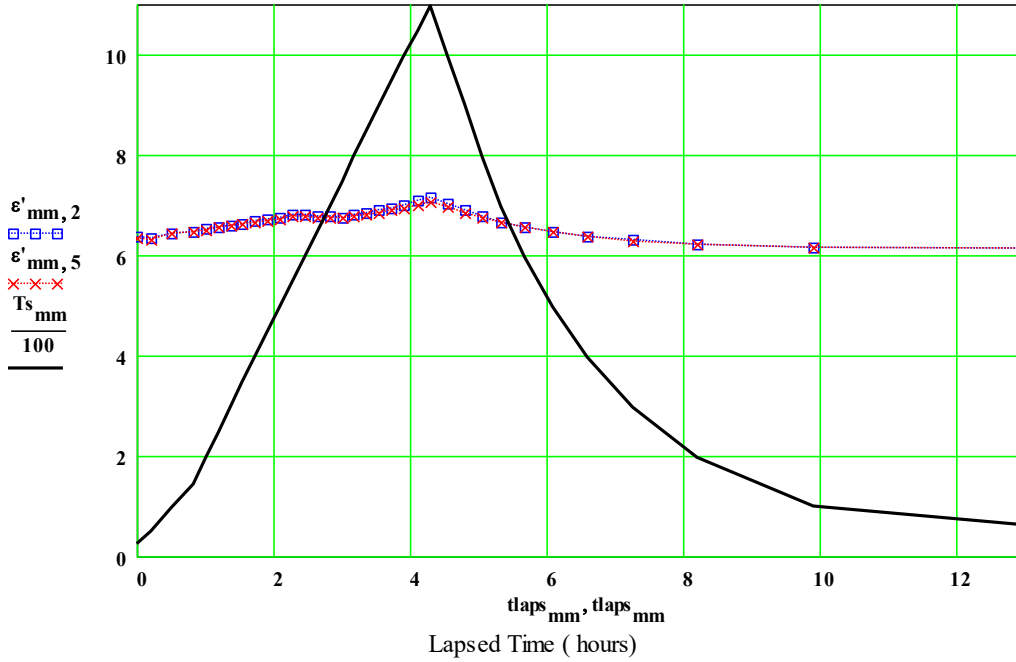
Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA , RT to 1100C, in < 1 milliTorr vacuum, for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.96 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.89 \text{ gm/cc}$        $\text{FracMassChange} = 0.99$

$\alpha_1 = 1.1 \cdot 10^{-5}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

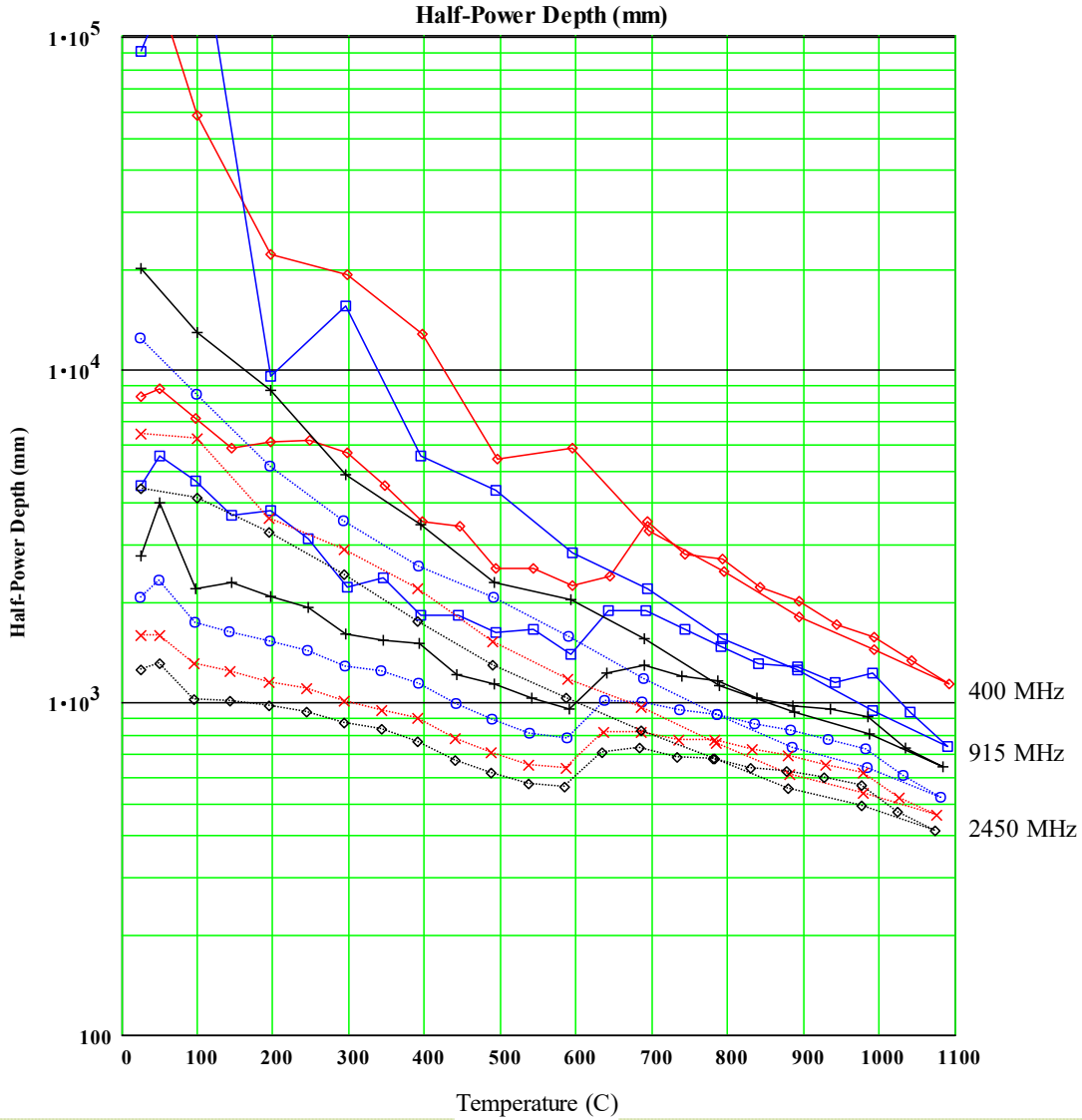
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021112601

MPN02180\_CalModLowCal.mod

AnDat = 20211129

Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA , RT to 1100C, in < 1 milliTorr vacuum, for MPN



# Appendix E. MPN Reports

Test = 2021112601

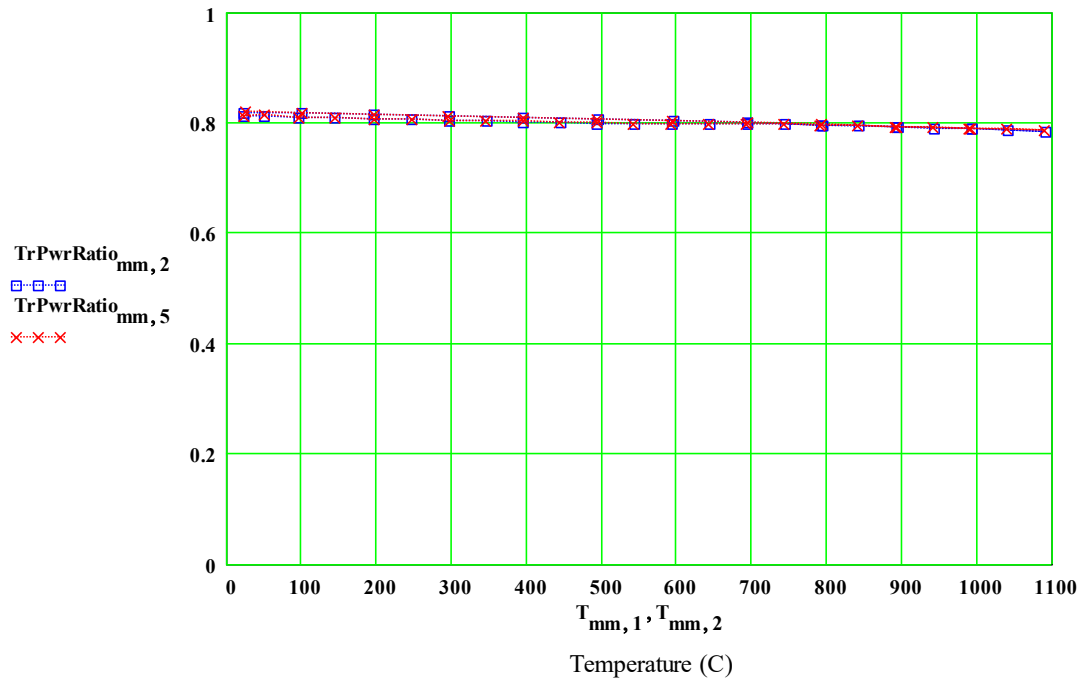
MPN02180\_CalModLowCal.mcd

AnDat = 20211128

Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA , RT to 1100C, in < 1 milliTorr vacuum, for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.96 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.89 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



# Appendix E. MPN Reports

Test = 2021112601

MPN02180\_CalModLowCal.mcd

AnDat = 20211129

Enstatite (Mg/Fe silicate), Mirabel Springs, Mt. St.Helena CA , RT to 1100C, in < 1 milliTorr vacuum, for MI

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.962$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.891$  gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz      Lapsed Time (hours)

| samdns <sub>mm</sub> | T <sub>mm,1</sub> | $\epsilon'_{\text{mm},1}$ | $\epsilon'_{\text{mm},2}$ | $\epsilon'_{\text{mm},3}$ | $\epsilon'_{\text{mm},4}$ | $\epsilon'_{\text{mm},5}$ | $\epsilon'_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |       |
|----------------------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------|----------------------|-------|
| 2.962                | 9                 | 24                        | 6.36                      | 6.36                      | 6.36                      | 6.36                      | 6.35                      | 6.36                | 0                    | 0.402 |
| 2.96                 | 10                | 50                        | 6.34                      | 6.34                      | 6.33                      | 6.34                      | 6.33                      | 6.33                | 0.21                 | 0.402 |
| 2.955                | 11                | 97                        | 6.45                      | 6.45                      | 6.43                      | 6.43                      | 6.43                      | 6.43                | 0.51                 | 0.402 |
| 2.95                 | 12                | 144                       | 6.49                      | 6.48                      | 6.47                      | 6.47                      | 6.46                      | 6.46                | 0.82                 | 0.402 |
| 2.945                | 13                | 197                       | 6.55                      | 6.53                      | 6.52                      | 6.52                      | 6.51                      | 6.51                | 1.01                 | 0.402 |
| 2.94                 | 14                | 247                       | 6.6                       | 6.57                      | 6.56                      | 6.55                      | 6.55                      | 6.55                | 1.19                 | 0.402 |
| 2.936                | 15                | 297                       | 6.62                      | 6.6                       | 6.6                       | 6.59                      | 6.59                      | 6.59                | 1.37                 | 0.402 |
| 2.931                | 16                | 346                       | 6.67                      | 6.64                      | 6.63                      | 6.62                      | 6.61                      | 6.62                | 1.55                 | 0.402 |
| 2.926                | 17                | 395                       | 6.7                       | 6.67                      | 6.67                      | 6.66                      | 6.65                      | 6.66                | 1.72                 | 0.402 |
| 2.921                | 18                | 445                       | 6.76                      | 6.72                      | 6.72                      | 6.7                       | 6.69                      | 6.7                 | 1.9                  | 0.402 |
| 2.917                | 19                | 493                       | 6.8                       | 6.76                      | 6.75                      | 6.74                      | 6.73                      | 6.73                | 2.09                 | 0.402 |
| 2.912                | 20                | 543                       | 6.85                      | 6.81                      | 6.79                      | 6.78                      | 6.77                      | 6.77                | 2.27                 | 0.402 |
| 2.907                | 21                | 593                       | 6.87                      | 6.82                      | 6.81                      | 6.8                       | 6.79                      | 6.79                | 2.45                 | 0.402 |
| 2.889                | 22                | 644                       | 6.8                       | 6.77                      | 6.76                      | 6.75                      | 6.74                      | 6.75                | 2.63                 | 0.402 |
| 2.87                 | 23                | 694                       | 6.8                       | 6.77                      | 6.75                      | 6.75                      | 6.74                      | 6.74                | 2.81                 | 0.402 |
| 2.852                | 24                | 744                       | 6.81                      | 6.76                      | 6.76                      | 6.75                      | 6.74                      | 6.74                | 3                    | 0.402 |
| 2.847                | 25                | 793                       | 6.84                      | 6.8                       | 6.79                      | 6.79                      | 6.78                      | 6.78                | 3.18                 | 0.402 |
| 2.842                | 26                | 843                       | 6.87                      | 6.85                      | 6.83                      | 6.83                      | 6.82                      | 6.82                | 3.36                 | 0.402 |
| 2.838                | 27                | 893                       | 6.95                      | 6.9                       | 6.87                      | 6.87                      | 6.86                      | 6.86                | 3.55                 | 0.402 |
| 2.833                | 28                | 943                       | 7                         | 6.95                      | 6.92                      | 6.92                      | 6.9                       | 6.9                 | 3.73                 | 0.402 |
| 2.829                | 29                | 992                       | 7.05                      | 7                         | 6.97                      | 6.96                      | 6.94                      | 6.94                | 3.92                 | 0.402 |
| 2.796                | 30                | 1042                      | 7.13                      | 7.09                      | 7.03                      | 7.03                      | 7.01                      | 7                   | 4.1                  | 0.398 |
| 2.791                | 31                | 1092                      | 7.22                      | 7.15                      | 7.09                      | 7.09                      | 7.06                      | 7.06                | 4.29                 | 0.398 |
| 2.8                  | 32                | 993                       | 7.08                      | 7.02                      | 6.98                      | 6.98                      | 6.96                      | 6.95                | 4.54                 | 0.398 |
| 2.809                | 33                | 894                       | 6.94                      | 6.9                       | 6.87                      | 6.87                      | 6.85                      | 6.85                | 4.79                 | 0.398 |
| 2.819                | 34                | 794                       | 6.81                      | 6.78                      | 6.76                      | 6.76                      | 6.75                      | 6.75                | 5.05                 | 0.398 |
| 2.828                | 35                | 695                       | 6.7                       | 6.67                      | 6.66                      | 6.66                      | 6.65                      | 6.65                | 5.33                 | 0.398 |
| 2.837                | 36                | 595                       | 6.58                      | 6.56                      | 6.57                      | 6.56                      | 6.55                      | 6.56                | 5.67                 | 0.398 |
| 2.846                | 37                | 495                       | 6.48                      | 6.47                      | 6.47                      | 6.47                      | 6.46                      | 6.46                | 6.08                 | 0.398 |
| 2.856                | 38                | 396                       | 6.41                      | 6.39                      | 6.4                       | 6.39                      | 6.39                      | 6.39                | 6.6                  | 0.398 |
| 2.865                | 39                | 296                       | 6.31                      | 6.31                      | 6.3                       | 6.3                       | 6.3                       | 6.3                 | 7.27                 | 0.398 |
| 2.875                | 40                | 196                       | 6.22                      | 6.22                      | 6.22                      | 6.21                      | 6.21                      | 6.22                | 8.21                 | 0.398 |
| 2.884                | 41                | 100                       | 6.14                      | 6.15                      | 6.15                      | 6.15                      | 6.15                      | 6.15                | 9.9                  | 0.398 |
| 2.891                | 42                | 24                        | 6.13                      | 6.13                      | 6.13                      | 6.13                      | 6.12                      | 6.12                | 16.07                | 0.398 |



MPN-218\_Shulman\_1\_JSC-1A

Mar. 12, 2021

JSC-1A ( Initially Heat Treated to 500C in Argon for 6 hours)  
Complex Dielectric Property Measurements from  
Room Temperature to 1100°C, in Flowing UHP Argon

Dr. Holly Shulman ( Shulman LLC) requested that Microwave Properties North measure the complex dielectric properties of a specially treated JSC-1A moon simulant up to 1100C in UHP argon. The powder sample material arrived at MPN on Mar. 5/ 2021. Dr. Shulman had already baked the powder at 500C for 6 hours in UHP argon.

MPN pressed pellets of the powder material ( in a uniaxial press, ~ 20,000 psi) achieving a density of ~ 1.97 g/cc . The pellets were baked for 2 hours at 140 C to ensure dryness.

MPN was requested to cycle the sample to an intermediate temperature, return it to room temperature, and then take it up to 1100C – all the while doing measurements, all in a 10 sccm flow of UHP argon ( which likely has ~ 10 ppm oxygen content).

Thus the dielectric measurement run cycle was as follows: the temperature was stepped from RT ( room temperature) to 900C, then stepped slowly down to RT, then stepped up to 1100C, and then back down. The return to room temperature was interrupted by a power failure just after the 300C measurement point.

The initial sample parameters were:

- a) diameter 3.64 +- 0.05 mm
- b) length 13.91 +- 0.10 mm
- c) mass 0.285 +- 0.002 gm
- u) room temperature density  $1.97 \pm 0.10$  gm/cc.
- v) appearance - three stacked grey-brown pellets ( see photo)
- w) Resistance : - not measured

The dielectric properties measurements were performed at RT, 50°C, and then 50°C steps to 900°C, then in -50C steps back down to 300°C, then room temperature. The sample was observed ( but not removed from the holder) and appeared unchanged ( colour also not changed). The temperature was then ramped up to 1100C in 50C steps, and then brought back down in 50C steps. Unfortunately, the run was interrupted just after the last 300C measurement by a power failure!

The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was later run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.71 \pm 0.05$  mm
- b) length  $13.88 \pm 0.1$  mm
- c) mass  $0.284 \pm 0.002$  gm
- u) room temperature density  $1.89 \pm 0.10$  gm/cc.
- v) appearance - three stacked reddish-brown pellets ( see photo)

Note: The percent mass loss was < 1 % .

The frequency coding is :

Legend for Data Plots :

| <u>#</u> | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|----------|-----------------------|----------------------------------------------------------|
| 1        | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2        | 912                   | blue square, solid line                                  |
| 3        | 1429                  | black cross, solid line                                  |
| 4        | 1948                  | blue circle, dotted line                                 |
| 5        | 2466                  | red cross, dotted line                                   |
| 6        | 2986                  | black diamond, dotted line                               |

Comments on the data analysis:

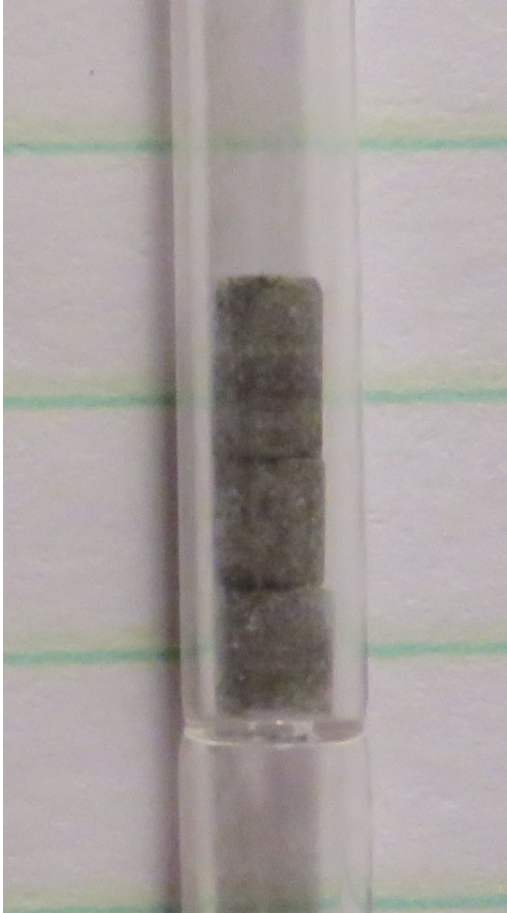
A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

The samples were visually checked at mid-run when the temperature was down at room temperature. They appeared unchanged.

The data for the first cycle to 900C shows a definite increase ( change of slope) of the values between 550C and 800C.

The 1<sup>st</sup> cycle values from 900C down to RT and then the 2<sup>nd</sup> cycle values up to 900C again track each other very well, and are essentially the same at each temperature. However, the increase to 1100 C seems to produce a change in the material that produces slightly elevated values on the return down to room temperature.

Appendix E. MPN Reports



Initial Sample Stack – 3 pellets



Final Sample Stack - 3 pellets



# Appendix E. MPN Reports

Final Sample Stack – after removal from holder. Bottom pellet is on the right .

Test = 2021031001

SHUL2117\_LowCal.mcd

AnDat = 20210312

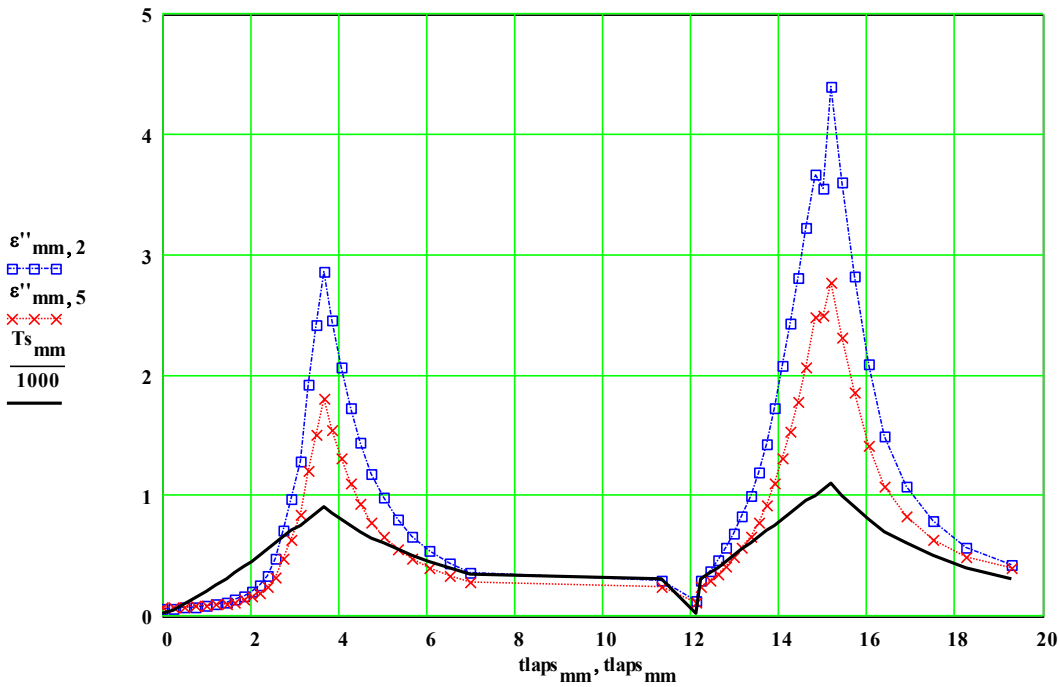
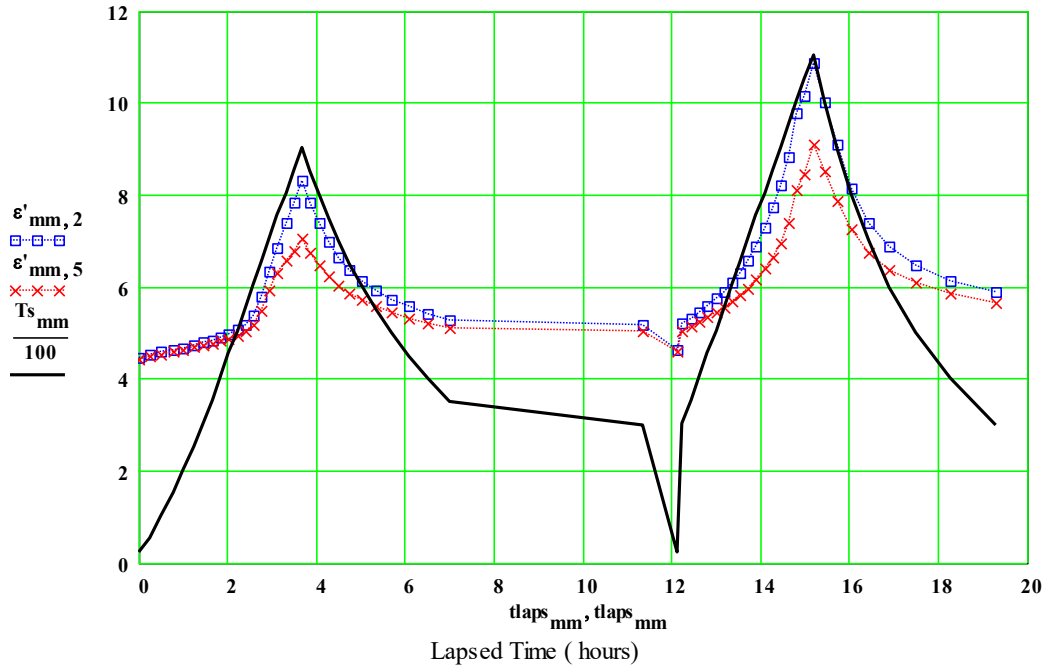
JSC-1A Pellets, 500 C Treated , RT to 900 C, then RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$        $\text{FracMassChange} = 1$

$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2021031001

SHUL2117\_LowCal.mcd

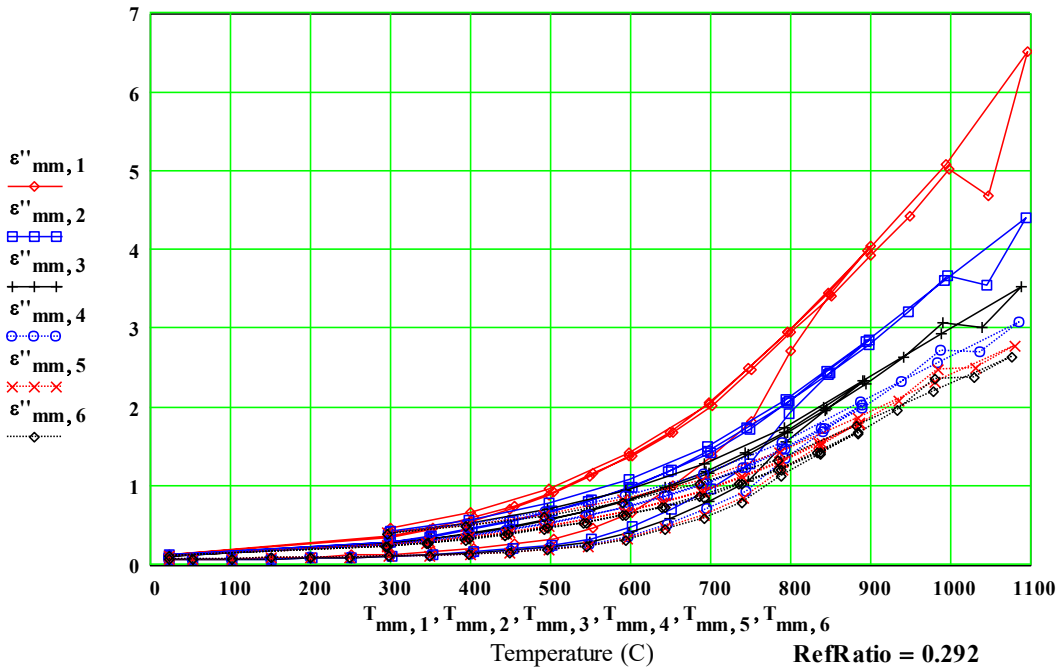
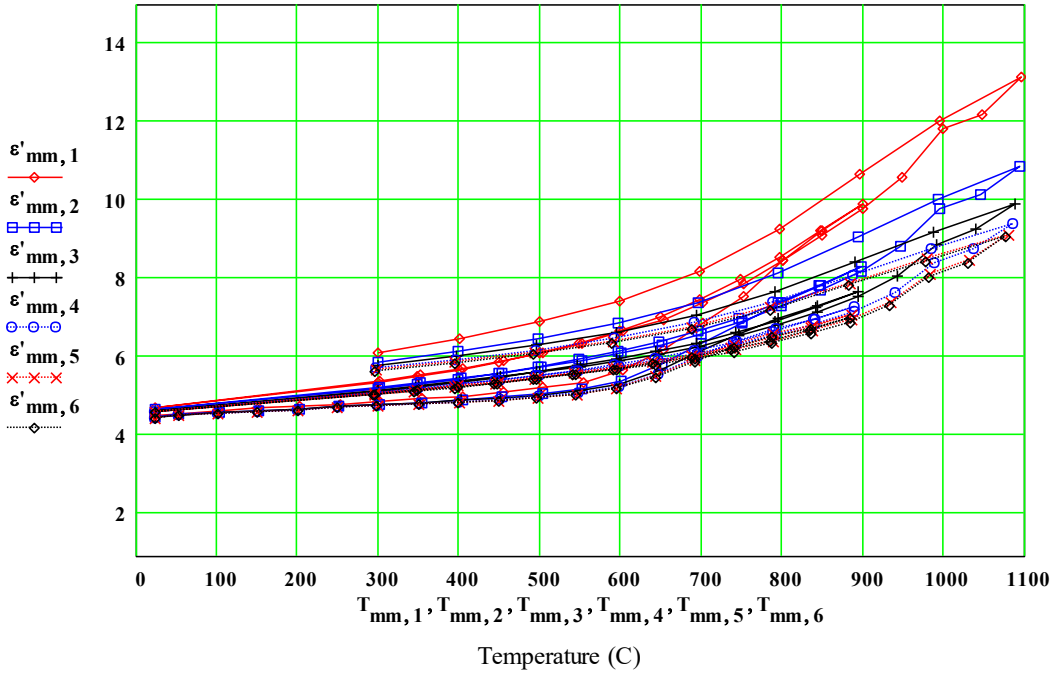
AnDat = 20210312

JSC-1A Pellets, 500 C Treated , RT to 900 C, then RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$

Final\_over\_Initial\_mass = 0.996



RefRatio = 0.292

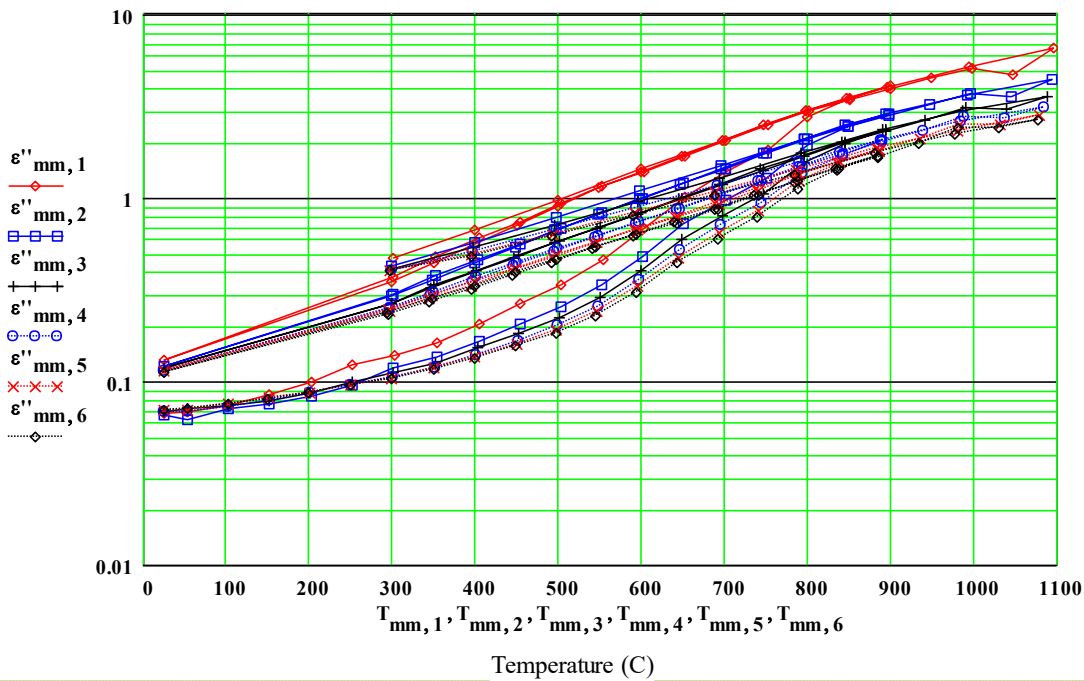
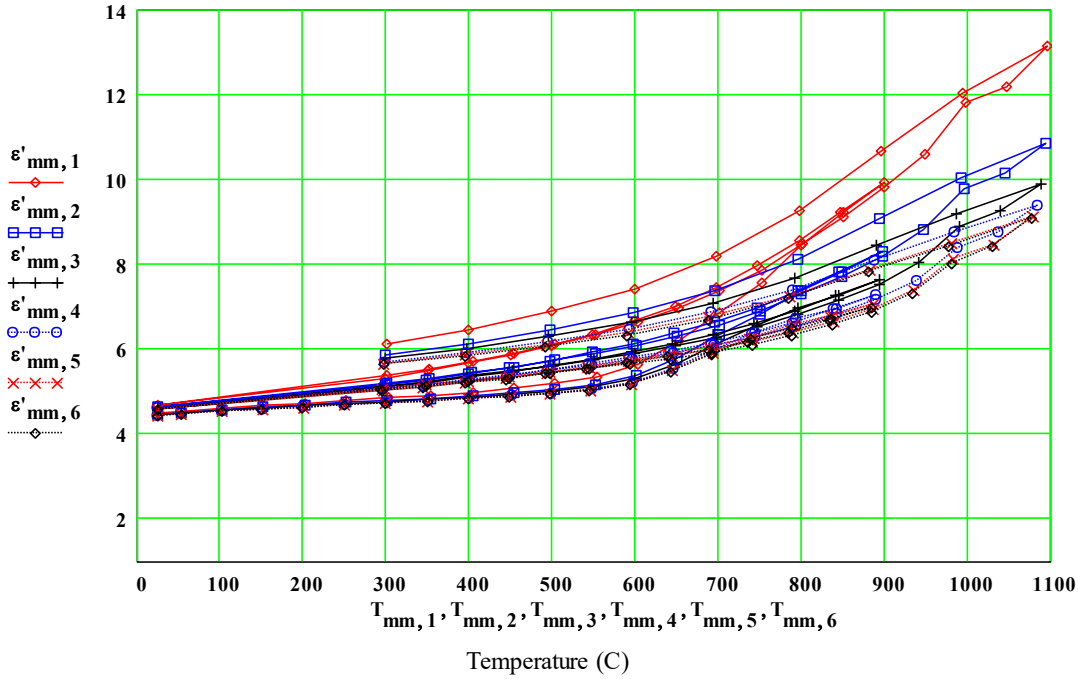
Values for the Two Temperature Cycles (to 900C and to 1100 C) :

Test = 2021031001 SHUL2117\_LowCal.mcd AnDat = 20210312 T

JSC-1A Pellets, 500C treated , RT to 900 C, then RT to 1100C, in flowing UHP Argon, for Holly Shulman LL

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$  I

FracMassChange = 1  $\alpha_1 = 0$  /C  $\alpha_2 = 0$  /C F



The initial  $\epsilon''$  values ( lower curve) are noticeably different from the values during the return down from 900C, suggesting a transformation in the material. Also the cycle up to 1100C

appears to have changed the final low temperature values somewhat, although the lack of the final few points makes this hard to quantify.

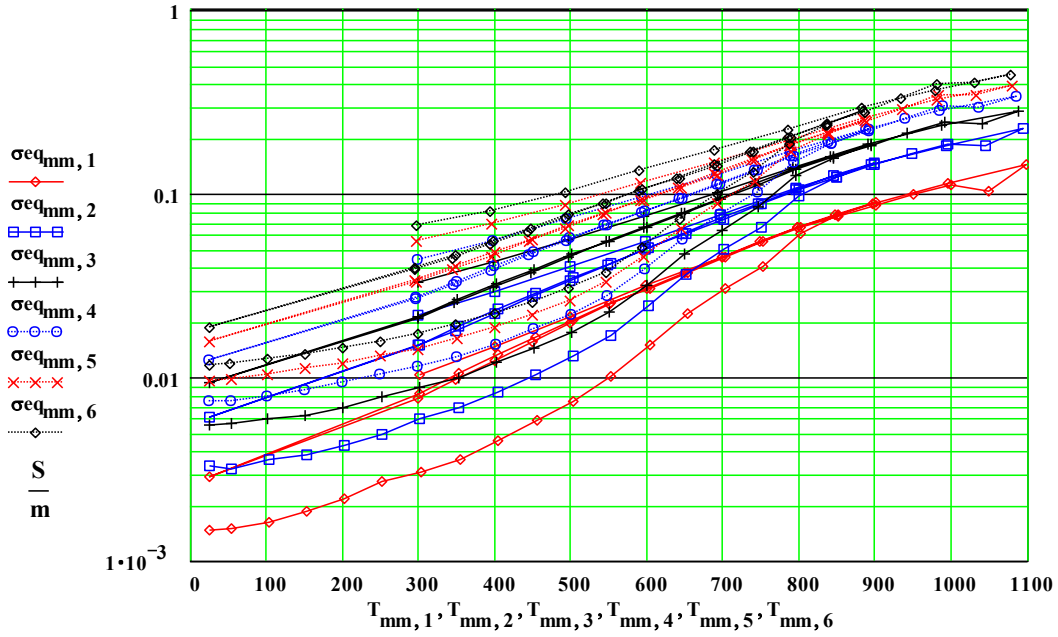
Test = 2021031001

SHUL2117\_LowCa1.mcd

AnDat = 20210312

JSC-1A Pellets , RT to 900 C, then RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2021031001

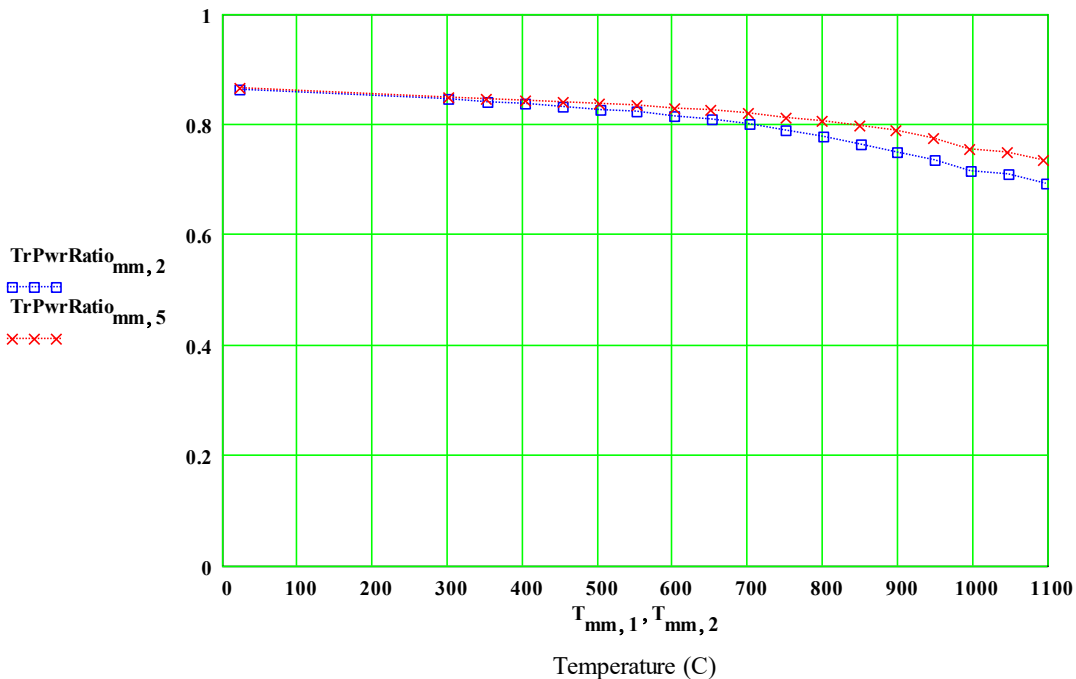
SHUL2117\_LowCal.med

AnDat = 20210312

JSC-1A Pellets, Pre-conditioned at 500C , RT to 1100C, in flowing UHP Argon, for H Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



# Appendix E. MPN Reports

Test = 2021031001

SHUL2117\_LowCal.med

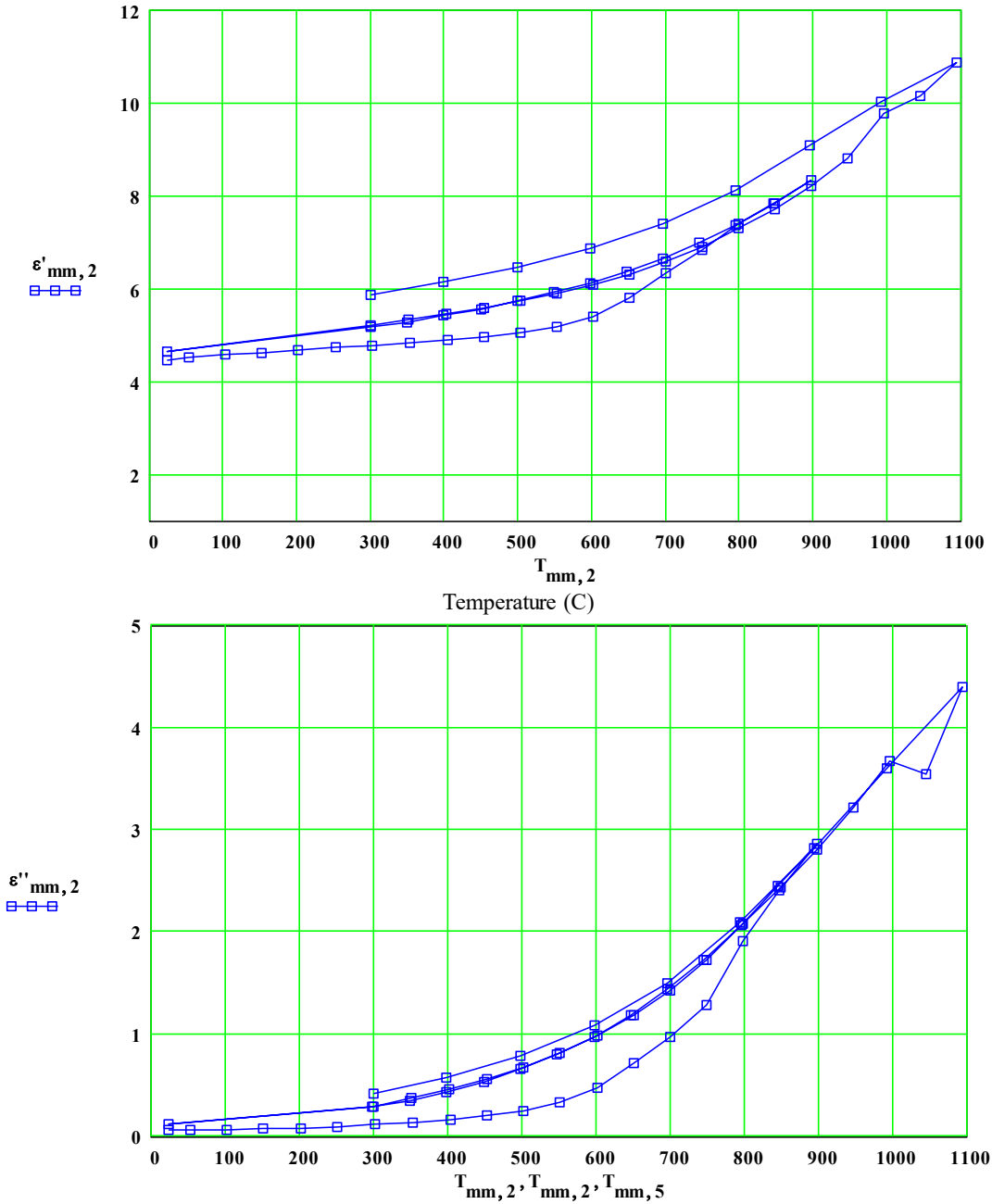
AnDat = 20210312

JSC-1A Pellets ,Heat Treated Material, RT to 900 C, then RT to 1100C, in flowing UHP Argon, for H Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ , Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021031001

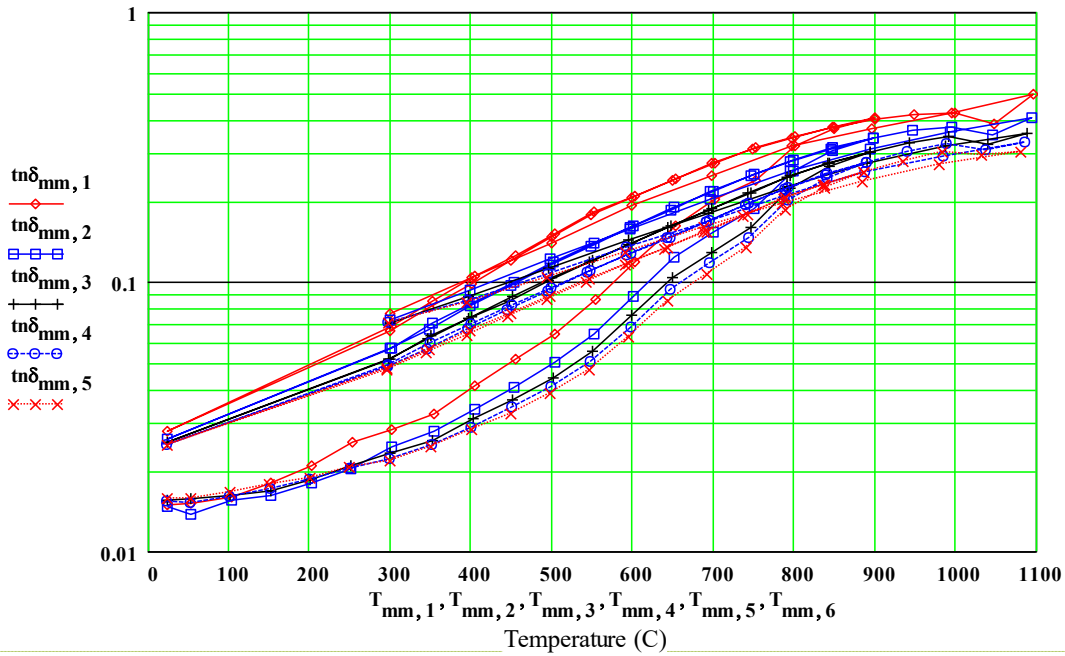
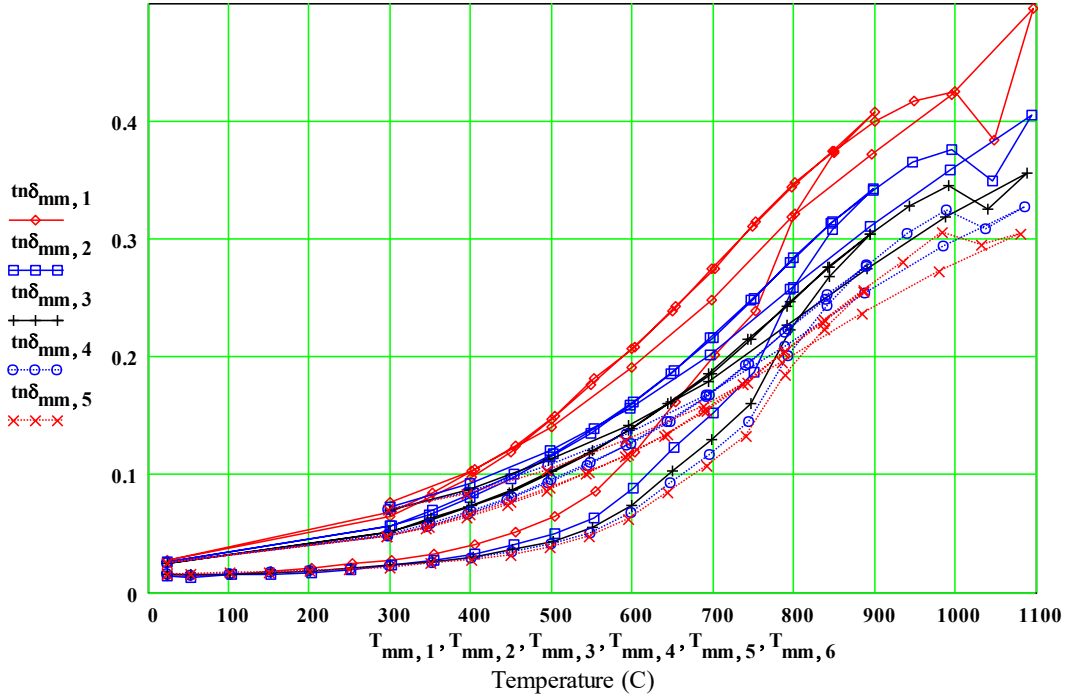
SHUL2117\_LowCal.mcd

AnDat = 20210312

JSC-1A Pellets, 500C treated , RT to 900 C, then RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$



Half-power Depth (millimeters)

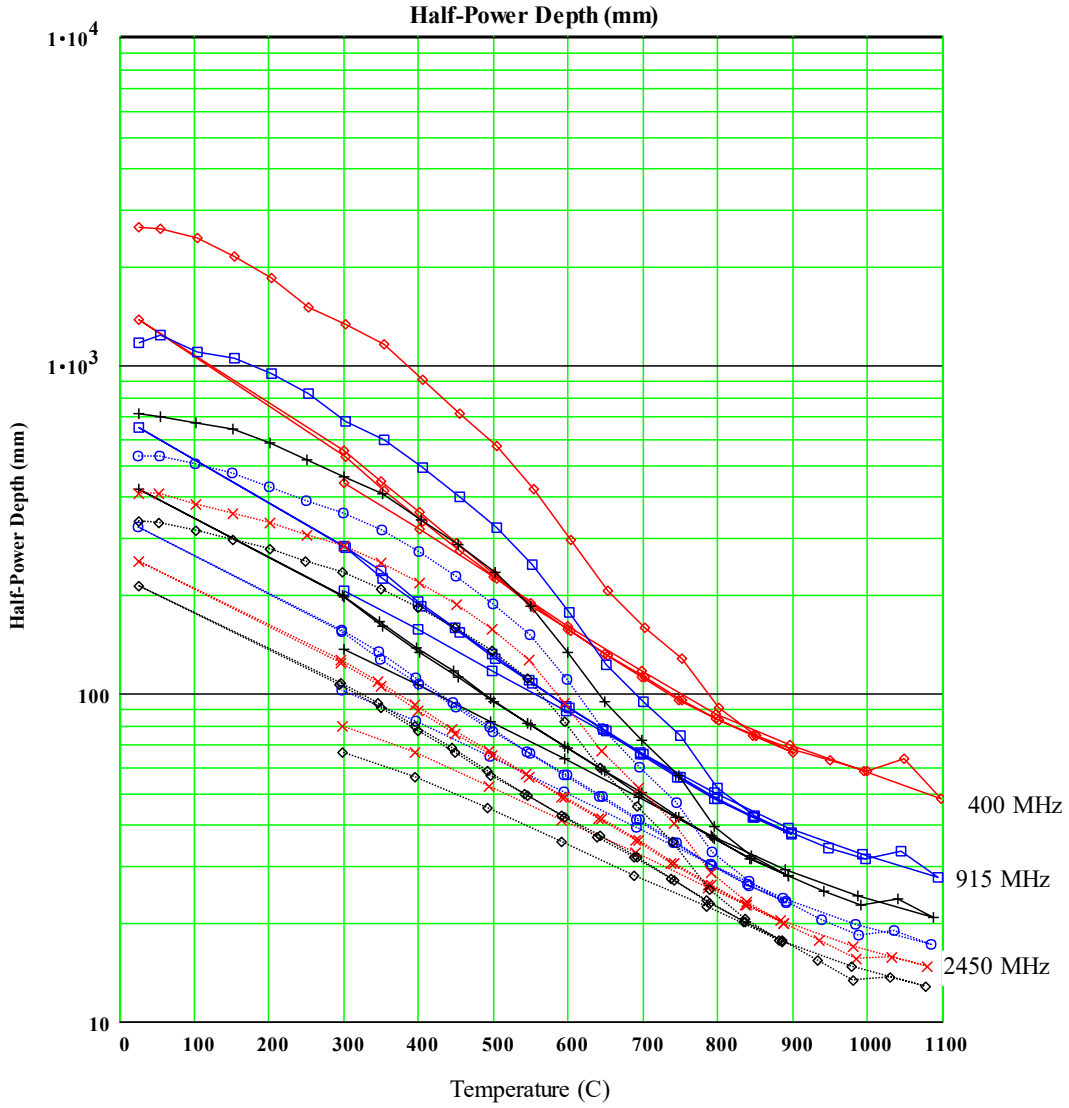
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021031001

SHUL2117\_LowCal.mcd

AnDat = 20210312

JSC-1A Pellets , RT to 900 C, then RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC



# Appendix E. MPN Reports

Test = 2021031001

SHUL2117\_LowCal.med

AnDat = 20210312

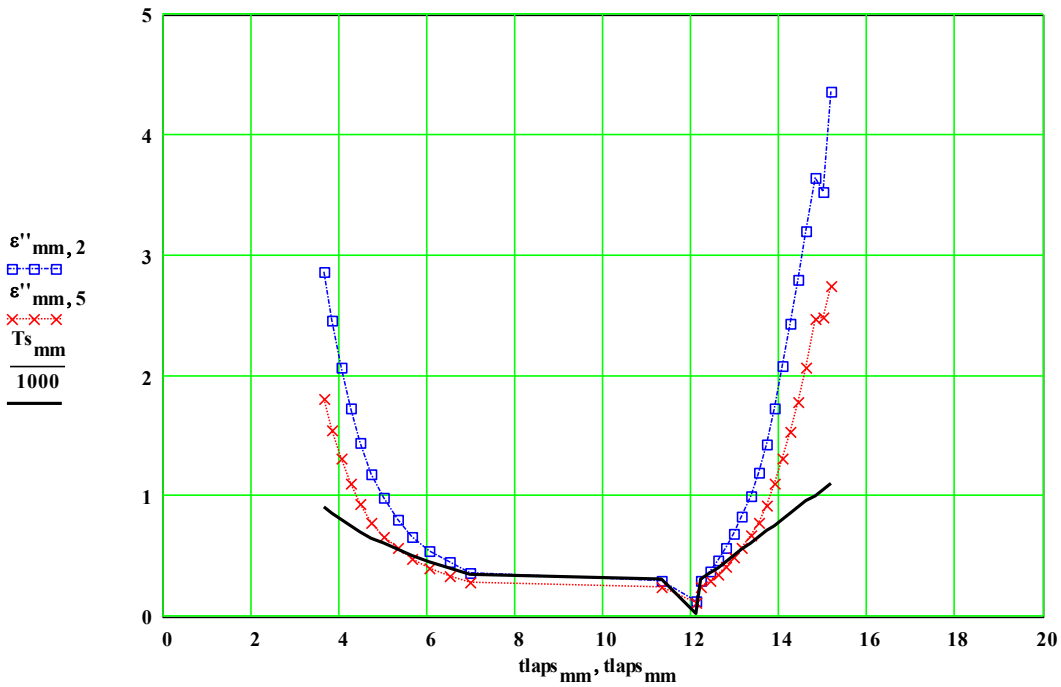
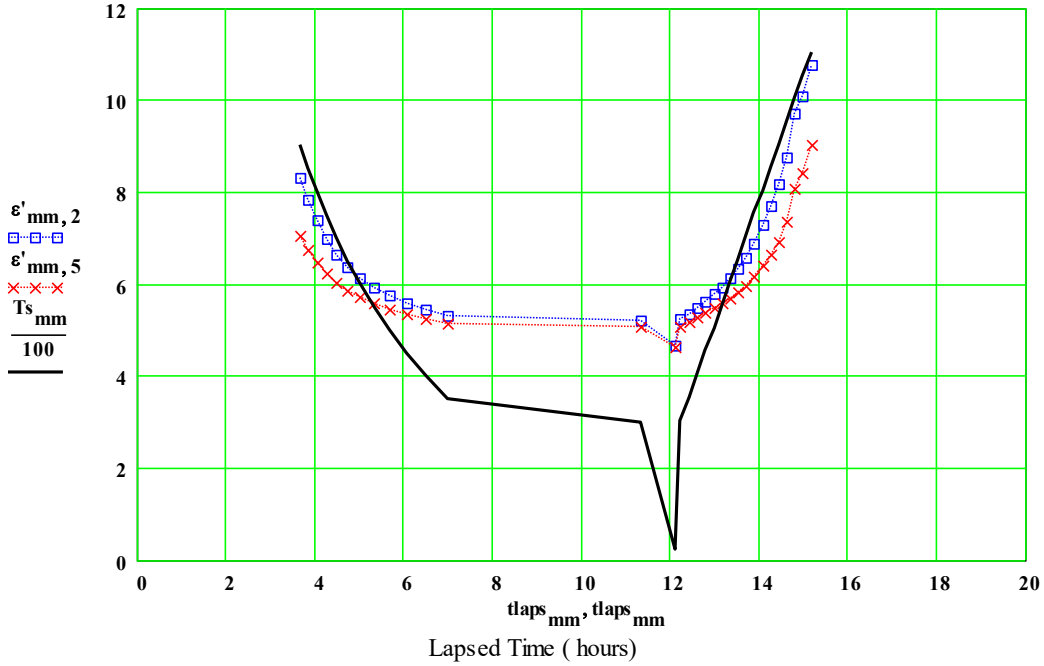
JSC-1A Pellets , 900 C then to RT, then to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$        $\text{FracMassChange} = 1$

$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2021031001

SHUL2117\_LowCal.mcd

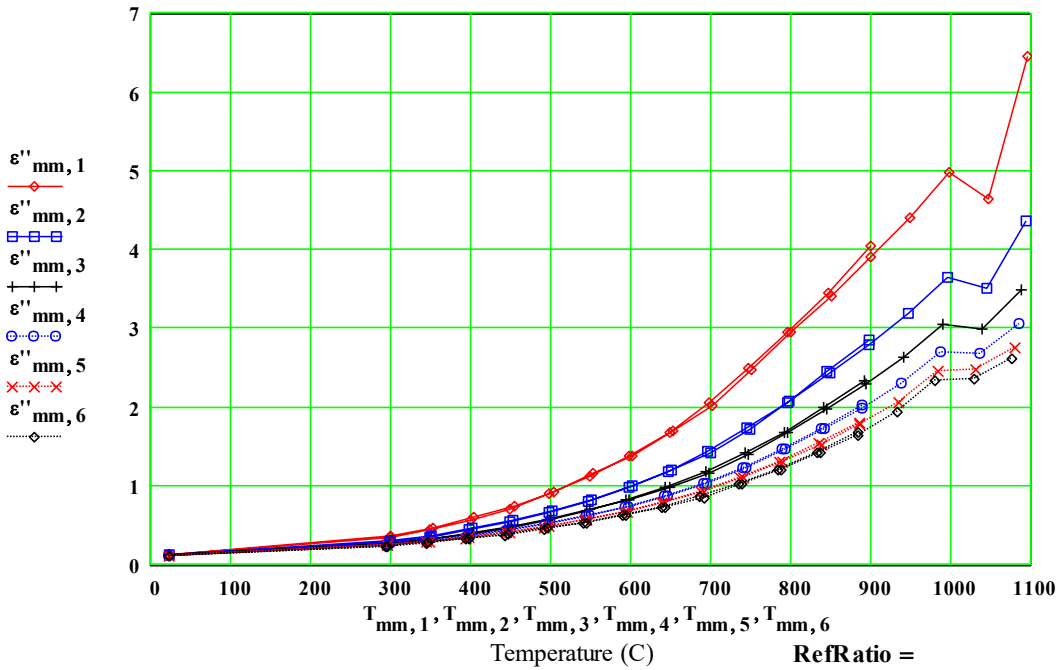
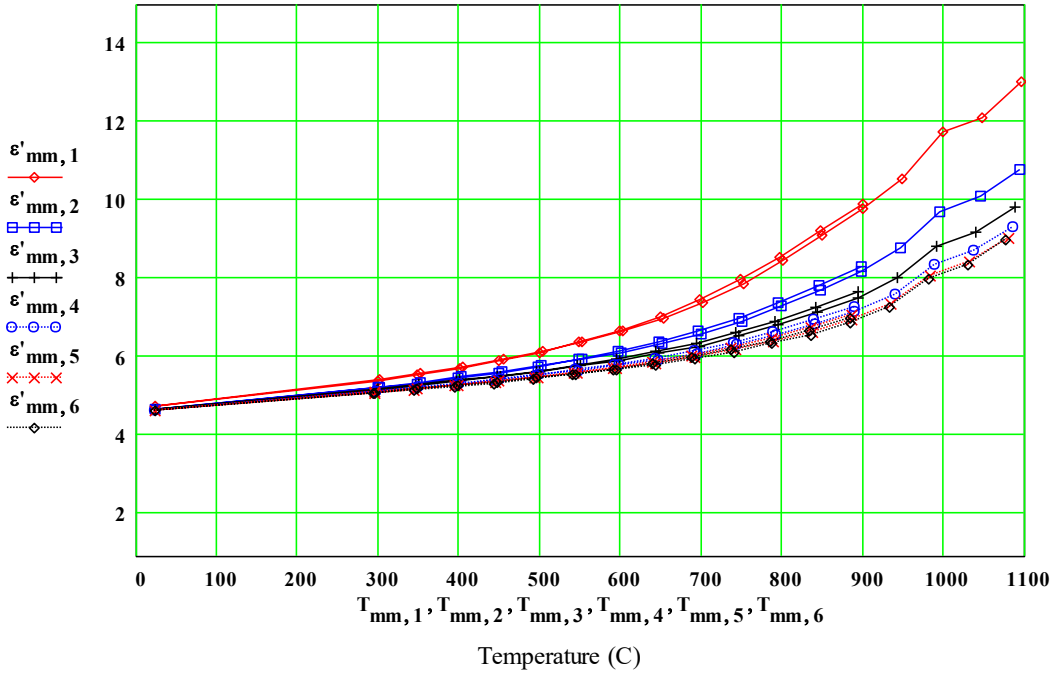
AnDat = 20210312

JSC-1A Pellets , 900 C then to RT, then to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.97 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$

Final\_over\_Initial\_mass = 0.996







Use the Jonscher Formalism to fit the Frequency and Thermal Dependence of  $\epsilon_{pp}$  and Conductivity  
Fit to Disordered Structure which Exists after the first cycle to 900C ( Extrinsic and Intrinsic Contribution

'Intrinsic' Range Values - High Temperature

$$E_{gn} := 0.68 \text{ eV}$$

$$\sigma_{intn} := 2.3 \cdot 10^0 \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.6$$

$$\epsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{gn}}{2 \cdot k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{f_n}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \epsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6} \quad \epsilon_{ppth_{(16,2)}} = 286.8$$

$$H_{activ} := \frac{E_{gn}}{2} = 0.34 \text{ eV} \quad \frac{E_{gn}}{2} = 0.34 \text{ eV}$$

$$H_{activ} = 33 \text{ Kjoule/mol} \quad E_a := \frac{E_{gn}}{2} \text{ Activation Energy}$$

'Extrinsic' Values - Low Temperature, Impurity Dependent

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{gm} := 0.06 \quad \sigma_{intm} := 0.0095 \quad m_J := 0.90$$

$$\epsilon_{ppthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{(2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6})} \cdot \exp \left[ \frac{-E_{gm}}{2 \cdot k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{f_n}{400} \right)^{m_J}$$

$$\sigma_{thJm_{mn,n}} := \epsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot f_n \cdot 8.85 \cdot 10^{-6}$$

$$\epsilon_{ppthTotal_{mn,n}} := \epsilon_{ppthJn_{mn,n}} + \epsilon_{ppthJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

Test = 2021031001

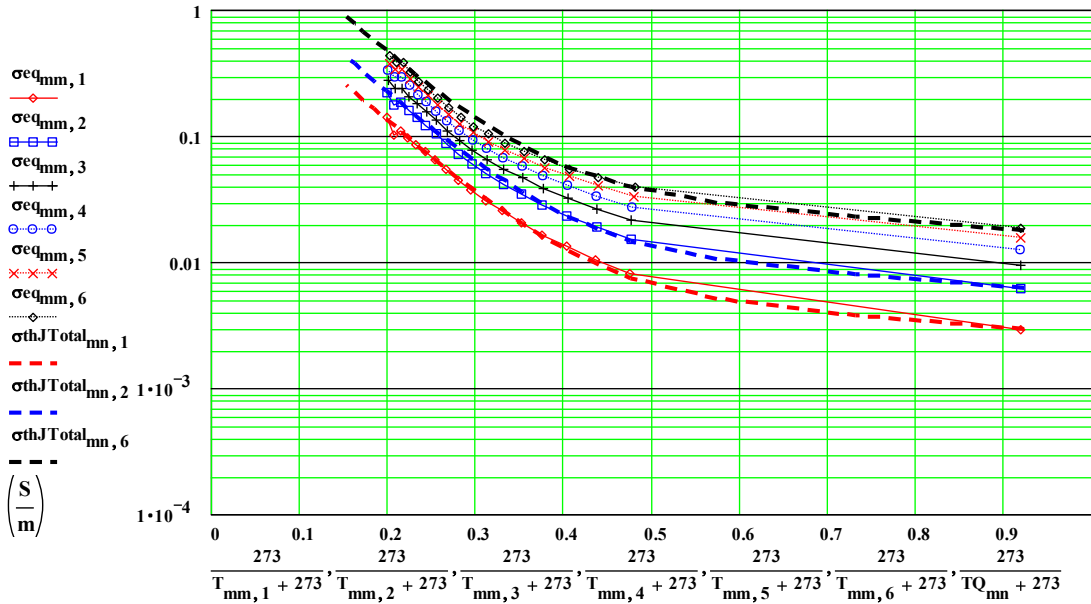
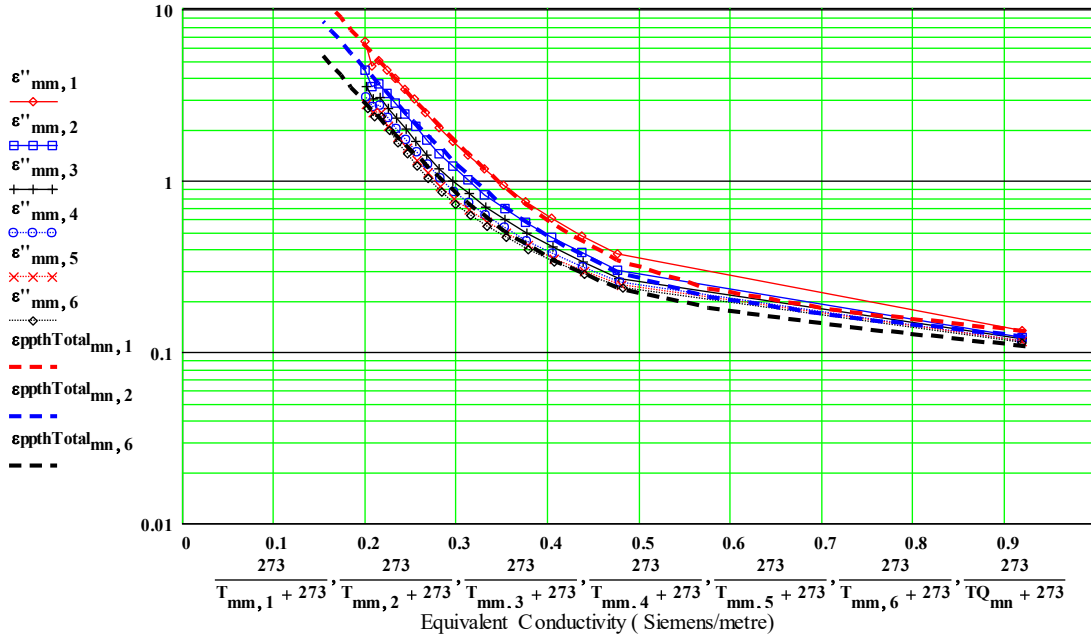
SHUL2117\_LowCal.mcd

AnDat = 20210312

JSC-1A Pellets, 500C treated , final cycle RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_0 = 1.97 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.89 \text{ gm/cc}$

Egn = 0.68 eV       $\sigma_{\text{intn}} = 2.3$  Siemens/metre      nJ = 0.6



# Appendix E. MPN Reports

Test = 2021031001

SHUL2117\_LowCal.mcd

AnDat = 20210312

SHUL2117\_LowCal.mcc

JSC-1A Pellets, 500C treated , final cycle RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.969 \text{ gm/cc}$       Final density(25C) =  $\text{dnsfinal} = 1.893 \text{ gm/cc}$   
 Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz      Time (hours)

| samdns | $r_{\text{mm}}$ | $T_{\text{mm},1}$ | $\epsilon'_{\text{mm},1}$ | $\epsilon'_{\text{mm},2}$ | $\epsilon'_{\text{mm},3}$ | $\epsilon'_{\text{mm},4}$ | $\epsilon'_{\text{mm},5}$ | $\epsilon'_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammass <sub>mm</sub> |
|--------|-----------------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------|-----------------------|
| 1.969  | 8               | 24                | 4.49                      | 4.47                      | 4.46                      | 4.44                      | 4.43                      | 4.43                      | 0                   | 0.285                 |
| 1.969  | 9               | 53                | 4.56                      | 4.53                      | 4.52                      | 4.49                      | 4.49                      | 4.49                      | 0.25                | 0.285                 |
| 1.969  | 10              | 102               | 4.63                      | 4.59                      | 4.58                      | 4.55                      | 4.55                      | 4.54                      | 0.5                 | 0.285                 |
| 1.969  | 11              | 152               | 4.69                      | 4.64                      | 4.63                      | 4.6                       | 4.59                      | 4.59                      | 0.77                | 0.285                 |
| 1.969  | 12              | 202               | 4.73                      | 4.68                      | 4.67                      | 4.64                      | 4.64                      | 4.63                      | 0.99                | 0.285                 |
| 1.969  | 13              | 252               | 4.8                       | 4.75                      | 4.74                      | 4.7                       | 4.69                      | 4.69                      | 1.22                | 0.285                 |
| 1.969  | 14              | 302               | 4.87                      | 4.8                       | 4.78                      | 4.75                      | 4.74                      | 4.73                      | 1.46                | 0.285                 |
| 1.969  | 15              | 354               | 4.93                      | 4.84                      | 4.83                      | 4.79                      | 4.78                      | 4.77                      | 1.65                | 0.285                 |
| 1.969  | 16              | 404               | 5                         | 4.91                      | 4.89                      | 4.84                      | 4.83                      | 4.82                      | 1.84                | 0.285                 |
| 1.969  | 17              | 454               | 5.09                      | 4.98                      | 4.95                      | 4.9                       | 4.88                      | 4.87                      | 2.02                | 0.285                 |
| 1.969  | 18              | 504               | 5.21                      | 5.06                      | 5.03                      | 4.97                      | 4.95                      | 4.94                      | 2.21                | 0.285                 |
| 1.969  | 19              | 553               | 5.36                      | 5.18                      | 5.13                      | 5.06                      | 5.03                      | 5.02                      | 2.39                | 0.285                 |
| 1.968  | 20              | 603               | 5.66                      | 5.4                       | 5.31                      | 5.23                      | 5.19                      | 5.17                      | 2.57                | 0.285                 |
| 1.967  | 21              | 652               | 6.2                       | 5.81                      | 5.67                      | 5.55                      | 5.5                       | 5.47                      | 2.76                | 0.285                 |
| 1.965  | 22              | 702               | 6.87                      | 6.34                      | 6.14                      | 6                         | 5.92                      | 5.88                      | 2.94                | 0.284                 |
| 1.964  | 23              | 751               | 7.57                      | 6.85                      | 6.58                      | 6.39                      | 6.29                      | 6.24                      | 3.12                | 0.284                 |
| 1.963  | 24              | 800               | 8.46                      | 7.4                       | 6.98                      | 6.71                      | 6.57                      | 6.5                       | 3.31                | 0.284                 |
| 1.962  | 25              | 850               | 9.23                      | 7.84                      | 7.29                      | 6.96                      | 6.78                      | 6.71                      | 3.49                | 0.284                 |
| 1.962  | 26              | 899               | 9.93                      | 8.33                      | 7.66                      | 7.27                      | 7.06                      | 6.97                      | 3.67                | 0.284                 |
| 1.962  | 27              | 847               | 9.24                      | 7.84                      | 7.27                      | 6.94                      | 6.75                      | 6.67                      | 3.86                | 0.284                 |
| 1.962  | 28              | 797               | 8.57                      | 7.38                      | 6.91                      | 6.63                      | 6.48                      | 6.4                       | 4.05                | 0.284                 |
| 1.962  | 29              | 747               | 8                         | 6.99                      | 6.61                      | 6.37                      | 6.25                      | 6.18                      | 4.26                | 0.284                 |
| 1.962  | 30              | 698               | 7.47                      | 6.66                      | 6.35                      | 6.15                      | 6.05                      | 5.99                      | 4.5                 | 0.284                 |
| 1.962  | 31              | 648               | 7.03                      | 6.37                      | 6.13                      | 5.96                      | 5.87                      | 5.82                      | 4.75                | 0.284                 |
| 1.962  | 32              | 599               | 6.68                      | 6.15                      | 5.94                      | 5.79                      | 5.72                      | 5.68                      | 5.03                | 0.284                 |
| 1.962  | 33              | 549               | 6.38                      | 5.95                      | 5.79                      | 5.66                      | 5.59                      | 5.56                      | 5.34                | 0.284                 |
| 1.962  | 34              | 499               | 6.11                      | 5.76                      | 5.63                      | 5.51                      | 5.46                      | 5.43                      | 5.69                | 0.284                 |
| 1.962  | 35              | 449               | 5.9                       | 5.6                       | 5.49                      | 5.39                      | 5.35                      | 5.32                      | 6.07                | 0.284                 |
| 1.962  | 36              | 400               | 5.71                      | 5.46                      | 5.37                      | 5.28                      | 5.25                      | 5.23                      | 6.51                | 0.284                 |
| 1.962  | 37              | 349               | 5.53                      | 5.32                      | 5.26                      | 5.18                      | 5.15                      | 5.13                      | 7                   | 0.284                 |
| 1.962  | 38              | 299               | 5.38                      | 5.21                      | 5.16                      | 5.09                      | 5.06                      | 5.05                      | 11.34               | 0.284                 |
| 1.962  | 39              | 24                | 4.75                      | 4.68                      | 4.67                      | 4.64                      | 4.64                      | 4.63                      | 12.11               | 0.284                 |
| 1.958  | 40              | 301               | 5.42                      | 5.25                      | 5.19                      | 5.12                      | 5.1                       | 5.08                      | 12.24               | 0.284                 |
| 1.954  | 41              | 352               | 5.59                      | 5.36                      | 5.3                       | 5.22                      | 5.19                      | 5.17                      | 12.43               | 0.284                 |
| 1.95   | 42              | 404               | 5.75                      | 5.49                      | 5.41                      | 5.32                      | 5.28                      | 5.26                      | 12.62               | 0.284                 |
| 1.945  | 43              | 454               | 5.94                      | 5.62                      | 5.52                      | 5.41                      | 5.37                      | 5.35                      | 12.8                | 0.284                 |
| 1.941  | 44              | 503               | 6.15                      | 5.78                      | 5.65                      | 5.53                      | 5.48                      | 5.45                      | 12.99               | 0.284                 |
| 1.937  | 45              | 553               | 6.38                      | 5.93                      | 5.77                      | 5.64                      | 5.58                      | 5.55                      | 13.17               | 0.284                 |
| 1.933  | 46              | 603               | 6.67                      | 6.12                      | 5.93                      | 5.78                      | 5.7                       | 5.66                      | 13.35               | 0.284                 |
| 1.929  | 47              | 652               | 6.98                      | 6.33                      | 6.09                      | 5.91                      | 5.83                      | 5.79                      | 13.54               | 0.284                 |
| 1.925  | 48              | 702               | 7.38                      | 6.58                      | 6.28                      | 6.08                      | 5.98                      | 5.93                      | 13.72               | 0.284                 |
| 1.921  | 49              | 752               | 7.88                      | 6.9                       | 6.53                      | 6.29                      | 6.17                      | 6.11                      | 13.9                | 0.284                 |
| 1.917  | 50              | 801               | 8.47                      | 7.29                      | 6.83                      | 6.55                      | 6.4                       | 6.33                      | 14.08               | 0.284                 |
| 1.913  | 51              | 850               | 9.11                      | 7.71                      | 7.15                      | 6.82                      | 6.65                      | 6.57                      | 14.27               | 0.284                 |
| 1.909  | 52              | 900               | 9.78                      | 8.18                      | 7.52                      | 7.14                      | 6.93                      | 6.85                      | 14.45               | 0.284                 |
| 1.905  | 53              | 949               | 10.57                     | 8.78                      | 8.03                      | 7.59                      | 7.35                      | 7.27                      | 14.63               | 0.284                 |
| 1.901  | 54              | 998               | 11.77                     | 9.72                      | 8.84                      | 8.34                      | 8.07                      | 8                         | 14.82               | 0.284                 |
| 1.897  | 55              | 1048              | 12.12                     | 10.1                      | 9.2                       | 8.69                      | 8.42                      | 8.36                      | 15                  | 0.284                 |
| 1.893  | 56              | 1097              | 13.05                     | 10.79                     | 9.85                      | 9.32                      | 9.04                      | 9.01                      | 15.18               | 0.284                 |
| 1.893  | 57              | 995               | 11.95                     | 9.98                      | 9.15                      | 8.69                      | 8.46                      | 8.38                      | 15.45               | 0.284                 |

# Appendix E. MPN Reports

| sdmns | $m_{mq}$ | $T_{mq,1}$ | $\epsilon'_{mq,1}$ | $\epsilon'_{mq,2}$ | $\epsilon'_{mq,3}$ | $\epsilon'_{mq,4}$ | $\epsilon'_{mq,5}$ | $\epsilon'_{mq,6}$ | $tlaps_{mq}$ | $sammas_{mq}$ |
|-------|----------|------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------|---------------|
| 1.893 | 58       | 896        | 10.63              | 9.05               | 8.41               | 8.04               | 7.85               | 7.78               | 15.71        | 0.284         |
| 1.893 | 59       | 797        | 9.23               | 8.11               | 7.66               | 7.38               | 7.23               | 7.17               | 16.03        | 0.284         |
| 1.893 | 60       | 698        | 8.18               | 7.38               | 7.07               | 6.85               | 6.74               | 6.69               | 16.42        | 0.284         |
| 1.893 | 61       | 598        | 7.43               | 6.87               | 6.64               | 6.46               | 6.37               | 6.33               | 16.89        | 0.284         |
| 1.893 | 62       | 499        | 6.9                | 6.47               | 6.3                | 6.16               | 6.09               | 6.06               | 17.5         | 0.284         |
| 1.893 | 63       | 400        | 6.46               | 6.15               | 6.03               | 5.92               | 5.87               | 5.84               | 18.27        | 0.284         |
| 1.893 | 64       | 300        | 6.12               | 5.88               | 5.8                | 5.71               | 5.67               | 5.65               | 19.28        | 0.284         |
| 1.893 | 65       | 106        | 1                  | 1                  | 1.01               | 1.01               | 1.01               | 1.02               | 23.18        | 0.284         |

SHUL2117\_LowCaImcc



# Appendix E. MPN Reports

| samdns <sub>mq</sub> | T <sub>mq,1</sub> | $\epsilon''_{mq,1}$ | $\epsilon''_{mq,2}$ | $\epsilon''_{mq,3}$ | $\epsilon''_{mq,4}$ | $\epsilon''_{mq,5}$ | $\epsilon''_{mq,6}$ | tlaps <sub>mq</sub> | sammas <sub>mq</sub> |       |
|----------------------|-------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------------|-------|
| 1.893                | 57                | 995                 | 5.048               | 3.577               | 2.917               | 2.545               | 2.3                 | 2.177               | 15.45                | 0.284 |
| 1.893                | 58                | 896                 | 3.959               | 2.812               | 2.317               | 2.04                | 1.852               | 1.745               | 15.71                | 0.284 |
| 1.893                | 59                | 797                 | 2.943               | 2.089               | 1.735               | 1.542               | 1.41                | 1.328               | 16.03                | 0.284 |
| 1.893                | 60                | 698                 | 2.036               | 1.491               | 1.271               | 1.144               | 1.069               | 1.028               | 16.42                | 0.284 |
| 1.893                | 61                | 598                 | 1.425               | 1.082               | 0.949               | 0.87                | 0.823               | 0.791               | 16.89                | 0.284 |
| 1.893                | 62                | 499                 | 0.969               | 0.787               | 0.709               | 0.66                | 0.633               | 0.612               | 17.5                 | 0.284 |
| 1.893                | 63                | 400                 | 0.671               | 0.575               | 0.532               | 0.504               | 0.491               | 0.482               | 18.27                | 0.284 |
| 1.893                | 64                | 300                 | 0.471               | 0.427               | 0.411               | 0.401               | 0.4                 | 0.398               | 19.28                | 0.284 |
| 1.893                | 65                | 106                 | -0.006              | -0.004              | -0                  | -0.001              | 0                   | -0                  | 23.18                | 0.284 |

SHUL2117\_LowCaLmcc

MPN-218\_Shulman\_2\_JSC-1A

Mar. 15, 2021

JSC-1A ( Initially Heat Treated to 500C in Argon for 6 hours)  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in Flowing UHP Argon  
2<sup>nd</sup> Run

Dr. Holly Shulman ( Shulman LLC) again requested that Microwave Properties North measure the complex dielectric properties of a specially treated JSC-1A moon simulant up to 1100C in UHP argon – but this time with a direct, uninterrupted, cycle . The powder sample material arrived at MPN on Mar. 5/ 2021. Dr. Shulman had already baked the powder at 500C for 6 hours in UHP argon.

MPN pressed pellets of the powder material ( in a uniaxial press, ~ 20,000 psi) achieving a density of ~ 1.97 g/cc . The pellets were baked for 2 hours at 140 C to ensure dryness.

MPN was requested to cycle the sample directly up to 1100C and then return to room temperature (RT) ,all in a 10 sccm flow of UHP argon ( which likely has ~ 1 to 10 ppm oxygen content).

The initial sample parameters were:

- a) diameter 3.63 +- 0.05 mm
- b) length 14.52 +- 0.10 mm
- c) mass 0.304 +- 0.002 gm
- x) room temperature density  $2.02 \pm 0.10$  gm/cc.
- y) appearance - three (stacked) grey pellets ( see photo). Four pellets were made, only three were used.

The dielectric properties measurements were performed at RT and then ramped the temperature was ramped up to 1100C in 50C steps, and then brought back down to RT in -100C steps.

The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was then run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.62 \pm 0.05$  mm
- b) length  $14.62 \pm 0.1$  mm
- c) mass  $0.304 \pm 0.002$  gm
- w) room temperature density  $2.02 \pm 0.10$  gm/cc.
- x) appearance - three dark-brown pellets ( see photo)

Note: The percent mass loss was  $< 0.5$  % .

The frequency coding is :

Legend for Data Plots :

| # | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|---|-----------------------|----------------------------------------------------------|
| 1 | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912                   | blue square, solid line                                  |
| 3 | 1429                  | black cross, solid line                                  |
| 4 | 1948                  | blue circle, dotted line                                 |
| 5 | 2466                  | red cross, dotted line                                   |
| 6 | 2986                  | black diamond, dotted line                               |

Comments on the data analysis:

A thermal expansion coefficient (CTE) of  $0.0 * 10^{-6}/C$  was used.

The final pellets were a different colour – a dark brown. One of the pellets broke during handling after the run, and it was clear the dark brown persisted through the bulk of the pellet. Otherwise, they appeared unchanged.

The data for the ramp up to 1100C is definitely different than for the ramp down. Some change has occurred. The cycle to 1100 C seems to produce a change in the material that produces slightly elevated values on the return down to room temperature.

The change in slope at 1050C suggests the beginnings of a reaction – possible with the holder.



Initial Pellets after pressing – 4 pellets



1 un-used pellet,

then the 3 pellets temperature cycled pellets

# Appendix E. MPN Reports

Test = 2021031301

SHUL2119\_LowCal.mcd

AnDat = 20210314

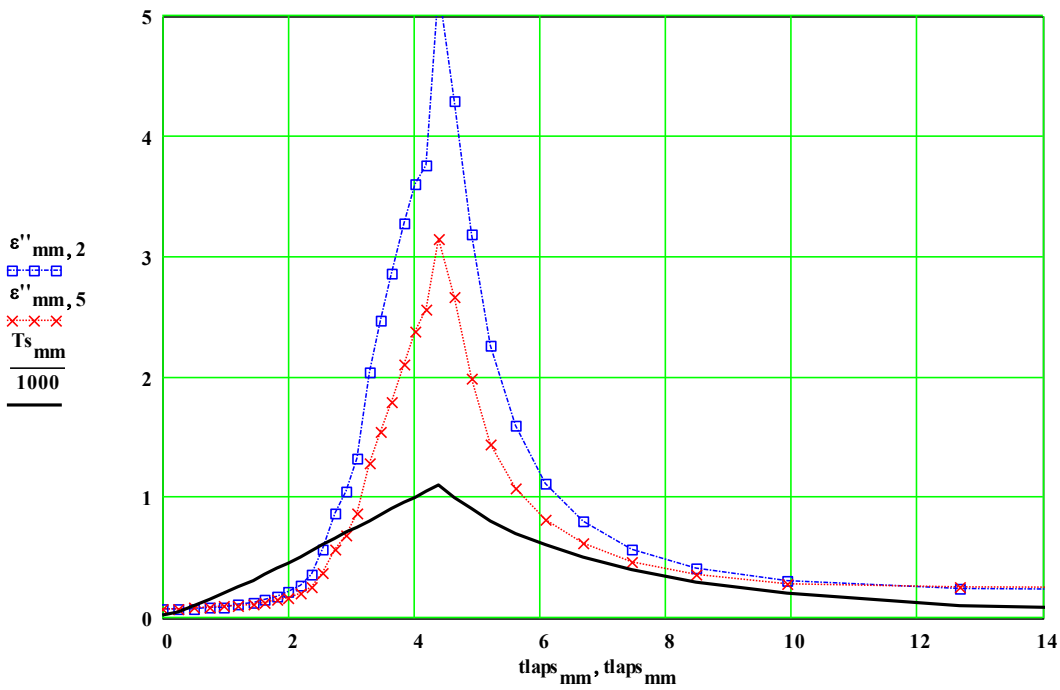
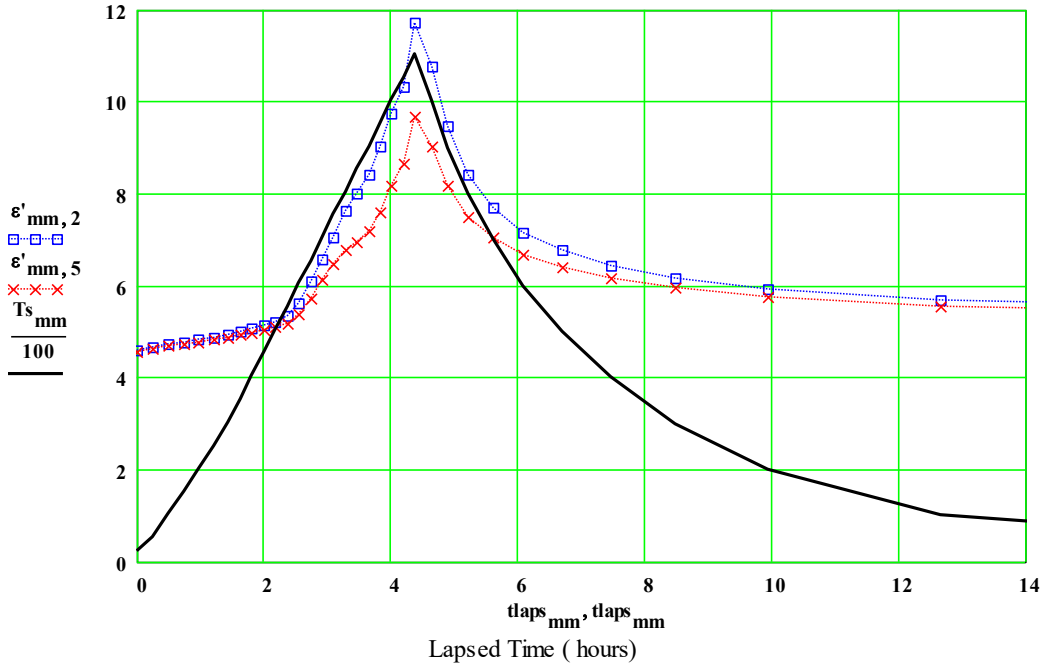
JSC-1A, 500C argon-conditioned Pellets , RT to 1100C, in 10 sccm flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.02 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$       **FracMassChange = 1**

$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2021031301

SHUL2119\_LowCal.mcd

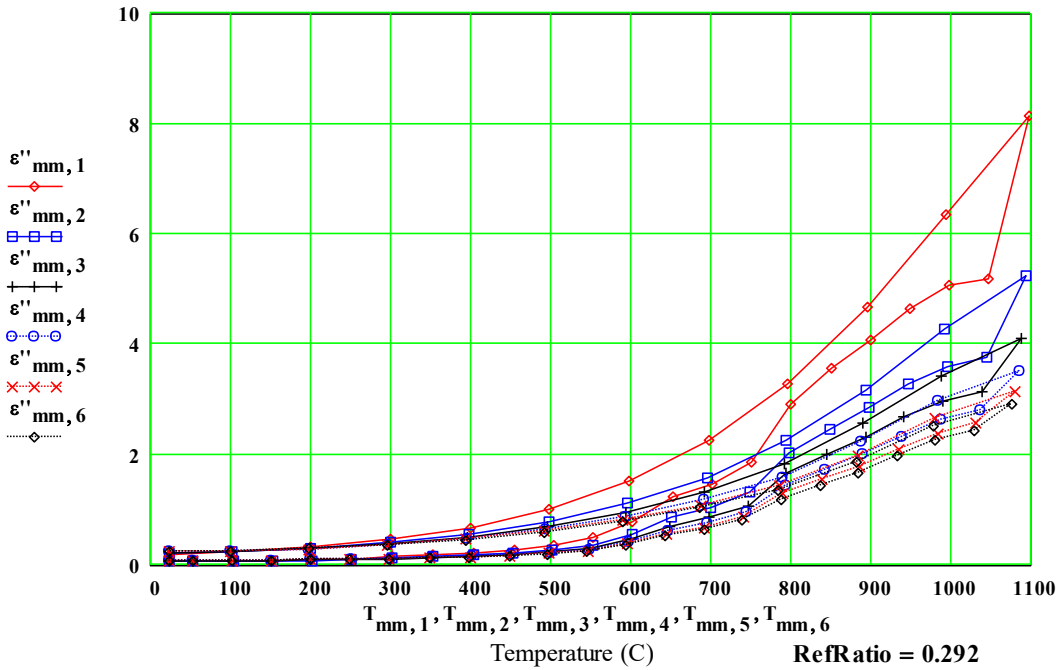
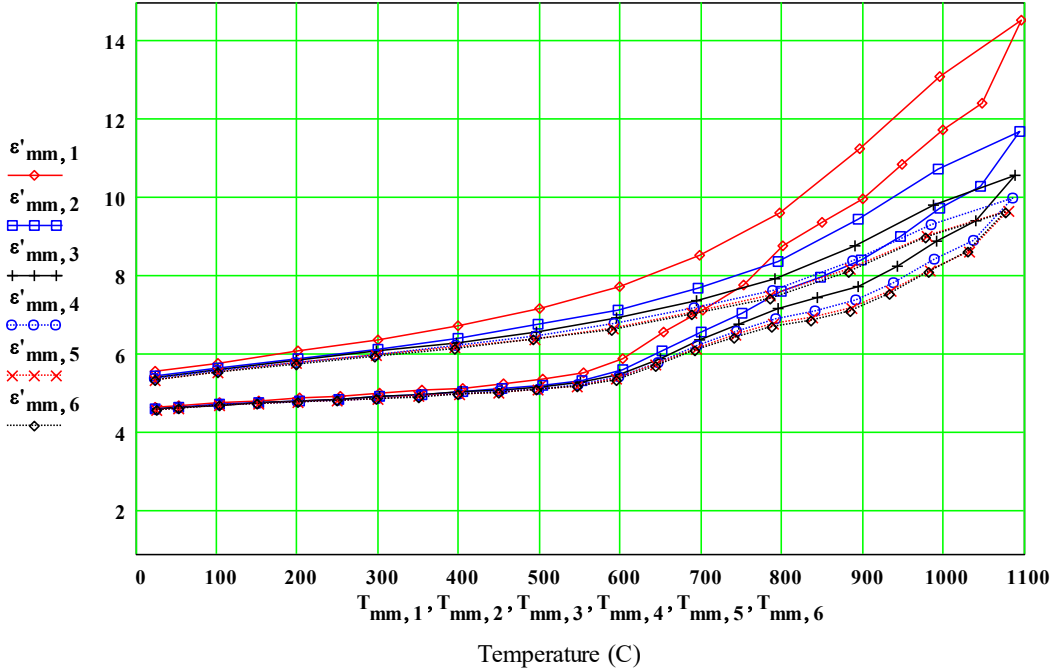
AnDat = 20210314

JSC-1A, 500C argon-conditioned Pellets , RT to 1100C, in 10 sccm flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.02 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



RefRatio = 0.292

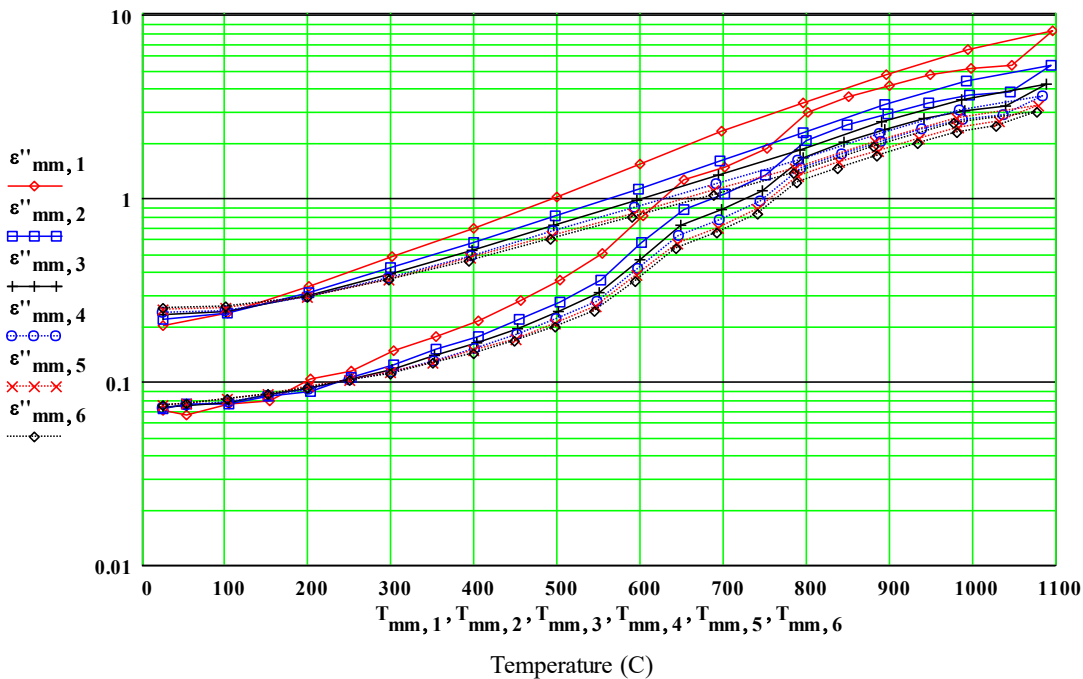
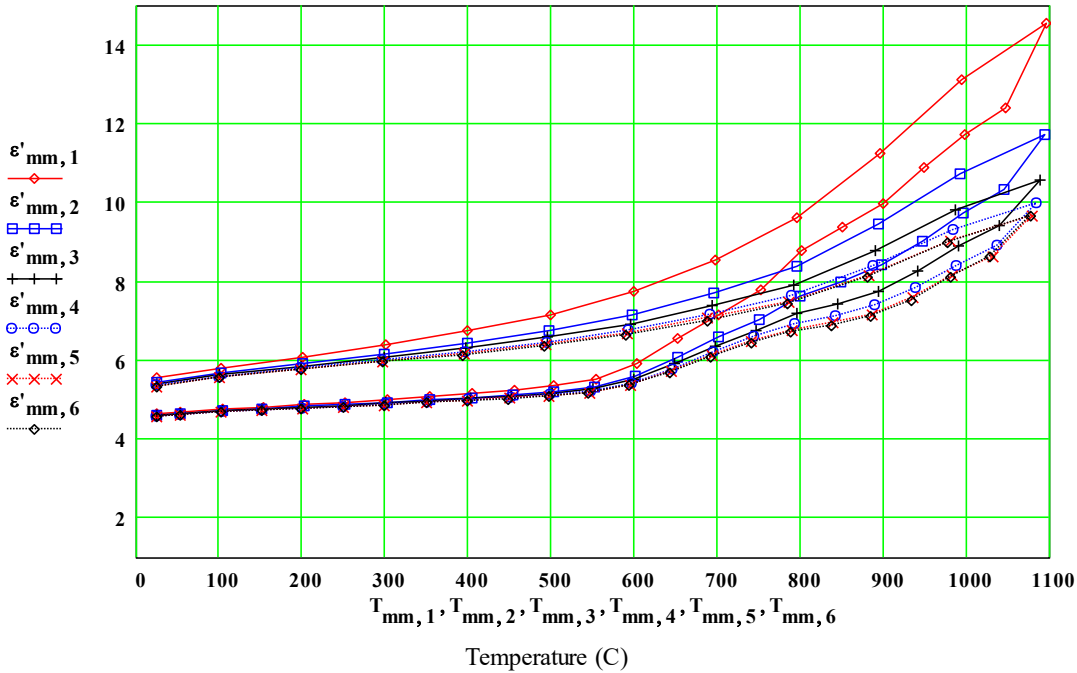
Values for the Temperature Cycle (to 1100 C and back to RT) :

Test = 2021031301 SHUL2119\_LowCal.mcd AnDat = 20210314 T

JSC-1A, 500C argon-conditioned Pellets , RT to 1100C, in 10 sccm flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.02 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$  I

FracMassChange = 1  $\alpha_1 = 0$  /C  $\alpha_2 = 0$  /C F



The initial  $\epsilon''$  values ( lower curve) are noticeably different from the values during the return, suggesting a transformation in the material. The cycle up to 1100C appears to have changed the final low temperature values.

# Appendix E. MPN Reports

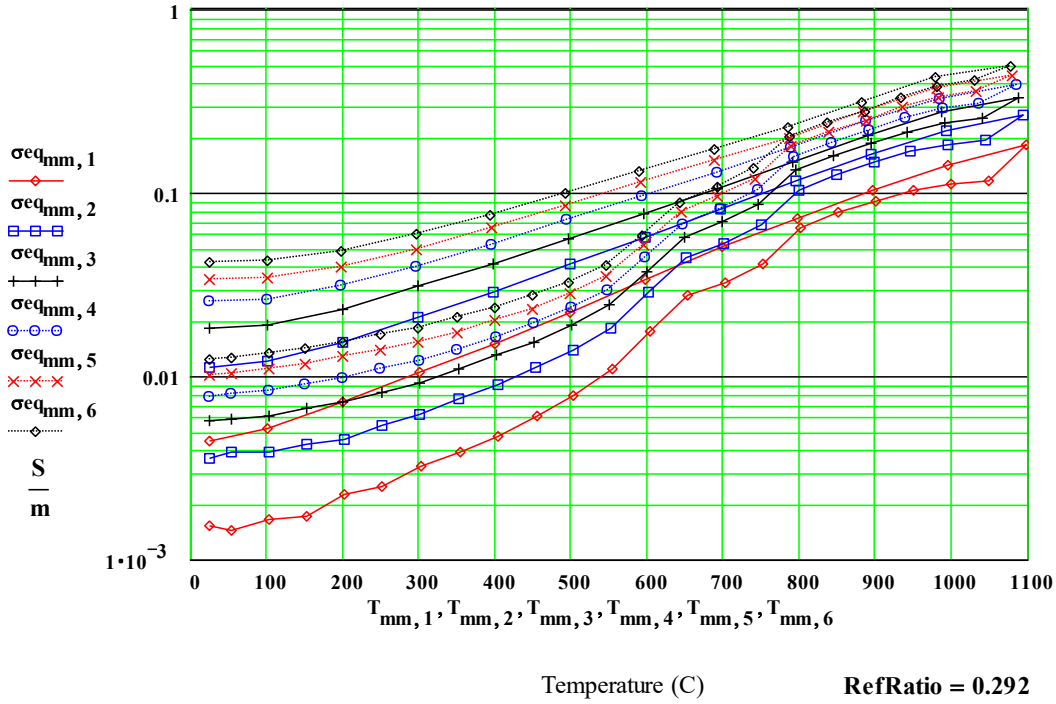
Test = 2021031301

SHUL2119\_LowCal.mcd

AnDat = 20210314

JSC-1A, 500C argon-conditioned Pellets , RT to 1100C, in 10 sccm flowing UHP Argon, for Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2021031301

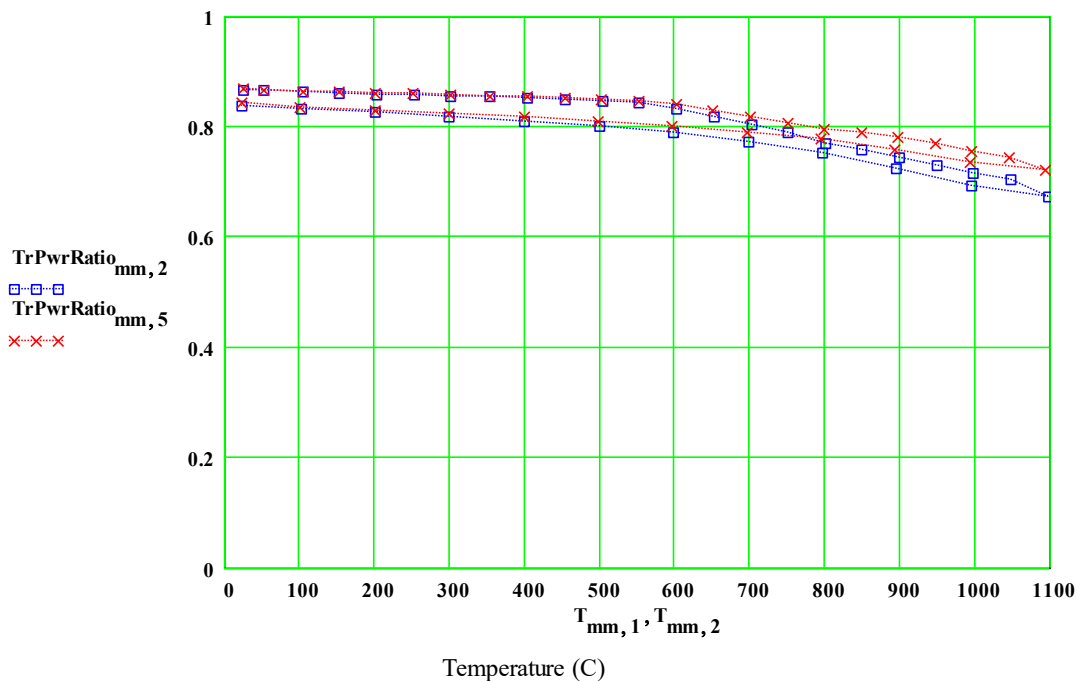
SHUL2119\_LowCal.med

AnDat = 20210314

JSC-1A Pellets, Pre-conditioned at 500C , RT to 1100C to RT, in flowing UHP Argon, for H Shulman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.02 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



# Appendix E. MPN Reports

Test = 2021031301

SHUL2119\_LowCal.med

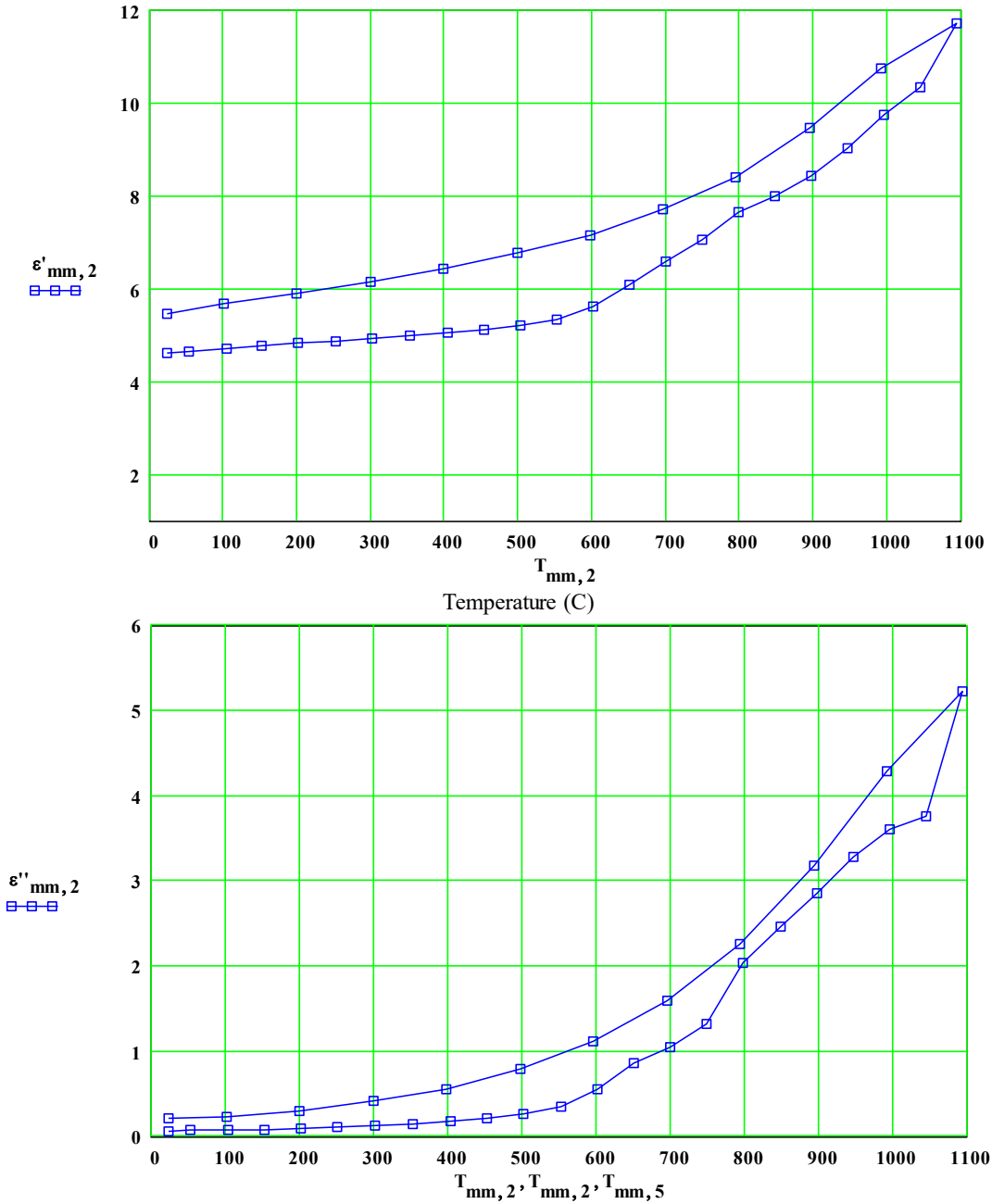
AnDat = 20210314

JSC-1A, 500C argon-conditioned Pellets , RT to 1100C, in 10 sccm flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.02 \text{ gm/cc}$ , Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021031301

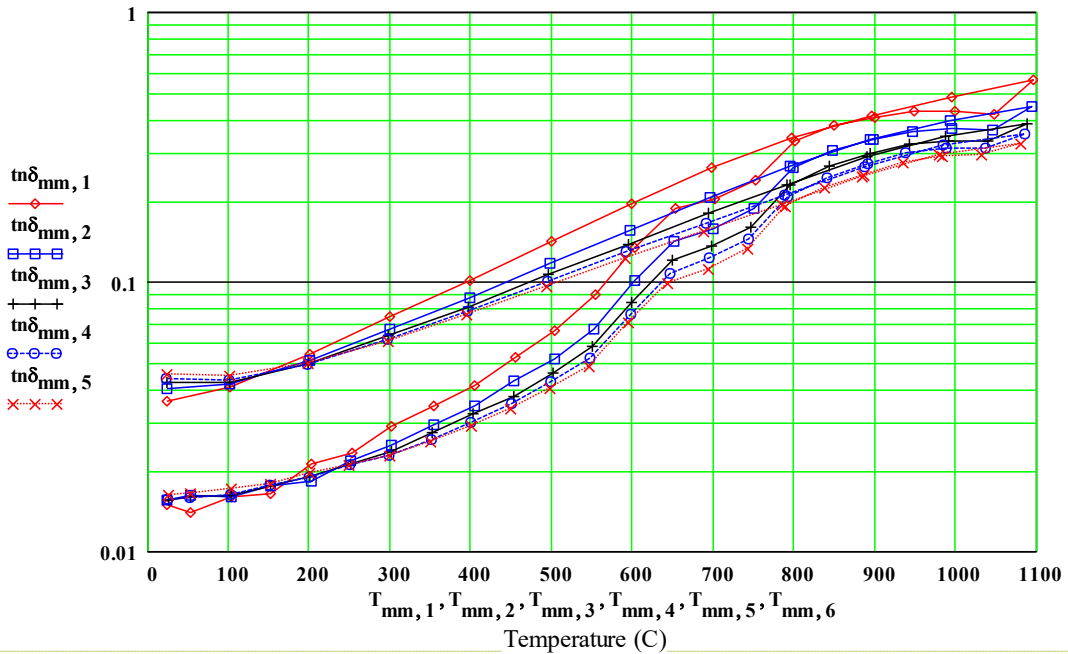
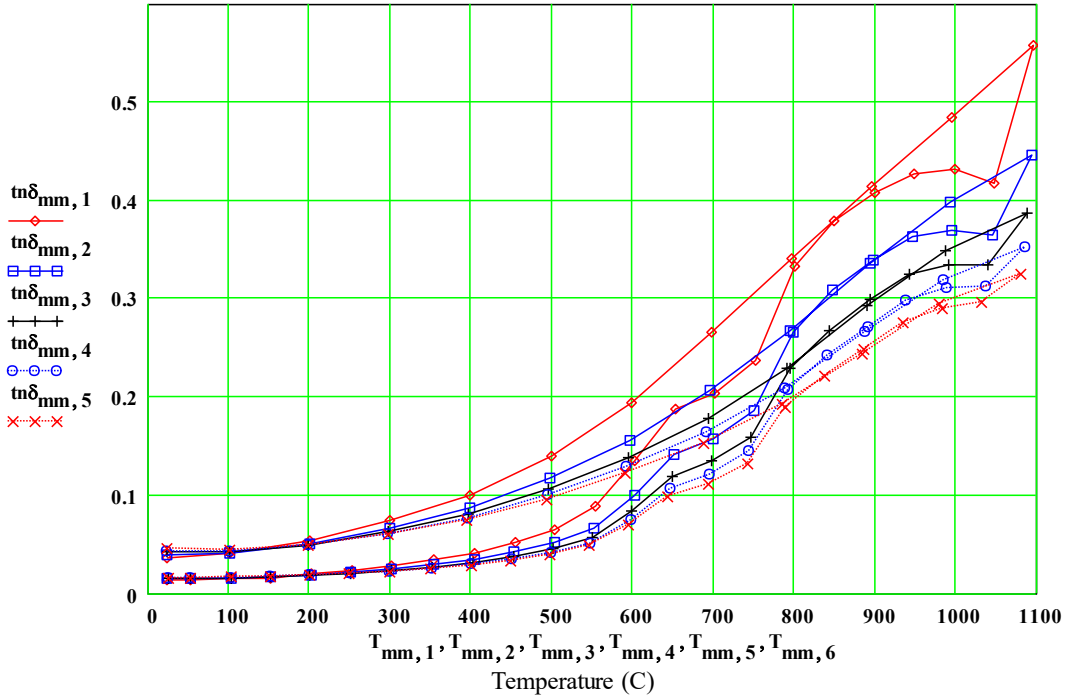
SHUL2119\_LowCal.mcd

AnDat = 20210314

JSC-1A, 500C argon-conditioned Pellets , RT to 1100C, in 10 sccm flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.02 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

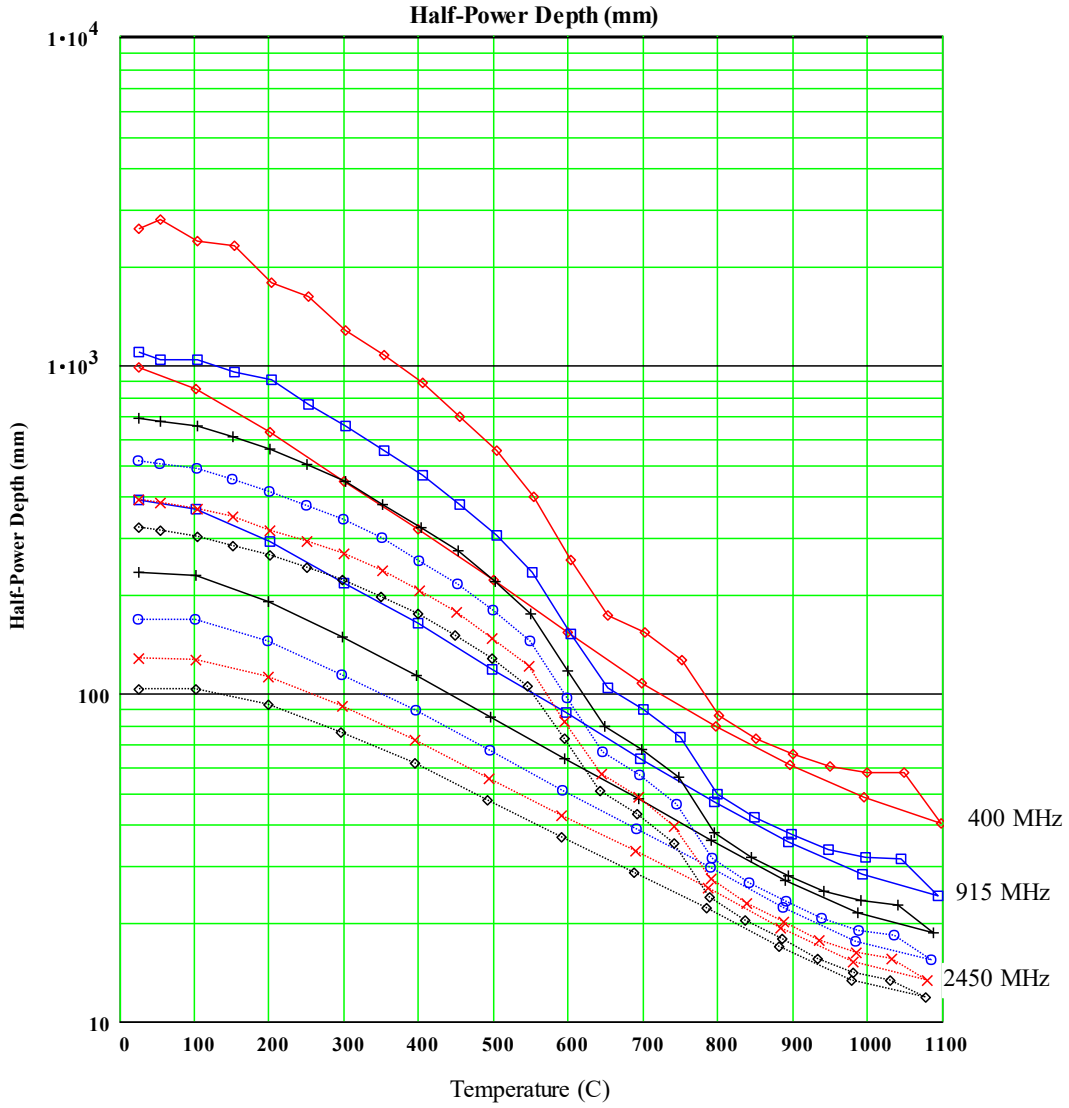
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021031301

SHUL2119\_LowCal.med

AnDat = 20210602

JSC-1A, 500C argon-conditioned Pellets, RT to 1100C, in 10 sccm flowing UHP Argon, for Holly Shulman LLC





Use the Jonscher Formalism to fit the Frequency and Thermal Dependence of  $\epsilon_{pp}$  and Conductivity  
Fit to Disordered Structure which Exists after the first cycle to 900C (Extrinsic and Intrinsic Contribution)

'Intrinsic' Range Values - High Temperature

$$E_{gn} := 0.75 \text{ eV}$$

$$\sigma_{intn} := 3.8 \cdot 10^0 \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.6$$

$$\epsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{gn}}{2 \cdot k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{fh_n}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \epsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6} \quad \epsilon_{ppth(16,2)} = 286.8$$

$$H_{activ} := \frac{E_{gn}}{2} \cdot 96.5 \text{ Kjoule/mol} \quad \frac{E_{gn}}{2} = 0.375 \text{ eV}$$

$$H_{activ} = 36 \text{ Kjoule/mol} \quad E_a := \frac{E_{gn}}{2} \text{ Activation Energy}$$

'Extrinsic' Values - Low Temperature, Impurity Dependent

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{gm} := 0.05 \quad \sigma_{intm} := 0.014 \quad m_J := 0.93$$

$$\epsilon_{ppthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{(2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6})} \cdot \exp \left[ \frac{-E_{gm}}{2 \cdot k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{fh_n}{400} \right)^{m_J}$$

$$\sigma_{thJm_{mn,n}} := \epsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}$$

$$\epsilon_{ppthTotal_{mn,n}} := \epsilon_{ppthJn_{mn,n}} + \epsilon_{ppthJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

Test = 2021031301

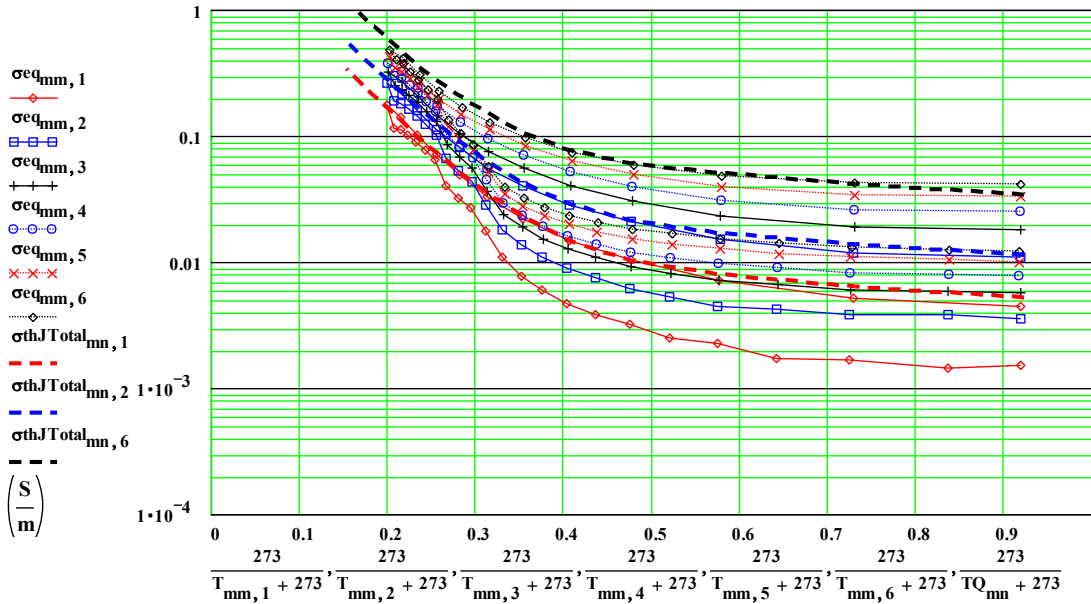
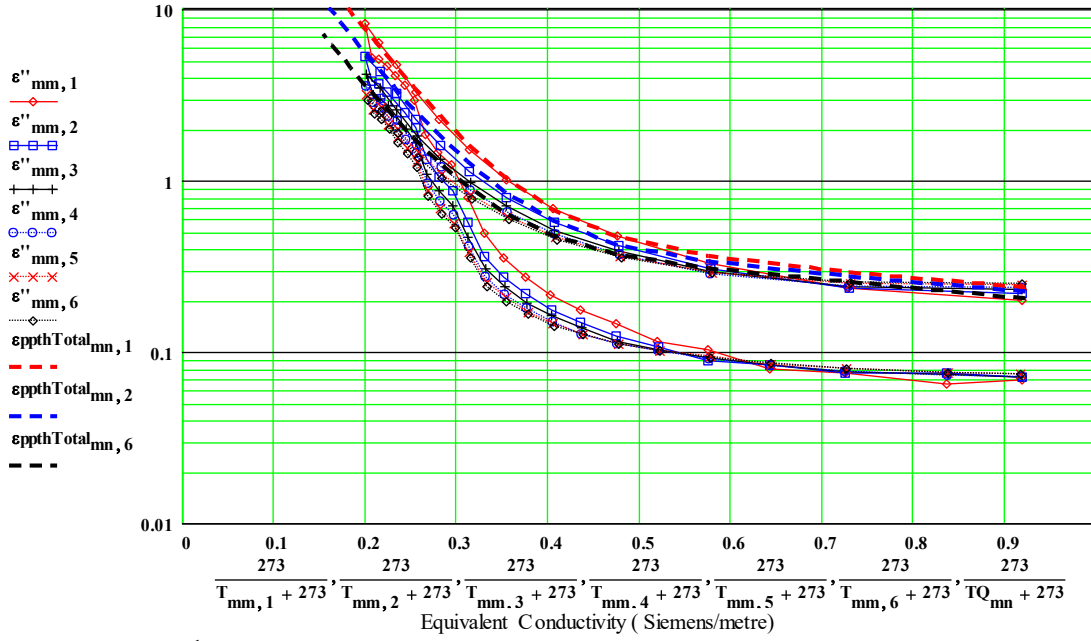
SHUL2119\_LowCal.mcd

AnDat = 20210314

JSC-1A Pellets, 500C treated , RT to 1100C, in flowing UHP Argon, for Holly Shulman LLC

Initial density =  $\text{samdns}_0 = 2.02 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$

Egn = 0.75 eV       $\sigma_{\text{intn}} = 3.8$  Siemens/metre      nJ = 0.6



# Appendix E. MPN Reports

Test = 2021031301

SHUL2119\_LowCal.med

AnDat = 20210314

JSC-1A Pellets, 500C treated , RT to 1100C to RT, in flowing UHP Argon, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density = **samdns**<sub>NCal + 1</sub> = **2.023** gm/cc      Final density(25C) = **dnsfinal** = **2.02** gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz      Lapsed Time (hours)

| samdns | $r_{mm}$ | $T_{mm,1}$ | $\epsilon'_{mm,1}$ | $\epsilon'_{mm,2}$ | $\epsilon'_{mm,3}$ | $\epsilon'_{mm,4}$ | $\epsilon'_{mm,5}$ | $\epsilon'_{mm,6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |
|--------|----------|------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|---------------------|----------------------|
| 2.023  | 8        | 24         | 4.65               | 4.61               | 4.61               | 4.58               | 4.58               | 4.58               | 0                   | 0.304                |
| 2.023  | 9        | 53         | 4.7                | 4.66               | 4.65               | 4.62               | 4.62               | 4.62               | 0.24                | 0.304                |
| 2.023  | 10       | 104        | 4.77               | 4.73               | 4.72               | 4.69               | 4.69               | 4.69               | 0.49                | 0.304                |
| 2.023  | 11       | 152        | 4.83               | 4.79               | 4.78               | 4.75               | 4.74               | 4.74               | 0.74                | 0.304                |
| 2.023  | 12       | 202        | 4.89               | 4.84               | 4.83               | 4.79               | 4.79               | 4.79               | 0.97                | 0.304                |
| 2.023  | 13       | 252        | 4.94               | 4.88               | 4.87               | 4.84               | 4.83               | 4.83               | 1.2                 | 0.304                |
| 2.022  | 14       | 302        | 5.01               | 4.94               | 4.93               | 4.89               | 4.88               | 4.87               | 1.44                | 0.304                |
| 2.022  | 15       | 354        | 5.09               | 5                  | 4.99               | 4.94               | 4.93               | 4.92               | 1.63                | 0.304                |
| 2.022  | 16       | 404        | 5.16               | 5.07               | 5.05               | 5                  | 4.98               | 4.98               | 1.82                | 0.304                |
| 2.022  | 17       | 455        | 5.26               | 5.14               | 5.11               | 5.06               | 5.04               | 5.03               | 2                   | 0.304                |
| 2.021  | 18       | 504        | 5.37               | 5.22               | 5.19               | 5.12               | 5.1                | 5.09               | 2.19                | 0.304                |
| 2.021  | 19       | 553        | 5.54               | 5.35               | 5.29               | 5.22               | 5.19               | 5.18               | 2.37                | 0.304                |
| 2.021  | 20       | 603        | 5.91               | 5.62               | 5.52               | 5.42               | 5.38               | 5.36               | 2.55                | 0.304                |
| 2.021  | 21       | 653        | 6.58               | 6.09               | 5.93               | 5.79               | 5.73               | 5.69               | 2.73                | 0.304                |
| 2.02   | 22       | 702        | 7.16               | 6.59               | 6.37               | 6.22               | 6.14               | 6.09               | 2.92                | 0.304                |
| 2.02   | 23       | 752        | 7.8                | 7.06               | 6.79               | 6.59               | 6.49               | 6.44               | 3.1                 | 0.304                |
| 2.02   | 24       | 801        | 8.78               | 7.65               | 7.2                | 6.93               | 6.78               | 6.71               | 3.28                | 0.304                |
| 2.02   | 25       | 850        | 9.4                | 8                  | 7.46               | 7.12               | 6.95               | 6.87               | 3.47                | 0.304                |
| 2.02   | 26       | 900        | 10                 | 8.43               | 7.77               | 7.38               | 7.18               | 7.12               | 3.65                | 0.304                |
| 2.02   | 27       | 949        | 10.89              | 9.03               | 8.28               | 7.84               | 7.62               | 7.54               | 3.83                | 0.304                |
| 2.02   | 28       | 998        | 11.74              | 9.75               | 8.9                | 8.41               | 8.17               | 8.12               | 4.01                | 0.304                |
| 2.02   | 29       | 1048       | 12.43              | 10.33              | 9.43               | 8.93               | 8.64               | 8.62               | 4.2                 | 0.304                |
| 2.02   | 30       | 1097       | 14.55              | 11.73              | 10.6               | 10                 | 9.68               | 9.65               | 4.38                | 0.304                |
| 2.02   | 31       | 995        | 13.11              | 10.76              | 9.83               | 9.3                | 9.04               | 9.01               | 4.64                | 0.304                |
| 2.02   | 32       | 896        | 11.27              | 9.48               | 8.79               | 8.38               | 8.18               | 8.13               | 4.91                | 0.304                |
| 2.02   | 33       | 797        | 9.62               | 8.4                | 7.93               | 7.64               | 7.49               | 7.44               | 5.22                | 0.304                |
| 2.02   | 34       | 698        | 8.55               | 7.71               | 7.4                | 7.17               | 7.07               | 7.02               | 5.61                | 0.304                |
| 2.02   | 35       | 598        | 7.75               | 7.17               | 6.94               | 6.77               | 6.68               | 6.64               | 6.09                | 0.304                |
| 2.02   | 36       | 499        | 7.18               | 6.77               | 6.61               | 6.47               | 6.4                | 6.37               | 6.69                | 0.304                |
| 2.02   | 37       | 399        | 6.75               | 6.44               | 6.33               | 6.21               | 6.17               | 6.15               | 7.46                | 0.304                |
| 2.02   | 38       | 300        | 6.39               | 6.17               | 6.09               | 6                  | 5.97               | 5.95               | 8.48                | 0.304                |
| 2.02   | 39       | 200        | 6.09               | 5.92               | 5.87               | 5.8                | 5.77               | 5.76               | 9.94                | 0.304                |
| 2.02   | 40       | 101        | 5.8                | 5.68               | 5.64               | 5.59               | 5.56               | 5.55               | 12.67               | 0.304                |
| 2.02   | 41       | 24         | 5.57               | 5.47               | 5.43               | 5.38               | 5.35               | 5.34               | 20.43               | 0.304                |

# Appendix E. MPN Reports

Test = 2021031301

SHUL2119\_LowCal.mcd

AnDat = 20210314

JSC-1A Pellets, 500C treated , RT to 1100C to RT, in flowing UHP Argon, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.023$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.02$  gm/cc

Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz 2466MHz 2986MHz

Time

(hours)

| samdns <sub>mm</sub> | T <sub>mm,1</sub> | $\epsilon''_{\text{mm},1}$ | $\epsilon''_{\text{mm},2}$ | $\epsilon''_{\text{mm},3}$ | $\epsilon''_{\text{mm},4}$ | $\epsilon''_{\text{mm},5}$ | $\epsilon''_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |       |
|----------------------|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|-------|
| 2.023                | 8                 | 24                         | 0.069                      | 0.071                      | 0.072                      | 0.072                      | 0.074                      | 0.074               | 0                    | 0.304 |
| 2.023                | 9                 | 53                         | 0.065                      | 0.076                      | 0.074                      | 0.073                      | 0.076                      | 0.076               | 0.24                 | 0.304 |
| 2.023                | 10                | 104                        | 0.076                      | 0.076                      | 0.077                      | 0.076                      | 0.08                       | 0.08                | 0.49                 | 0.304 |
| 2.023                | 11                | 152                        | 0.079                      | 0.084                      | 0.084                      | 0.083                      | 0.085                      | 0.086               | 0.74                 | 0.304 |
| 2.023                | 12                | 202                        | 0.103                      | 0.089                      | 0.092                      | 0.09                       | 0.093                      | 0.092               | 0.97                 | 0.304 |
| 2.023                | 13                | 252                        | 0.115                      | 0.106                      | 0.103                      | 0.101                      | 0.101                      | 0.101               | 1.2                  | 0.304 |
| 2.022                | 14                | 302                        | 0.147                      | 0.123                      | 0.116                      | 0.111                      | 0.111                      | 0.11                | 1.44                 | 0.304 |
| 2.022                | 15                | 354                        | 0.176                      | 0.149                      | 0.138                      | 0.127                      | 0.127                      | 0.125               | 1.63                 | 0.304 |
| 2.022                | 16                | 404                        | 0.214                      | 0.177                      | 0.163                      | 0.15                       | 0.146                      | 0.142               | 1.82                 | 0.304 |
| 2.022                | 17                | 455                        | 0.275                      | 0.22                       | 0.193                      | 0.177                      | 0.17                       | 0.166               | 2                    | 0.304 |
| 2.021                | 18                | 504                        | 0.353                      | 0.273                      | 0.24                       | 0.216                      | 0.205                      | 0.196               | 2.19                 | 0.304 |
| 2.021                | 19                | 553                        | 0.496                      | 0.358                      | 0.306                      | 0.271                      | 0.253                      | 0.24                | 2.37                 | 0.304 |
| 2.021                | 20                | 603                        | 0.798                      | 0.565                      | 0.463                      | 0.411                      | 0.377                      | 0.352               | 2.55                 | 0.304 |
| 2.021                | 21                | 653                        | 1.241                      | 0.863                      | 0.71                       | 0.621                      | 0.564                      | 0.525               | 2.73                 | 0.304 |
| 2.02                 | 22                | 702                        | 1.458                      | 1.045                      | 0.864                      | 0.756                      | 0.685                      | 0.638               | 2.92                 | 0.304 |
| 2.02                 | 23                | 752                        | 1.854                      | 1.319                      | 1.082                      | 0.953                      | 0.864                      | 0.809               | 3.1                  | 0.304 |
| 2.02                 | 24                | 801                        | 2.925                      | 2.04                       | 1.659                      | 1.436                      | 1.289                      | 1.196               | 3.28                 | 0.304 |
| 2.02                 | 25                | 850                        | 3.563                      | 2.472                      | 1.997                      | 1.722                      | 1.545                      | 1.426               | 3.47                 | 0.304 |
| 2.02                 | 26                | 900                        | 4.089                      | 2.867                      | 2.327                      | 2.004                      | 1.792                      | 1.661               | 3.65                 | 0.304 |
| 2.02                 | 27                | 949                        | 4.661                      | 3.286                      | 2.69                       | 2.336                      | 2.1                        | 1.974               | 3.83                 | 0.304 |
| 2.02                 | 28                | 998                        | 5.077                      | 3.609                      | 2.979                      | 2.624                      | 2.374                      | 2.254               | 4.01                 | 0.304 |
| 2.02                 | 29                | 1048                       | 5.2                        | 3.767                      | 3.158                      | 2.799                      | 2.565                      | 2.449               | 4.2                  | 0.304 |
| 2.02                 | 30                | 1097                       | 8.138                      | 5.237                      | 4.11                       | 3.522                      | 3.145                      | 2.926               | 4.38                 | 0.304 |
| 2.02                 | 31                | 995                        | 6.357                      | 4.297                      | 3.429                      | 2.971                      | 2.666                      | 2.518               | 4.64                 | 0.304 |
| 2.02                 | 32                | 896                        | 4.681                      | 3.189                      | 2.576                      | 2.228                      | 1.994                      | 1.874               | 4.91                 | 0.304 |
| 2.02                 | 33                | 797                        | 3.286                      | 2.258                      | 1.827                      | 1.596                      | 1.444                      | 1.362               | 5.22                 | 0.304 |
| 2.02                 | 34                | 698                        | 2.273                      | 1.596                      | 1.327                      | 1.183                      | 1.082                      | 1.032               | 5.61                 | 0.304 |
| 2.02                 | 35                | 598                        | 1.513                      | 1.115                      | 0.963                      | 0.873                      | 0.819                      | 0.78                | 6.09                 | 0.304 |
| 2.02                 | 36                | 499                        | 1.013                      | 0.798                      | 0.705                      | 0.65                       | 0.618                      | 0.593               | 6.69                 | 0.304 |
| 2.02                 | 37                | 399                        | 0.682                      | 0.566                      | 0.512                      | 0.48                       | 0.464                      | 0.45                | 7.46                 | 0.304 |
| 2.02                 | 38                | 300                        | 0.478                      | 0.415                      | 0.387                      | 0.366                      | 0.358                      | 0.354               | 8.48                 | 0.304 |
| 2.02                 | 39                | 200                        | 0.328                      | 0.303                      | 0.294                      | 0.284                      | 0.287                      | 0.289               | 9.94                 | 0.304 |
| 2.02                 | 40                | 101                        | 0.237                      | 0.237                      | 0.241                      | 0.241                      | 0.249                      | 0.255               | 12.67                | 0.304 |
| 2.02                 | 41                | 24                         | 0.201                      | 0.219                      | 0.23                       | 0.235                      | 0.244                      | 0.249               | 20.43                | 0.304 |

MPN-231\_Shulman\_3\_JSC-1A(A)

August 1, 2021

JSC-1A(A) ( Initially Heat Treated to 750C in Argon)  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in < 1 milli Torr Vacuum

Dr. Holly Shulman ( Shulman LLC) again requested that Microwave Properties North measure the complex dielectric properties of a specially treated JSC-1A moon simulant up to 1100C with a direct, uninterrupted, temperature cycle, in as good a vacuum as we could produce in the MPN system. The powder sample material arrived at MPN on July 21/ 2021. Dr. Shulman had already baked the powder at 750C in UHP argon.

MPN pressed pellets of the powder material in a uniaxial press. The previously used press pressure ( ~ 18,000 psi) was a not sufficient and produced a fragile pellet that crumbled somewhat. The pressure was increased to ~ 32,000 psi , and produced pellets with sufficient strength for handling, achieving a density of ~ 2.08 g/cc . The pellets were not baked to ensure dryness.

MPN was requested to cycle the sample directly up to 1100C and then return to room temperature (RT) , ) in as good a vacuum as we could produce in the MPN system. This was our first run under vacuum, ever!

The initial sample parameters were:

- a) diameter 3.64 +- 0.05 mm
- b) length 14.25 +- 0.10 mm
- c) mass 0.309 +- 0.002 gm
- z) room temperature density  $2.08 \pm 0.07$  gm/cc.
- aa) appearance - three (stacked) grey pellets ( see photo). Four pellets were made, only three were used.

The dielectric properties measurements were performed at RT and then the temperature was ramped up to 1100C in 50C steps. Due to a mistuning of the temperature controller, it sat at ~ 1090 C for ~ 45 minutes before the actual measurement was done. After this, the temperature was brought back down to RT in - 100C steps.

The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was then run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.64 \pm 0.05$  mm
- b) length  $13.86 \pm 0.1$  mm
- c) mass  $0.309 \pm 0.002$  gm
- y) room temperature density  $2.14 \pm 0.07$  gm/cc.
- z) appearance - three dark-grey-brown pellets ( see photo)

Note: The percent mass loss was zero ( +- 0.7 % ) .

The frequency coding is :

Legend for Data Plots :

| # | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|---|-----------------------|----------------------------------------------------------|
| 1 | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912                   | blue square, solid line                                  |
| 3 | 1429                  | black cross, solid line                                  |
| 4 | 1948                  | blue circle, dotted line                                 |
| 5 | 2466                  | red cross, dotted line                                   |
| 6 | 2986                  | black diamond, dotted line                               |

Comments on the data analysis:

A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

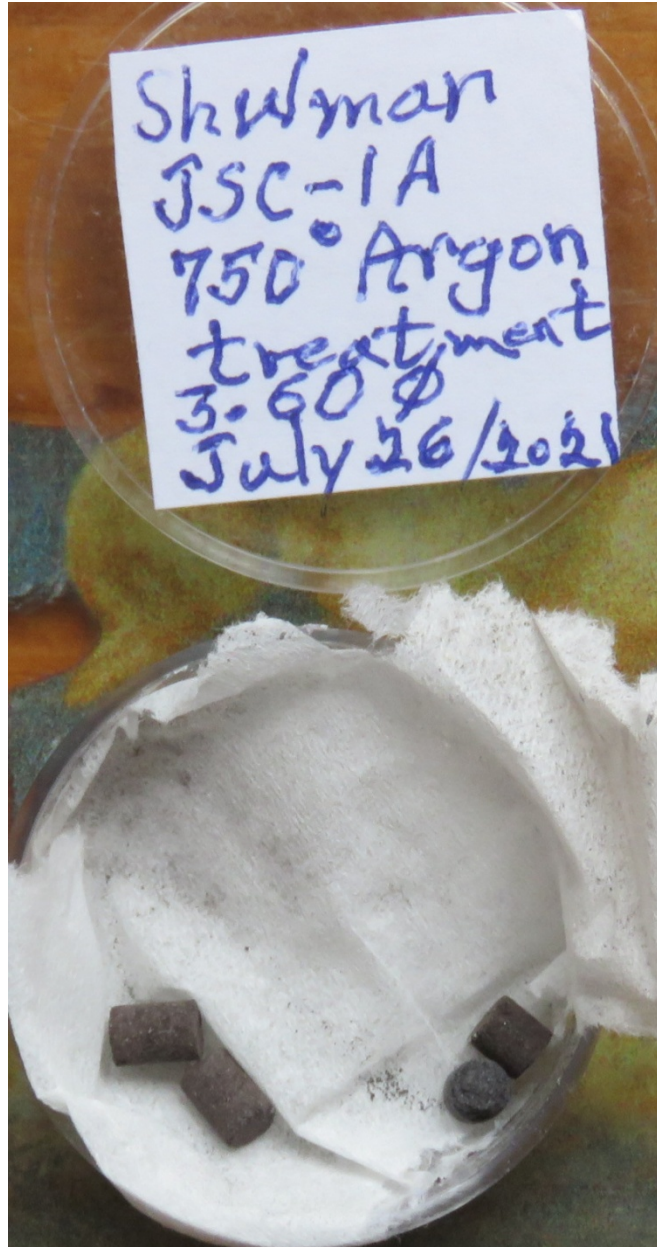
The final pellets were a slightly different colour – a dark brown.

The data for the ramp up to 1100C is definitely different than for the ramp down. Some change has occurred. The cycle to 1100 C seemed to produce a change in the material that produces slightly elevated values on the return down to room temperature.

The long 45 minute soak at ~ 1090C produced the beginnings of a reaction, either a melting of one component or the onset of sintering.



Initial 3 Pellets in Holder  
the run .



The three brownish pellets are the test sample after

Four pellets were made, but only three were used as the test sample.

# Appendix E. MPN Reports

Test = 2021072901

SHUL2146\_LowCal.med

AnDat = 20210730

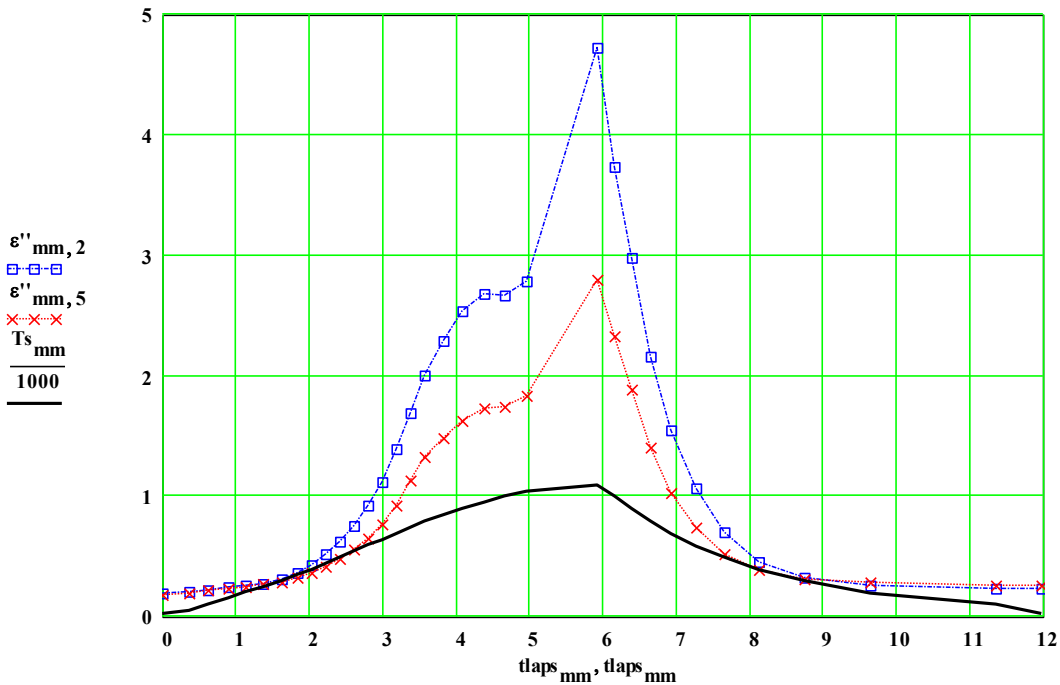
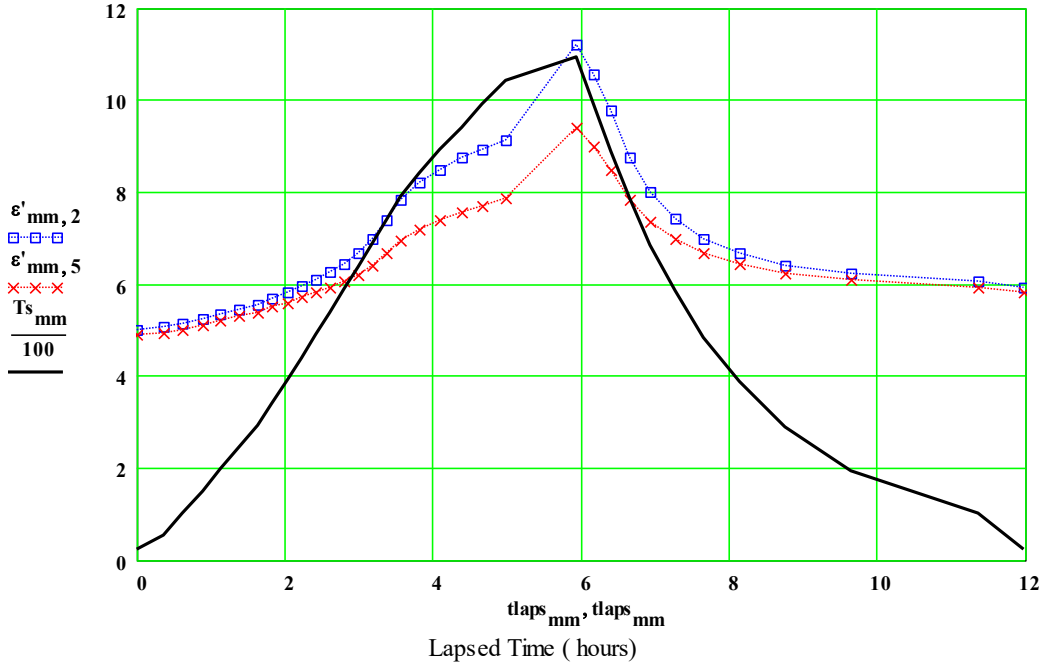
JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.08 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.14 \text{ gm/cc}$       **FracMassChange = 1**

$\alpha_1 = 0$



Note that due to mistuning of the temperature controller, there was almost 1 hour of soak at 1090 C.

The graph is misleading, as it implies a slow ramp up to 1094C from 1044 C. In fact the system probably took 15 minutes to step up to 1090C from 1044 C, but then did not start the measurement ( which was set to happen at ~ 1095C).

# Appendix E. MPN Reports

Test = 2021072901

SHUL2146\_LowCal.mcd

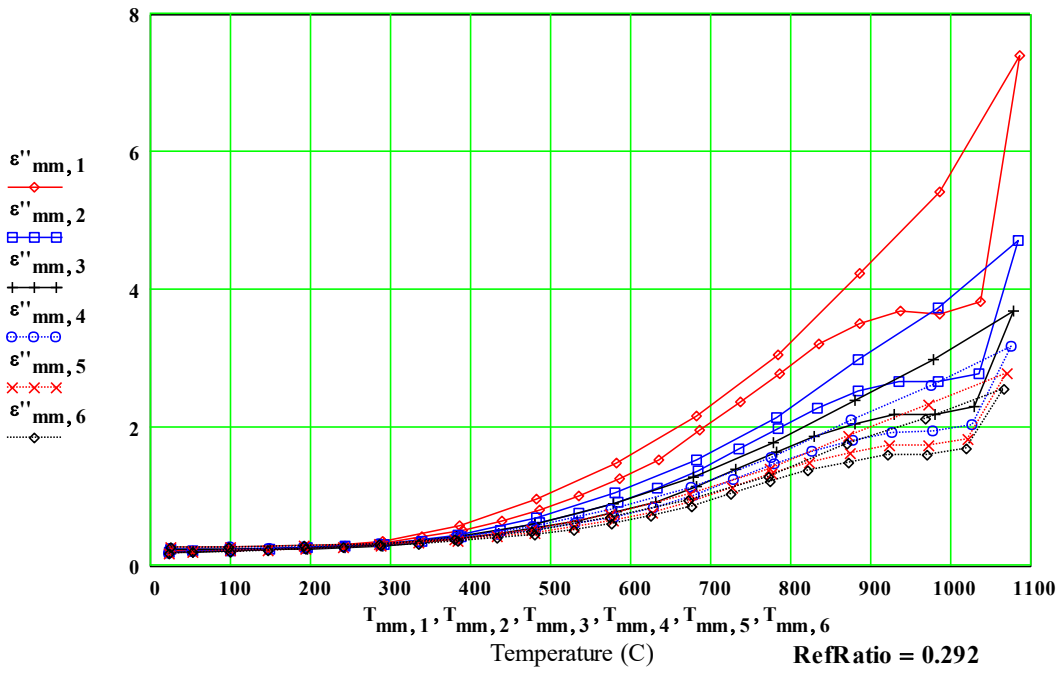
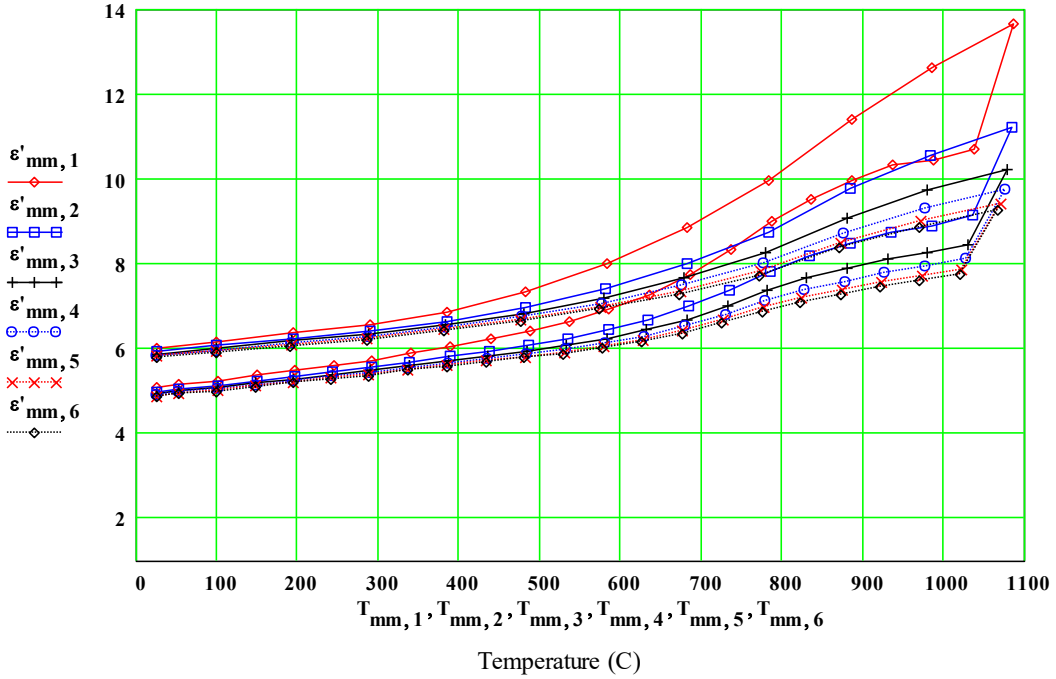
AnDat = 20210730

JSC-1A (A) , 750C argon-c-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.08 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.14 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1





Values for the Temperature Cycle (to 1100 C and back to RT) :

Test = 2021072901

SHUL2146\_LowCal.mcd

AnDat = 20210730

T

JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.08 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.14 \text{ gm/cc}$

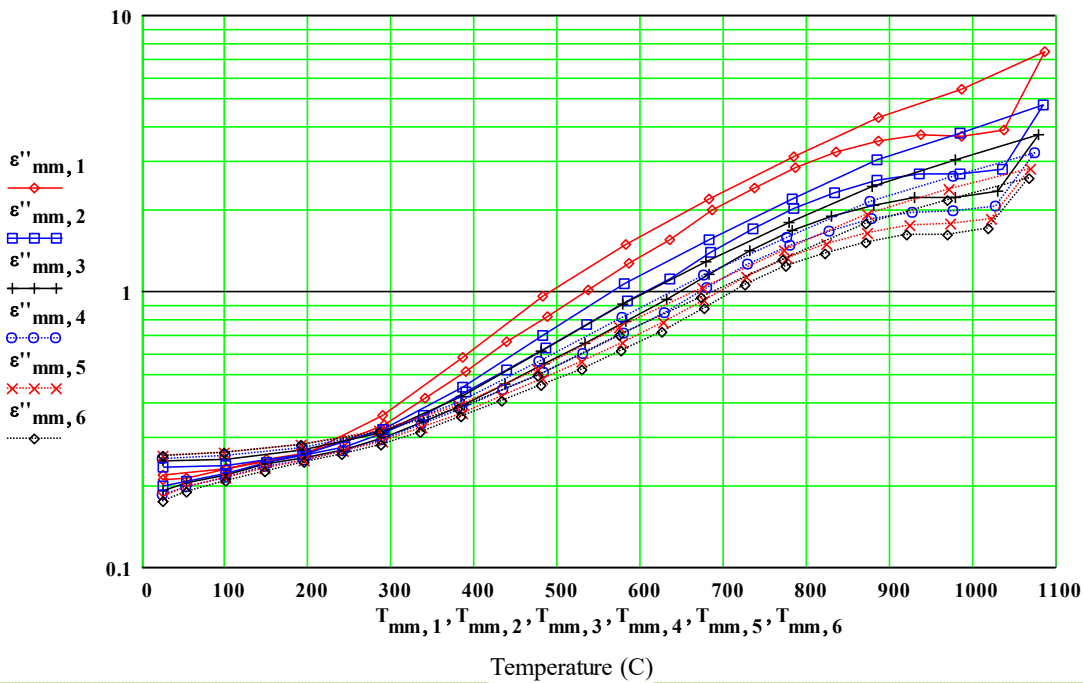
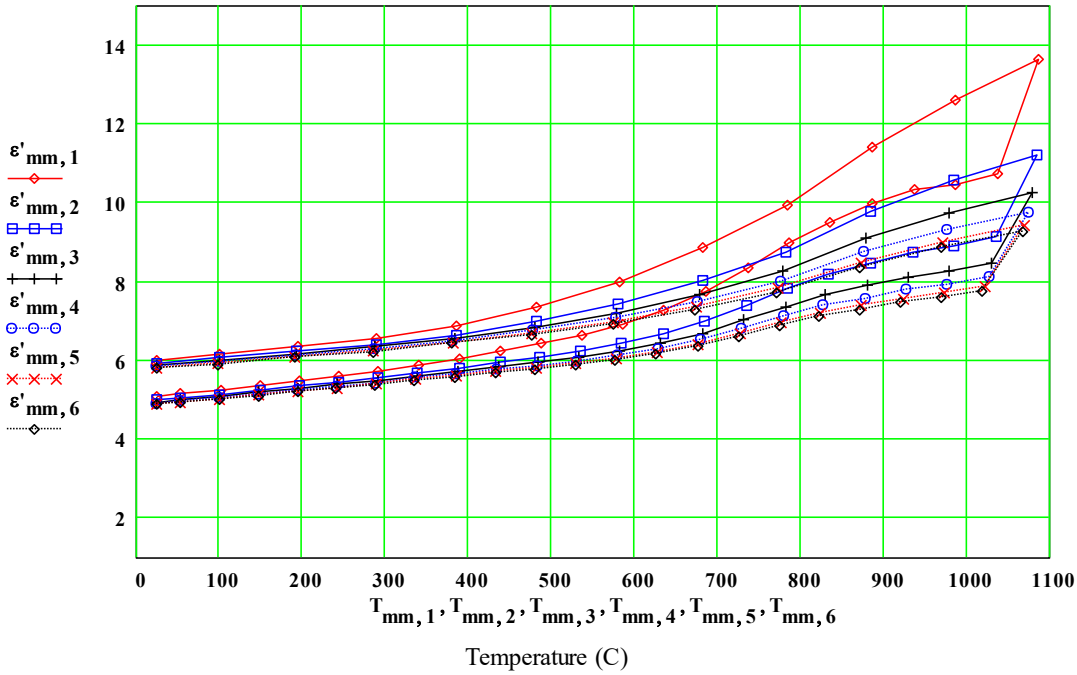
h

FracMassChange = 1

$\alpha_1 = 0$  /C

$\alpha_2 = 0$  /C

F



# Appendix E. MPN Reports

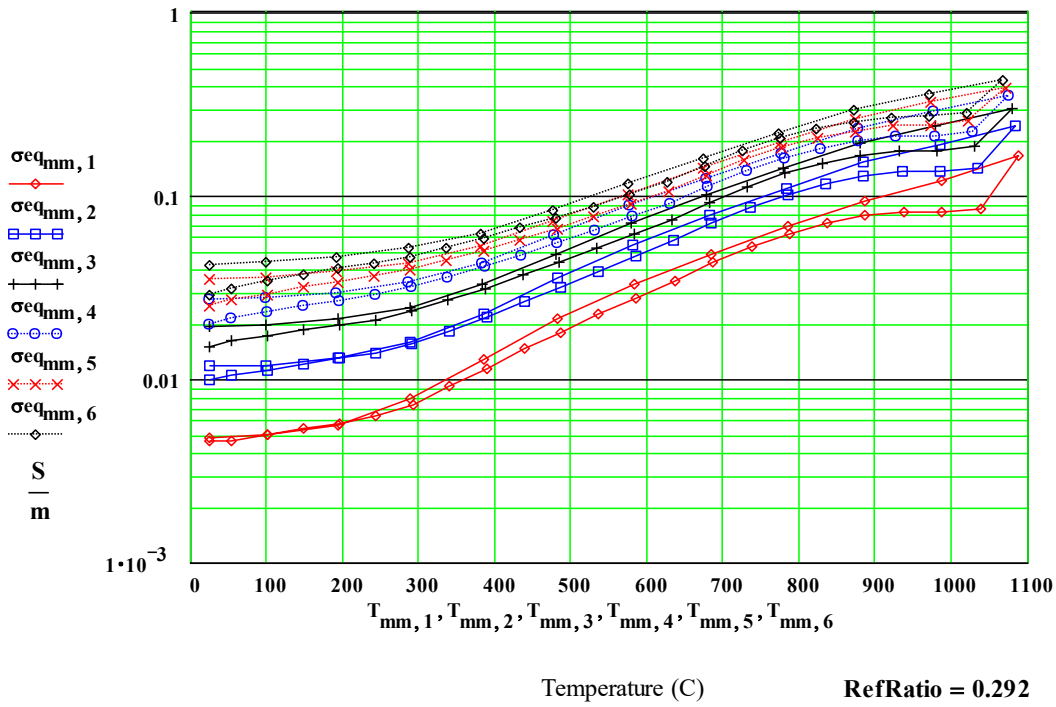
Test = 2021072901

SHUL2146\_LowCal.mcd

AnDat = 20210730

JSC-1A (A), 750C argon-conditioned Pellets, RT to 1100C, in vacuum, for Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2021072901

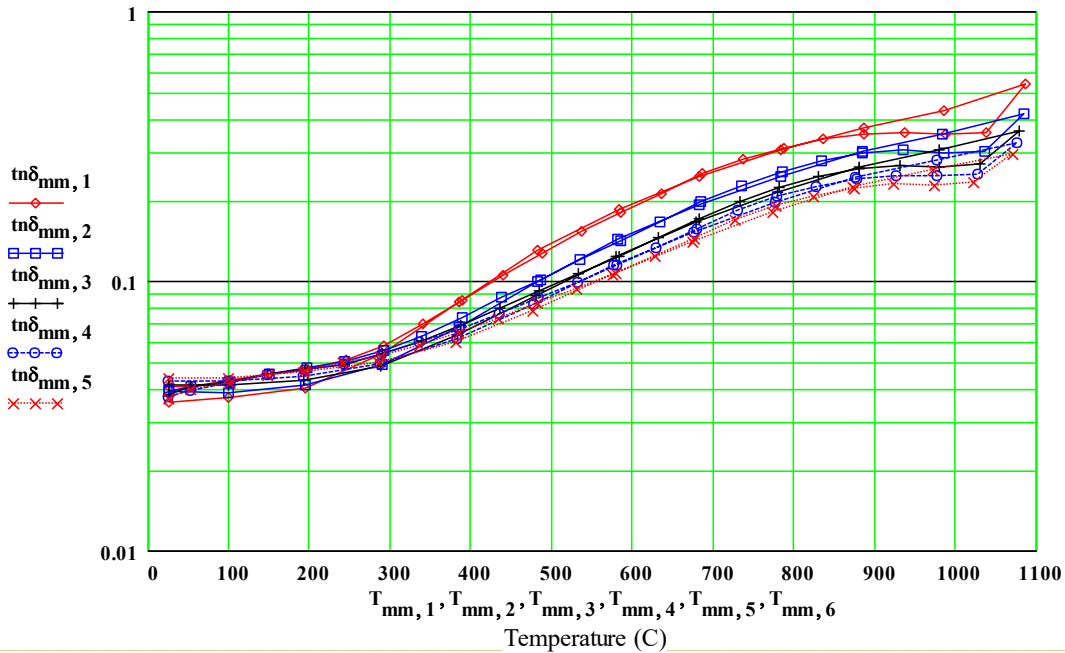
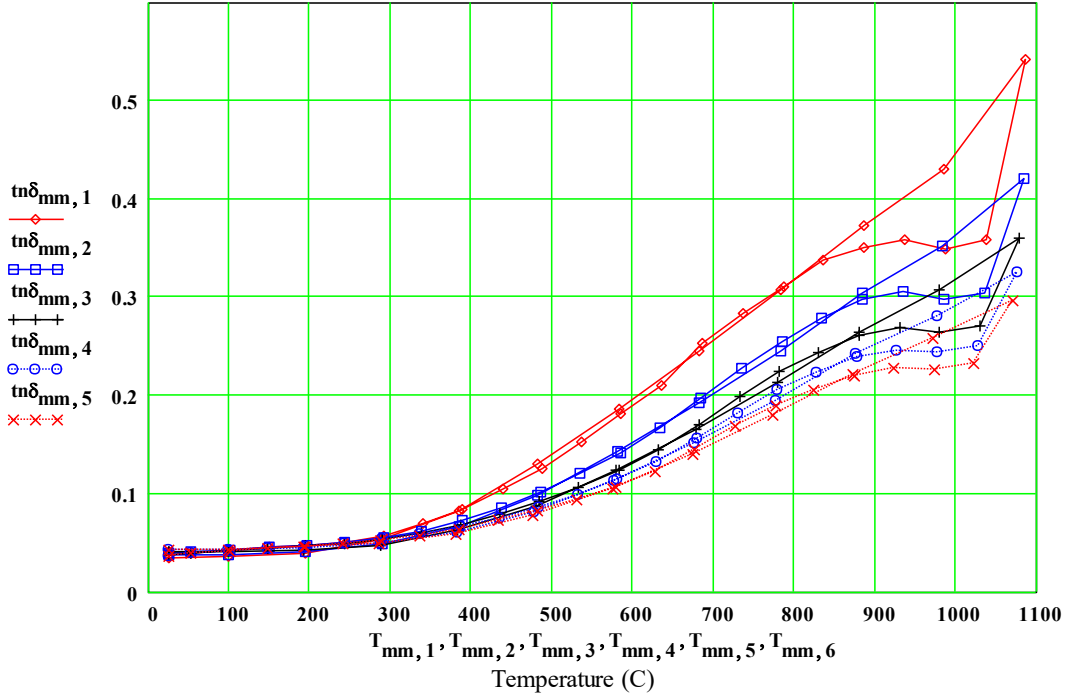
SHUL2146\_LowCal.mcd

AnDat = 20210730

JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.08 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.14 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2021072901

SHUL2146\_LowCal.mcd

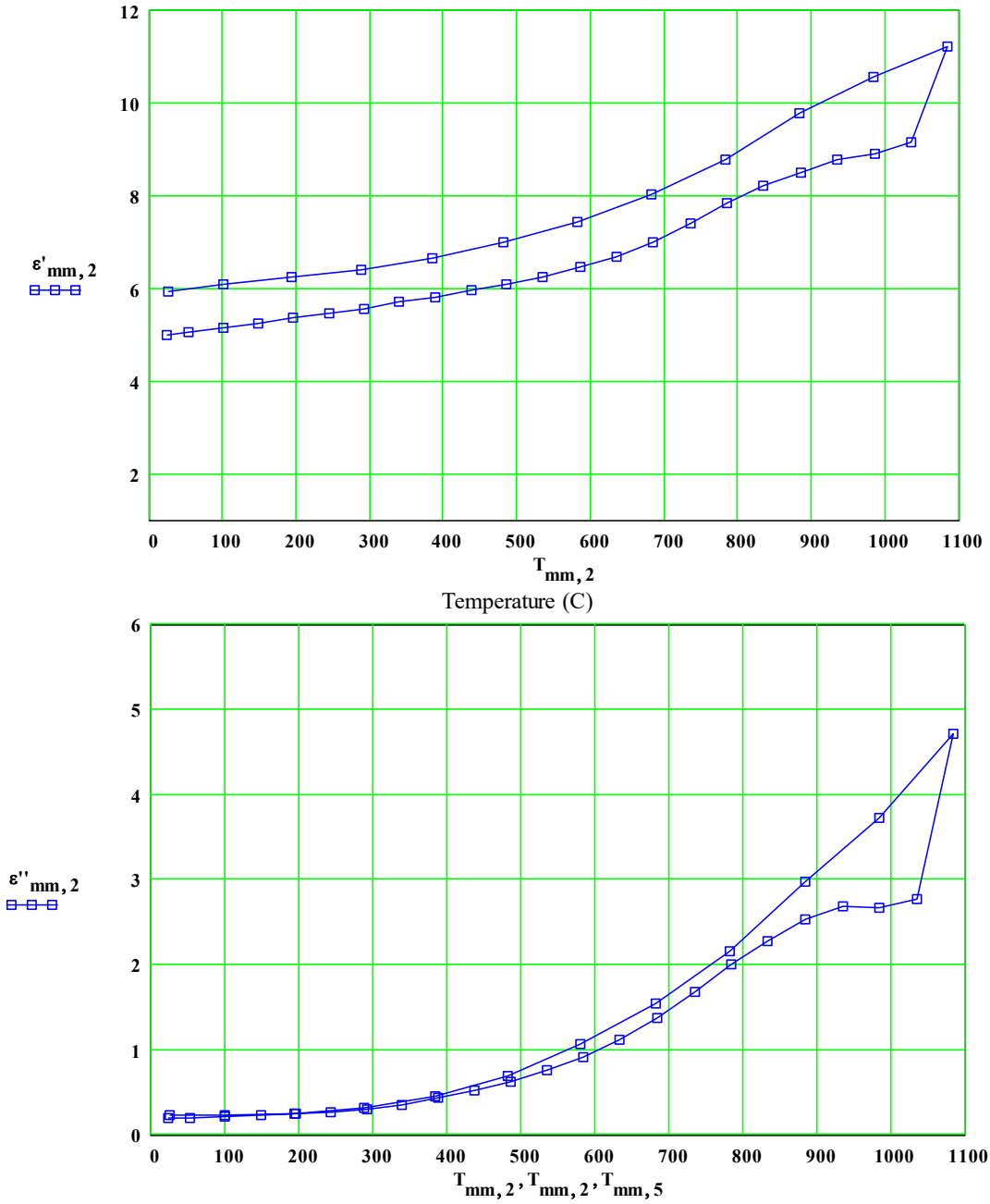
AnDat = 20210730

JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.08$  gm/cc, Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 2.14$  gm/cc

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021072901

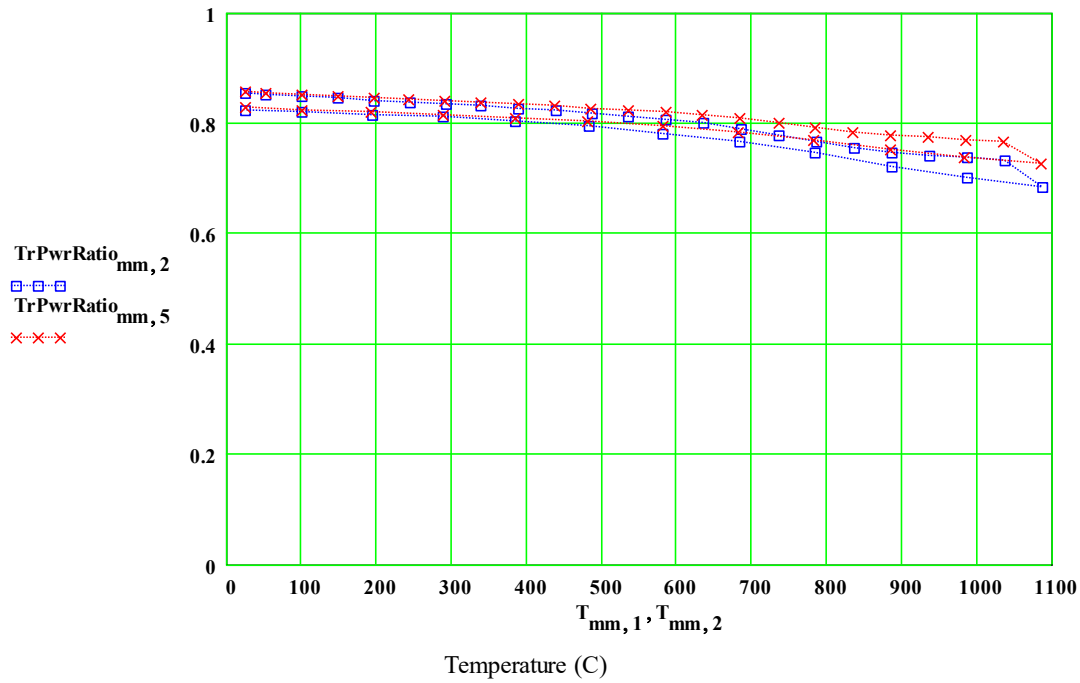
SHUL2146\_LowCal.mcd

AnDat = 20210730

JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.08 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.14 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.





Use the Jonscher Formalism to fit the Frequency and Thermal Dependence of  $\epsilon_p$ ,  $\epsilon_{pp}$  and Conductivity

Fit to 'Disordered' Structure which Exists after the Highest Temperature was Attained ( 1100C)

Fit to 'Intrinsic' Values - High Temperature

$$E_{an} := 0.33 \text{ eV}$$

$$\sigma_{intn} := 3.7 \cdot 10^0 \text{ Siemens/metre}$$

$$\epsilon_{infin} := 6.0$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.53$$

$$\epsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \cos \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{f_{h_n}}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \overbrace{\epsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}}$$

$$\epsilon_{infin_{mn}} := 6.0 + 0.35 \cdot \frac{TQ_{mn}}{400}$$

$$\epsilon_{pthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{f_{h_n}}{400} \right)^{n_J}$$

$$\epsilon_{pthTotal_{mn,n}} := \epsilon_{pthJn_{mn,n}} + \epsilon_{infin_{mn}}$$

$$H_{activ} := E_{an} \cdot 96.5 \text{ Kjoule/mol}$$

$$H_{activ} = 32 \text{ Kjoule/mol}$$

$$E_{gn} := 2 \cdot E_{an} \text{ Conduction Gap Energy}$$

$$\frac{E_{gn}}{2} = 0.33 \text{ eV}$$

**Fit to 'Extrinsic' Values - Low Temperature, Impurity Dependent :**

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{am} := 0.0025 \quad \sigma_{intm} := 0.0055 \quad mJ := 1.05$$

$$0.0055$$

$$\varepsilon_{ppthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{(2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6})} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

$$\sigma_{thJm_{mn,n}} := \overbrace{\varepsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}}$$

$$\varepsilon_{pthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( mJ \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

**Sum up Extrinsic and Intrinsic Contributions :**

$$\varepsilon_{pthTotal_{mn,n}} := \varepsilon_{pthJn_{mn,n}} + \varepsilon_{pthJm_{mn,n}} + \varepsilon_{infin_{mn}}$$

$$\varepsilon_{ppthTotal_{mn,n}} := \varepsilon_{ppthJn_{mn,n}} + \varepsilon_{ppthJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

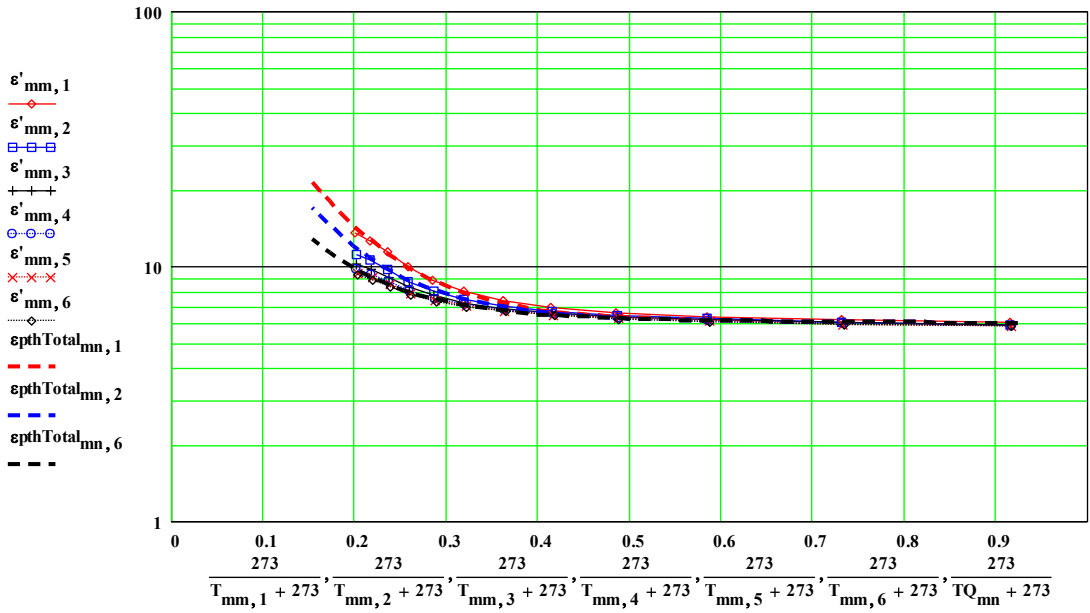
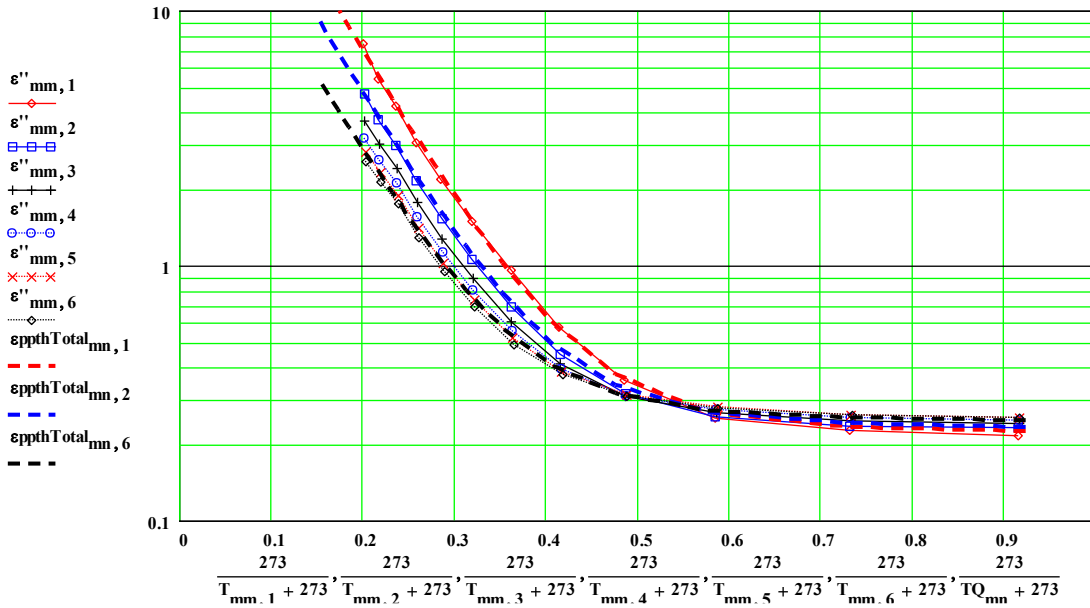
Test = 2021072901

SHUL2146\_LowCal.mcd

AnDat = 20210801

JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Final density(25C) = **dnsfinal = 2.14** gm/cc



# Appendix E. MPN Reports

Test = 2021072901

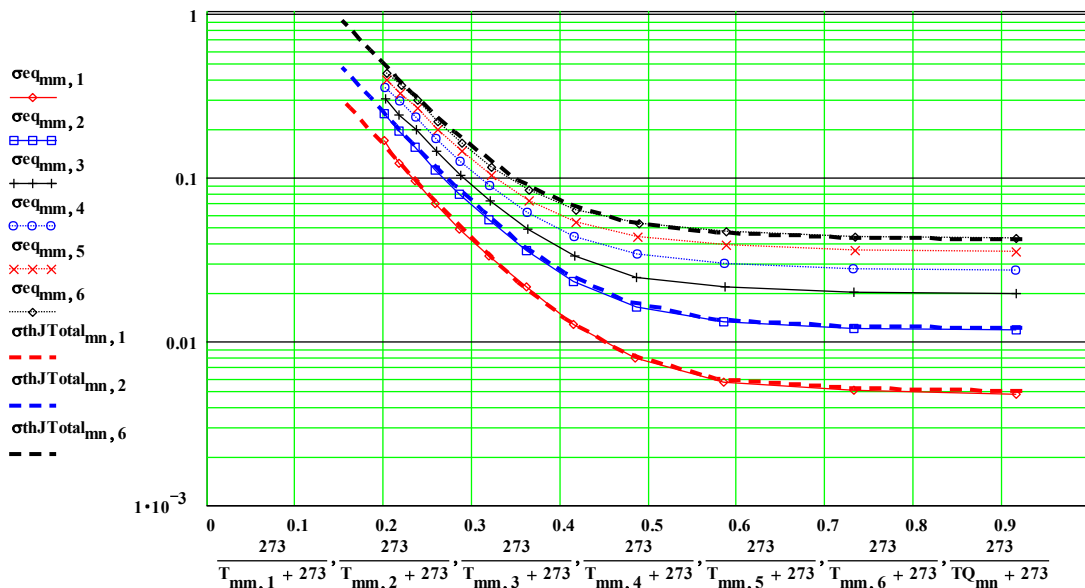
SHUL2146\_LowCa.lmcd

AnDat = 20210801

JSC-1A (A), 750C argon-conditioned Pellets, RT to 1100C, in vacuum, for Holly Shulman LLC

Final density(25C) = **dnsfinal = 2.14** gm/cc

Equivalent Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2021072901

SHUL2146\_LowCal.mcd

AnDat = 20210730

JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density = **samdns**<sub>NCal + 1</sub> = **2.084** gm/cc      Final density(25C) = **dnsfinal** = **2.142** gm/cc

Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz

Time  
(hours)

| samdns | r <sub>mm</sub> | T <sub>mm,1</sub> | $\epsilon'_{mm,1}$ | $\epsilon'_{mm,2}$ | $\epsilon'_{mm,3}$ | $\epsilon'_{mm,4}$ | $\epsilon'_{mm,5}$ | $\epsilon'_{mm,6}$ | tlaps <sub>mm</sub> | sammass <sub>mm</sub> |
|--------|-----------------|-------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|---------------------|-----------------------|
| 2.084  | 8               | 24                | 5.1                | 5                  | 4.95               | 4.92               | 4.89               | 4.88               | 0                   | 0.309                 |
| 2.084  | 9               | 53                | 5.17               | 5.06               | 5.01               | 4.97               | 4.95               | 4.93               | 0.35                | 0.309                 |
| 2.084  | 10              | 101               | 5.25               | 5.15               | 5.09               | 5.05               | 5.02               | 5.01               | 0.62                | 0.309                 |
| 2.084  | 11              | 149               | 5.39               | 5.26               | 5.2                | 5.15               | 5.12               | 5.11               | 0.9                 | 0.309                 |
| 2.084  | 12              | 196               | 5.49               | 5.36               | 5.3                | 5.24               | 5.21               | 5.2                | 1.13                | 0.309                 |
| 2.084  | 13              | 244               | 5.62               | 5.46               | 5.4                | 5.34               | 5.31               | 5.29               | 1.38                | 0.309                 |
| 2.084  | 14              | 292               | 5.73               | 5.56               | 5.49               | 5.43               | 5.4                | 5.38               | 1.63                | 0.309                 |
| 2.084  | 15              | 340               | 5.9                | 5.7                | 5.62               | 5.55               | 5.52               | 5.49               | 1.83                | 0.309                 |
| 2.084  | 16              | 389               | 6.04               | 5.82               | 5.73               | 5.65               | 5.61               | 5.58               | 2.03                | 0.309                 |
| 2.084  | 17              | 439               | 6.24               | 5.97               | 5.85               | 5.77               | 5.72               | 5.69               | 2.22                | 0.309                 |
| 2.084  | 18              | 487               | 6.43               | 6.1                | 5.97               | 5.87               | 5.81               | 5.78               | 2.42                | 0.309                 |
| 2.084  | 19              | 536               | 6.66               | 6.26               | 6.1                | 5.99               | 5.92               | 5.89               | 2.6                 | 0.309                 |
| 2.084  | 20              | 586               | 6.94               | 6.46               | 6.26               | 6.13               | 6.06               | 6.01               | 2.79                | 0.309                 |
| 2.084  | 21              | 636               | 7.3                | 6.69               | 6.45               | 6.3                | 6.21               | 6.16               | 2.99                | 0.309                 |
| 2.084  | 22              | 686               | 7.77               | 7                  | 6.7                | 6.52               | 6.41               | 6.36               | 3.18                | 0.309                 |
| 2.084  | 23              | 737               | 8.35               | 7.41               | 7.04               | 6.81               | 6.68               | 6.61               | 3.37                | 0.309                 |
| 2.084  | 24              | 787               | 9                  | 7.84               | 7.38               | 7.12               | 6.97               | 6.88               | 3.57                | 0.309                 |
| 2.084  | 25              | 836               | 9.53               | 8.21               | 7.67               | 7.39               | 7.21               | 7.11               | 3.82                | 0.309                 |
| 2.084  | 26              | 886               | 9.97               | 8.49               | 7.9                | 7.58               | 7.39               | 7.28               | 4.1                 | 0.309                 |
| 2.084  | 27              | 937               | 10.33              | 8.77               | 8.13               | 7.79               | 7.58               | 7.47               | 4.38                | 0.309                 |
| 2.084  | 28              | 987               | 10.46              | 8.92               | 8.28               | 7.93               | 7.71               | 7.6                | 4.66                | 0.309                 |
| 2.084  | 29              | 1038              | 10.73              | 9.15               | 8.48               | 8.12               | 7.88               | 7.76               | 4.97                | 0.309                 |
| 2.142  | 30              | 1087              | 13.66              | 11.23              | 10.25              | 9.76               | 9.42               | 9.29               | 5.93                | 0.309                 |
| 2.142  | 31              | 986               | 12.62              | 10.58              | 9.74               | 9.31               | 9.01               | 8.87               | 6.16                | 0.309                 |
| 2.142  | 32              | 886               | 11.4               | 9.77               | 9.09               | 8.74               | 8.5                | 8.37               | 6.41                | 0.309                 |
| 2.142  | 33              | 784               | 9.96               | 8.77               | 8.28               | 8.01               | 7.83               | 7.74               | 6.65                | 0.309                 |
| 2.142  | 34              | 683               | 8.87               | 8.02               | 7.69               | 7.49               | 7.37               | 7.29               | 6.94                | 0.309                 |
| 2.142  | 35              | 582               | 8.01               | 7.43               | 7.21               | 7.07               | 6.98               | 6.93               | 7.27                | 0.309                 |
| 2.142  | 36              | 482               | 7.37               | 7                  | 6.85               | 6.75               | 6.69               | 6.66               | 7.66                | 0.309                 |
| 2.142  | 37              | 385               | 6.88               | 6.67               | 6.58               | 6.5                | 6.45               | 6.43               | 8.14                | 0.309                 |
| 2.142  | 38              | 289               | 6.56               | 6.42               | 6.35               | 6.29               | 6.25               | 6.22               | 8.75                | 0.309                 |
| 2.142  | 39              | 194               | 6.38               | 6.25               | 6.19               | 6.13               | 6.09               | 6.07               | 9.65                | 0.309                 |
| 2.142  | 40              | 100               | 6.19               | 6.08               | 6.02               | 5.97               | 5.93               | 5.91               | 11.36               | 0.309                 |
| 2.142  | 41              | 25                | 6.02               | 5.94               | 5.89               | 5.84               | 5.82               | 5.81               | 11.97               | 0.309                 |

Appendix E. MPN Reports

Test = 2021072901

SHUL2146\_LowCal.mcd

AnDat = 20210730

JSC-1A (A) , 750C argon-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.084 \text{ gm/cc}$  Final density(25C) =  $\text{dnsfinal} = 2.142 \text{ gm/cc}$

Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz

Time

(hours)

| samdns <sub>mm</sub> | T <sub>mm,1</sub> | $\epsilon''_{\text{mm},1}$ | $\epsilon''_{\text{mm},2}$ | $\epsilon''_{\text{mm},3}$ | $\epsilon''_{\text{mm},4}$ | $\epsilon''_{\text{mm},5}$ | $\epsilon''_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |       |
|----------------------|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|-------|
| 2.084                | 8                 | 24                         | 0.209                      | 0.197                      | 0.189                      | 0.183                      | 0.18                       | 0.174               | 0                    | 0.309 |
| 2.084                | 9                 | 53                         | 0.21                       | 0.207                      | 0.204                      | 0.196                      | 0.195                      | 0.189               | 0.35                 | 0.309 |
| 2.084                | 10                | 101                        | 0.227                      | 0.219                      | 0.217                      | 0.212                      | 0.21                       | 0.205               | 0.62                 | 0.309 |
| 2.084                | 11                | 149                        | 0.246                      | 0.24                       | 0.236                      | 0.23                       | 0.229                      | 0.222               | 0.9                  | 0.309 |
| 2.084                | 12                | 196                        | 0.26                       | 0.256                      | 0.25                       | 0.244                      | 0.245                      | 0.24                | 1.13                 | 0.309 |
| 2.084                | 13                | 244                        | 0.289                      | 0.275                      | 0.266                      | 0.264                      | 0.264                      | 0.257               | 1.38                 | 0.309 |
| 2.084                | 14                | 292                        | 0.329                      | 0.308                      | 0.297                      | 0.29                       | 0.285                      | 0.279               | 1.63                 | 0.309 |
| 2.084                | 15                | 340                        | 0.413                      | 0.358                      | 0.339                      | 0.328                      | 0.32                       | 0.31                | 1.83                 | 0.309 |
| 2.084                | 16                | 389                        | 0.512                      | 0.43                       | 0.392                      | 0.376                      | 0.361                      | 0.349               | 2.03                 | 0.309 |
| 2.084                | 17                | 439                        | 0.66                       | 0.519                      | 0.464                      | 0.436                      | 0.417                      | 0.399               | 2.22                 | 0.309 |
| 2.084                | 18                | 487                        | 0.816                      | 0.621                      | 0.549                      | 0.507                      | 0.479                      | 0.456               | 2.42                 | 0.309 |
| 2.084                | 19                | 536                        | 1.016                      | 0.756                      | 0.651                      | 0.594                      | 0.556                      | 0.523               | 2.6                  | 0.309 |
| 2.084                | 20                | 586                        | 1.259                      | 0.919                      | 0.78                       | 0.701                      | 0.651                      | 0.607               | 2.79                 | 0.309 |
| 2.084                | 21                | 636                        | 1.539                      | 1.117                      | 0.933                      | 0.834                      | 0.766                      | 0.715               | 2.99                 | 0.309 |
| 2.084                | 22                | 686                        | 1.968                      | 1.385                      | 1.15                       | 1.021                      | 0.927                      | 0.862               | 3.18                 | 0.309 |
| 2.084                | 23                | 737                        | 2.375                      | 1.687                      | 1.4                        | 1.244                      | 1.131                      | 1.048               | 3.37                 | 0.309 |
| 2.084                | 24                | 787                        | 2.797                      | 2                          | 1.657                      | 1.469                      | 1.321                      | 1.229               | 3.57                 | 0.309 |
| 2.084                | 25                | 836                        | 3.224                      | 2.288                      | 1.879                      | 1.651                      | 1.485                      | 1.375               | 3.82                 | 0.309 |
| 2.084                | 26                | 886                        | 3.507                      | 2.536                      | 2.067                      | 1.816                      | 1.625                      | 1.494               | 4.1                  | 0.309 |
| 2.084                | 27                | 937                        | 3.708                      | 2.685                      | 2.19                       | 1.92                       | 1.731                      | 1.6                 | 4.38                 | 0.309 |
| 2.084                | 28                | 987                        | 3.66                       | 2.667                      | 2.197                      | 1.939                      | 1.747                      | 1.605               | 4.66                 | 0.309 |
| 2.084                | 29                | 1038                       | 3.847                      | 2.784                      | 2.306                      | 2.029                      | 1.834                      | 1.69                | 4.97                 | 0.309 |
| 2.142                | 30                | 1087                       | 7.411                      | 4.725                      | 3.694                      | 3.181                      | 2.791                      | 2.554               | 5.93                 | 0.309 |
| 2.142                | 31                | 986                        | 5.428                      | 3.737                      | 2.994                      | 2.609                      | 2.332                      | 2.135               | 6.16                 | 0.309 |
| 2.142                | 32                | 886                        | 4.254                      | 2.984                      | 2.411                      | 2.116                      | 1.887                      | 1.755               | 6.41                 | 0.309 |
| 2.142                | 33                | 784                        | 3.064                      | 2.158                      | 1.778                      | 1.563                      | 1.407                      | 1.296               | 6.65                 | 0.309 |
| 2.142                | 34                | 683                        | 2.178                      | 1.544                      | 1.279                      | 1.133                      | 1.029                      | 0.95                | 6.94                 | 0.309 |
| 2.142                | 35                | 582                        | 1.49                       | 1.069                      | 0.897                      | 0.803                      | 0.738                      | 0.689               | 7.27                 | 0.309 |
| 2.142                | 36                | 482                        | 0.966                      | 0.696                      | 0.605                      | 0.553                      | 0.521                      | 0.494               | 7.66                 | 0.309 |
| 2.142                | 37                | 385                        | 0.576                      | 0.45                       | 0.416                      | 0.394                      | 0.385                      | 0.374               | 8.14                 | 0.309 |
| 2.142                | 38                | 289                        | 0.356                      | 0.315                      | 0.307                      | 0.307                      | 0.312                      | 0.309               | 8.75                 | 0.309 |
| 2.142                | 39                | 194                        | 0.255                      | 0.258                      | 0.266                      | 0.272                      | 0.279                      | 0.277               | 9.65                 | 0.309 |
| 2.142                | 40                | 100                        | 0.228                      | 0.235                      | 0.248                      | 0.253                      | 0.26                       | 0.259               | 11.36                | 0.309 |
| 2.142                | 41                | 25                         | 0.216                      | 0.232                      | 0.243                      | 0.248                      | 0.254                      | 0.253               | 11.97                | 0.309 |

MPN-231\_Shulman\_3\_JSC-1A (B)

August 2, 2021

JSC-1A (B) ( Initially Heat Treated to 750C in Argon/Hydrogen)  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in < 1 milliTorr Vacuum

Dr. Holly Shulman ( Shulman LLC) again requested that Microwave Properties North measure the complex dielectric properties of a specially treated JSC-1A moon simulant up to 1100C with a direct, uninterrupted, temperature cycle, in as good a vacuum as we could produce in the MPN system. The powder sample material arrived at MPN on July 21/ 2021. Dr. Shulman had already baked the powder at 750C in UHP argon/hydrogen gas mix.

MPN pressed pellets of the powder material in a uniaxial press. The press pressure was increased to ~ 32,000 psi to match the previous run, and produced pellets with sufficient strength for handling, achieving a density of ~ 2.14 g/cc . The pellets were not baked to ensure dryness.

MPN was requested to cycle the sample directly up to 1100C and then return to room temperature (RT) , ) in as good a vacuum as we could produce in the MPN system. The base pressure was less than 1 milliTorr, using a Varian 810 readout with a Varian 531 TC gauge head.

The initial sample parameters were:

- a) diameter 3.65 +- 0.05 mm
- b) length 14.62 +- 0.10 mm
- c) mass 0.330 +- 0.002 gm
- bb) room temperature density  $2.16 \pm 0.07$  gm/cc.
- cc) appearance - three (stacked) dark grey pellets ( see photo).

The dielectric properties measurements were performed at RT and then the temperature was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus and it and the the final sample were weighed. The empty sample holder was then run up to 1100C in +100 steps to measure background and check for contamination. In spite of a slight reddish-brown tinge in the region of the sample, there was only modest contamination ( see photo) , which was low enough to not affect the values.

The final sample properties, at room temperature were :

- a) diameter  $3.63 \pm 0.05$  mm
- b) length  $14.61 \pm 0.1$  mm
- c) mass  $0.330 \pm 0.002$  gm
- aa) room temperature density  $2.18 \pm 0.07$  gm/cc.
- bb) appearance - three slightly brownish grey pellets ( see photo)

Note: The percent mass loss was zero ( +- 0.7 %) .

The frequency coding is :

Legend for Data Plots :

| # | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|---|-----------------------|----------------------------------------------------------|
| 1 | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912                   | blue square, solid line                                  |
| 3 | 1429                  | black cross, solid line                                  |
| 4 | 1948                  | blue circle, dotted line                                 |
| 5 | 2466                  | red cross, dotted line                                   |
| 6 | 2986                  | black diamond, dotted line                               |

Comments on the data analysis:

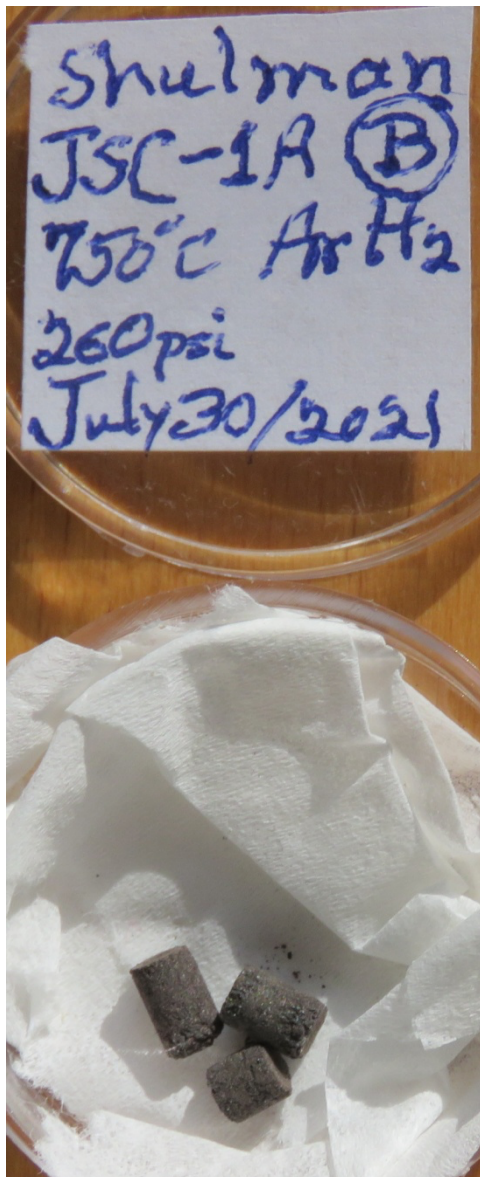
A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

The final pellets were a slightly different colour – with only a slight brownish tinge.

The data for the ramp up to 1100C is definitely different than for the ramp down. Some change has occurred. The cycle to 1100 C seemed to produce a change in the material that produces slightly elevated values on the return down to room temperature.



Final Three pellets of JSC-1A (B) after cycle to 1100C in vacuum .



Final holder after exposure to air during empty run the run .  
after end of measurement run.  
(A) pellets.

The slightly brown tinged pellets after  
Not as much brown as the JSC-1A

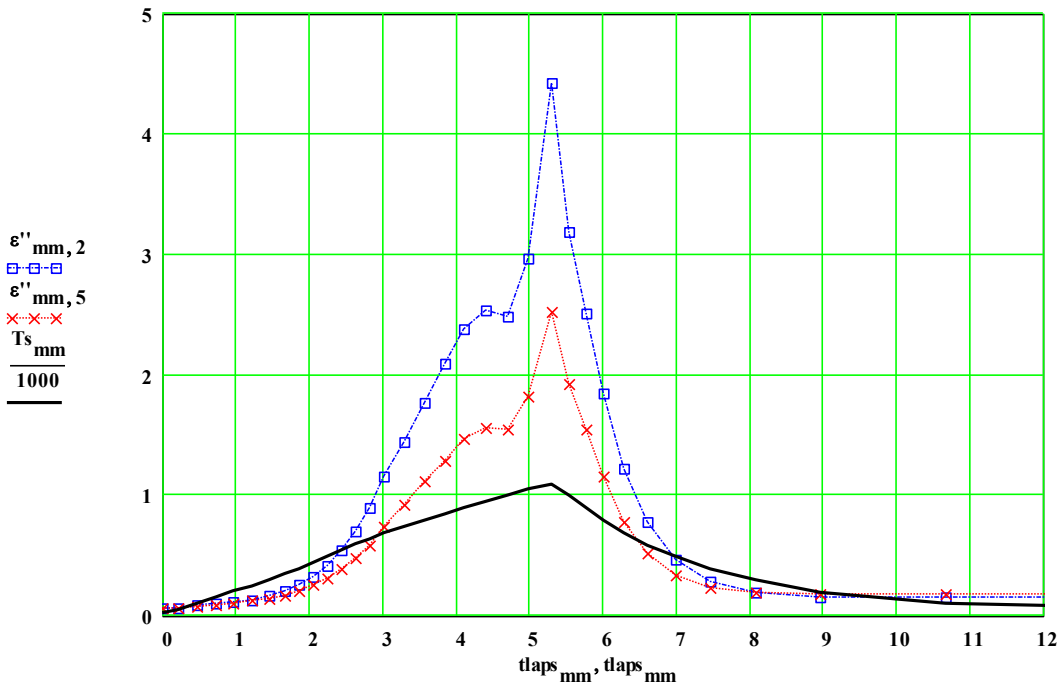
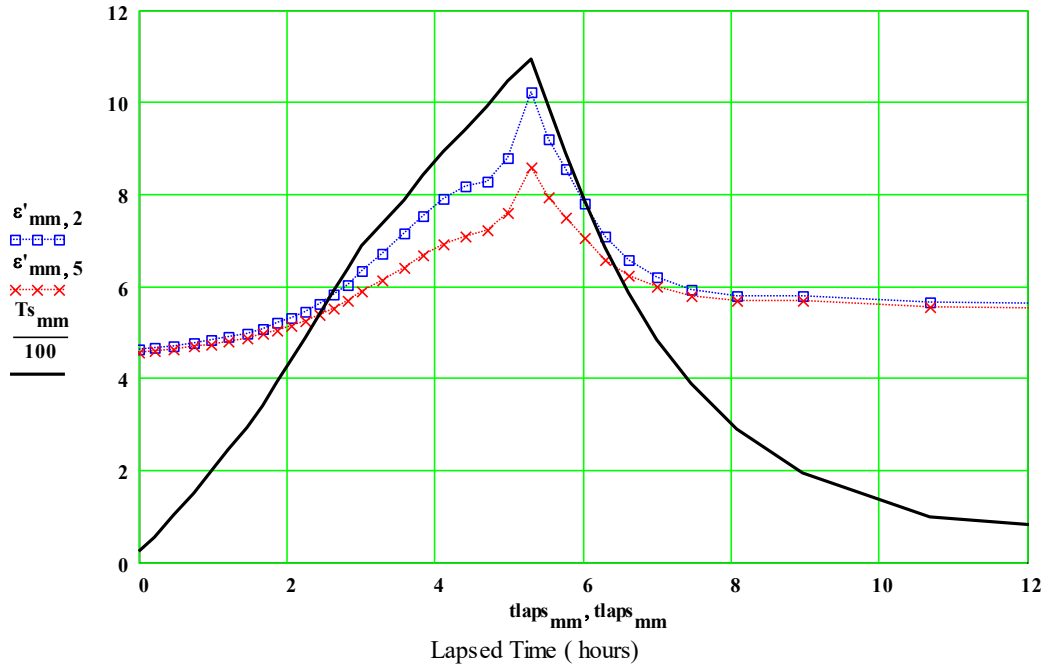
After the run on the JSC-1A (A) sample ( the previous run), the holder did not look contaminated until after it was exposed to air when the sample was removed and the empty holder evaluation was run up to 1100C. Then there were a few reddish-brown areas. The holder was only slightly contaminated.

After the JSC-1A (B) run ( this run) the reddish areas were a bit more pronounced. This implies that after each run, the surface coating on the holder in the region where the pellets were was

# Appendix E. MPN Reports

either pure iron or wustite, and that it oxidized during the exposure to air on the empty holder run at the end of the measurement cycle. We are guessing the red colouring is hematite.

**Test = 2021073101**                      SHUL2147\_LowCal.mcd                      **AnDat = 20210802**  
 JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC  
 Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ ,                      Thermal exp. coeff.  
 Final density(25C) =  $\text{dnsfinal} = 2.18 \text{ gm/cc}$                       **FracMassChange = 1**                       $\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2021073101

SHUL2147\_LowCal.med

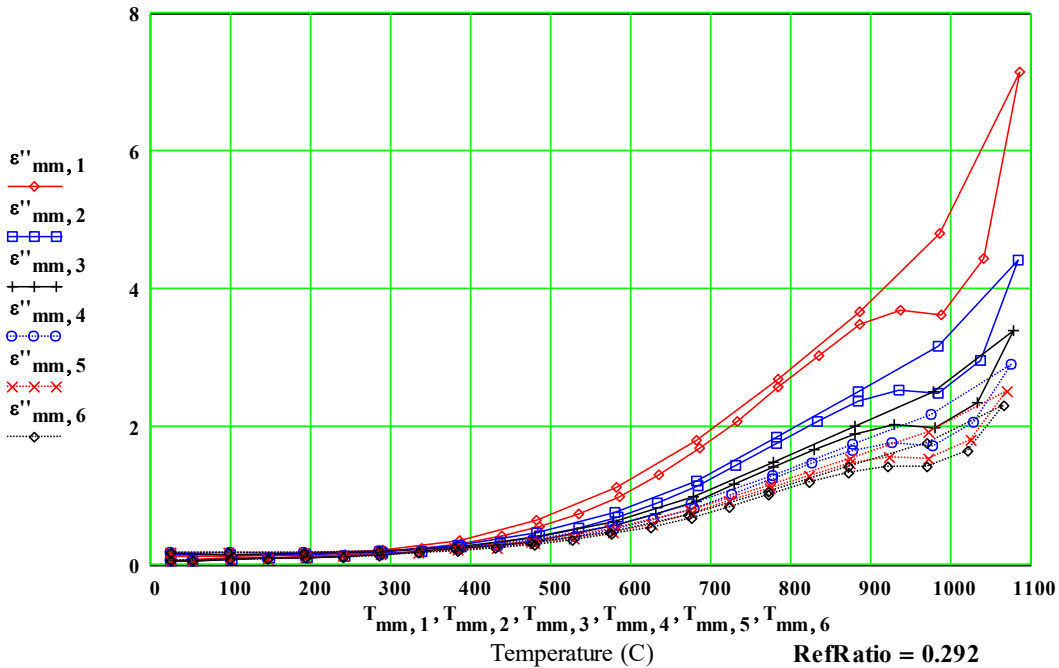
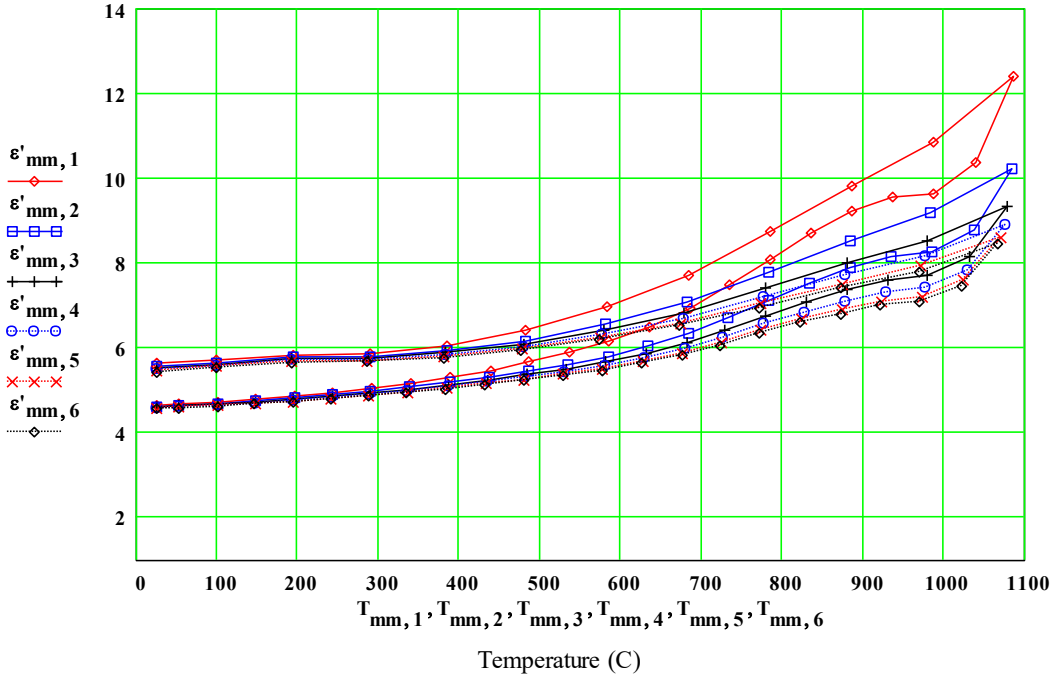
AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen -conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.18 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



Values for the Temperature Cycle (to 1100 C and back to RT) :

Test = 2021073101

SHUL2147\_LowCal.mcd

AnDat = 20210802

T

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.18 \text{ gm/cc}$

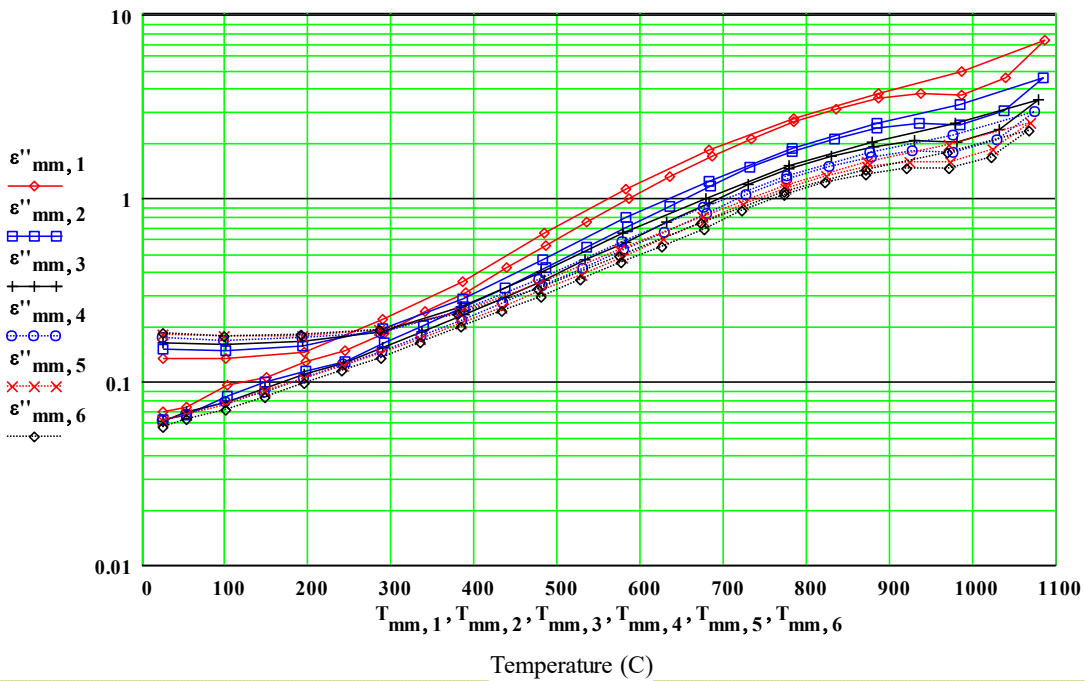
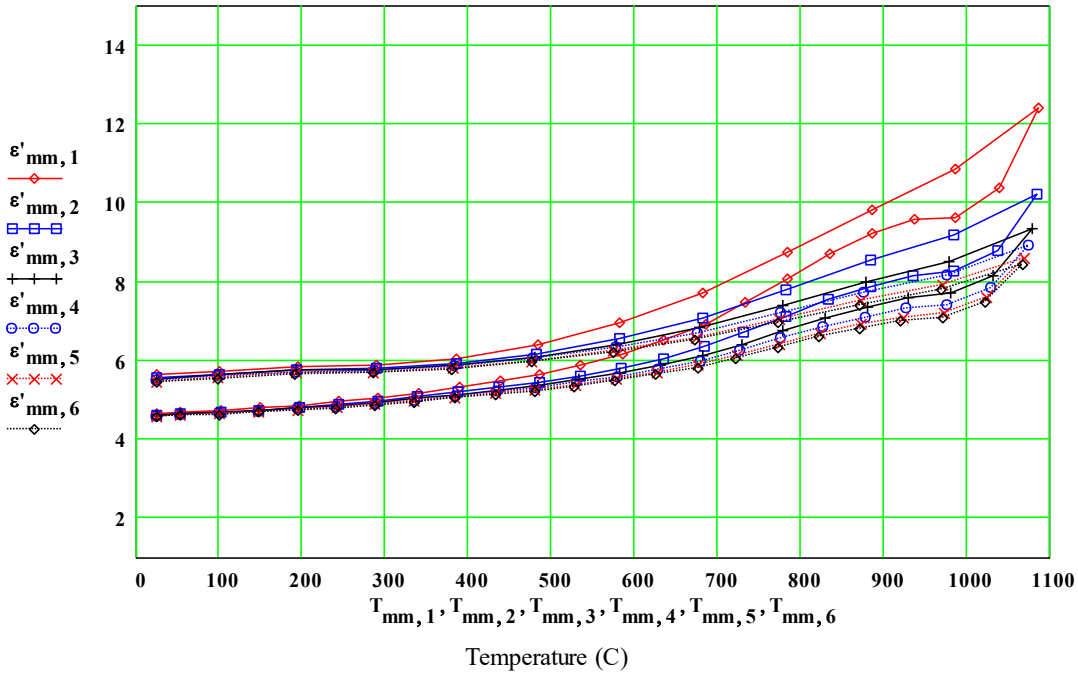
h

FracMassChange = 1

$\alpha_1 = 0$  /C

$\alpha_2 = 0$  /C

F



# Appendix E. MPN Reports

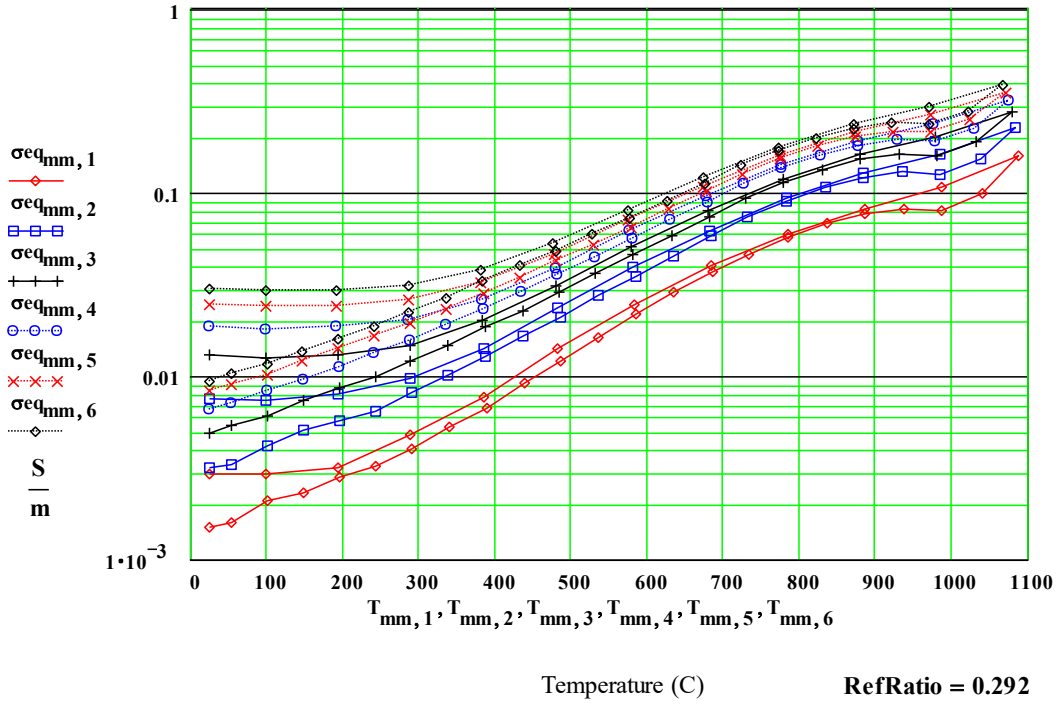
Test = 2021073101

SHUL2147\_LowCal.mcd

AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2021073101

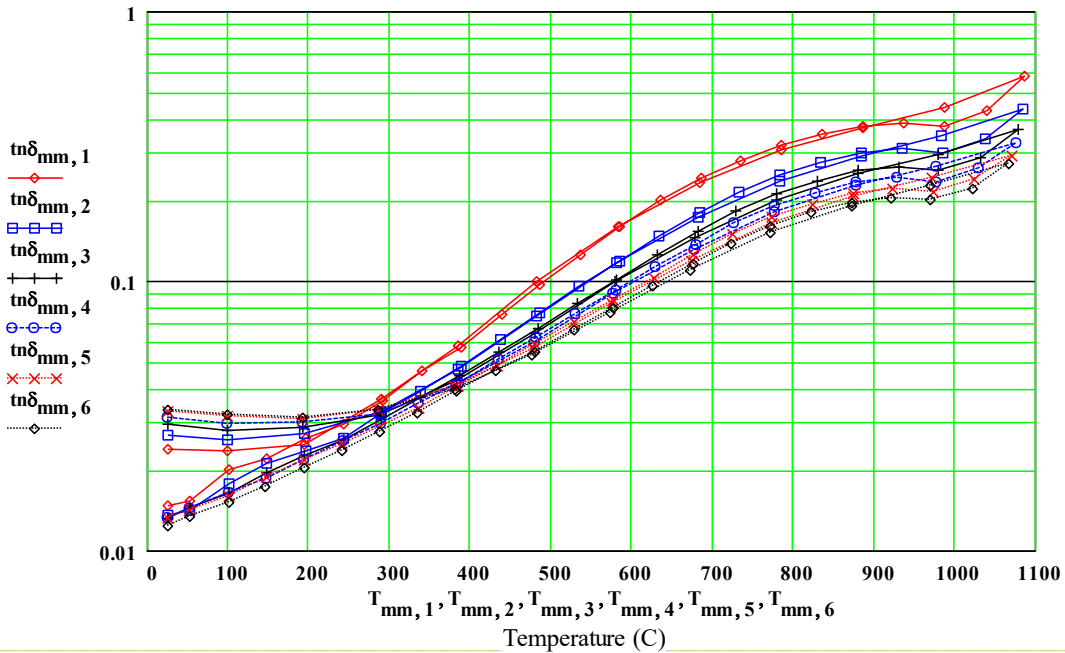
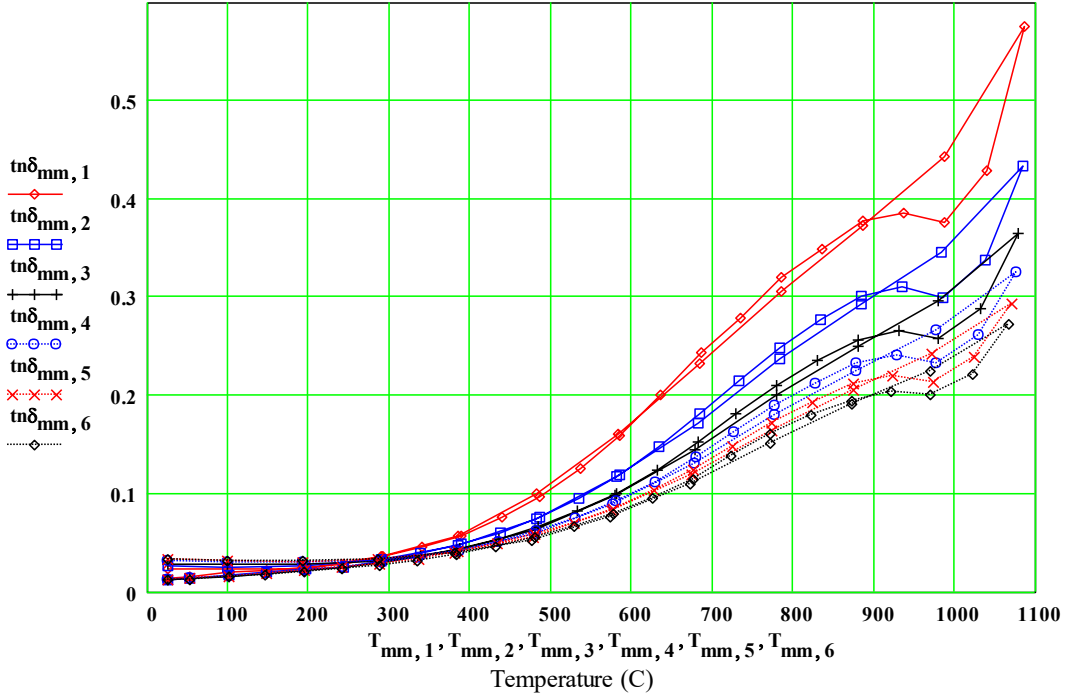
SHUL2147\_LowCal.med

AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.18 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2021073101

SHUL2147\_LowCal.mcd

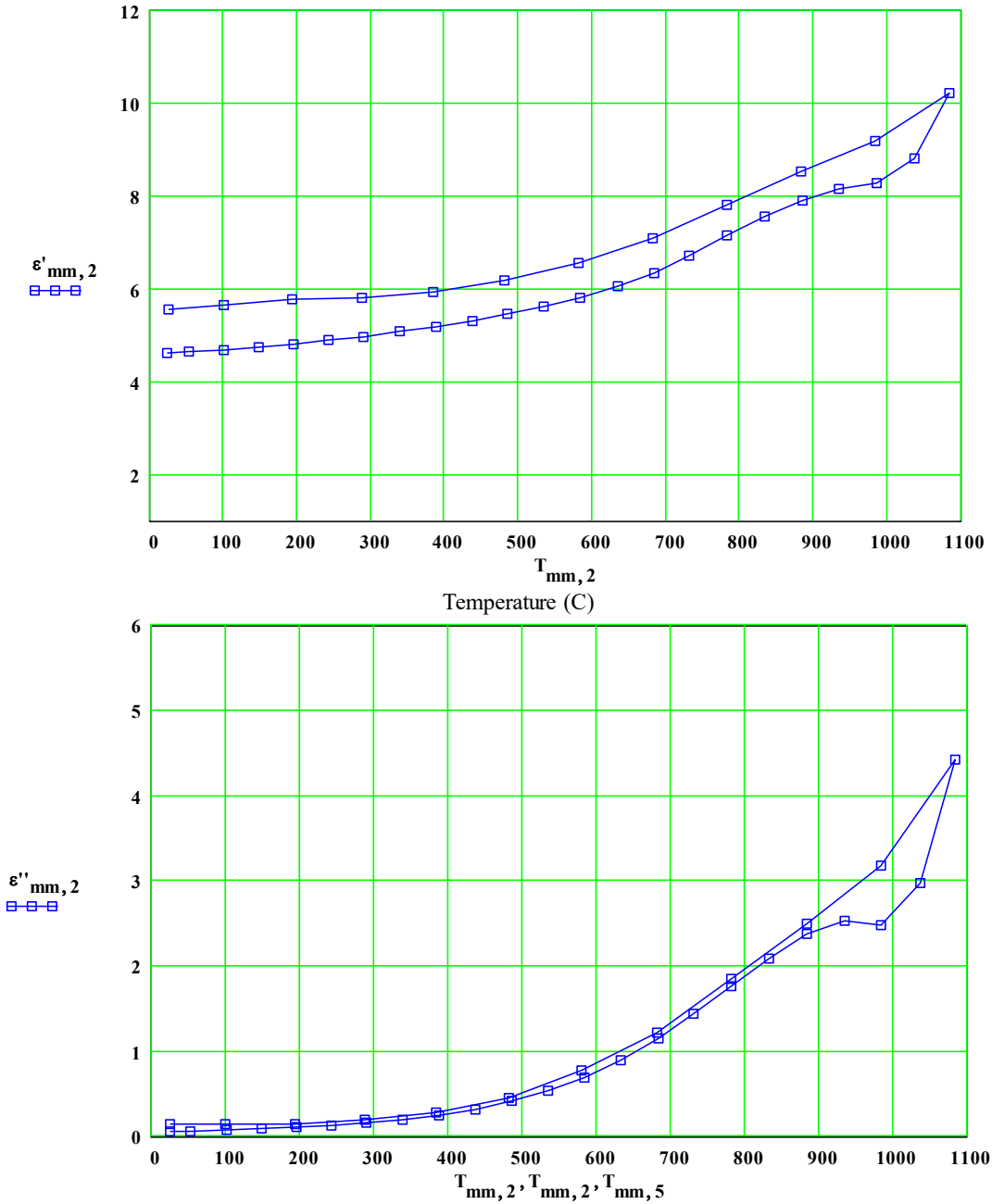
AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16$  gm/cc, Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 2.18$  gm/cc

## Values for 912 MHz



# Appendix E. MPN Reports

Test = 2021073101

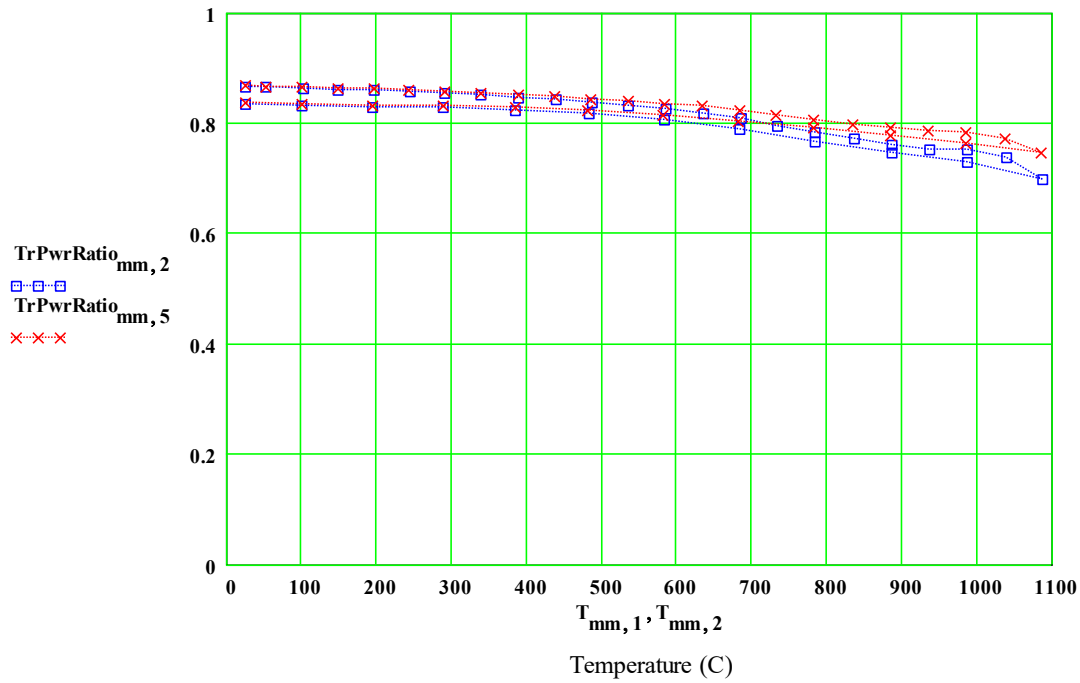
SHUL2147\_LowCal.mcd

AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C , in vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.18 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



# Appendix E. MPN Reports

Half-power Depth (millimeters)

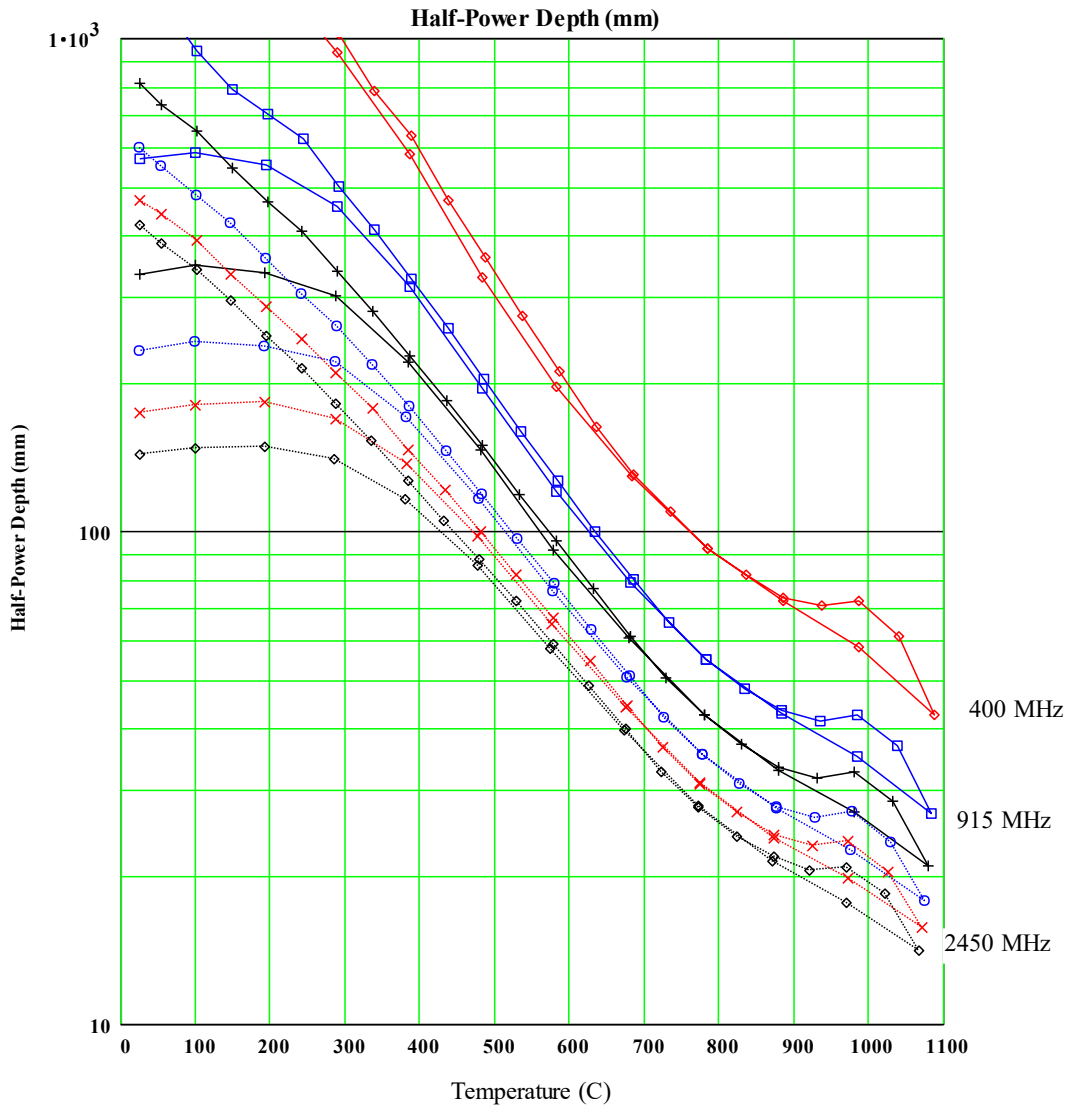
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021073101

SHUL2147\_LowCal.mcd

AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC



Fit to 'Disordered' Structure which Exists after the Highest Temperature was Attained ( 1100CFit to 'Intrinsic' Values - High Temperature

$$E_{an} := 0.37 \text{ eV}$$

$$\sigma_{intn} := 4.4 \cdot 10^0 \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \text{ eV/K}$$

$$n_J := 0.51$$

$$\varepsilon_{ppthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \cos \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{f_{h_n}}{400} \right)^{n_J}$$

$$\sigma_{thJn_{mn,n}} := \varepsilon_{ppthJn_{mn,n}} \cdot 2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}$$

$$\varepsilon_{infin_{mn}} := 5.4 + 0.35 \cdot \frac{TQ_{mn}}{400}$$

$$\varepsilon_{pthJn_{mn,n}} := \left[ \frac{\sigma_{intn}}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{an}}{k_B \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( n_J \cdot \frac{\pi}{2} \right) \cdot \left( \frac{f_{h_n}}{400} \right)^{n_J}$$

$$\varepsilon_{pthTotal_{mn,n}} := \varepsilon_{pthJn_{mn,n}} + \varepsilon_{infin_{mn}}$$

$$H_{activ} := E_{an} \cdot 96.5 \text{ Kjoule/mol}$$

$$H_{activ} = 36 \text{ Kjoule/mol}$$

$$E_{gn} := 2 \cdot E_{an} \text{ Conduction Gap Energy}$$

$$\frac{E_{gn}}{2} = 0.37 \text{ eV}$$

**Fit to 'Extrinsic' Values - Low Temperature, Impurity Dependent :**

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{am} := 0.0025 \quad \sigma_{intm} := 0.0033 \quad mJ := 1.12$$

$$\varepsilon_{ppthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{(2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6})} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

$$\sigma_{thJm_{mn,n}} := \overbrace{\varepsilon_{ppthJm_{mn,n}} \cdot 2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}}$$

$$\varepsilon_{pthJm_{mn,n}} := \left[ \frac{\sigma_{intm}}{2 \cdot \pi \cdot fh_n \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_{am}}{kB \cdot (TQ_{mn} + 273.)} \right] \right] \cdot \sin \left( mJ \cdot \frac{\pi}{2} \right) \cdot \left( \frac{fh_n}{400} \right)^{mJ}$$

**Sum up Extrinsic and Intrinsic Contributions :**

$$\varepsilon_{pthTotal_{mn,n}} := \varepsilon_{pthJn_{mn,n}} + \varepsilon_{pthJm_{mn,n}} + \varepsilon_{infin_{mn}}$$

$$\varepsilon_{ppthTotal_{mn,n}} := \varepsilon_{ppthJn_{mn,n}} + \varepsilon_{ppthJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

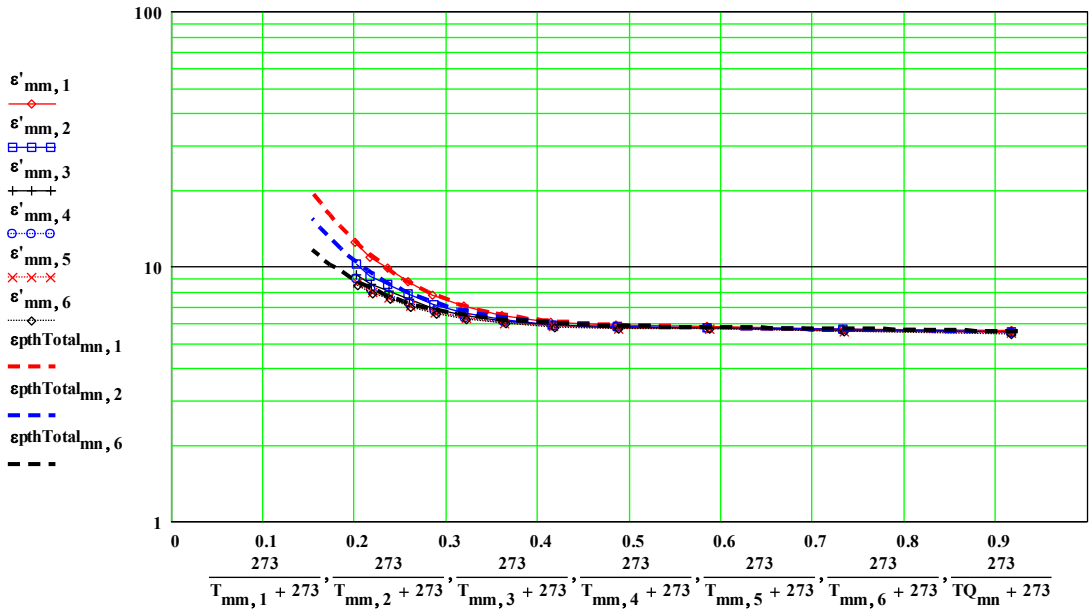
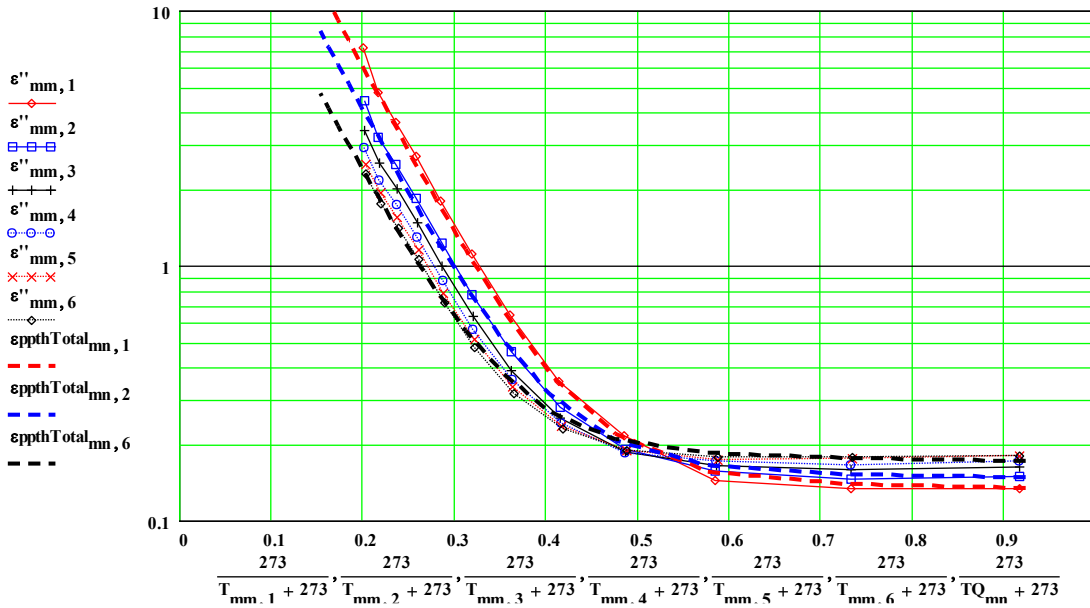
Test = 2021073101

SHUL2147\_LowCal.mcd

AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Final density(25C) = **dnsfinal = 2.18** gm/cc



# Appendix E. MPN Reports

Test = 2021073101

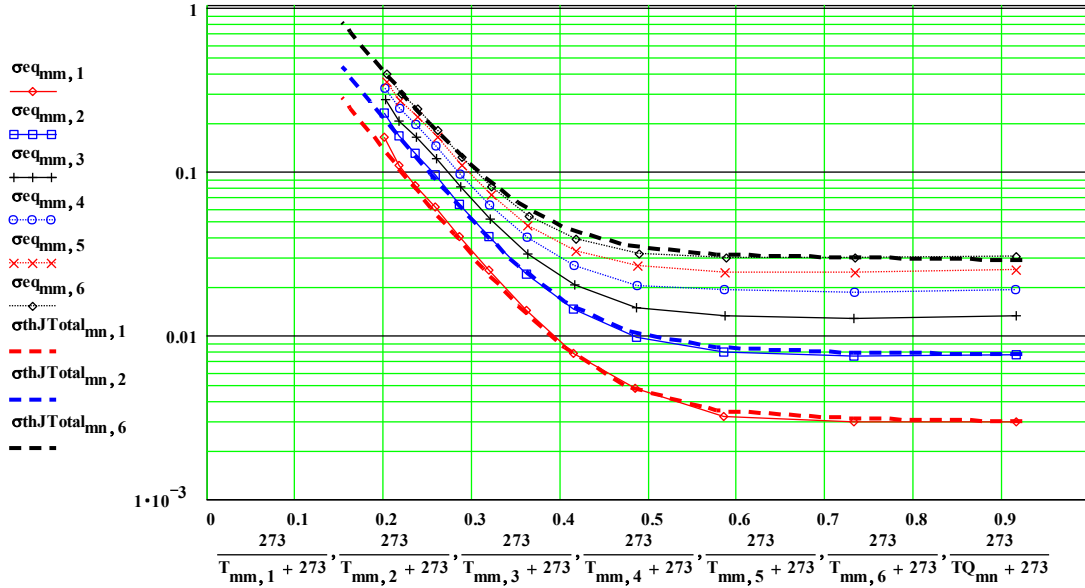
SHUL2147\_LowCal.mcd

AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

Final density(25C) = **dnsfinal = 2.18** gm/cc

Equivalent Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2021073101                      SHUL2147\_LowCal.mcd                      AnDat = 20210802  
 JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ~~~~~

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.157 \text{ gm/cc}$                       Final density(25C) =  $\text{dnsfinal} = 2.183 \text{ gm/cc}$

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz                      Lapsed Time (hours)

samdns	mm	T <sub>mm,1</sub>	$\epsilon'_{\text{mm},1}$	$\epsilon'_{\text{mm},2}$	$\epsilon'_{\text{mm},3}$	$\epsilon'_{\text{mm},4}$	$\epsilon'_{\text{mm},5}$	$\epsilon'_{\text{mm},6}$	tlaps <sub>mm</sub>	sammas <sub>mm</sub>
2.157	10	25	4.65	4.63	4.62	4.6	4.58	4.57	0	0.33
2.157	11	53	4.69	4.66	4.64	4.62	4.61	4.6	0.21	0.33
2.157	12	102	4.74	4.7	4.69	4.66	4.65	4.64	0.47	0.33
2.157	13	148	4.81	4.76	4.74	4.71	4.69	4.68	0.73	0.33
2.157	14	196	4.88	4.83	4.8	4.77	4.75	4.73	0.97	0.33
2.157	15	244	4.96	4.9	4.87	4.83	4.81	4.79	1.22	0.33
2.157	16	291	5.06	4.98	4.95	4.91	4.88	4.86	1.46	0.33
2.157	17	339	5.19	5.09	5.04	5	4.97	4.95	1.67	0.33
2.157	18	389	5.33	5.2	5.15	5.09	5.06	5.04	1.86	0.33
2.157	19	438	5.47	5.33	5.26	5.2	5.16	5.14	2.06	0.33
2.157	20	487	5.67	5.46	5.38	5.31	5.27	5.24	2.25	0.33
2.157	21	536	5.89	5.62	5.52	5.44	5.38	5.35	2.44	0.33
2.157	22	585	6.17	5.82	5.68	5.58	5.52	5.48	2.63	0.33
2.157	23	635	6.51	6.05	5.88	5.76	5.68	5.63	2.82	0.33
2.157	24	686	6.93	6.35	6.12	5.98	5.88	5.82	3.02	0.33
2.157	25	734	7.49	6.72	6.43	6.25	6.13	6.06	3.3	0.33
2.157	26	784	8.09	7.14	6.78	6.56	6.42	6.34	3.58	0.33
2.157	27	836	8.71	7.55	7.1	6.85	6.69	6.6	3.84	0.33
2.157	28	886	9.22	7.9	7.38	7.09	6.91	6.81	4.12	0.33
2.157	29	937	9.58	8.17	7.61	7.31	7.1	7.01	4.4	0.33
2.166	30	987	9.63	8.28	7.72	7.41	7.21	7.1	4.7	0.33
2.174	31	1040	10.38	8.81	8.16	7.82	7.6	7.48	4.99	0.33
2.183	32	1087	12.4	10.23	9.34	8.91	8.6	8.45	5.3	0.33
2.183	33	987	10.85	9.19	8.53	8.17	7.93	7.81	5.53	0.33
2.183	34	886	9.83	8.55	8.01	7.71	7.51	7.41	5.77	0.33
2.183	35	785	8.77	7.8	7.42	7.19	7.04	6.96	6.01	0.33
2.183	36	683	7.74	7.09	6.85	6.69	6.59	6.53	6.29	0.33
2.183	37	582	6.97	6.57	6.42	6.32	6.25	6.21	6.61	0.33
2.183	38	483	6.41	6.19	6.11	6.04	5.99	5.96	7	0.33
2.183	39	386	6.07	5.94	5.89	5.84	5.8	5.78	7.47	0.33
2.183	40	289	5.89	5.81	5.78	5.73	5.7	5.68	8.08	0.33
2.183	41	194	5.84	5.79	5.75	5.71	5.69	5.66	8.97	0.33
2.183	42	100	5.73	5.67	5.63	5.59	5.57	5.55	10.68	0.33
2.183	43	25	5.64	5.57	5.54	5.5	5.46	5.44	16.69	0.33
2.858	44	25	1.04	1.04	1.04	1.04	1.04	1.04	16.84	0.33
2.858	45	101	1.04	1.03	1.03	1.02	1.02	1.02	17	0.33
2.858	46	197	1.04	1.03	1.03	1.02	1.02	1.02	17.22	0.33
2.858	47	294	1.04	1.03	1.03	1.02	1.02	1.02	17.46	0.33
2.858	48	390	1.04	1.03	1.04	1.03	1.03	1.03	17.67	0.33
2.858	49	488	1.04	1.03	1.04	1.03	1.03	1.03	17.89	0.33
2.858	50	587	1.04	1.04	1.05	1.03	1.03	1.03	18.1	0.33
2.858	51	687	1.03	1.03	1.04	1.03	1.03	1.03	18.38	0.33
2.858	52	788	1.03	1.03	1.04	1.03	1.03	1.03	18.69	0.33
2.858	53	892	1.03	1.03	1.03	1.03	1.03	1.03	18.99	0.33
2.858	54	992	1.03	1.03	1.03	1.03	1.03	1.03	19.31	0.33
2.858	55	1088	1.02	1.04	1.03	1.03	1.03	1.03	19.69	0.33

# Appendix E. MPN Reports

Test = 2021073101

SHUL2147\_LowCa.lmcd

AnDat = 20210802

JSC-1A (B) , 750C argon/hydrogen-conditioned Pellets , RT to 1100C, in vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.157 \text{ gm/cc}$  Final density(25C) =  $\text{dnsfinal} = 2.183 \text{ gm/cc}$

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz Lapsed Time (hours)

samdns	mm	T	$\epsilon'$ mm, 1	$\epsilon''$ mm, 1	$\epsilon''$ mm, 2	$\epsilon''$ mm, 3	$\epsilon''$ mm, 4	$\epsilon''$ mm, 5	$\epsilon''$ mm, 6	tlaps mm	sammas mm
2.157	10	25	0.069	0.063	0.061	0.061	0.061	0.057	0	0.33	
2.157	11	53	0.072	0.066	0.068	0.066	0.065	0.062	0.21	0.33	
2.157	12	102	0.095	0.083	0.077	0.077	0.074	0.07	0.47	0.33	
2.157	13	148	0.106	0.1	0.092	0.087	0.087	0.082	0.73	0.33	
2.157	14	196	0.128	0.114	0.109	0.104	0.102	0.097	0.97	0.33	
2.157	15	244	0.146	0.128	0.125	0.123	0.12	0.113	1.22	0.33	
2.157	16	291	0.184	0.162	0.153	0.145	0.141	0.134	1.46	0.33	
2.157	17	339	0.242	0.199	0.186	0.175	0.169	0.161	1.67	0.33	
2.157	18	389	0.304	0.254	0.232	0.215	0.207	0.197	1.86	0.33	
2.157	19	438	0.416	0.324	0.287	0.266	0.252	0.24	2.06	0.33	
2.157	20	487	0.55	0.415	0.359	0.329	0.308	0.288	2.25	0.33	
2.157	21	536	0.741	0.539	0.457	0.41	0.38	0.354	2.44	0.33	
2.157	22	585	0.985	0.693	0.575	0.513	0.471	0.438	2.63	0.33	
2.157	23	635	1.308	0.894	0.735	0.647	0.587	0.54	2.82	0.33	
2.157	24	686	1.688	1.15	0.934	0.818	0.737	0.673	3.02	0.33	
2.157	25	734	2.092	1.448	1.168	1.021	0.914	0.842	3.3	0.33	
2.157	26	784	2.593	1.773	1.43	1.242	1.111	1.018	3.58	0.33	
2.157	27	836	3.049	2.094	1.679	1.459	1.292	1.192	3.84	0.33	
2.157	28	886	3.493	2.378	1.902	1.652	1.462	1.328	4.12	0.33	
2.157	29	937	3.705	2.542	2.031	1.763	1.559	1.431	4.4	0.33	
2.166	30	987	3.625	2.482	1.996	1.731	1.54	1.424	4.7	0.33	
2.174	31	1040	4.459	2.973	2.361	2.052	1.821	1.657	4.99	0.33	
2.183	32	1087	7.147	4.432	3.415	2.894	2.52	2.303	5.3	0.33	
2.183	33	987	4.816	3.182	2.526	2.173	1.927	1.759	5.53	0.33	
2.183	34	886	3.665	2.508	2.01	1.736	1.545	1.416	5.77	0.33	
2.183	35	785	2.692	1.85	1.489	1.296	1.155	1.058	6.01	0.33	
2.183	36	683	1.8	1.226	0.996	0.871	0.783	0.72	6.29	0.33	
2.183	37	582	1.119	0.775	0.638	0.566	0.517	0.478	6.61	0.33	
2.183	38	483	0.644	0.461	0.391	0.358	0.336	0.317	7	0.33	
2.183	39	386	0.352	0.281	0.254	0.241	0.236	0.229	7.47	0.33	
2.183	40	289	0.216	0.192	0.186	0.184	0.189	0.189	8.08	0.33	
2.183	41	194	0.144	0.157	0.165	0.171	0.175	0.178	8.97	0.33	
2.183	42	100	0.134	0.147	0.159	0.166	0.176	0.177	10.68	0.33	
2.183	43	25	0.134	0.15	0.163	0.171	0.18	0.181	16.69	0.33	
2.858	44	25	0.004	0.002	0.001	0.001	0.001	0.001	16.84	0.33	
2.858	45	101	0.008	-0.005	-0.001	0	0	-0	17	0.33	
2.858	46	197	-0.006	0.001	0	0.001	0.001	0.002	17.22	0.33	
2.858	47	294	-0.012	0.001	0.001	0.002	0.002	0	17.46	0.33	
2.858	48	390	0.004	-0	-0.001	0.003	0.001	0.001	17.67	0.33	
2.858	49	488	0.002	0.007	0.003	0.003	0.003	0.002	17.89	0.33	
2.858	50	587	0.006	-0	0.003	0.004	0.004	0.002	18.1	0.33	
2.858	51	687	0.001	0.006	0.002	0.004	0.004	0.002	18.38	0.33	
2.858	52	788	0.005	0.003	0.004	0.004	0.004	0.004	18.69	0.33	
2.858	53	892	0.014	0.009	0.003	0.003	0.004	0.003	18.99	0.33	
2.858	54	992	0.001	0.001	-0	-0	0.002	0.002	19.31	0.33	
2.858	55	1088	-0.001	0	-0.002	-0.001	-0.001	-0	19.69	0.33	

CERALINK\_NYSERDA\_10

Apr. 29, 2009

Greetings Shawn:

Here is the report on your pressed JSC-1, Lunar Simulant powder pellets, run in UHP argon.

The sample was prepared by pressing two pellets, each ~ 6 mm long , and stacking them in the holder.

The initial sample parameters were:

- a) length 12.37 mm +/- 0.05
- b) diameter 3.63 - 0.05 mm
- c) mass 0.267 +/- 0.002 gm
- d) appearance - dark grey cylinders
- e) room temperature density  $2.09 \pm 0.15$  gm/cc.

Two cycles of dielectric measurements were performed on the same sample, without removing it from the holder. Each cycle consisted of measurements at room temperature, 100C, and then in 50°C steps to 1100°C, and then in -100C steps back down to 200C, then at room temperature. The empty holder could not be measured at the end of the run because the sample had expanded and adhered to the walls of the holder ( see photo of sample, which broke when we broke the holder to get it out!).

Final sample parameters were:

- a) length 10.15 mm +/- 0.20
- b) diameter 3.90 - 0.15 mm
- c) mass 0.265 +/- 0.002 gm
- d) appearance - pellets adhered to each other, and darker!
- e) room temperature density  $2.19 \pm 0.20$  gm/cc.

For the data analysis, a value of the thermal expansion coefficient of  $\alpha = 0.0 * 10^{-6}/K$  was used, since sintering or melting occurred!

The frequency coding is :

Legend for Data Plots :

#	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	912	blue square, solid line
2	2466	red cross, dotted line



# Appendix E. MPN Reports

Code Calculates Sample Volume and Plots Sample Density As a Function of Temperature or Lapsed Time

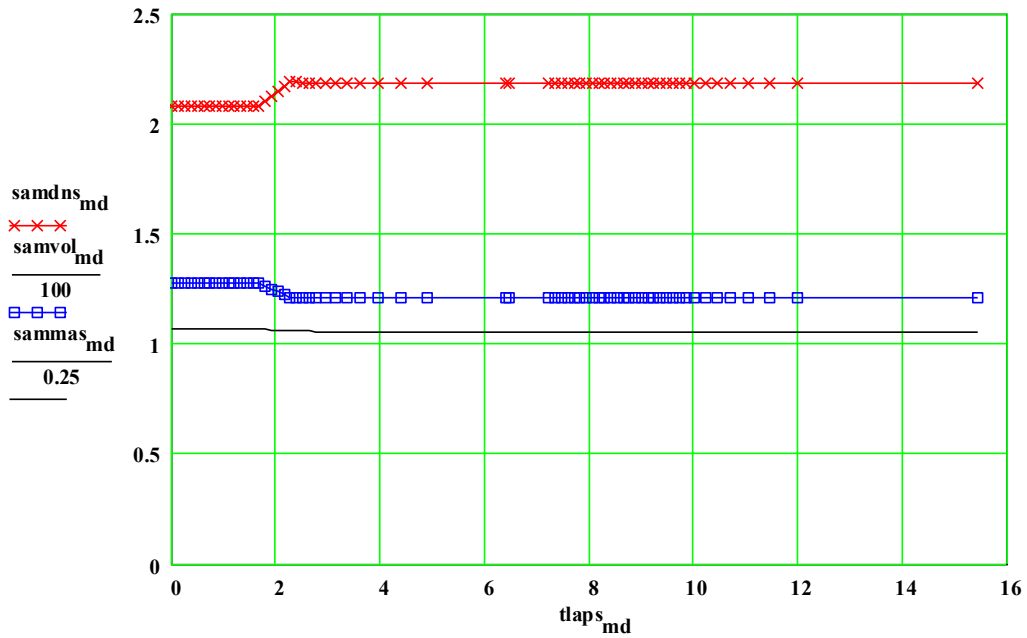
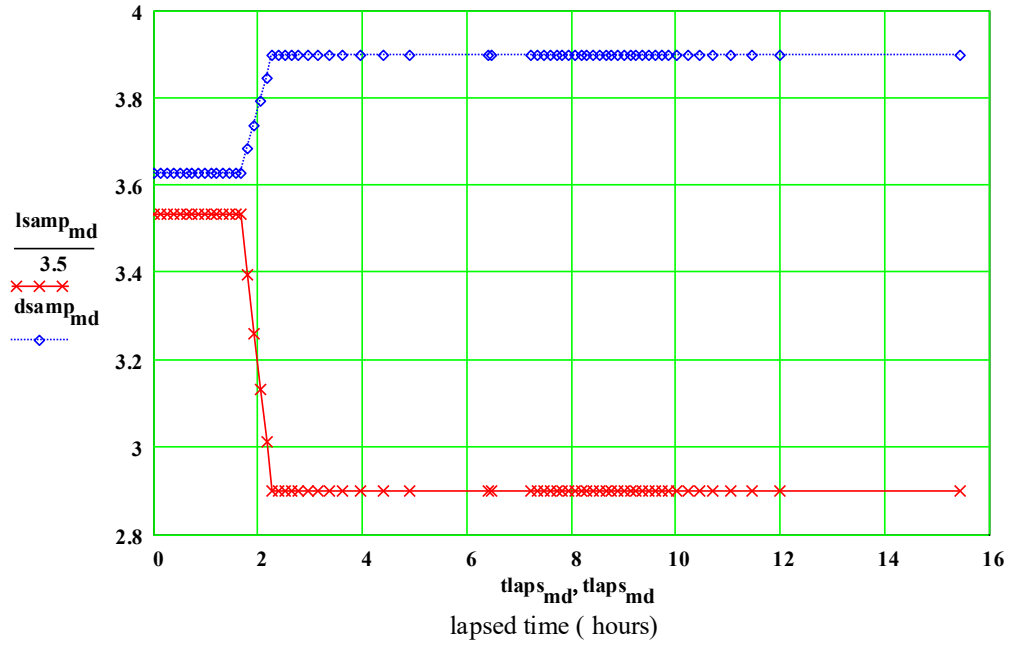
**Test = 2009042601**

CERL0960.mcd

**AnDat = 20090428**

JSC-1 Linear Simulant, RT to 1100C, in flowing UHP argon , Shawn Allen, CERALINK

Assumed Dimensions (mm), Mass( gm ) and Density (gm/cc) as a Function of Temperature for Pellet Stack



# Appendix E. MPN Reports

Test = 2009042601

CERL0960A.mcd

AnDat = 20090428

JSC-1 Linear Simulant, First Cycle, RT to 1100C, in flowing UHP argon , Shawn Allen, CERLINK

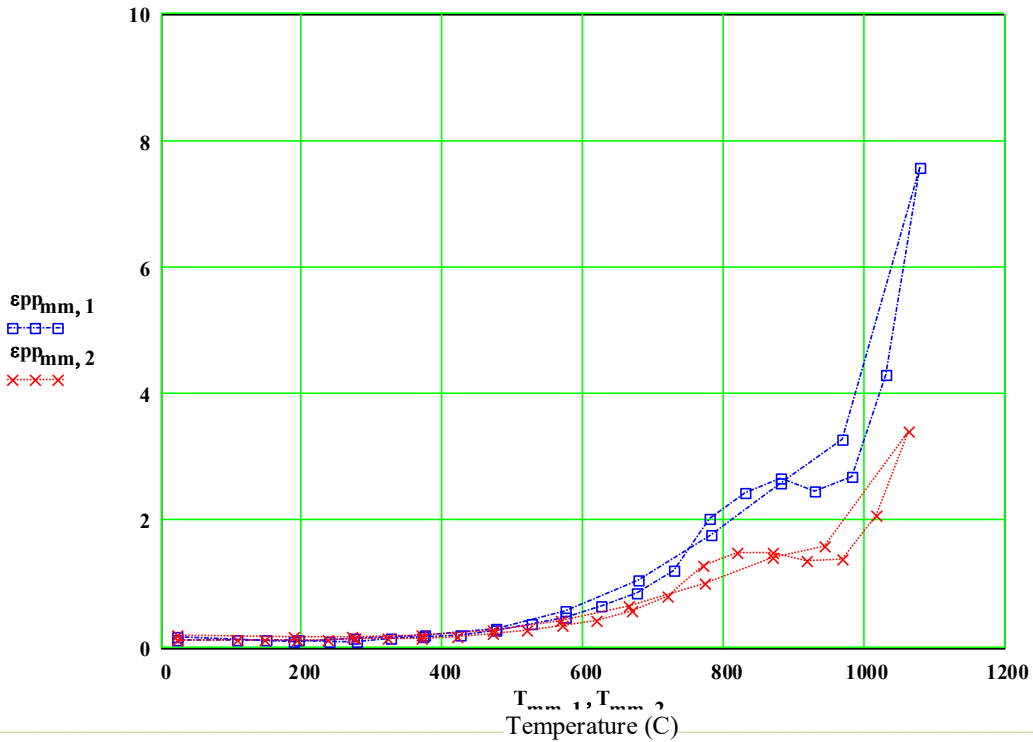
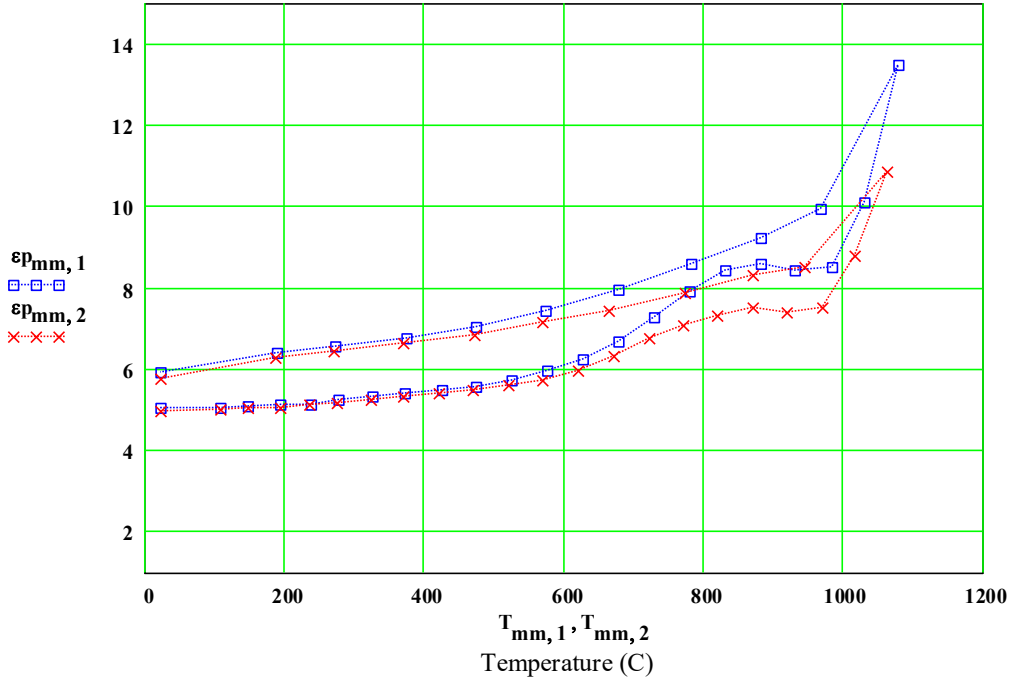
Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$

$\text{FracMassChange} = -7.49 \cdot 10^{-3}$

$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2009042601

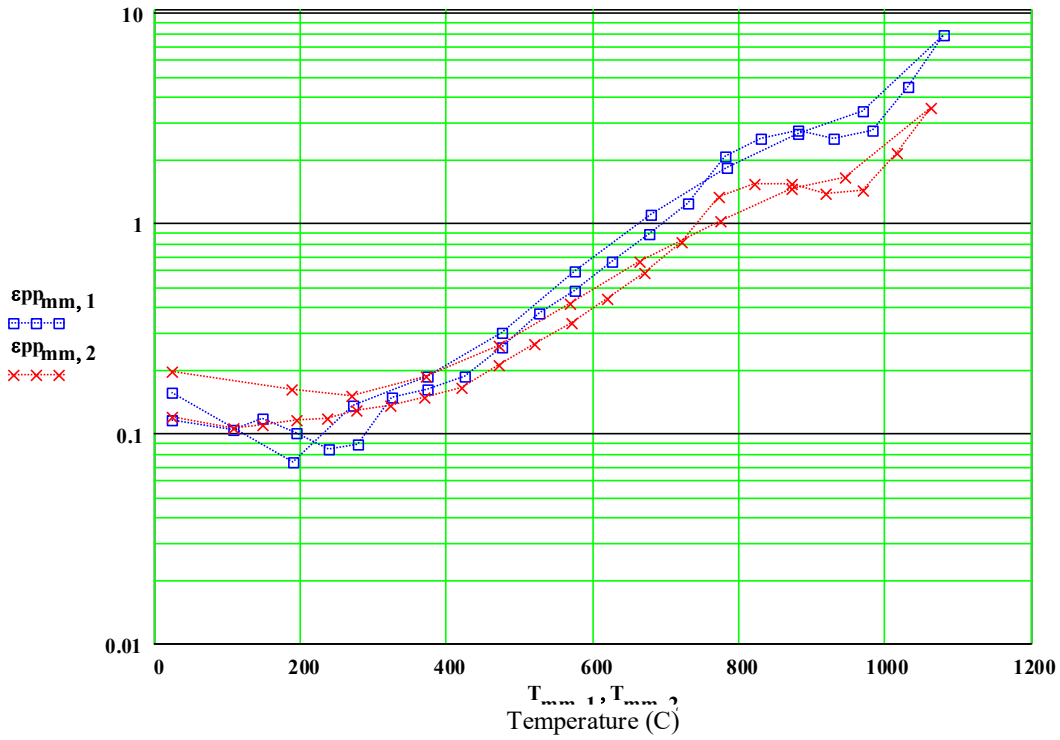
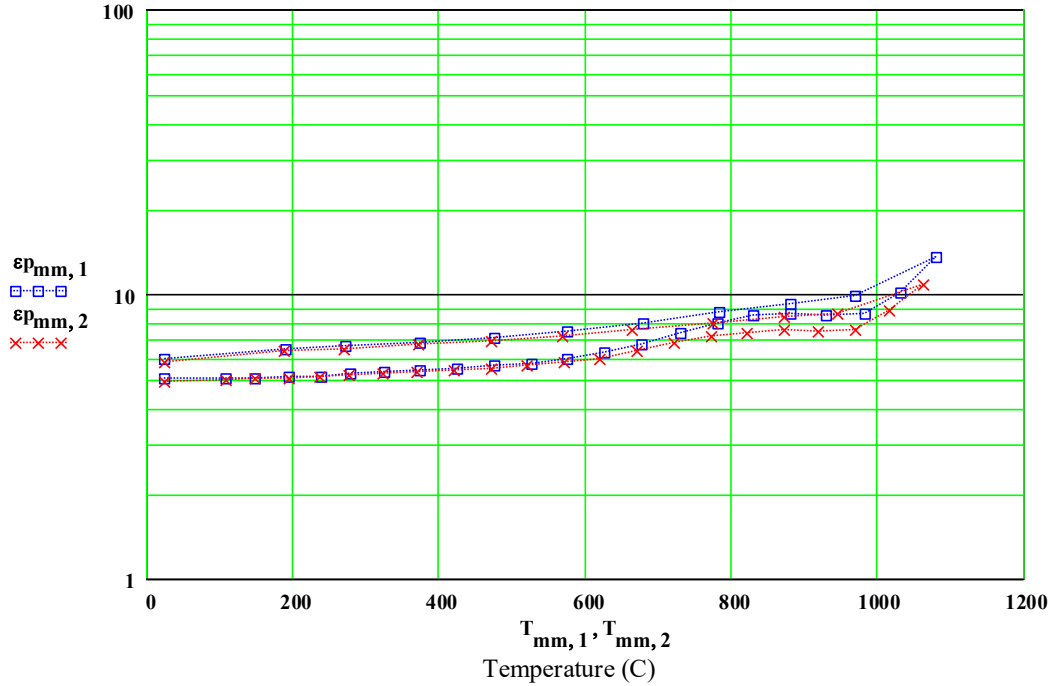
CERL0960A.mcd

AnDat = 20090428

JSC-1 Linar Simulant, First Cycle, RT to 1100C, in flowing UHP argon , Shawn Allen, CERALINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ . Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$

FracMassChange =  $-7.49 \cdot 10^{-3}$        $\alpha_1 = 0$       /C



# Appendix E. MPN Reports

Test = 2009042601

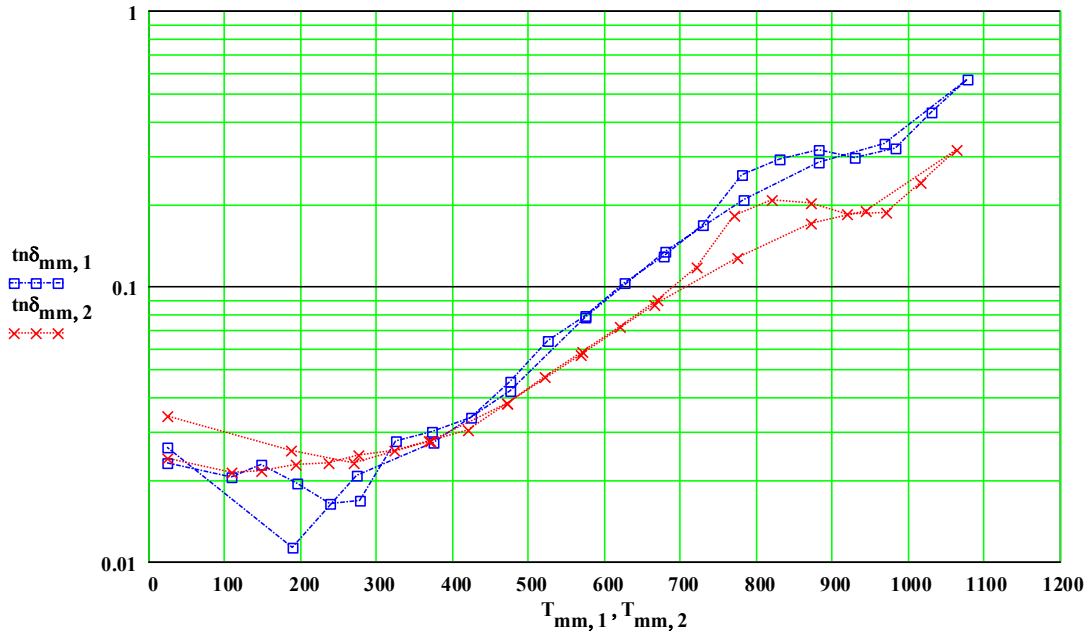
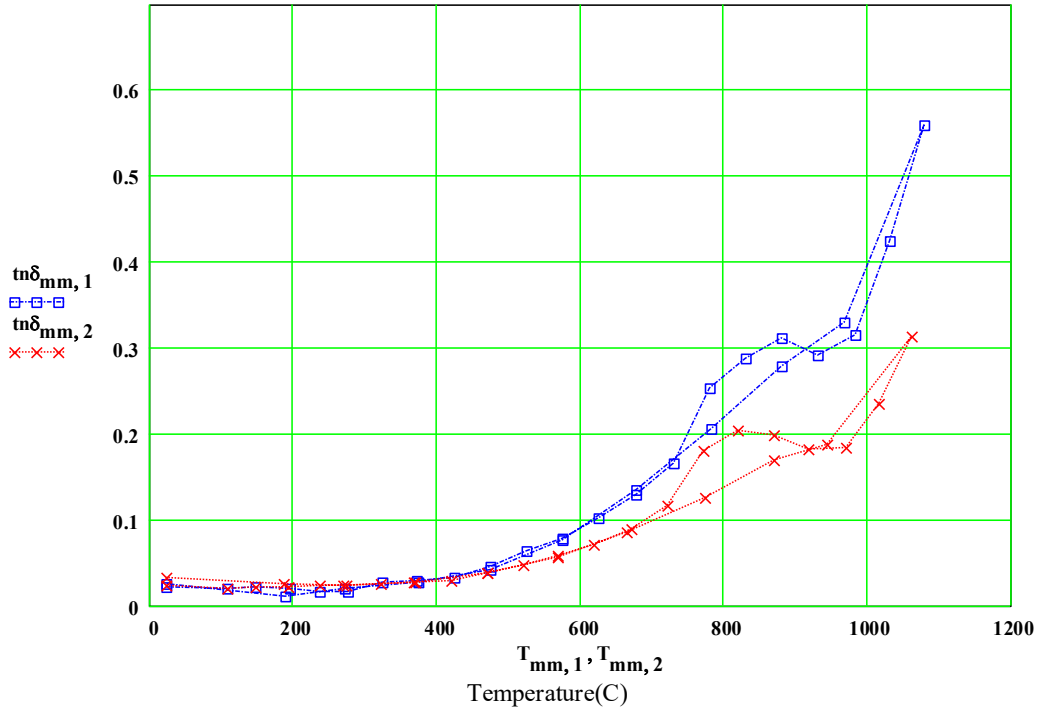
CERL0960A.mcd

AnDat = 20090428

JSC-1 Linear Simulant, First Cycle, RT to 1100C, in flowing UHP argon , Shawn Allen, CERLINK

Initial density =  $\text{sam dns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$



Appendix E. MPN Reports

Test = 2009042601

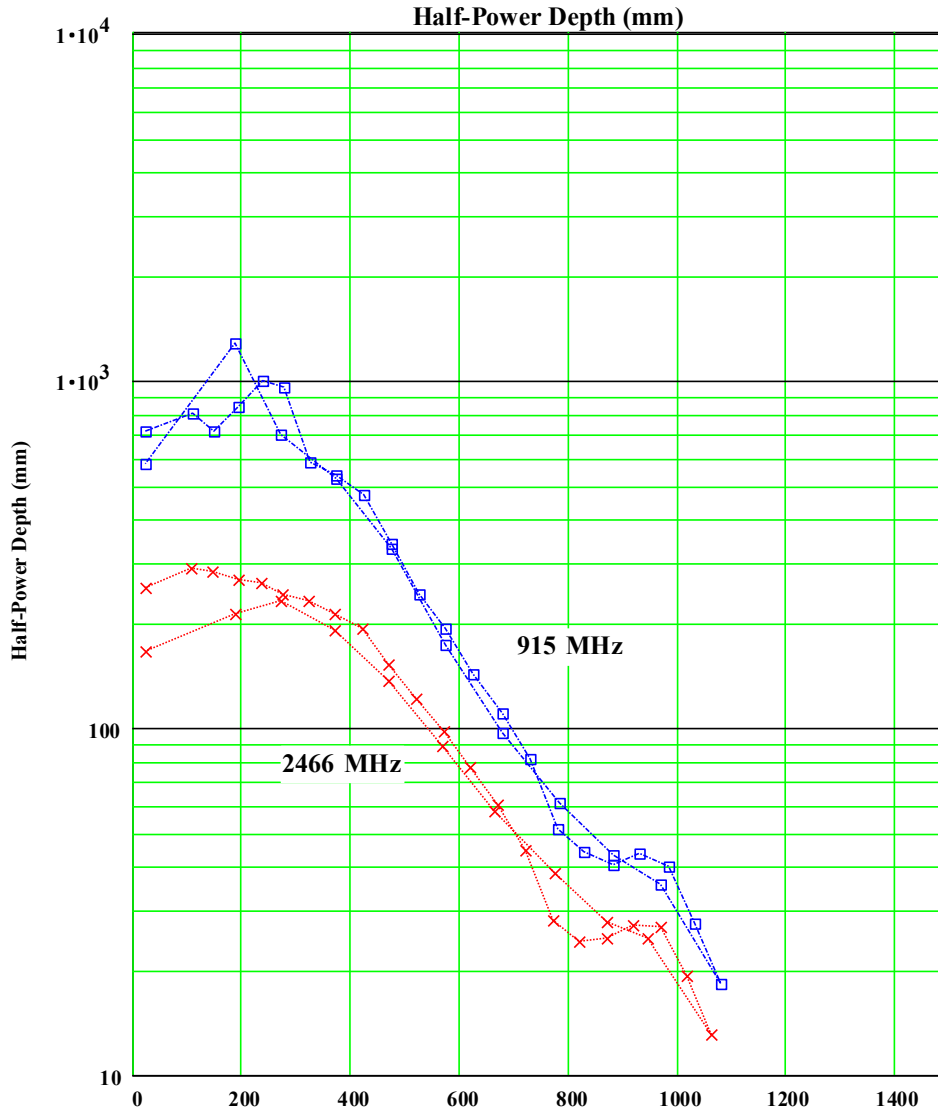
CERL0960A.mcd

AnDat = 20090428

JSC-1 Linar Simulant, First Cycle, RT to 1100C, in flowing UHP argon , Shawn Allen, CERLINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$

$\alpha_1 = 0$  /C



# Appendix E. MPN Reports

Test = 2009042601

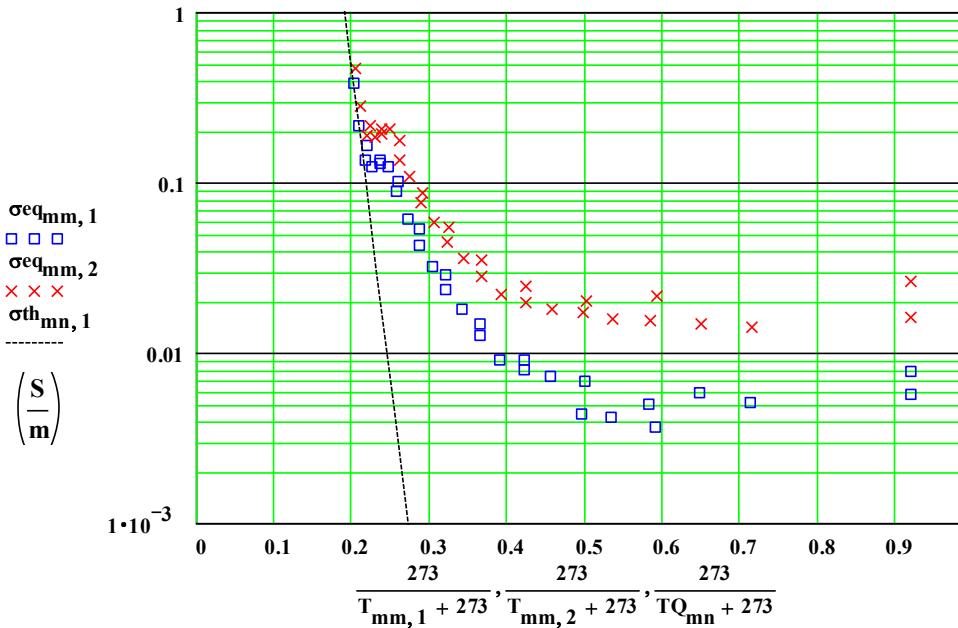
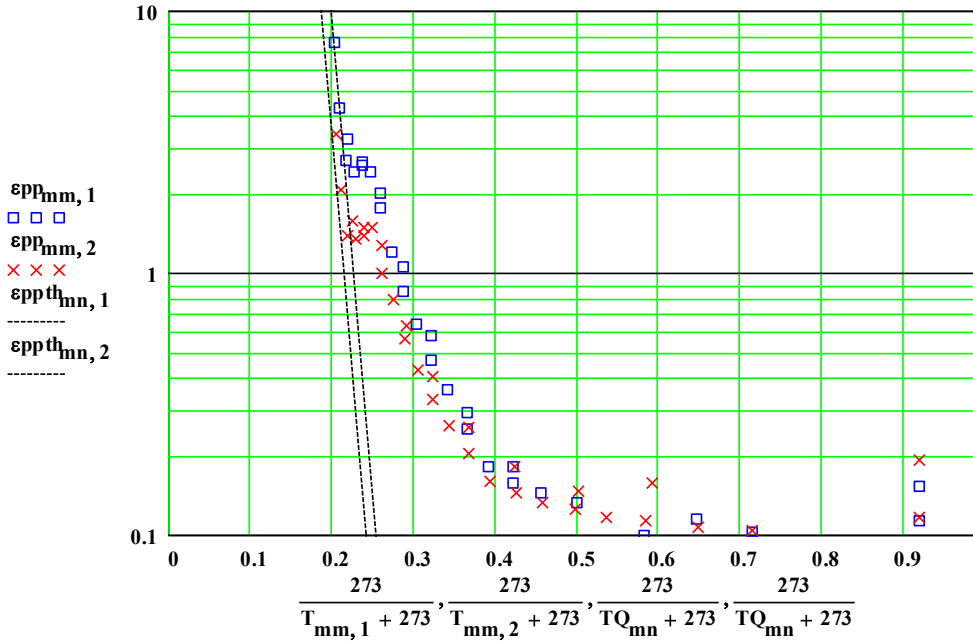
CERL0960A.mcd

AnDat = 20090428

JSC-1 Linear Simulant, RT to 1100C, in flowing UHP argon , Shawn Allen, CERALINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09$  gm/cc, Final density(25C) =  $\text{dnsfinal} = 2.19$  gm/cc

$E_g = 4$  eV  $\sigma_{\text{int}} = 1.2 \cdot 10^7$  Siemens/metre  $\alpha_1 = 0$  /C



Operator: Chose the Functional Dependence, Input the Chosen Values for Eg and the Intrinsic Condu $\sigma_{int}$

$$E_g := 4.0 \quad \text{eV}$$

$$\sigma_{int} := 1.2 \cdot 10^7 \quad \text{Siemens/metre}$$

$$H_{activ} := \frac{E_g}{2} \cdot 96.5 \quad \text{Kjoule/mol}$$

$$m_n := 1..16$$

$$H_{activ} = 193$$

$$k_B := 8.617 \cdot 10^{-5} \quad \text{eV/K}$$

$$\epsilon_{ppth_{mn,n}} := \left[ \frac{\sigma_{int}}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_g}{2 \cdot k_B \cdot (T_{Q_{mn}} + 273.)} \right] \right]$$

$$\sigma_{th_{mn,n}} := \epsilon_{ppth_{mn,n}} \cdot 2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}$$

$$\epsilon_{ppth}_{(16,2)} = 180.57$$

# Appendix E. MPN Reports

Test = 2009042601

CERL0960B.mcd

AnDat = 20090428

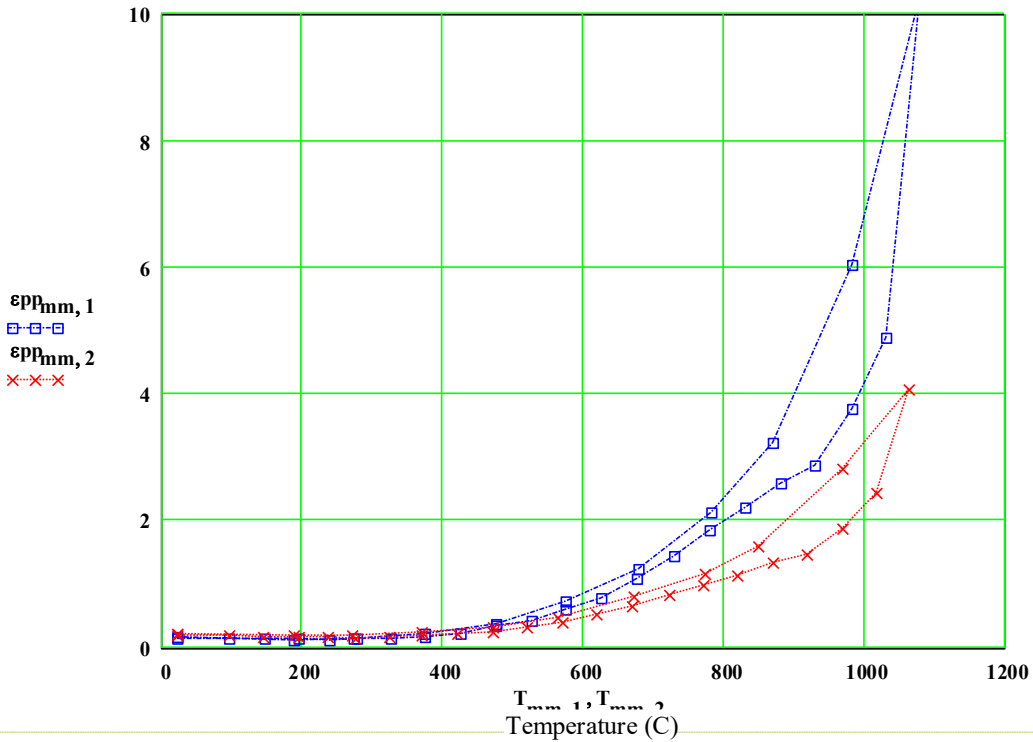
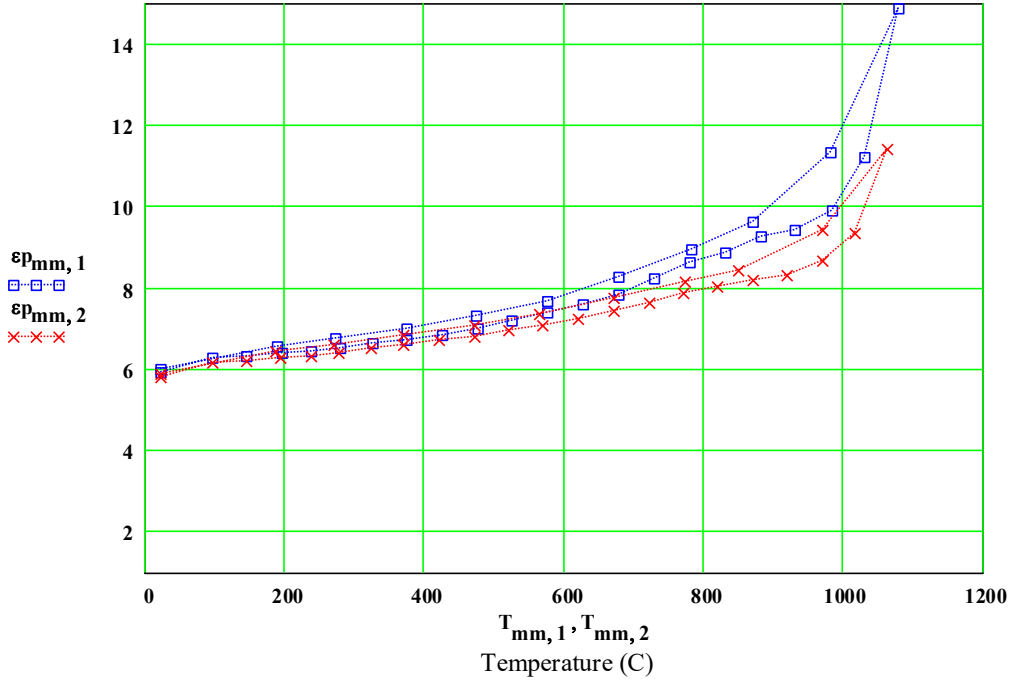
JSC-1 Linear Simulant, 2nd Cycle, RT to 1100C, flowing UHP argon, Shawn Allen, CERALINK

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$

$\text{FracMassChange} = -7.49 \cdot 10^{-3}$

$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2009042601

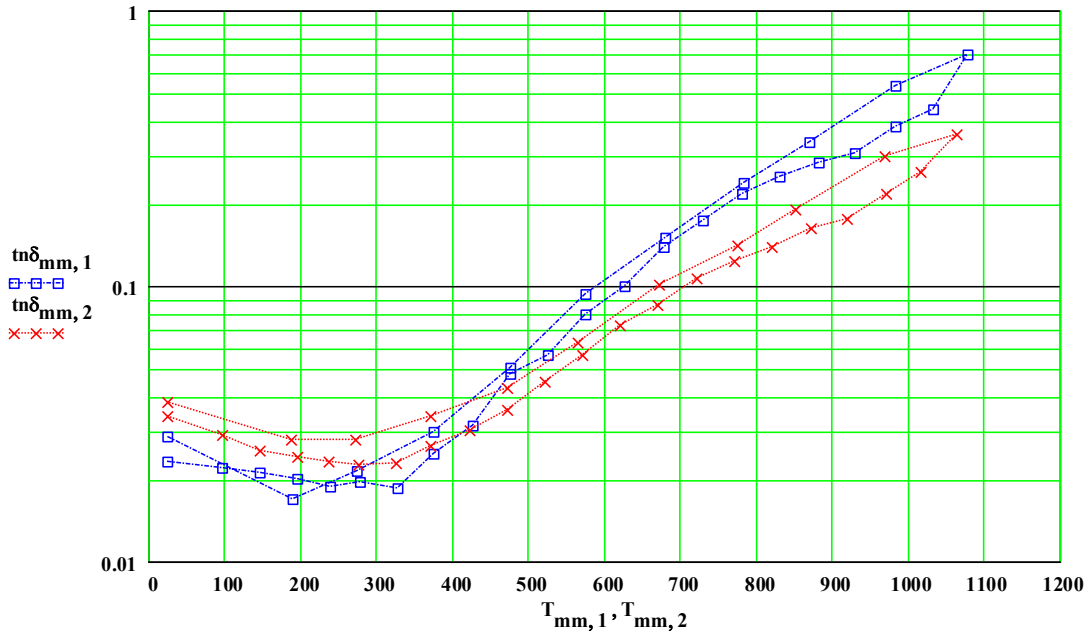
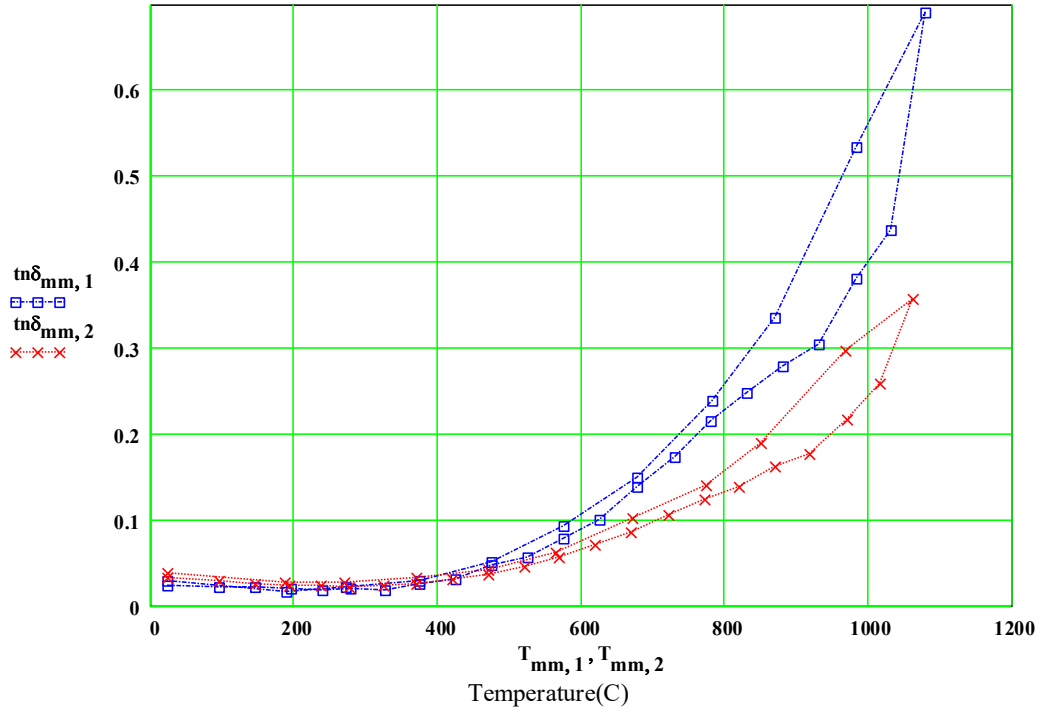
CERL0960B.mcd

AnDat = 20090428

JSC-1 Linear Simulant, 2nd Cycle, RT to 1100C, flowing UHP argon, Shawn Allen, CERALINK

Initial density =  $\text{sam dns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2009042601

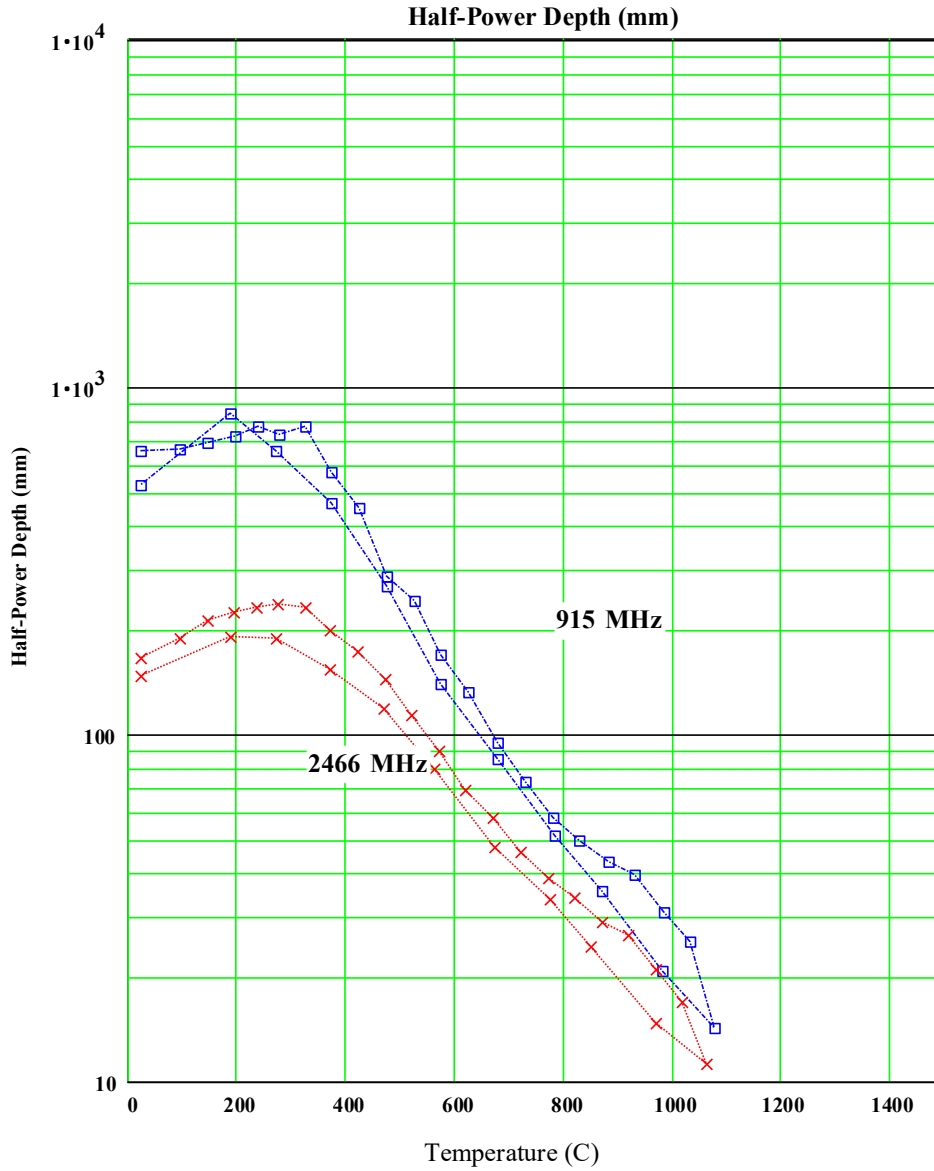
CERL0960B.mcd

AnDat = 20090428

JSC-1 Linar Simulant, 2nd Cycle, RT to 1100C, flowing UHP argon Shawn Allen, CERLINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$

$\alpha_1 = 0 \text{ /C}$



# Appendix E. MPN Reports

Test = 2009042601

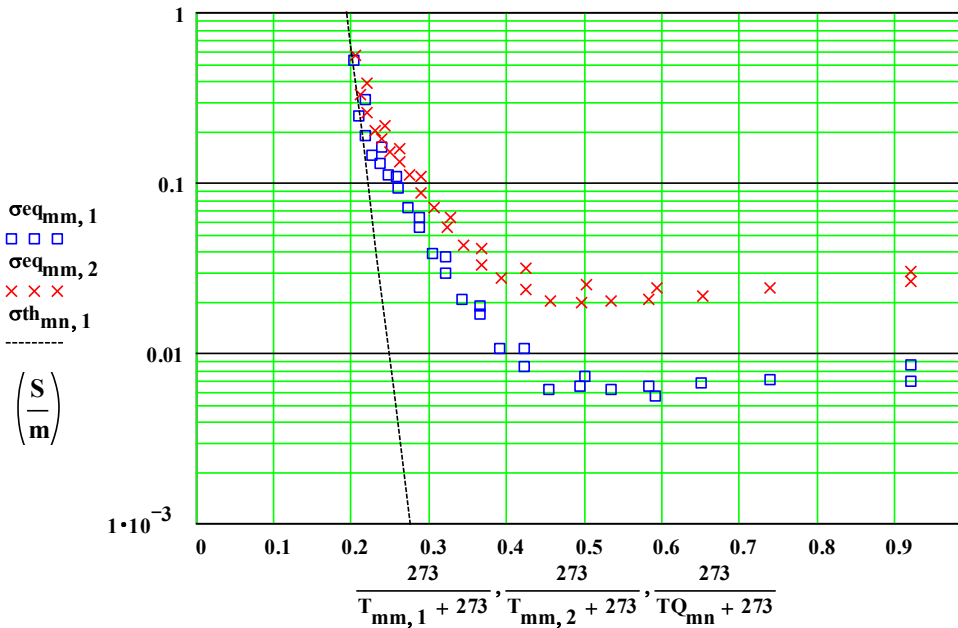
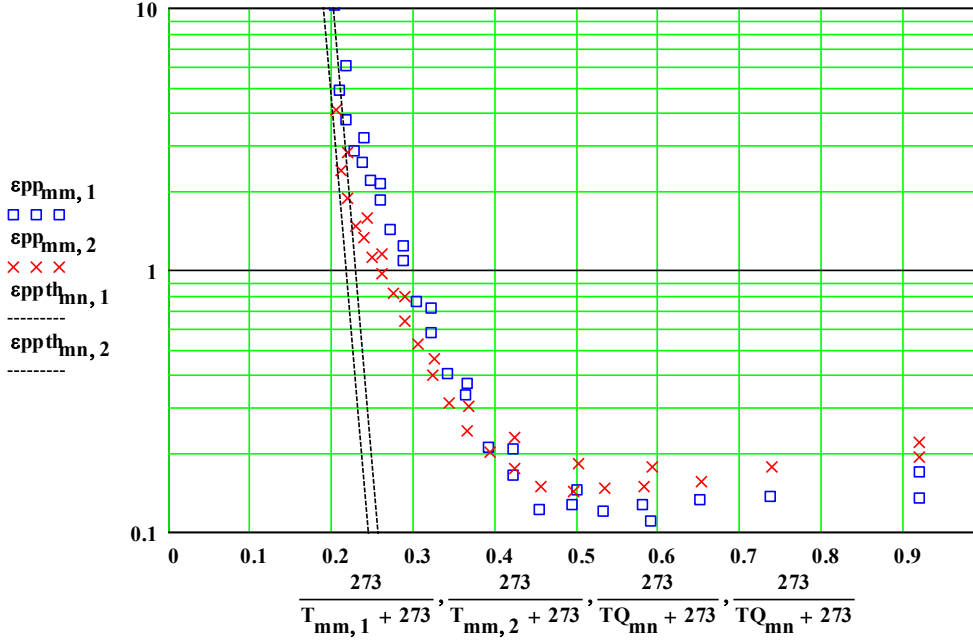
CERL0960B.mcd

AnDat = 20090428

JSC-1 Linear Simulant, 2nd Cycle, RT to 1100C, flowing UHP argon, Shawn Allen, CERLINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09$  gm/cc, Final density(25C) =  $\text{dnsfinal} = 2.19$  gm/cc

$E_g = 4$  eV  $\sigma_{\text{int}} = 1.5 \cdot 10^7$  Siemens/metre  $\alpha_1 = 0$  /C



# Appendix E. MPN Reports

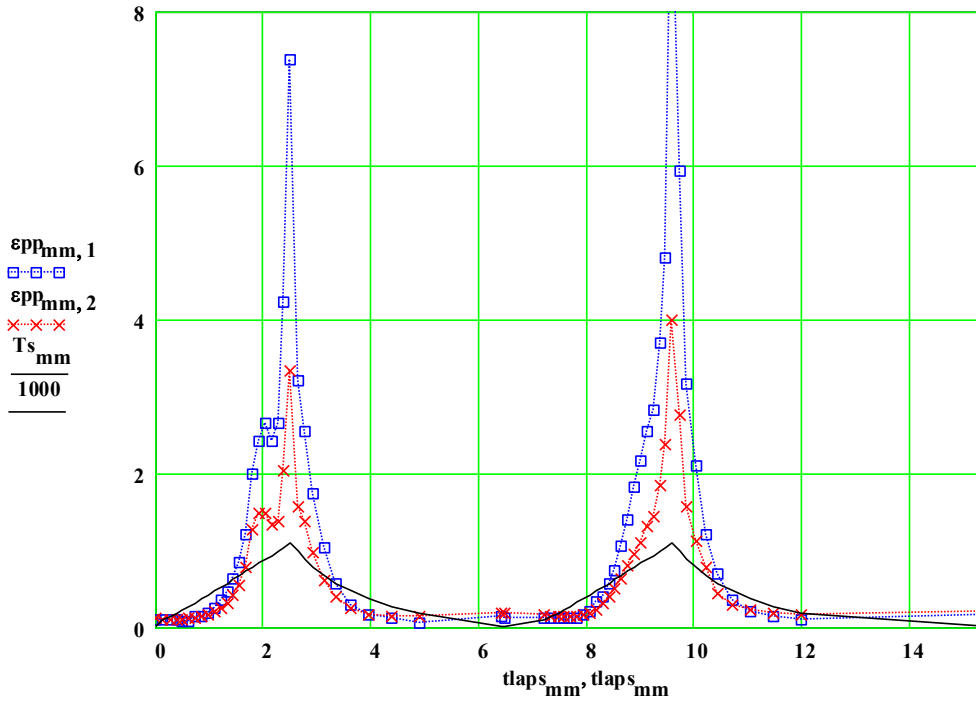
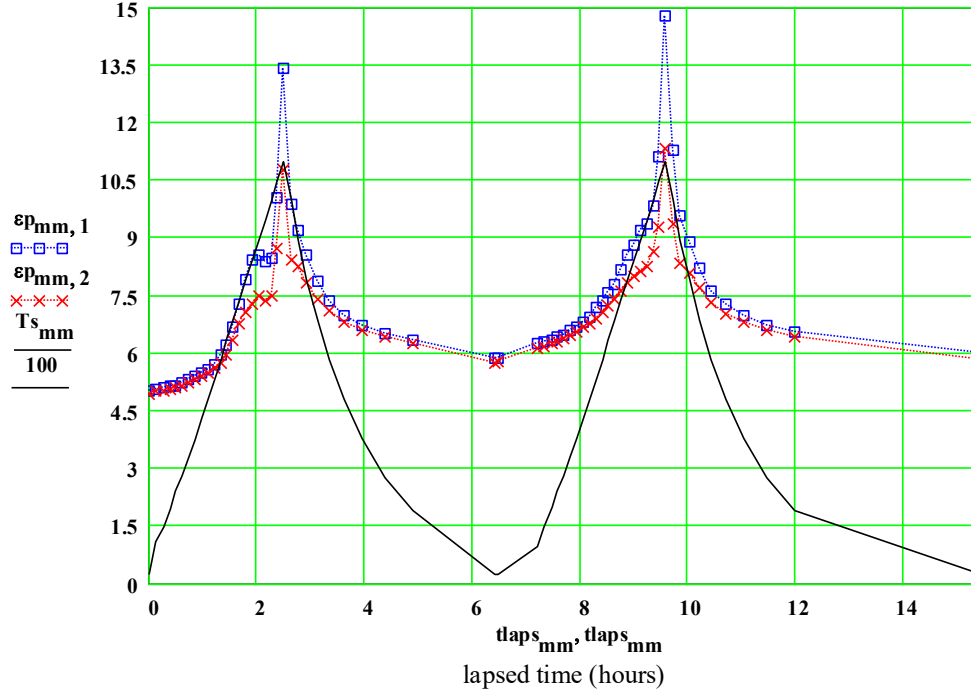
Test = 2009042601

CERL0960.mcd

AnDat = 20090428

JSC-1 Linear Simulant, RT to 1100C, in flowing UHP argon , Shawn Allen, CERALINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.19 \text{ gm/cc}$



Appendix E. MPN Reports

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  and  $\tan\delta$  :

Test = 2009042601

CERL0960A.mcd

AnDat = 20090428

JSC-1 Linear Simulant, First Cycle, RT to 1100C, in flowing UHP argon , Shawn Allen, CERALINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.086$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.186$  gm/cc

samdns	mm	912 MHz				Lapsed	2460 MHz			
		T(degC)	$\epsilon'_{\text{mm},1}$	$\epsilon''_{\text{mm},1}$	$\tan\delta_{\text{mm},1}$	Time(minutes)	T(degC)	$\epsilon'_{\text{mm},2}$	$\epsilon''_{\text{mm},2}$	$\tan\delta_{\text{mm},2}$
2.086	1	24	5.04	0.1146	0.0227	0	24	4.96	0.1178	0.0238
2.086	2	109	5.07	0.1026	0.0202	8	109	5.01	0.1049	0.0209
2.086	3	149	5.1	0.1152	0.0226	15.5	148	5.04	0.1076	0.0213
2.086	4	195	5.14	0.0987	0.0192	22.8	194	5.07	0.1138	0.0224
2.086	5	239	5.15	0.0831	0.0161	30	237	5.12	0.1168	0.0228
2.086	6	278	5.25	0.087	0.0166	37.1	276	5.17	0.1256	0.0243
2.086	7	326	5.34	0.1453	0.0272	44.2	323	5.25	0.133	0.0253
2.086	8	373	5.4	0.1596	0.0296	51.2	370	5.32	0.1451	0.0273
2.086	9	425	5.49	0.1825	0.0333	58.3	421	5.41	0.1617	0.0299
2.086	10	476	5.59	0.253	0.0453	65.4	471	5.49	0.2068	0.0377
2.086	11	526	5.73	0.3612	0.0631	72.4	521	5.6	0.262	0.0468
2.086	12	576	5.96	0.4631	0.0776	79.5	570	5.74	0.3298	0.0575
2.086	13	627	6.24	0.6374	0.1022	86.6	620	5.95	0.4262	0.0716
2.086	14	678	6.67	0.8581	0.1286	93.6	671	6.33	0.5636	0.089
2.086	15	730	7.3	1.2119	0.1661	100.7	722	6.78	0.7889	0.1164
2.108	16	781	7.92	2.0128	0.254	107.8	772	7.09	1.2847	0.1812
2.129	17	831	8.43	2.4358	0.2888	114.8	821	7.31	1.4993	0.205
2.15	18	882	8.6	2.6766	0.3112	121.9	871	7.51	1.4985	0.1995
2.172	19	931	8.42	2.4538	0.2913	129	919	7.42	1.3521	0.1823
2.194	20	984	8.51	2.6882	0.3158	136.1	970	7.54	1.3906	0.1845
2.192	21	1032	10.13	4.2996	0.4246	143.1	1017	8.78	2.0702	0.2358
2.19	22	1079	13.5	7.5632	0.5604	150.2	1063	10.88	3.4016	0.3127
2.188	23	969	9.93	3.2683	0.329	157.8	945	8.5	1.5878	0.1869
2.186	24	882	9.25	2.5877	0.2798	166.4	871	8.3	1.4019	0.1689
2.186	25	783	8.61	1.7707	0.2057	176.1	774	7.87	0.9935	0.1263
2.186	26	680	7.95	1.0658	0.1341	187.5	665	7.46	0.6351	0.0851
2.186	27	576	7.43	0.575	0.0774	201.1	570	7.15	0.4044	0.0565
2.186	28	476	7.03	0.2942	0.0418	217.2	471	6.87	0.2579	0.0376
2.186	29	375	6.78	0.1825	0.0269	237.1	371	6.64	0.182	0.0274
2.186	30	273	6.56	0.1343	0.0205	262.7	271	6.45	0.1476	0.0229
2.186	31	190	6.4	0.0724	0.0113	294.5	188	6.3	0.1587	0.0252
2.186	32	24	5.91	0.1543	0.0261	384.9	24	5.79	0.1943	0.0336

Appendix E. MPN Reports

List of Measured Values of  $\epsilon''$  and  $\epsilon''$  and  $\tan\delta$  :

Test = 2009042601

CERL0960B.mcd

AnDat = 20090428

JSC-1 Linear Simulant, 2nd Cycle, RT to 1100C, in flowing UHP argon , Shawn Allen, CERALINK

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.086$  gm/cc

Final density(25C) =  $\text{dnsfinal} = 2.186$  gm/cc

samdns	mm	912 MHz				Lapsed	2460 MHz			
		T(degC)	$\epsilon''$	$\epsilon''$	$\tan\delta$	Time(minutes)	T(degC)	$\epsilon''$	$\epsilon''$	$\tan\delta$
		$T_{\text{mm},1}$	$\epsilon''_{\text{mm},1}$	$\epsilon''_{\text{mm},1}$	$\tan\delta_{\text{mm},1}$	60-flaps <sub>mm</sub>	$T_{\text{mm},2}$	$\epsilon''_{\text{mm},2}$	$\epsilon''_{\text{mm},2}$	$\tan\delta_{\text{mm},2}$
2.186	33	24	5.92	0.136	0.023	387.9	24	5.8	0.1949	0.0336
2.186	34	97	6.27	0.138	0.022	432.5	96	6.16	0.1766	0.0287
2.186	35	147	6.33	0.1333	0.0211	440.7	146	6.22	0.157	0.0253
2.186	36	197	6.39	0.1274	0.0199	448.1	195	6.27	0.1505	0.024
2.186	37	239	6.45	0.1204	0.0187	455.2	237	6.34	0.1465	0.0231
2.186	38	279	6.51	0.127	0.0195	462.4	277	6.4	0.1436	0.0224
2.186	39	328	6.64	0.1222	0.0184	469.4	325	6.52	0.1486	0.0228
2.186	40	375	6.72	0.1655	0.0246	476.5	371	6.61	0.1742	0.0264
2.186	41	426	6.84	0.2128	0.0311	483.6	422	6.71	0.2021	0.0301
2.186	42	476	6.99	0.3365	0.0481	490.6	472	6.82	0.2432	0.0356
2.186	43	527	7.22	0.4052	0.0561	497.7	522	6.96	0.3121	0.0449
2.186	44	576	7.39	0.5826	0.0788	504.8	570	7.09	0.4002	0.0564
2.186	45	627	7.61	0.7634	0.1003	511.8	620	7.26	0.5211	0.0718
2.186	46	678	7.83	1.0835	0.1383	518.9	671	7.44	0.6378	0.0857
2.186	47	730	8.24	1.429	0.1735	526	722	7.65	0.8134	0.1063
2.186	48	781	8.62	1.8572	0.2153	533	772	7.89	0.9749	0.1236
2.186	49	831	8.87	2.2046	0.2487	540.1	821	8.04	1.1206	0.1394
2.186	50	882	9.27	2.5894	0.2794	547.2	871	8.19	1.3344	0.163
2.186	51	931	9.43	2.8675	0.3041	554.2	919	8.33	1.4697	0.1765
2.186	52	984	9.91	3.771	0.3806	561.3	971	8.7	1.8813	0.2163
2.186	53	1032	11.21	4.9002	0.4371	568.4	1017	9.33	2.4224	0.2596
2.186	54	1079	14.88	10.2868	0.6915	575.4	1063	11.4	4.0729	0.3572
2.186	55	983	11.34	6.0473	0.5332	583.1	970	9.44	2.8083	0.2975
2.186	56	871	9.63	3.2232	0.3347	591.6	851	8.42	1.5909	0.1889
2.186	57	784	8.94	2.1338	0.2387	601.3	775	8.16	1.1521	0.1412
2.186	58	679	8.27	1.2369	0.1496	612.7	672	7.77	0.7908	0.1017
2.186	59	576	7.69	0.7212	0.0938	626.3	564	7.36	0.4583	0.0623
2.186	60	476	7.32	0.3709	0.0507	642.5	471	7.08	0.3015	0.0426
2.186	61	375	7.02	0.2086	0.0297	662.3	372	6.84	0.2295	0.0336
2.186	62	274	6.77	0.1453	0.0215	687.8	271	6.62	0.1837	0.0278
2.186	63	190	6.57	0.1109	0.0169	719.6	188	6.44	0.1784	0.0277
2.186	64	24	6.01	0.1706	0.0284	926.9	24	5.88	0.2222	0.0378

MPN-241\_Shulman\_4\_Merriam Crater Basalt

Nov. 26, 2021

Merriam Crater Basalt  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1100°C, in < 1 milli Torr Vacuum

Dr. Holly Shulman ( Shulman LLC) again requested that Microwave Properties North measure the complex dielectric properties of Merriam Crater Basalt powder, up to 1100C with a direct, uninterrupted, temperature cycle, in as good a vacuum as we could produce in the MPN system. The powder sample material arrived at MPN on Nov. 12/ 2021.

MPN pressed pellets of the powder material in a uniaxial press. The press pressure of ~ 32 ,000 psi was sufficient to produce pellets that could be handled. This produced pellets of a density of ~ 2.10 g/cc . The pellets were not baked to ensure dryness, but the measurement run cycled up to 200C, soaked for 1 hour, then measured again at room temperature and went through the cycle. There appeared to have been very little moisture!

MPN was requested to cycle the sample directly up to 1100C and then return to room temperature (RT) , ) in as good a vacuum as we could produce in the MPN system.

The initial sample parameters were:

- a) diameter 3.63 +- 0.05 mm
- b) length 12.41 +- 0.1 mm
- c) mass 0.270+- 0.002 gm
- dd) room temperature density  $2.10 \pm 0.10$  gm/cc.
- ee) appearance - three (stacked) dark grey/brown pellets .

The dielectric properties measurements were performed at RT and then up to 200C, with a 1 hour soak at 200C. The temperature was brought back to RT, and the temperature was ramped up to 1100C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus and the final sample was weighed. The empty sample holder was then run up to 1000C in +200 steps to measure background and check for contamination ( there was none.).

The final sample properties, at room temperature were :

- a) diameter  $3.59 \pm 0.05$  mm
- b) length  $12.31 \pm 0.1$  mm
- c) mass  $0.271 \pm 0.002$  gm
- cc) room temperature density  $2.17 \pm 0.10$  gm/cc.
- dd) appearance - three dark grey/brown pellets

Note: The percent mass loss was zero ( +- 1 %).

The frequency coding is :

Legend for Data Plots :

#	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line

6

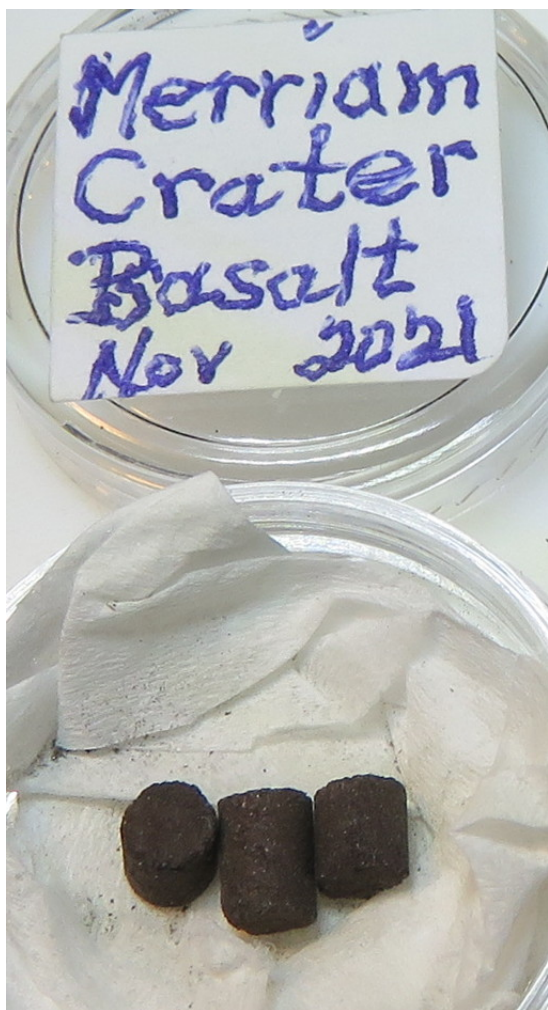
2986

black diamond, dotted line

Comments on the data analysis:

A thermal expansion coefficient (CTE) of  $0.0 \times 10^{-6}/\text{C}$  was used.

The data for the ramp up to 1100C shows evidence of a phase transition at  $\sim 750\text{C}$ . This produced an irreversible change in the material, although there was no mass loss!



Final Pellets after run to 1100C in Vacuum.



Final Pellets after run to 1100C in Vacuum.

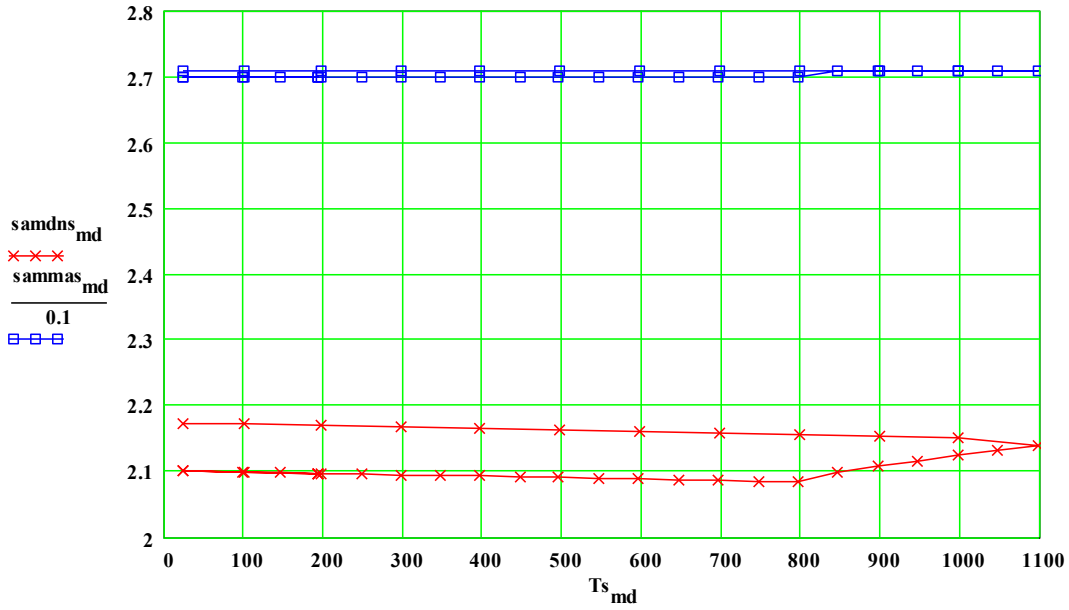
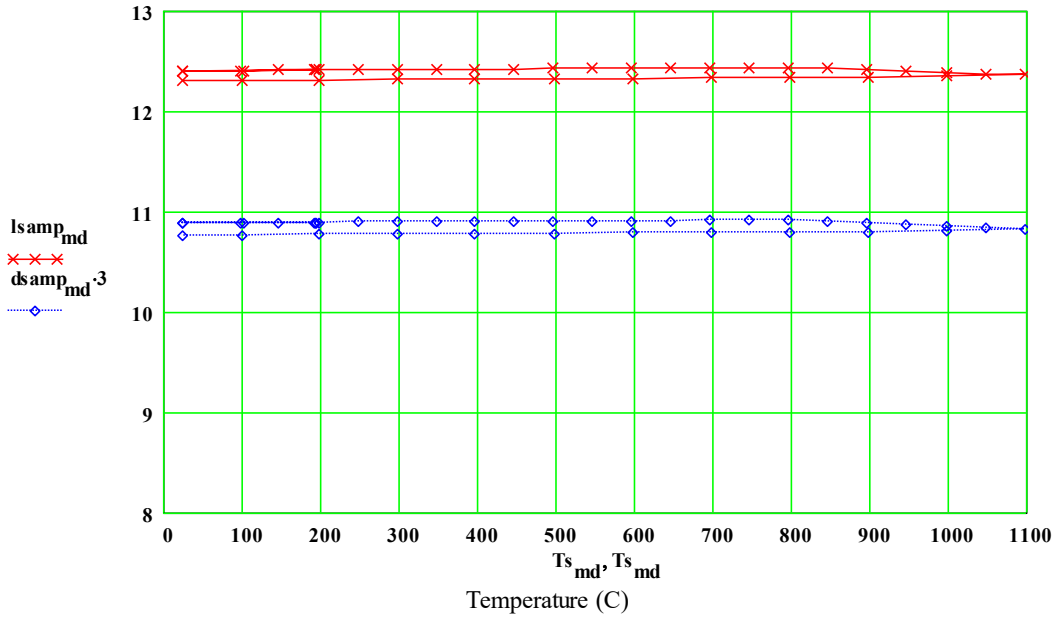
# Appendix E. MPN Reports

Test = 2021112401

SHUL2179\_CalModLowCa.mcd

AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 millTorr vacuum, for Holly Shulman LLC  
 Assumed Effective Dimensions (mm) and Density (gm/cc) as a Function of Temperature for Solid



# Appendix E. MPN Reports

Test = 2021112401

SHUL2179\_CalModLowCal.med

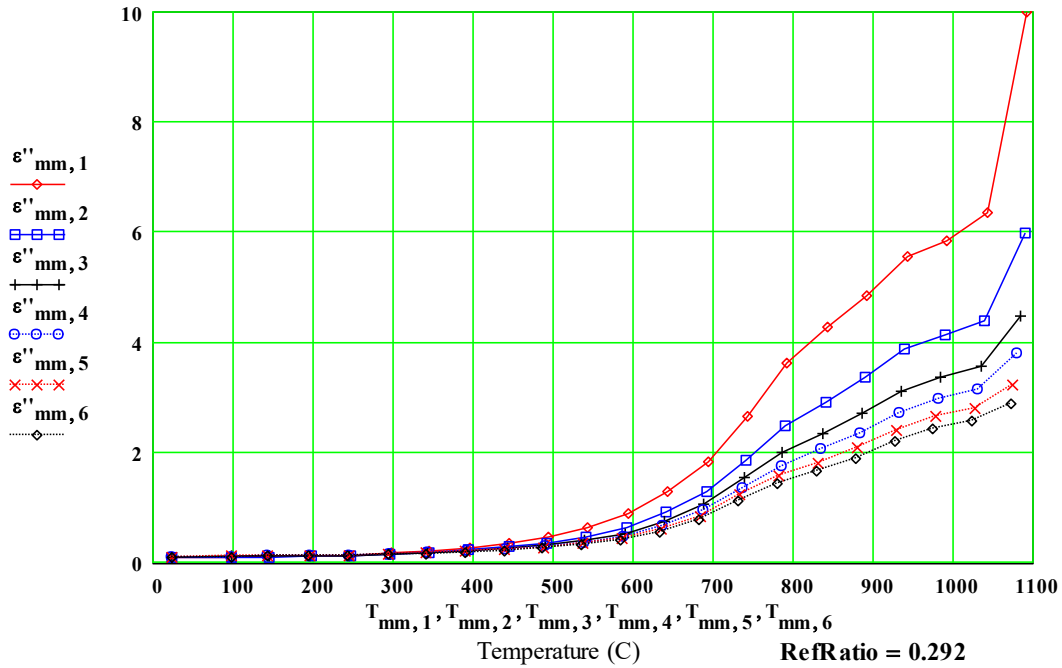
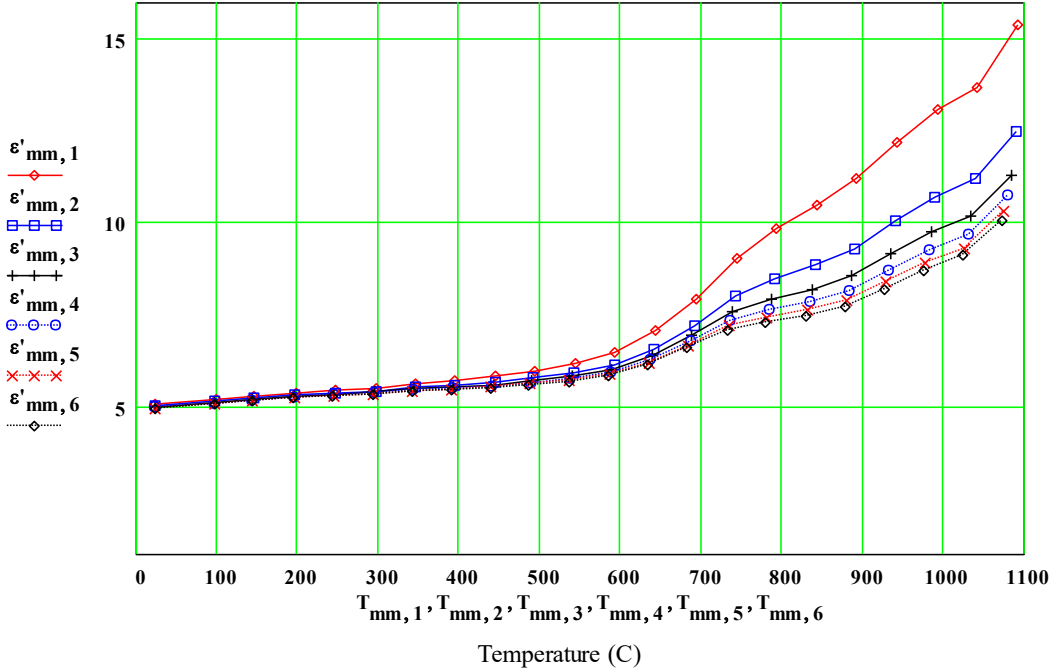
AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.17 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1.004



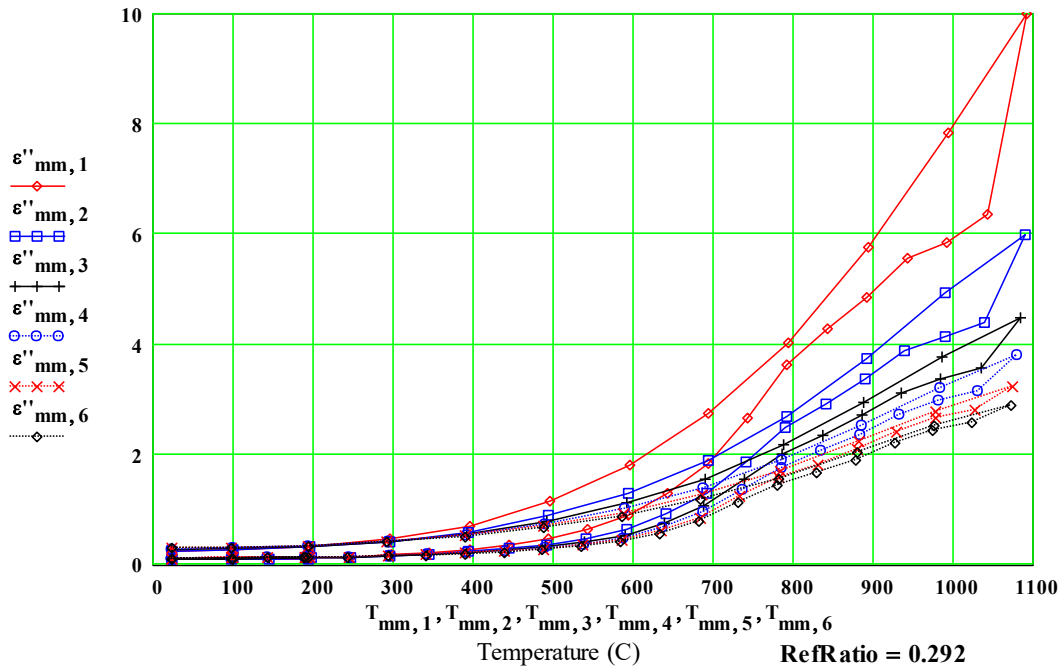
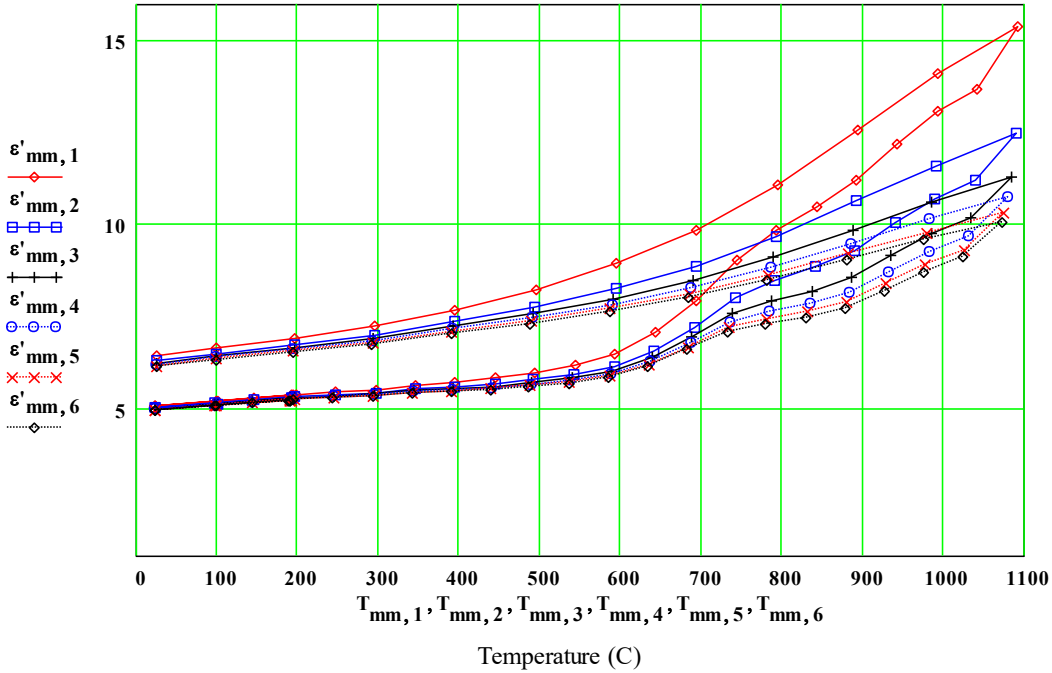
Values for the Temperature Cycle (to 1100 C and back to RT) :

Test = 2021112401                      SHUL2179\_CalModLowCal.med                      AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ ,                      Final density(25C) =  $\text{dnsfinal} = 2.17 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1.004



# Appendix E. MPN Reports

Test = 2021112401

SHUL2179\_CalModLowCal.mcd

AnDat = 20211126

T

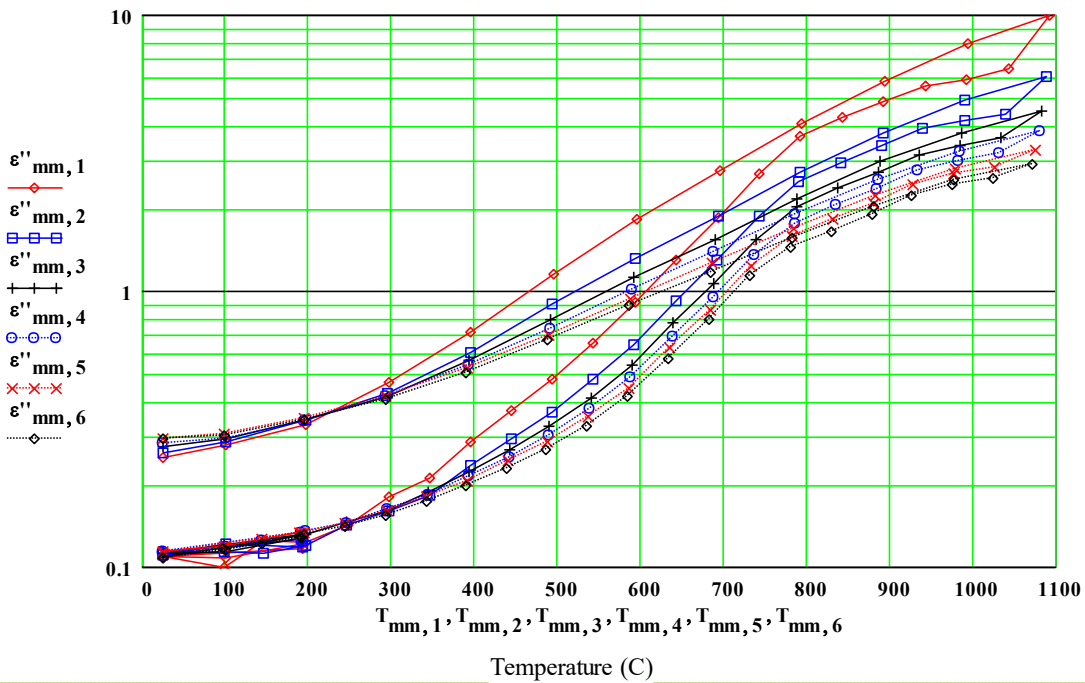
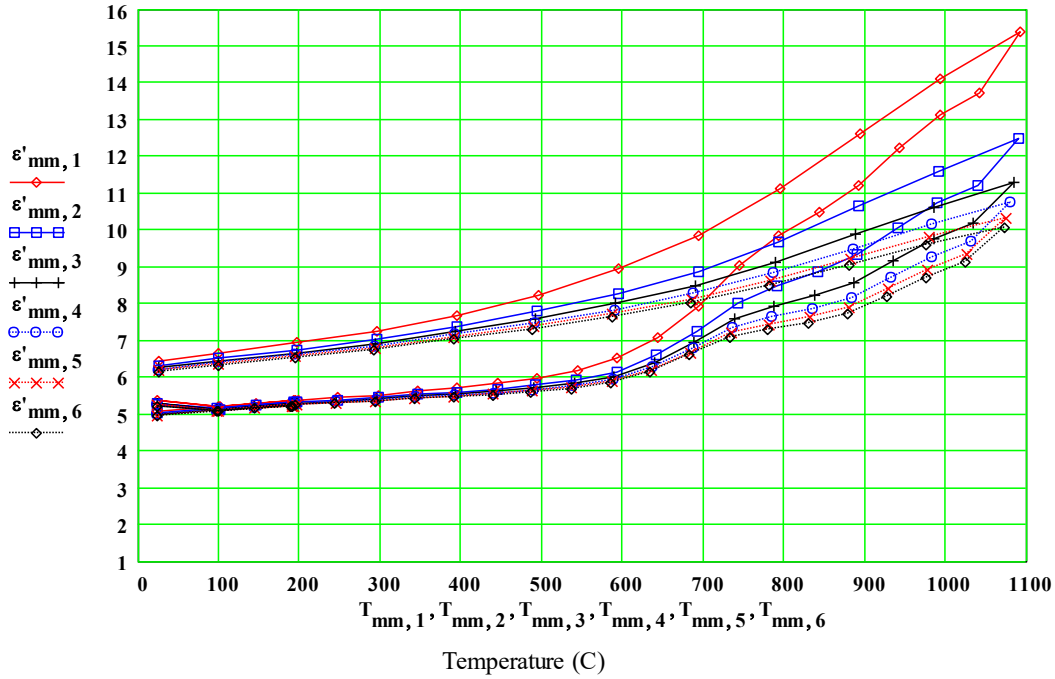
Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.17 \text{ gm/cc}$

It

FracMassChange = 1       $\alpha_1 = 3.5 \cdot 10^{-6} \text{ /C}$        $\alpha_2 = 0 \text{ /C}$

F



# Appendix E. MPN Reports

Test = 2021112401

SHUL2179\_CalModLowCal.mcd

AnDat = 20211126

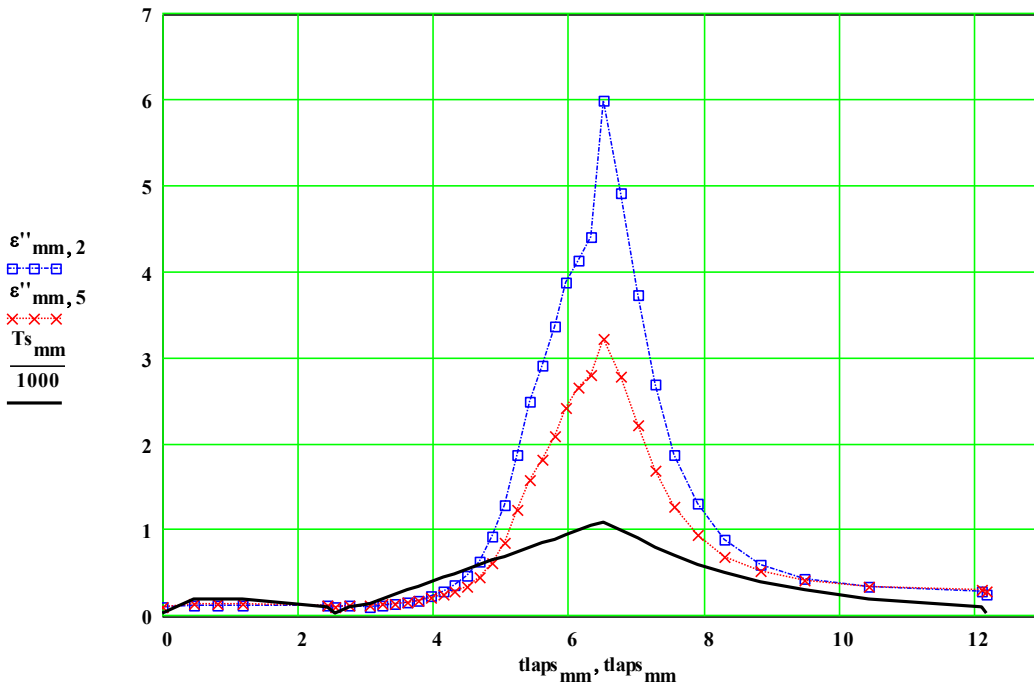
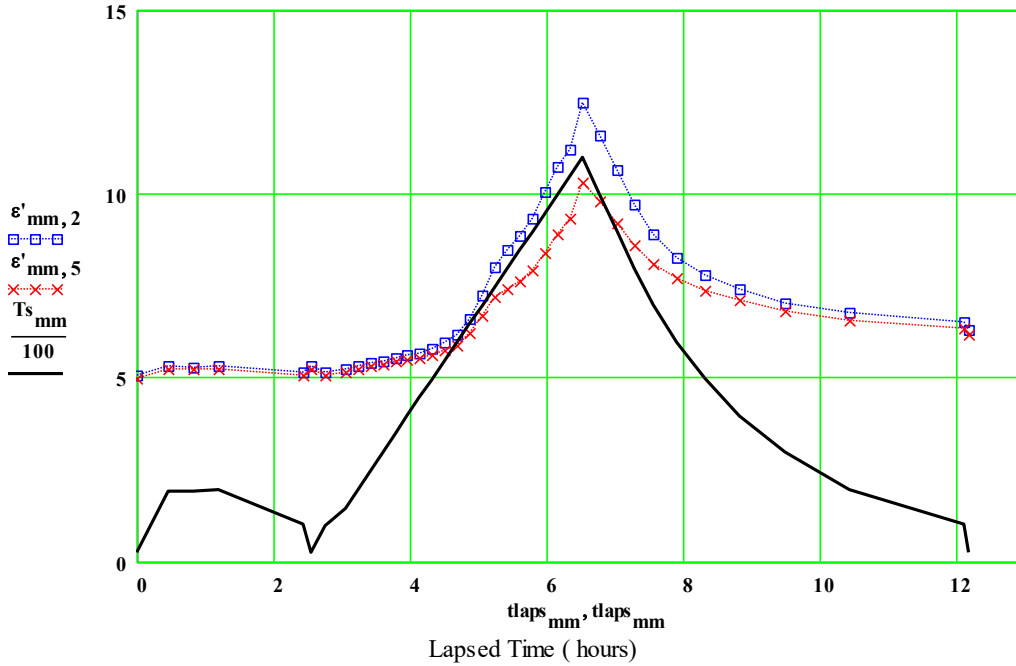
Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.17 \text{ gm/cc}$       **FracMassChange = 1**

$\alpha_1 = 3.5 \cdot 10^{-6}$



# Appendix E. MPN Reports

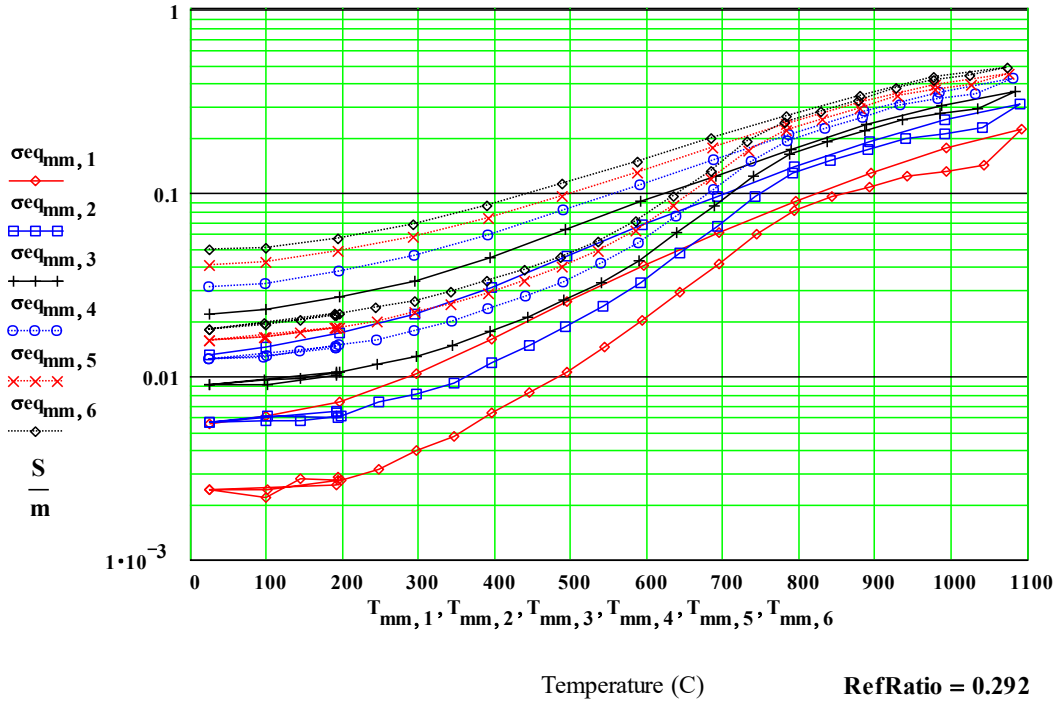
Test = 2021112401

SHUL2179\_CalModLowCal.mcd

AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

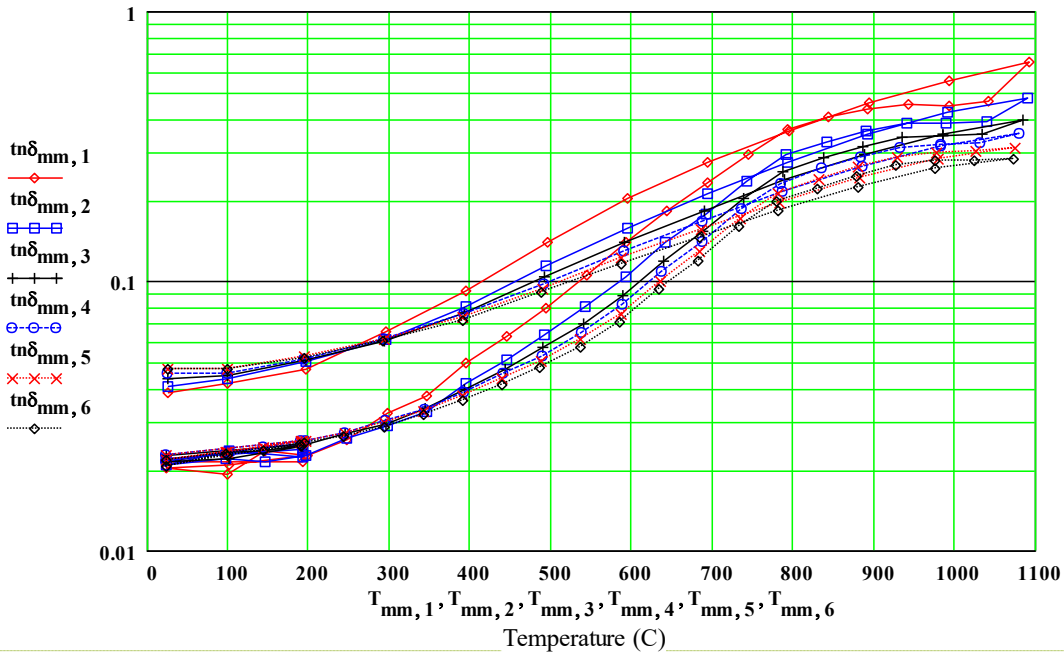
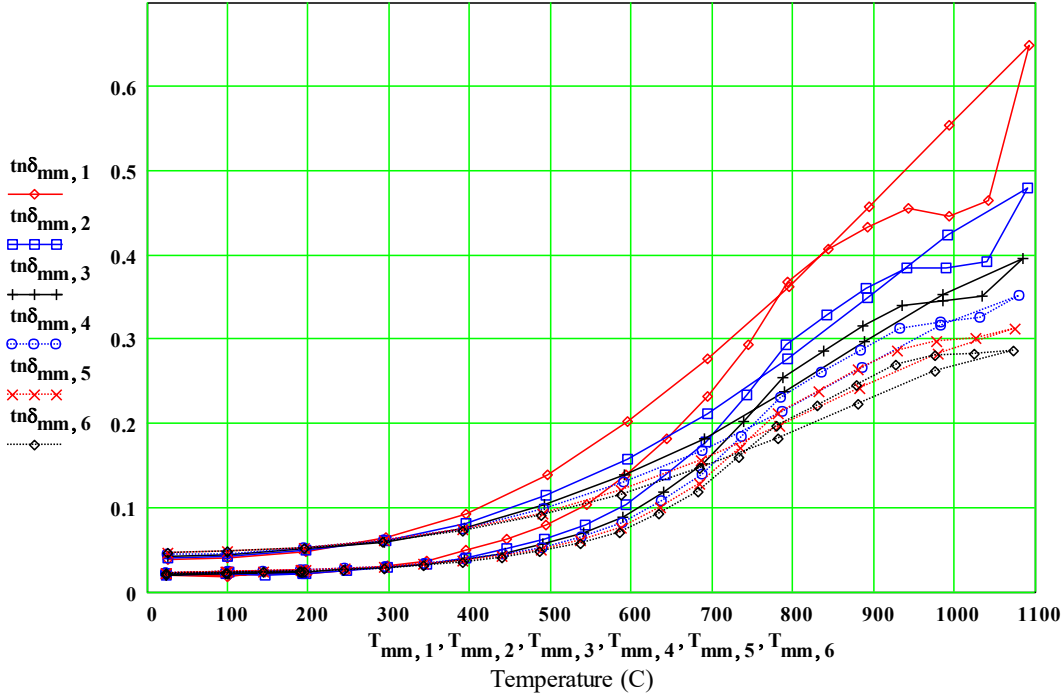
Test = 2021112401

SHUL2179\_CalModLowCal.mcd

AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.17 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

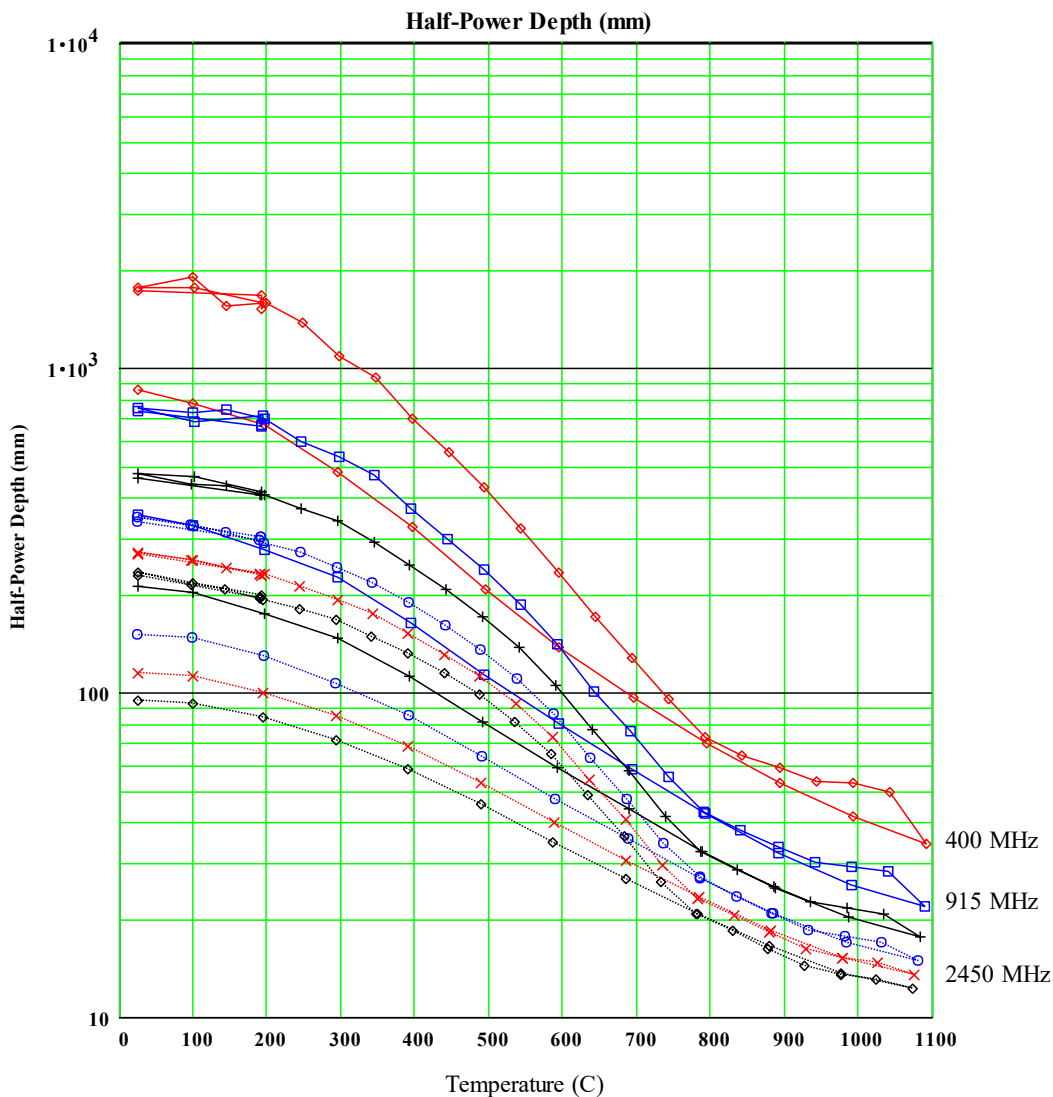
$$D_{\text{halfP}}(\text{mm}, n) := \left(\frac{\ln(2)}{2}\right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2021112401

SHUL2179\_CalModLowCal.mcd

AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC



# Appendix E. MPN Reports

Test = 2021112401

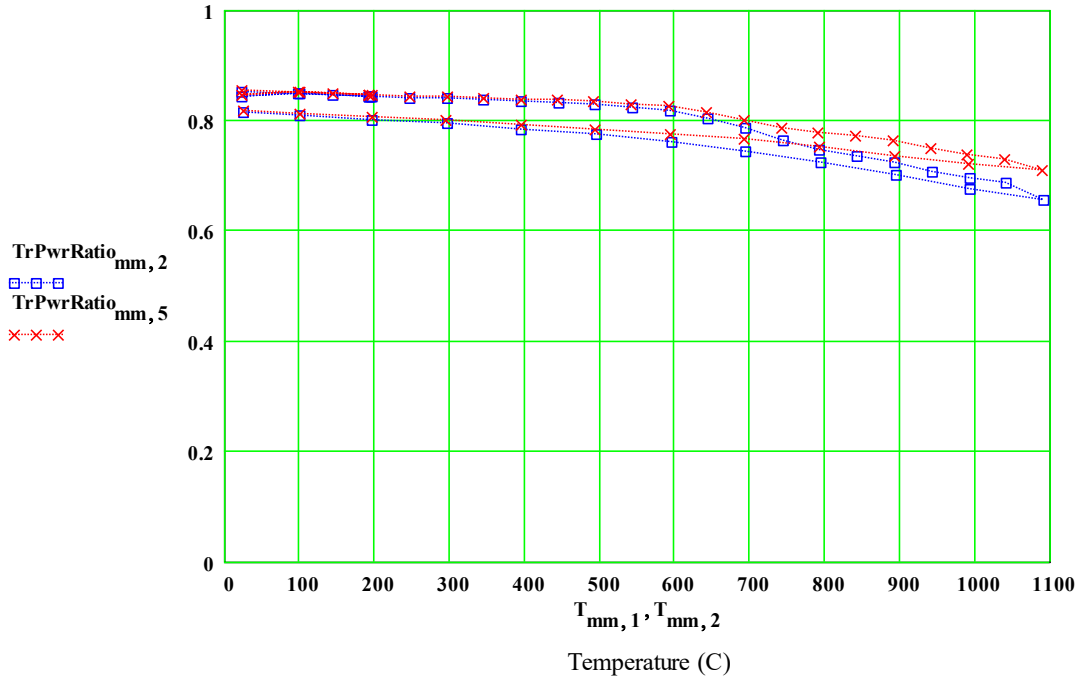
SHUL2179\_CalModLowCal.med

AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.17 \text{ gm/cc}$

Ratio of the Power Transmitted through the interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material - The power transmission coefficient as a function of temperature.



## Appendix E. MPN Reports

Test = 2021112401

SHUL2179\_CalModLowCal.mcd

AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milliTorr vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

^^

Initial density = **samdns**<sub>N<sub>Cal</sub> + 1</sub> = **2.102** gm/cc      Final density(25C) = **dnsfinal** = **2.175** gm/cc

Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz 2466MHz 2986MHz

Time

(hours)

samdns <sub>mm</sub>	T <sub>mm,1</sub>	$\epsilon'$ <sub>mm,1</sub>	$\epsilon'$ <sub>mm,2</sub>	$\epsilon'$ <sub>mm,3</sub>	$\epsilon'$ <sub>mm,4</sub>	$\epsilon'$ <sub>mm,5</sub>	$\epsilon'$ <sub>mm,6</sub>	tlaps <sub>mm</sub>	sammas <sub>mm</sub>	
2.102	9	24	5.1	5.05	5.02	4.99	4.98	4.97	0	0.27
2.099	10	192	5.4	5.32	5.29	5.26	5.24	5.23	0.46	0.27
2.099	11	193	5.36	5.3	5.27	5.25	5.23	5.22	0.82	0.27
2.099	12	193	5.37	5.31	5.28	5.25	5.23	5.22	1.19	0.27
2.101	13	101	5.21	5.15	5.12	5.1	5.09	5.08	2.43	0.27
2.102	14	24	5.09	5.04	5.01	4.99	4.98	4.97	2.56	0.27
2.101	15	98	5.21	5.16	5.12	5.1	5.09	5.08	2.75	0.27
2.1	16	145	5.31	5.24	5.21	5.18	5.17	5.16	3.06	0.27
2.098	17	197	5.4	5.33	5.3	5.27	5.25	5.24	3.25	0.27
2.097	18	247	5.46	5.39	5.36	5.33	5.31	5.3	3.43	0.27
2.096	19	297	5.53	5.45	5.41	5.38	5.36	5.35	3.61	0.27
2.095	20	346	5.64	5.54	5.5	5.46	5.44	5.42	3.78	0.27
2.094	21	395	5.73	5.61	5.56	5.51	5.49	5.47	3.96	0.27
2.093	22	445	5.84	5.68	5.62	5.57	5.54	5.52	4.14	0.27
2.092	23	493	5.99	5.8	5.72	5.67	5.63	5.6	4.32	0.27
2.091	24	543	6.2	5.95	5.85	5.78	5.74	5.71	4.5	0.27
2.09	25	593	6.51	6.17	6.04	5.95	5.89	5.86	4.68	0.27
2.089	26	643	7.09	6.6	6.41	6.29	6.21	6.15	4.87	0.27
2.088	27	693	7.93	7.23	6.96	6.79	6.68	6.61	5.05	0.27
2.086	28	744	9.05	8.01	7.6	7.37	7.2	7.11	5.23	0.27
2.085	29	793	9.85	8.48	7.93	7.63	7.43	7.31	5.41	0.27
2.101	30	843	10.51	8.87	8.22	7.87	7.63	7.49	5.6	0.271
2.109	31	893	11.23	9.33	8.57	8.18	7.91	7.75	5.78	0.271
2.117	32	942	12.22	10.06	9.17	8.72	8.4	8.22	5.97	0.271
2.125	33	992	13.11	10.73	9.76	9.26	8.91	8.71	6.15	0.271
2.133	34	1042	13.71	11.22	10.21	9.68	9.32	9.12	6.33	0.271
2.141	35	1092	15.39	12.49	11.29	10.75	10.31	10.09	6.52	0.271
2.153	36	994	14.12	11.61	10.63	10.15	9.8	9.61	6.77	0.271
2.155	37	894	12.6	10.66	9.88	9.49	9.2	9.04	7.03	0.271
2.157	38	794	11.11	9.7	9.14	8.83	8.62	8.5	7.29	0.271
2.16	39	695	9.85	8.89	8.5	8.28	8.11	8.02	7.56	0.271
2.162	40	595	8.97	8.28	8.01	7.83	7.71	7.64	7.9	0.271
2.164	41	495	8.24	7.79	7.6	7.48	7.38	7.33	8.31	0.271
2.166	42	395	7.7	7.4	7.27	7.17	7.1	7.05	8.82	0.271
2.169	43	296	7.25	7.03	6.93	6.85	6.8	6.77	9.48	0.271
2.171	44	196	6.94	6.76	6.68	6.61	6.57	6.54	10.42	0.271
2.173	45	100	6.65	6.51	6.45	6.4	6.36	6.33	12.1	0.271
2.175	46	24	6.45	6.33	6.26	6.21	6.18	6.15	12.17	0.271

Appendix E. MPN Reports

Test = 2021112401

SHUL2179\_CaModLowCa.lmcd

AnDat = 20211126

Merriam Crater Basalt, three pellets, RT to 1100C, in < 1 milli Torr vacuum, for Holly Shulman LLC

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ^^^

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.102$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.175$  gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz  
 Lapsed Time (hours)

samdns <sub>mmmm</sub>	T <sub>mm,1</sub>	$\epsilon''_{\text{mm},1}$	$\epsilon''_{\text{mm},2}$	$\epsilon''_{\text{mm},3}$	$\epsilon''_{\text{mm},4}$	$\epsilon''_{\text{mm},5}$	$\epsilon''_{\text{mm},6}$	tlaps <sub>mm</sub>	sammas <sub>mm</sub>	
2.102	9	24	0.109	0.111	0.113	0.114	0.113	0.108	0	0.27
2.099	10	192	0.116	0.127	0.132	0.133	0.133	0.13	0.46	0.27
2.099	11	193	0.128	0.125	0.131	0.129	0.132	0.129	0.82	0.27
2.099	12	193	0.122	0.118	0.129	0.13	0.134	0.128	1.19	0.27
2.101	13	101	0.109	0.121	0.113	0.119	0.119	0.115	2.43	0.27
2.102	14	24	0.11	0.111	0.113	0.113	0.114	0.108	2.56	0.27
2.101	15	98	0.1	0.114	0.12	0.117	0.119	0.117	2.75	0.27
2.1	16	145	0.124	0.112	0.123	0.125	0.126	0.122	3.06	0.27
2.098	17	197	0.122	0.121	0.132	0.135	0.134	0.132	3.25	0.27
2.097	18	247	0.141	0.142	0.146	0.145	0.145	0.141	3.43	0.27
2.096	19	297	0.18	0.159	0.16	0.163	0.161	0.154	3.61	0.27
2.095	20	346	0.212	0.182	0.187	0.182	0.179	0.174	3.78	0.27
2.094	21	395	0.286	0.234	0.22	0.213	0.206	0.197	3.96	0.27
2.093	22	445	0.368	0.291	0.265	0.251	0.242	0.227	4.14	0.27
2.092	23	493	0.478	0.366	0.325	0.299	0.284	0.267	4.32	0.27
2.091	24	543	0.652	0.478	0.409	0.374	0.349	0.326	4.5	0.27
2.09	25	593	0.912	0.642	0.539	0.485	0.445	0.414	4.68	0.27
2.089	26	643	1.3	0.926	0.767	0.681	0.62	0.572	4.87	0.27
2.088	27	693	1.846	1.291	1.068	0.944	0.856	0.787	5.05	0.27
2.086	28	744	2.661	1.879	1.543	1.357	1.23	1.14	5.23	0.27
2.085	29	793	3.627	2.498	2.021	1.759	1.577	1.44	5.41	0.27
2.101	30	843	4.287	2.919	2.354	2.054	1.818	1.654	5.6	0.271
2.109	31	893	4.864	3.362	2.707	2.347	2.089	1.909	5.78	0.271
2.117	32	942	5.569	3.877	3.123	2.729	2.417	2.223	5.97	0.271
2.125	33	992	5.851	4.141	3.383	2.966	2.653	2.444	6.15	0.271
2.133	34	1042	6.37	4.405	3.586	3.159	2.813	2.572	6.33	0.271
2.141	35	1092	10.002	5.99	4.474	3.79	3.22	2.884	6.52	0.271
2.153	36	994	7.834	4.929	3.761	3.212	2.781	2.528	6.77	0.271
2.155	37	894	5.77	3.732	2.941	2.529	2.226	2.025	7.03	0.271
2.157	38	794	4.038	2.699	2.17	1.899	1.694	1.558	7.29	0.271
2.16	39	695	2.738	1.882	1.547	1.383	1.265	1.172	7.56	0.271
2.162	40	595	1.817	1.31	1.118	1.014	0.938	0.884	7.9	0.271
2.164	41	495	1.149	0.895	0.787	0.731	0.694	0.664	8.31	0.271
2.166	42	395	0.714	0.6	0.558	0.538	0.524	0.508	8.82	0.271
2.169	43	296	0.47	0.427	0.416	0.416	0.414	0.406	9.48	0.271
2.171	44	196	0.33	0.342	0.342	0.339	0.345	0.34	10.42	0.271
2.173	45	100	0.278	0.284	0.29	0.292	0.302	0.301	12.1	0.271
2.175	46	24	0.248	0.258	0.272	0.281	0.29	0.291	12.17	0.271

MPN-218\_Shulman\_1\_NU-LHT-2M

Apr. 15, 2021

Synthetic Agglutinate USGS NU-LHT-2M  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1000°C, in Flowing UHP Argon

Dr. Holly Shulman ( Shulman LLC) again requested that Microwave Properties North measure the complex dielectric properties of a specially produced agglutinate moon regolith simulant (NU-LHT-2M) up to 1230°C in flowing UHP argon. The powder sample material arrived at MPN on Mar. 5/ 2021.

MPN pressed three pellets of the powder material ( in a uniaxial press, ~ 28,000 psi) achieving a density of ~ 1.9 +- 0.1 g/cc ( See photo). The three pellets were baked for 1/4 hour at 200 C to ensure dryness.

MPN was requested to cycle the sample directly up to 1230C and then return to room temperature (RT) ,all in a 5 sccm flow of UHP argon ( which likely has ~ 1 to 10 ppm oxygen content). Infact, a short cycle to 200C was done initially to meet NASA standards of dryness.

The initial sample parameters were:

- a) diameter 3.65 +- 0.05 mm
- b) length 13.29 +- 0.10 mm ( three stacked pellets)
- c) mass 0.263 +- 0.002 gm
- ff) room temperature density  $1.89 \pm 0.10$  gm/cc.
- gg) appearance - three (stacked) pellets.

The dielectric properties measurements were performed at RT and then ramped in 50C steps up to 200C, where the temperature was held for . After this the temperature was returned to RT, and measurements done at RT, 200C, and then in 50C steps to 1200C. Then a step to 1230C, then 1200C, then back down in -100C steps to RT. At this point, it was discovered that the holder had moved up in the clamping fixture by ~ 2.5 cm. This likely was produced by the buildup of gas pressure when the pellets expanded/melted and sealed off the gas flow. There is evidence this happened above 950° C. Also, the alumina plug in the top of the holder was gone ( it was found later in the furnace, completely clean!). A small amount ( ~ 0.020 mg ) of black material ( looked as if it had been molten) had collected in a ring around the inside of the top of the holder. The remaining, final, sample was fused to the holder. ( See photos).

The holder was removed from the apparatus and the final sample weight was obtained by subtraction.

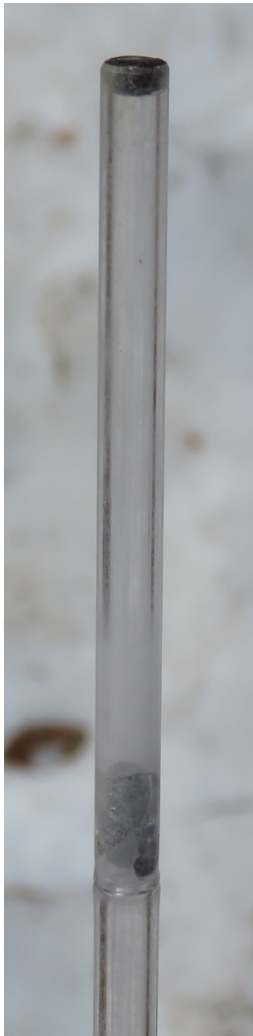
The final sample properties, ( excluding the black ring at the top of the holder) at room temperature, were :

- a) diameter  $3.95 \pm 0.05$  mm
- b) length  $10.1 \pm 0.3$  mm
- c) mass  $0.200 \pm 0.020$  gm
- ee) room temperature density  $1.62 \pm 0.15$  gm/cc.
- ff) appearance - single crazed plug in holder ( see photo)

Note: The percent mass loss was less than or equal to 25 % , but with great uncertainty as to what actually happened!



Three initial pellets after baking at 200 C in air.



Holder after run to 1230C.



Close-up of sample in holder at end of run .

The frequency coding is :

Legend for Data Plots :

#	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line
6	2986	black diamond, dotted line

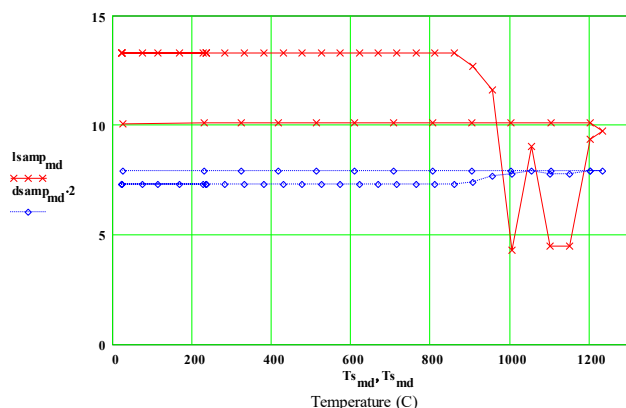
Comments on the run and the data analysis:

This run had serious things happen at high temperatures that make the data above 950C unreliable. Note that an ~ 10 mm long plug, with an ~ 6 mm long, 3.7 mm diameter section was placed in the top of the holder before the run, to prevent back-streaming of air into the holder. The clearances are sufficient to allow the 5 sccm argon gas to flow past the plug without lifting it.

- 1) The sample slumped or expanded and took up the whole diameter. The data shows that above 950C, one or more of the pellets moved up in the holder more than 2.5 cm, taking them out of the measurement zone. Because the pellet sizes are known, there were only two options for the number of pellets left in the sensitive region at each measurement – so it was fairly easy to decide what had happened at any point ! Estimates of the sample height based on this technique allowed the data to be used up to 1100 C – but with large potential errors.

Code Calculates Estimated Sample Dimensions & Volume As a Function of Temperature

Test = 2021040201 SHUL2127\_lowcal\_HTnew.mcd AnDat = 20210404  
 USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argon  
 Assumed Effective Dimensions (mm) (length & diameter) as a Function of Temperature for Solid



Note: The length changes in ~ 4.5 mm increments, the length of a pellet .

- 2) Some black material was evolved and eventually deposited as a ring just inside the top of the holder.

The hole in the ring of apparently condensed material may be the result of having been deposited around the bottom of the alumina plug.

- 3) It appears likely that the movement of the holder out of the clamp fixture at the base of the holder occurred at 1150 C during the return down in temperature. This movement would remove the sample up, out of the cavity, leaving the system to measure the empty portion of the holder below the sample – resulting in  $\epsilon' \sim 1$ . **The following plot is of the data assuming no movement of the pellets.** Clearly the lack of pellets at some of the high temperatures is seen. However, the unity values at 1150C on the return down in temperature suggest the holder has been moved upwards!

# Appendix E. MPN Reports

Test = 2021040201

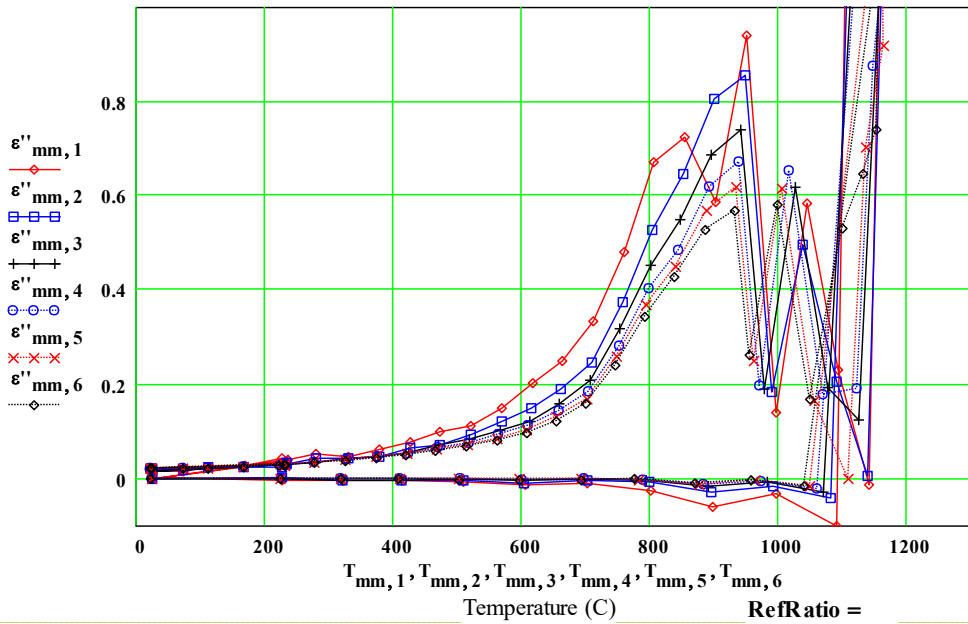
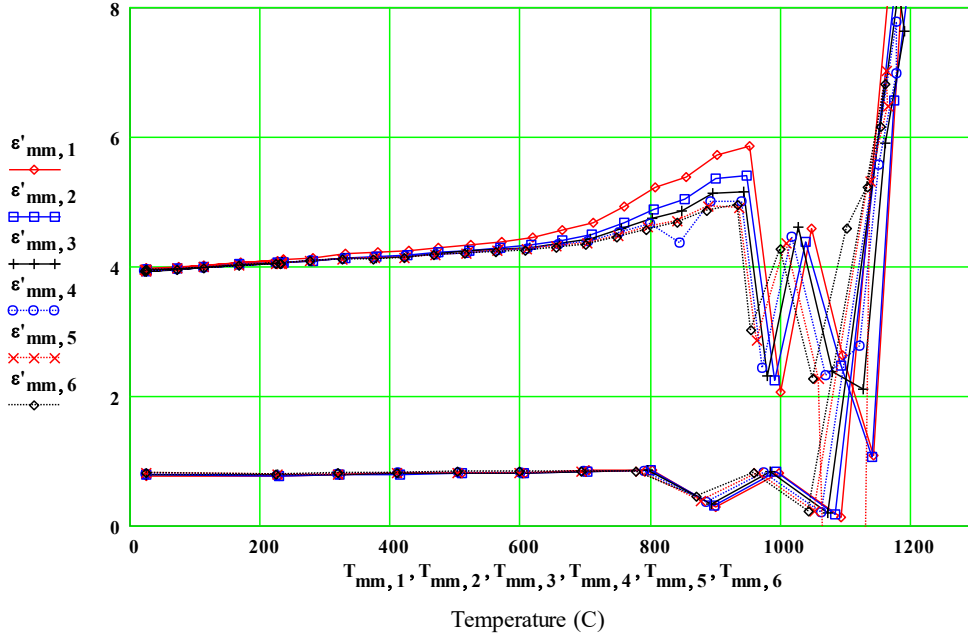
SHUL2127\_up\_down\_lowcal\_HTnew.med

AnDat = 20210404

USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.89 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.62 \text{ gm/cc}$        $\alpha_1 = 3.5 \cdot 10^{-6}$      $\alpha_2 = 3.5 \cdot 10^{-6}$      $\alpha_3 = 3.5 \cdot 10^{-6}$



Values for the Temperature Ramp Up to 1050 °C :

Test = 2021040201

SHUL2127\_up\_down\_lowcal\_HTnew.mcd

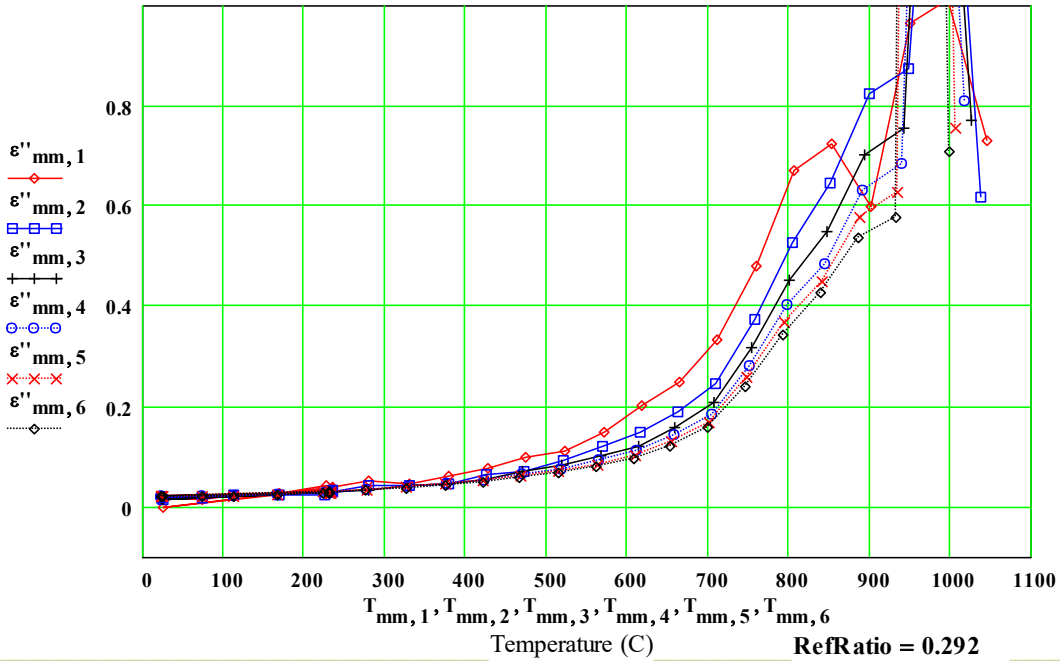
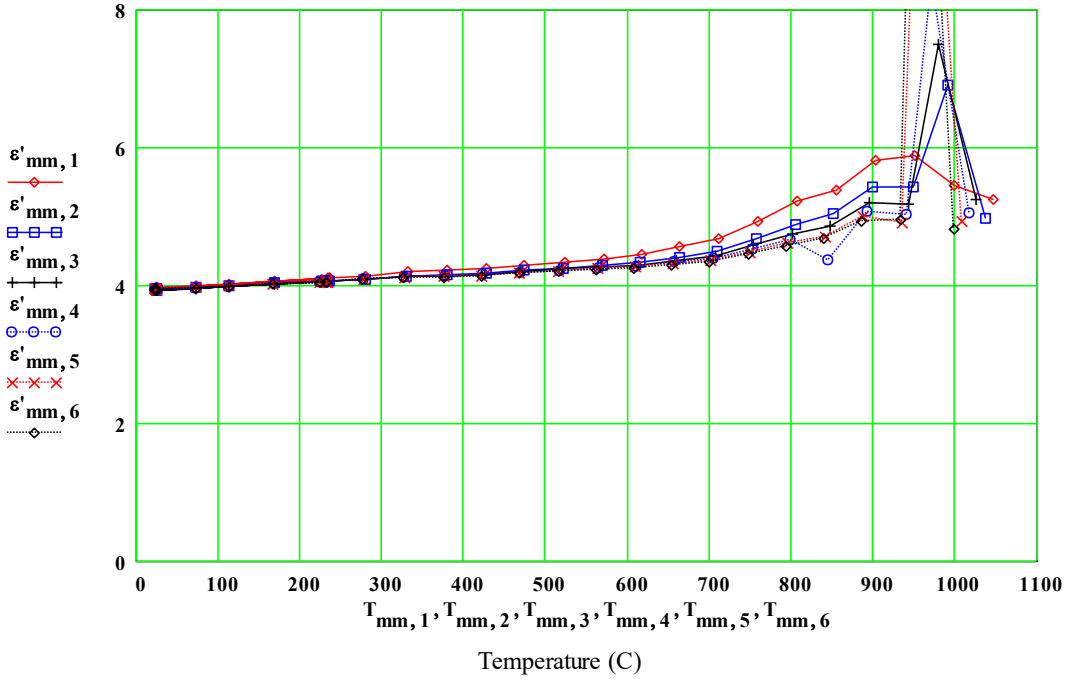
AnDat = 20210404

USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.89 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.62 \text{ gm/cc}$

$$\alpha_1 = 3.5 \cdot 10^{-6} \quad \alpha_2 = 3.5 \cdot 10^{-6} \quad \alpha_3 = 3.5 \cdot 10^{-6}$$



# Appendix E. MPN Reports

Test = 2021040201

SHUL2127\_lowcal\_HTnew.mcd

AnDat = 20210404

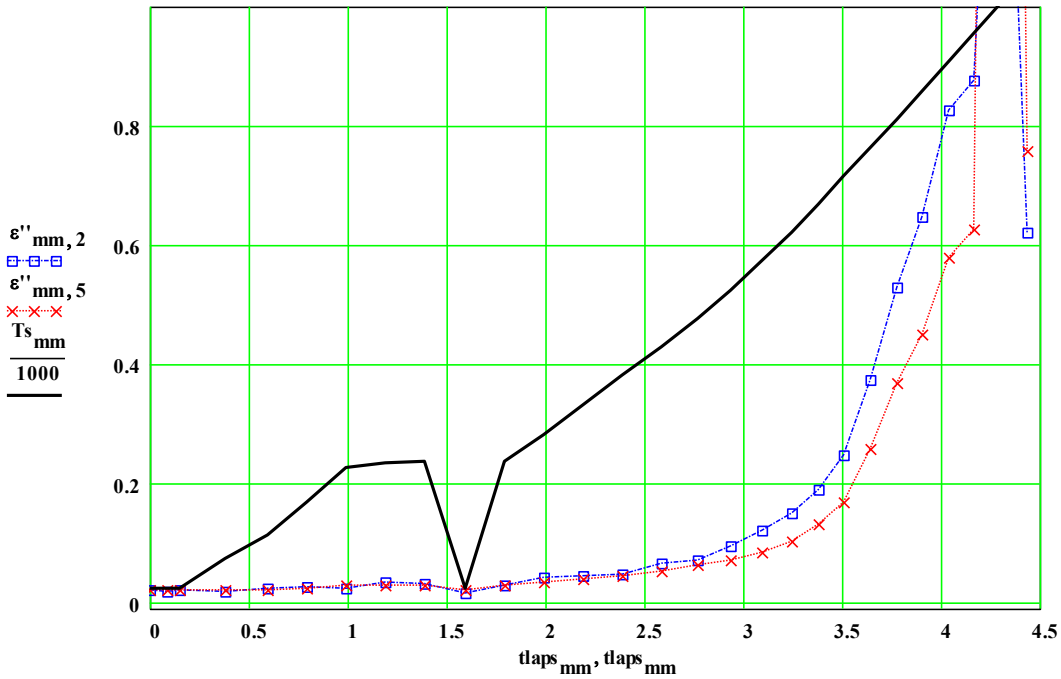
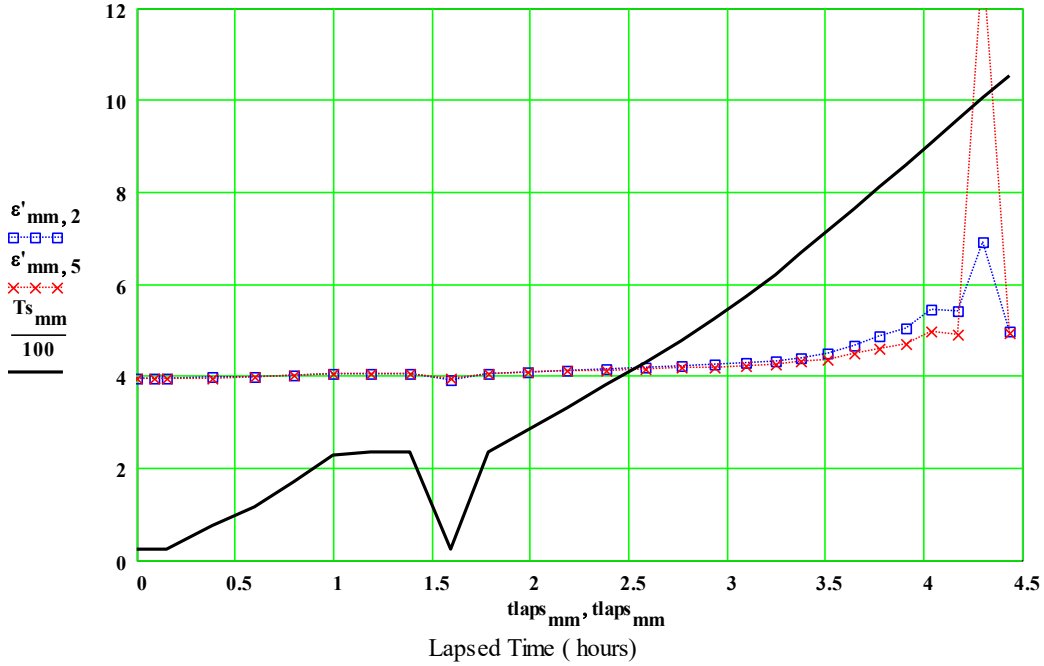
USGS Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.89 \text{ gm/cc}$ ,

Thermal exp. coeff.

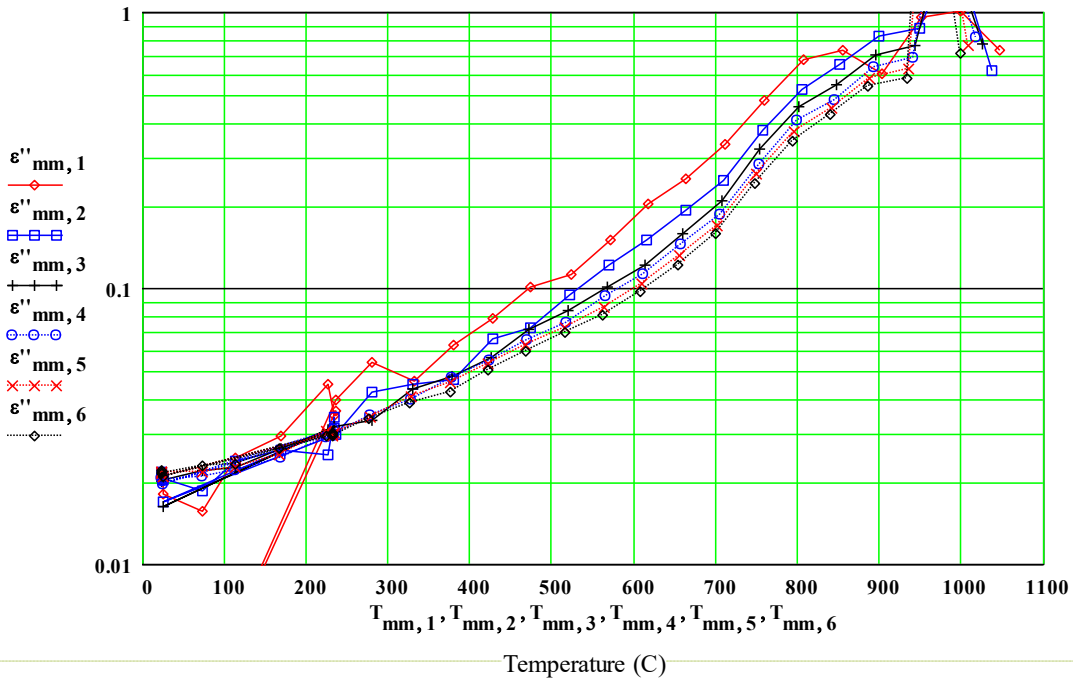
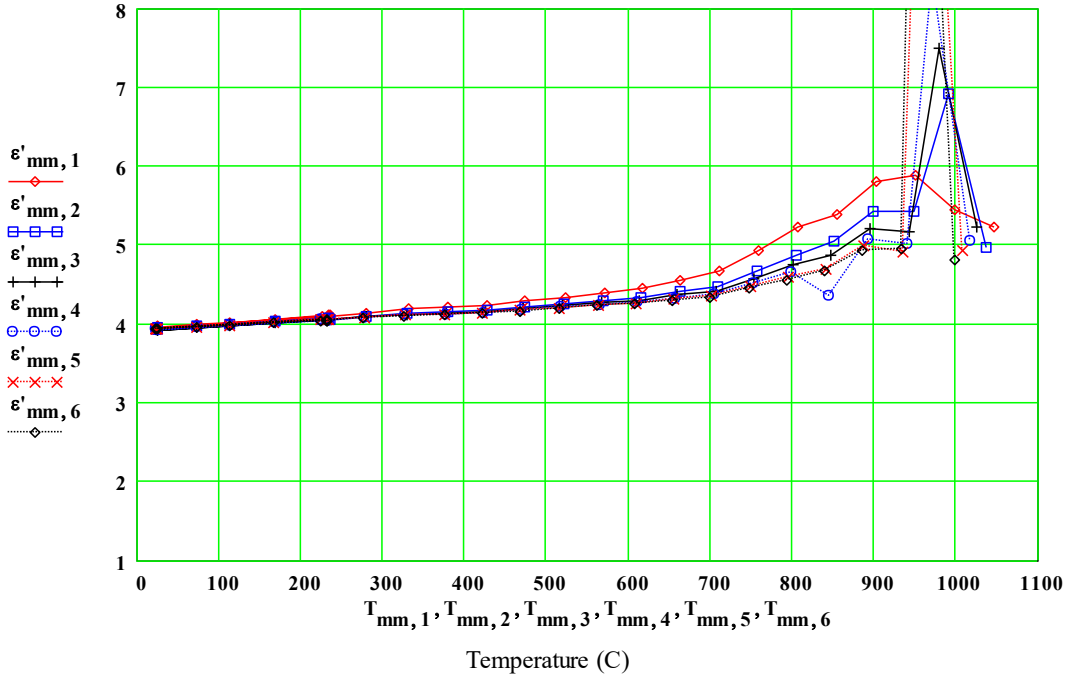
Final density(25C) =  $\text{dnsfinal} = 1.62 \text{ gm/cc}$        $\text{FracMassChange} = 0.76$

$\alpha_1 = 3.5 \cdot 10^{-6}$



# Appendix E. MPN Reports

**Test = 2021040201**                      SHUL2127\_lowcal\_HTnew.mcd                      **AnDat = 20210404**  
 USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argo  
 Initial density = **samdns<sub>NCal + 1</sub> = 1.89 gm/cc**,                      Final density(25C) = **dnsfinal = 1.62 gm/cc**  
**FracMassChange = 0.76**                       **$\alpha_1 = 3.5 \cdot 10^{-6}$  /C**



# Appendix E. MPN Reports

Test = 2021040201

SHUL2127\_lowcal\_HTnew.mcd

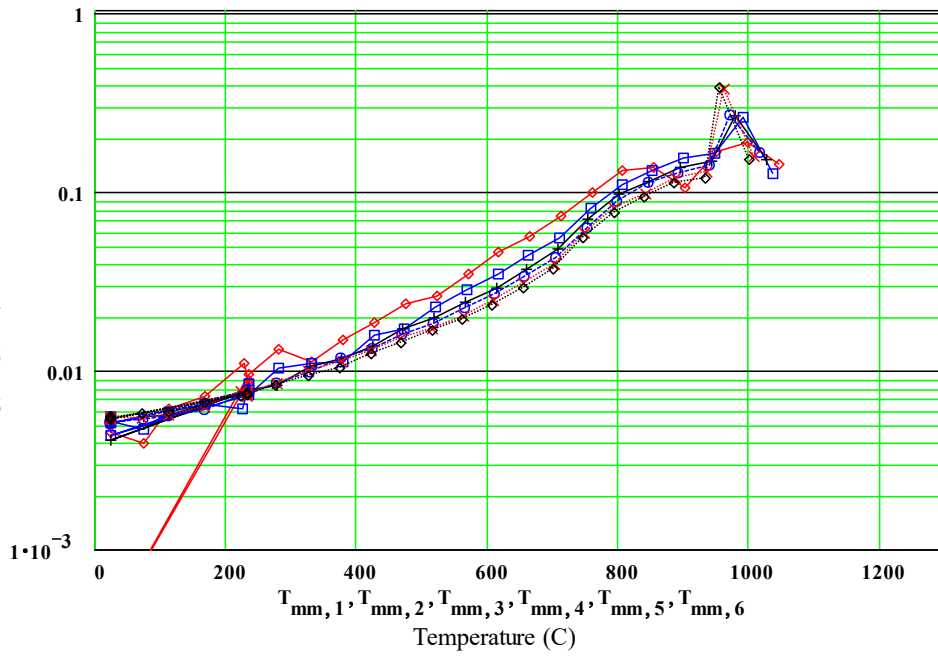
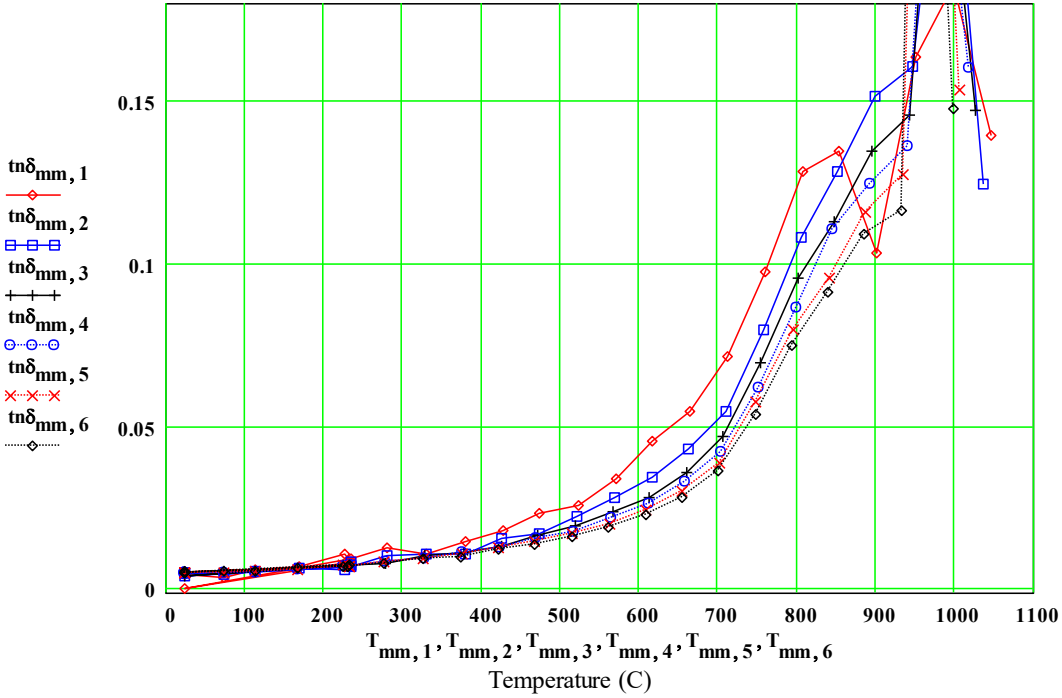
AnDat = 20210404

USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.89 \text{ gm/cc}$ ,

FracMassChange = 0.76

Final density(25C) =  $\text{dnsfinal} = 1.62 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2021040201

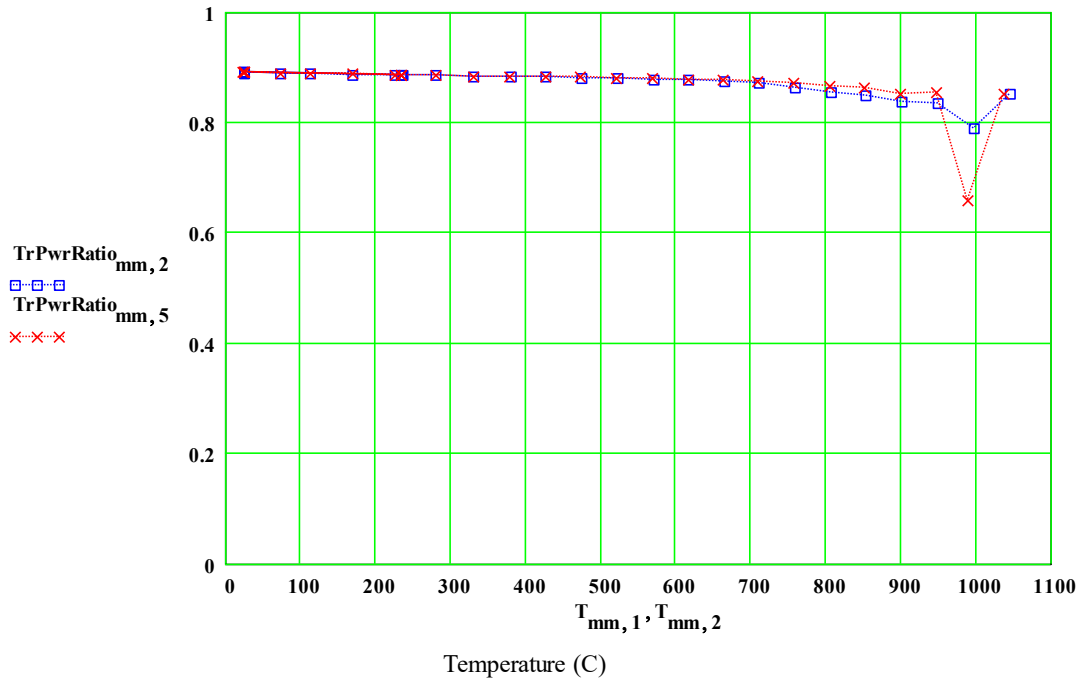
SHUL2127\_lowcal\_HTnew.mcd

AnDat = 20210404

USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1050C, in 5 sccm flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.89 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.62 \text{ gm/cc}$

Ratio of the Power Transmitted through an interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material





# Appendix E. MPN Reports

Test = 2021040201

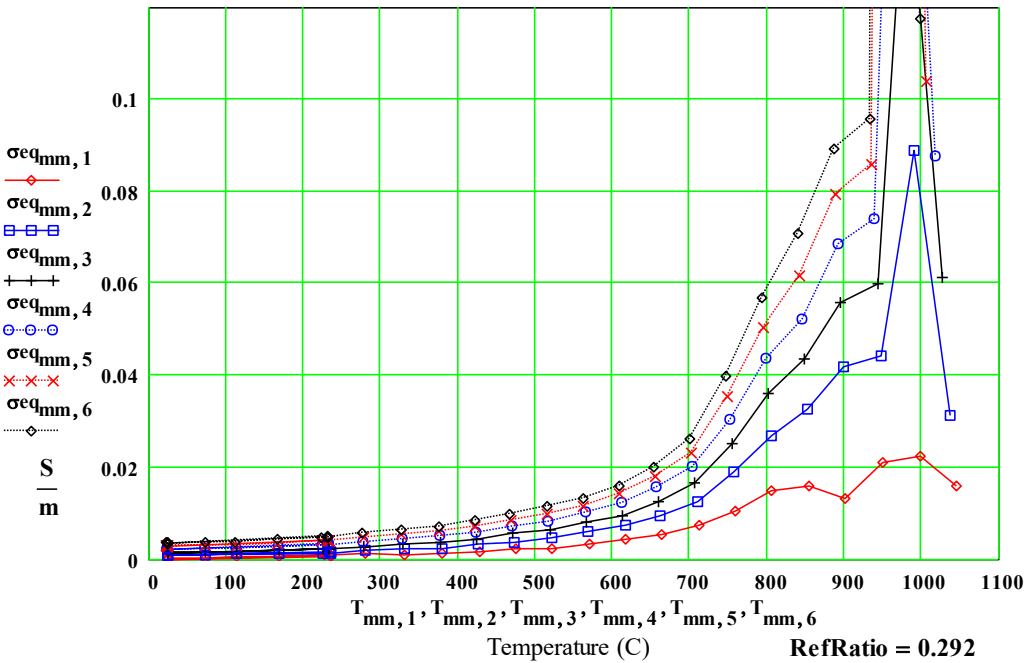
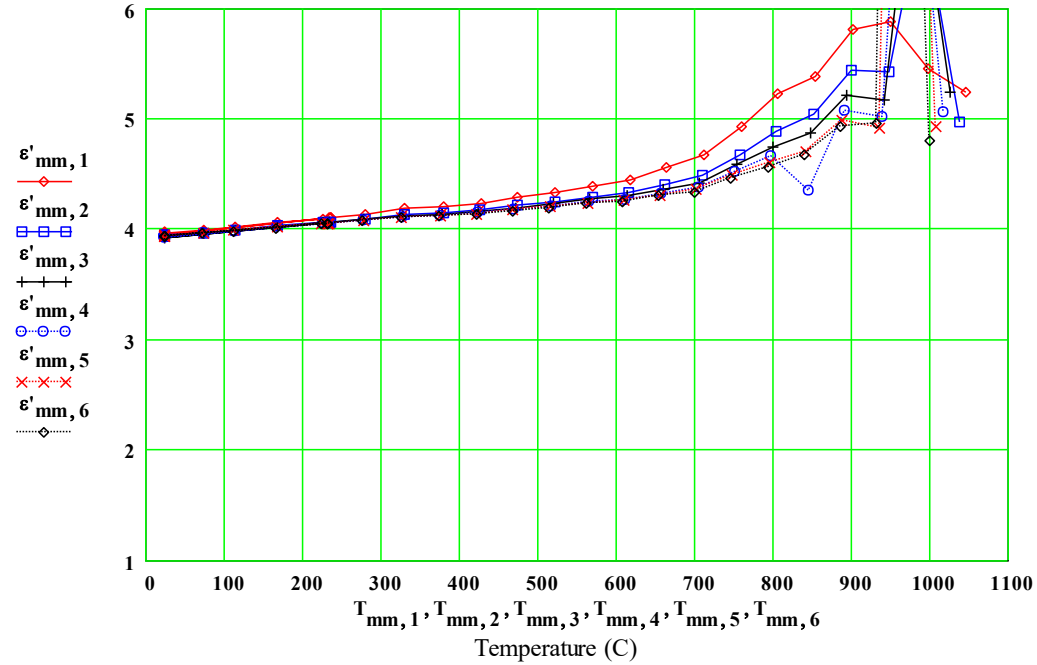
SHUL2127\_lowcal\_HTnew.mcd

AnDat = 20210404

USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C. in 5 sccm flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.89 \text{ gm/cc}$ , Thermal exp. coeff.  $\alpha_1 = 3.5 \cdot 10^{-6}$   $\alpha_2 = 3.5 \cdot 10^{-6}$

Final density(25C) =  $\text{dnsfinal} = 1.62 \text{ gm/cc}$  **FracMassChange = 0.76**  $\alpha_3 = 3.5 \cdot 10^{-6}$



Here is a fit to the data with my Jonscher-based theory.

Use the Jonscher Formalism to fit the Frequency and Thermal Dependence of  $\epsilon_{pp}$  and Conductivity

$$k_B := 8.617 \cdot 10^{-5} \quad \text{eV/K}$$

$$E_a := 1.6 \quad \text{eV}$$

$$H_{\text{activ}} := E_a \cdot 96.5 \quad \text{Kjoule/mol}$$

$$E_a = 1.6 \quad \text{eV} \quad H_{\text{activ}} = 154 \quad \text{Kjoule/mol}$$

$$A_{\text{Fact}}(E_a, T_c) := \exp\left[\frac{-E_a}{k_B \cdot (T_c + 273.)}\right] \quad T_c \text{ in Celcius}$$

$$n_J := 0.70$$

$$\sigma_{\text{max}} := 1.4 \cdot 10^5 \quad \text{Siemens/metre} \quad 1.5 \cdot 10^3$$

$$\sigma_{\text{not}}(T) := \sigma_{\text{max}} \cdot A_{\text{Fact}}(E_a, T) \quad \text{Siemens/m}$$

$$\sigma_{\text{not}}(715) = 9.643 \cdot 10^{-4} \quad \text{Siemens/metre}$$

$$\omega_{\text{max}} := 0.85 \cdot 10^{10} \quad \text{radians/sec} \quad 10^{10}$$

$$\frac{\omega_{\text{max}}}{(2 \cdot \pi)} = 1.353 \cdot 10^9 \quad \text{MHz}$$

$$\omega_p(E_a, T_c) := \omega_{\text{max}} \cdot A_{\text{Fact}}(E_a, T_c) \quad \text{MHz} \quad T_c \text{ in Celcius}$$

$$\omega_p(E_a, 715) = 58.549$$

$$\frac{\omega_p(E_a, 715)}{(2 \cdot \pi)} = 9.318 \quad \text{MHz}$$

$$m_n := 1..16$$

$$\epsilon''_{\text{th}J_{n_{mn},n}} := \left( \frac{\sigma_{\text{max}} \cdot A_{\text{Fact}}(E_a, T_{Q_{mn}})}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \right) \cdot \left[ 1 + \cos\left(\frac{n_J \cdot \pi}{2}\right) \cdot \left(\frac{2 \cdot \pi \cdot f_{h_n}}{\omega_p(E_a, T_{Q_{mn}})}\right)^{n_J} \right] \quad T_{Q_{mn}} \text{ is in Celcius}$$

$$\sigma_{\text{th}J_{n_{mn},n}} := \epsilon''_{\text{th}J_{n_{mn},n}} \cdot 2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}$$

$$\epsilon_{\text{inf}} := 4.1$$

$$\epsilon'_{\text{th}J_{n_{mn},n}} := \left[ \frac{\sigma_{\text{max}} \cdot A_{\text{Fact}}(E_a, T_{Q_{mn}})}{\omega_p(E_a, T_{Q_{mn}}) \cdot (8.85 \cdot 10^{-6})} \right] \cdot \left[ \sin\left(\frac{n_J \cdot \pi}{2}\right) \cdot \left(\frac{2 \cdot \pi \cdot f_{h_n}}{\omega_p(E_a, T_{Q_{mn}})}\right)^{n_J - 1} \right] + \epsilon_{\text{inf}}$$

The  $J_m$  means an intermediate temperature Jonscher term, with a lower activation energy than the high temperature range.

$$E_{am} := 0.9 \text{ eV}$$

$$E_a = 1.6 \text{ eV} \quad H_{activ} := E_a \cdot 96.5 \text{ Kjoule/mol}$$

$$H_{activ} = 154 \text{ Kjoule/mol}$$

$$A_{Factm}(E_a, T_c) := \exp\left[\frac{-E_{am}}{k_B \cdot (T_c + 273.)}\right] \quad T_c \text{ in Celcius}$$

$$m_J := 0.975$$

$$\sigma_{maxm} := 1.4 \cdot 10^{-2} \text{ Siemens/metre} \quad 1.5 \cdot 10^3$$

$$\sigma_{notm}(T) := \sigma_{maxm} \cdot A_{Fact}(E_{am}, T) \text{ Siemens/m}$$

$$\sigma_{notm}(715) = 3.59 \cdot 10^{-7} \text{ Siemens/metre}$$

$$\omega_{maxm} := 1.20 \cdot 10^3 \text{ radians/sec} \quad 10^{10}$$

$$\frac{\omega_{maxm}}{(2 \cdot \pi)} = 190.986 \text{ MHz}$$

$$\omega_{pm}(E_{am}, T_c) := \omega_{maxm} \cdot A_{Fact}(E_{am}, T_c) \text{ MHz} \quad T_c \text{ in Celcius}$$

$$\omega_{pm}(E_{am}, 715) = 0.031$$

$$\frac{\omega_{pm}(E_{am}, 715)}{(2 \cdot \pi)} = 4.897 \cdot 10^{-3} \text{ MHz}$$

$$m_n := 1..16$$

$$\varepsilon''_{thJm_{mn,n}} := \left( \frac{\sigma_{maxm} \cdot A_{Factm}(E_{am}, T_{Q_{mn}})}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \right) \cdot \left[ 1 + \cos\left(\frac{m_J \cdot \pi}{2}\right) \cdot \left(\frac{2 \cdot \pi \cdot f_{h_n}}{\omega_{pm}(E_{am}, T_{Q_{mn}})}\right)^{m_J} \right] \quad T_Q \text{ is in Celcius}$$

$$\sigma_{thJm_{mn,n}} := \varepsilon''_{thJm_{mn,n}} \cdot 2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}$$

$$\varepsilon''_{thTotal_{mn,n}} := \varepsilon''_{thJn_{mn,n}} + \varepsilon''_{thJm_{mn,n}}$$

$$\sigma_{thJTotal_{mn,n}} := (\sigma_{thJn_{mn,n}} + \sigma_{thJm_{mn,n}})$$

$$\rho_{thJTotal_{mn,n}} := \frac{1}{\sigma_{thJTotal_{mn,n}}}$$

# Appendix E. MPN Reports

Test = 2021040201

SHUL2127\_up\_down\_lowcal\_HTnew.med

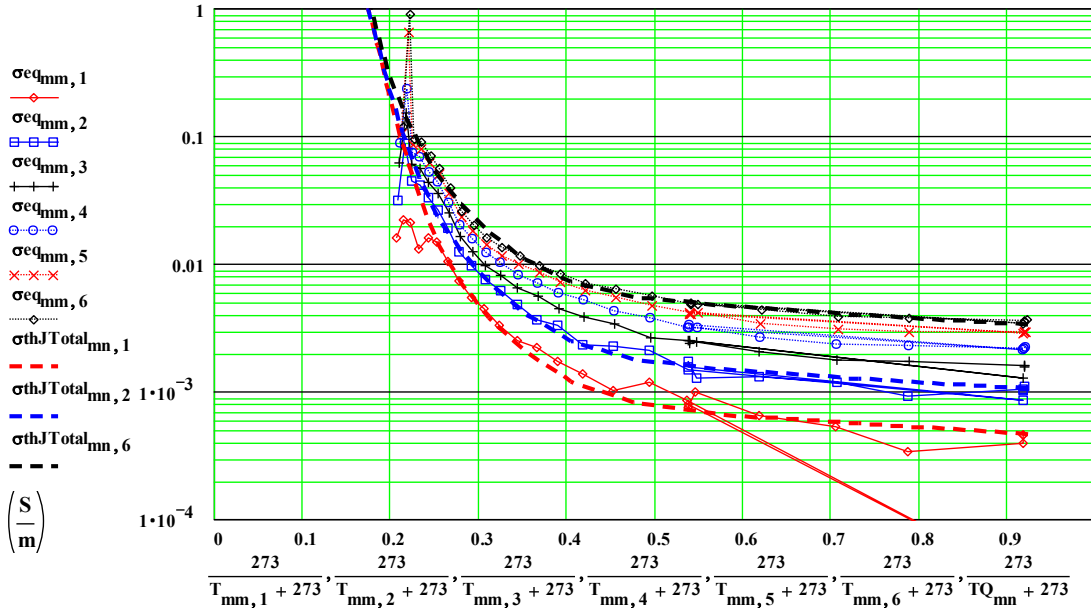
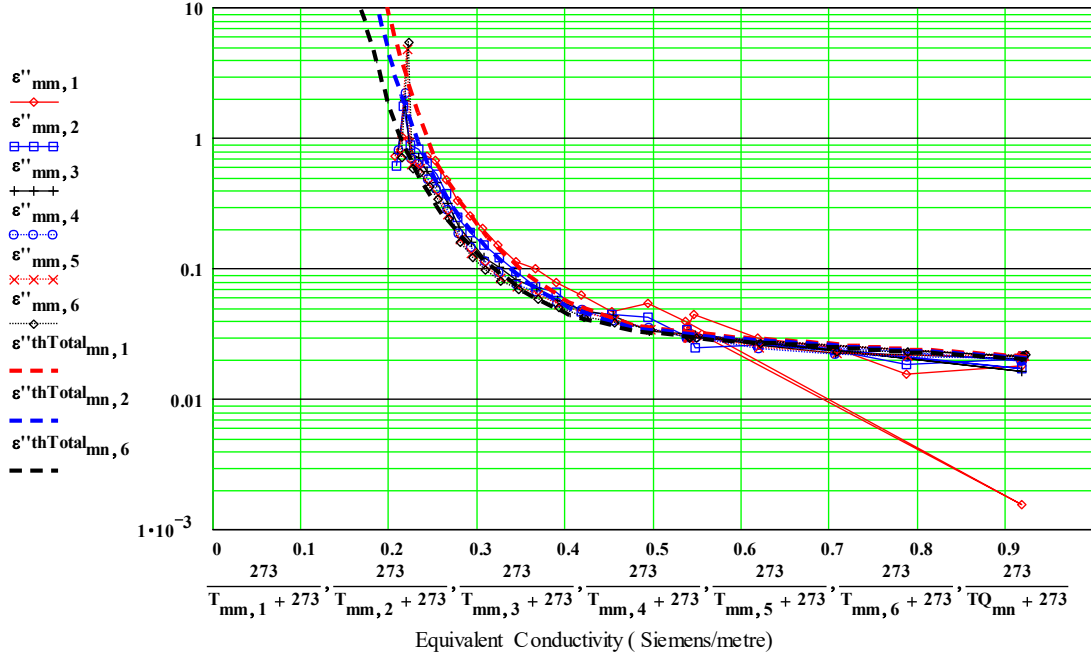
AnDat = 20210415

USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argon

Initial density =  $\text{samdns.} = 0.87 \text{ gm/cc.}$  Final density(25C) =  $\text{dnsfinal} = 1.62 \text{ gm/cc}$

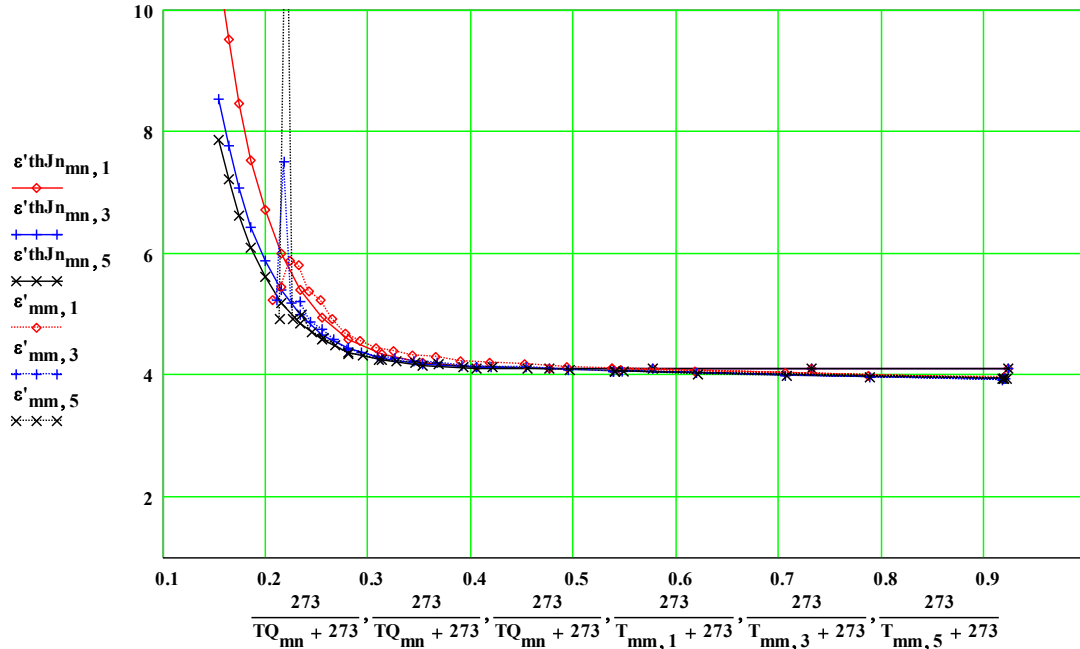
$E_a = 1.6 \text{ eV}$       $\sigma_{\text{max}} = 1.4 \cdot 10^5 \text{ Siemens/metre}$       $n_J = 0.7$

$E_{\text{am}} = 0.9 \text{ eV}$       $\sigma_{\text{maxm}} = 0.014 \text{ Siemens/metre}$       $m_J = 0.975$



The Jonscher theory allows one to calculate  $\epsilon'$ , as well as  $\epsilon''$  and the conductivity,  $\sigma$  – as a function of frequency and temperature. The frequency independent part of  $\epsilon'$  ( called  $\epsilon_\infty$  ) is also determined during fitting to the data. The fit below assumes a temperature independent value of  $\epsilon_\infty \sim 4.0$ , as seen below.

Test = 2021040201                      SHUL2127\_up\_down\_lowcal\_HTnew.mcd                      AnDat = 20210415  
 USGS NU-LHT-2M , Synthetic Agglutinate Pellets, H. Shulman, RT - 1230C, in 5 sccm flowing UHP argon







MPN-258\_MPN\_NU-LHT-4M

July 15, 2022

Lunar Simulant NU-LHT- 4M,  
Measurements of Complex Dielectric Constant from  
Room Temperature to 1400°C, in Flowing UHP Argon

Microwave Properties North decided to measure the complex dielectric properties of NU-LHT-4M lunar simulant powder pellets. The powder sample material had been supplied by Dr. Holly Shulman for previous measurements requested by her up to 1200C in UHP argon.

This measurement was done using a modification of our usual perturbation system – a larger diameter fused silica holder was used ( 8 mm OD, 6 mm ID ), and the three test pellets were placed inside a high purity alumina crucible (5.71 mm OD , 4.03 mm ID mm, 15.09 mm high), which itself was placed in the 6 mm ID fused silica ( GE-214 ) holder.

For this measurement, MPN pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness.

The initial sample parameters were:

- a) pellet diameter 3.65 +- 0.05 mm
- b) length of stack 12.53 +- 0.10 mm
- c) mass 0.283 +- 0.002 gm
- hh) room temperature density  $2.16 \pm 0.09$  gm/cc.
- ii) appearance - three (stacked) light grey pellets
- jj) magnetic response - no response to strong magnet

The initial background measurements and calibrations were done on the holder containing the empty alumina crucible up to 1400C ( see photo). Then the pellets were loaded into the crucible, and the dielectric properties measurements were performed at RT and then the temperature was ramped up to 1400C in 50C steps. After this, the temperature was brought back down to RT in -100C steps.

The holder was removed from the apparatus, the crucible was removed from the holder, and the final sample was weighed. The crucible was easily removed, but the sample had “melted” and adhered to the crucible. The crucible, with sample) was sectioned with a thin diamond saw to reveal the shape of the final sample ( melting had occurred – see photo).

The final sample properties, at room temperature were :

- a) diameter  $4.03 \pm 0.05$  mm ( The ID of the crucible)
- b) length ~ 9.8 mm to top of meniscus, 8.4 mm at centre of sample ( see photo)  $\pm 0.3$  mm
- c) mass  $0.279 \pm 0.002$  gm
- gg) room temperature bulk density ( pores included)  $2.35 \pm 0.15$  gm/cc.
- hh) appearance - dark brown glassy solid with pores , with meniscus indicating melting ( see photo)
- ii) magnetic response - No response to strong magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

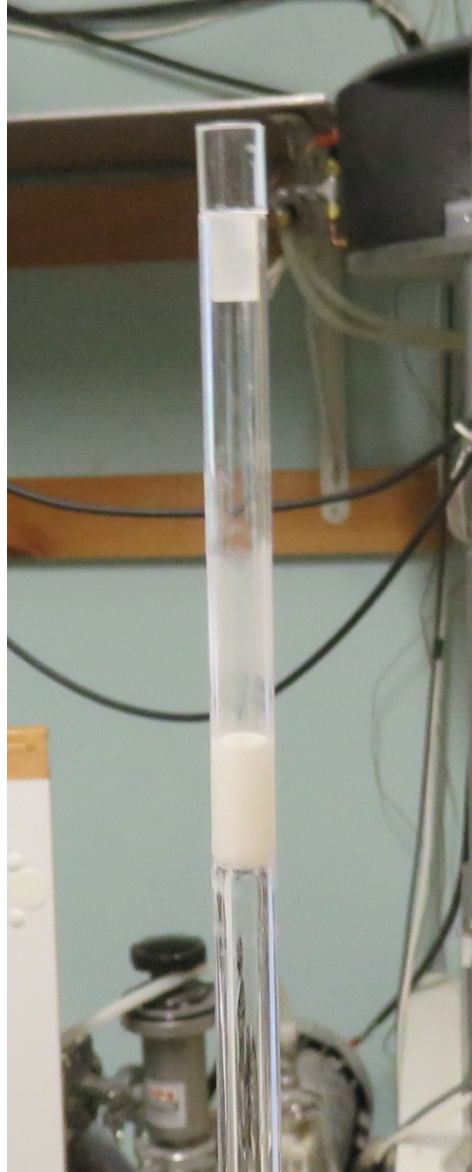
<u>#</u>	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line
6	2986	black diamond, dotted line

Comments on the data analysis:

A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

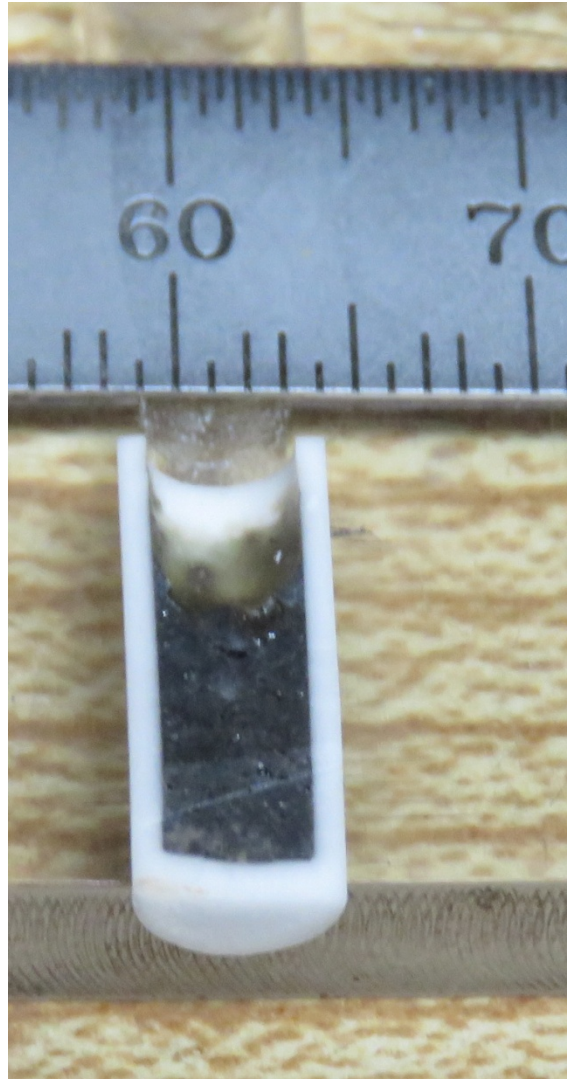
The initial and final sample dimensions, the internal staining of the alumina crucible, and the high temperature dielectric constant behaviour were used to estimate the dimensions of the sample as a function of temperature. The lack of exact, detailed, knowledge of the sample dimensions as a function of temperature does introduce some uncertainty in the high temperature values. If it is important, I can show estimates of the possible dielectric constant variation induced by reasonable uncertainties !

The fitting of the dielectric loss and the “equivalent conductivity” to an Arrhenius dependence ( pages 15 and 16 of this report) suggest some form of glass melting occurred above 1100 C.



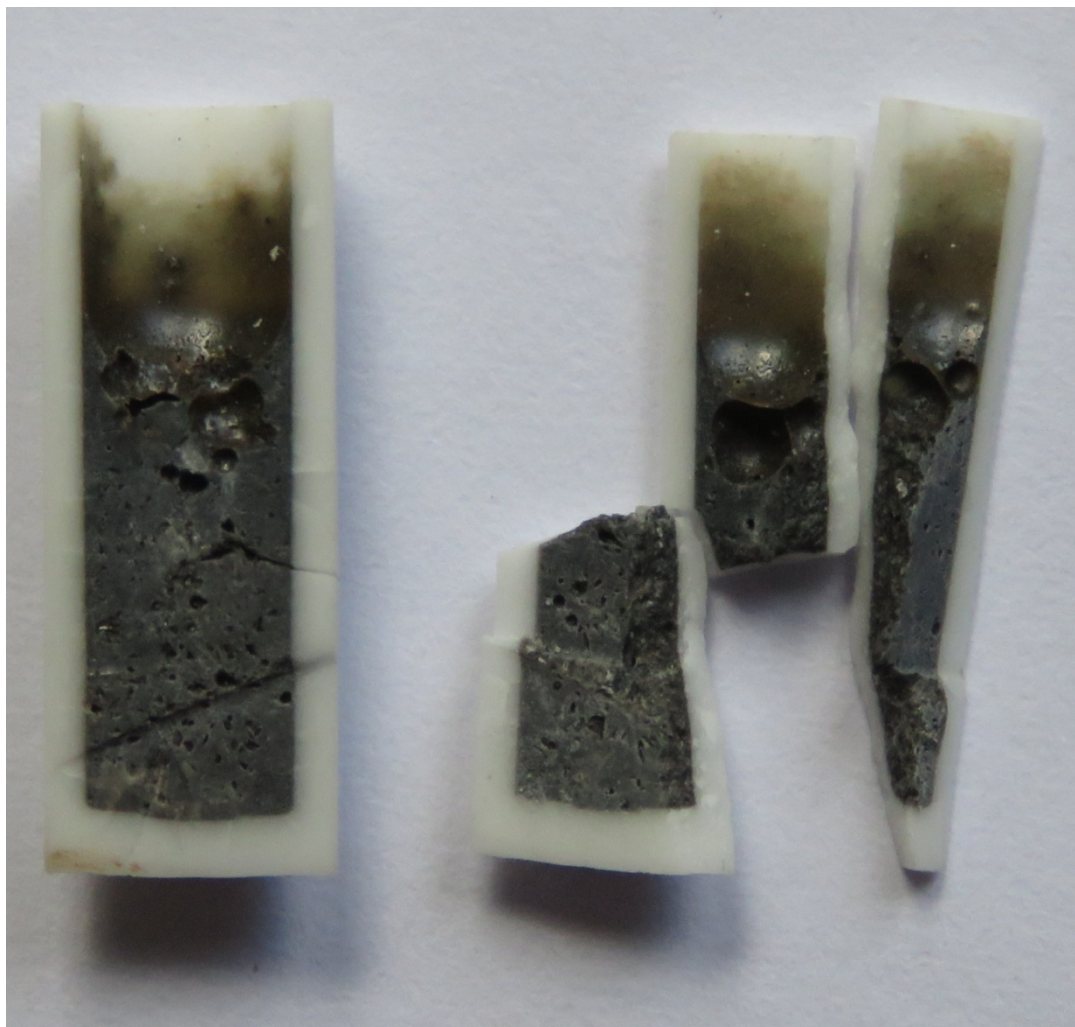
( left) Alumina crucible in holder after cycle to 1400 C in 10 sccm flowing UHP argon.  
(right) Holder with crucible and fused silica “plug” ,before insertion of test pellets .

Note: The gas flows up the interior of the holder, past the outside wall of the crucible.

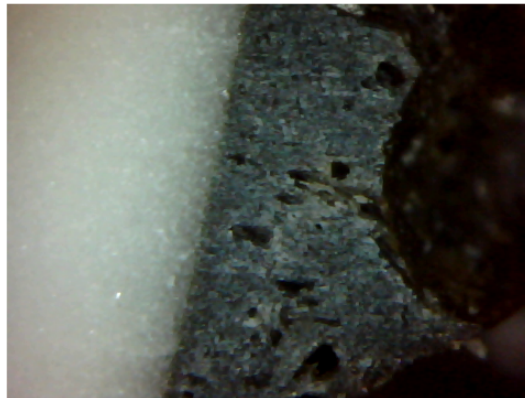
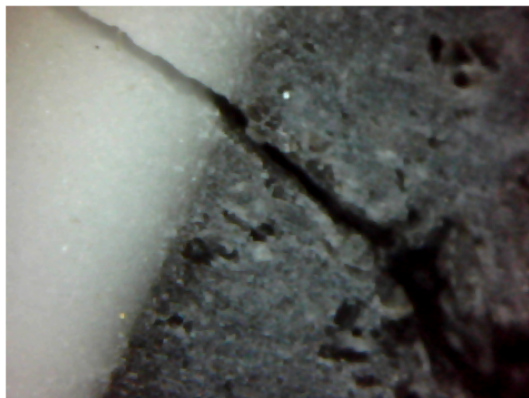
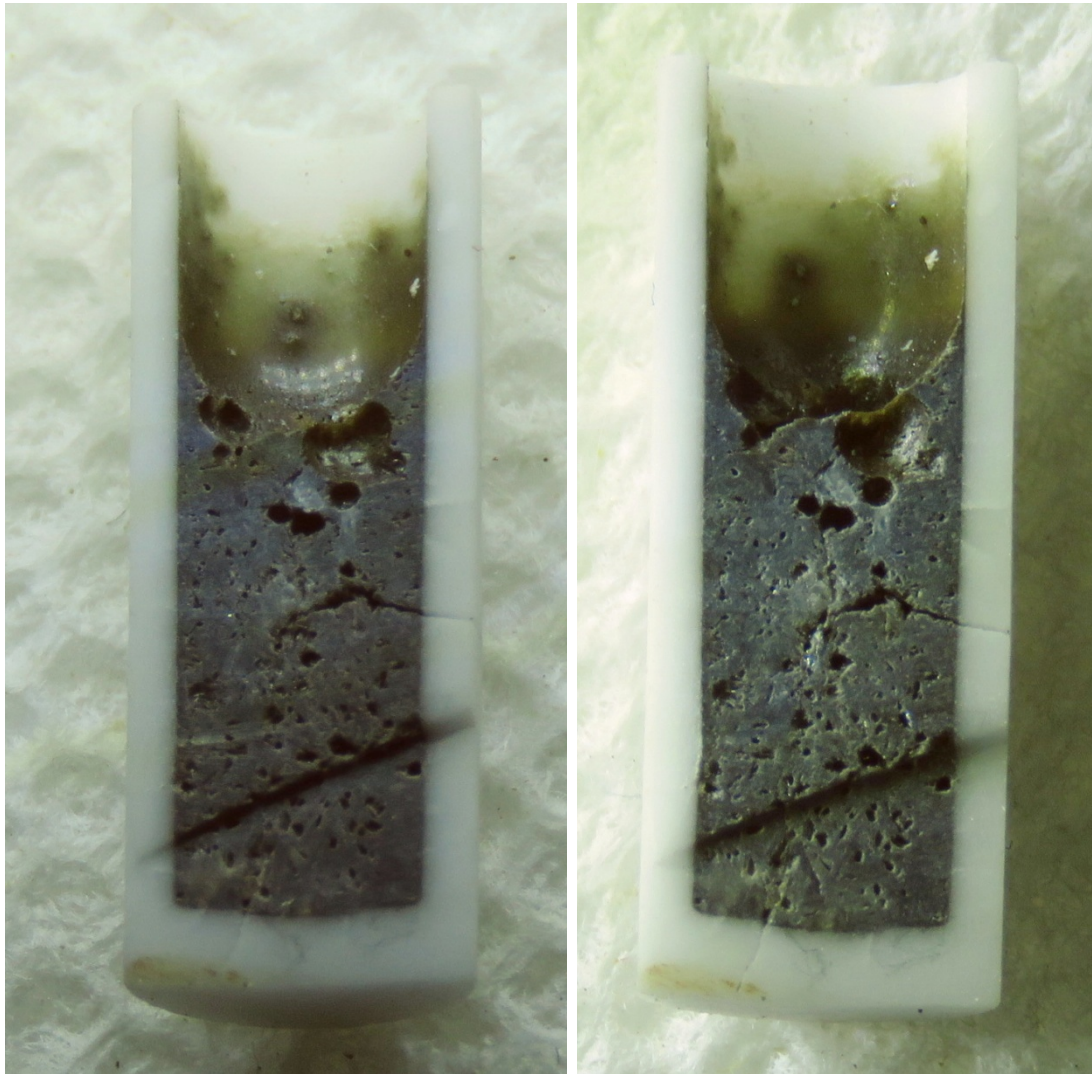


(left) Crucible with test sample after run ,

(right ) After sectioning with thin diamond saw.



Details of final NU-LHT-4M sample after run to 1400C in argon. There is no indication of the original three-stacked-pellet structure, or of the discontinuities between the pellets, indicating the achievement of low viscosity and melting/mixing. The pores suggest gas entrainment and/or incomplete “sintering”. The final density was ~ 9% higher than the initial density.



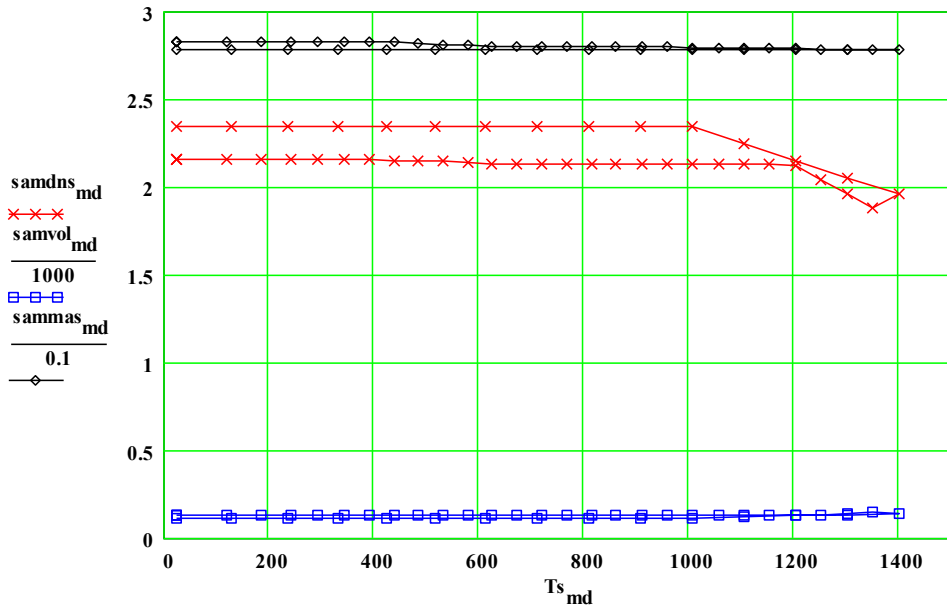
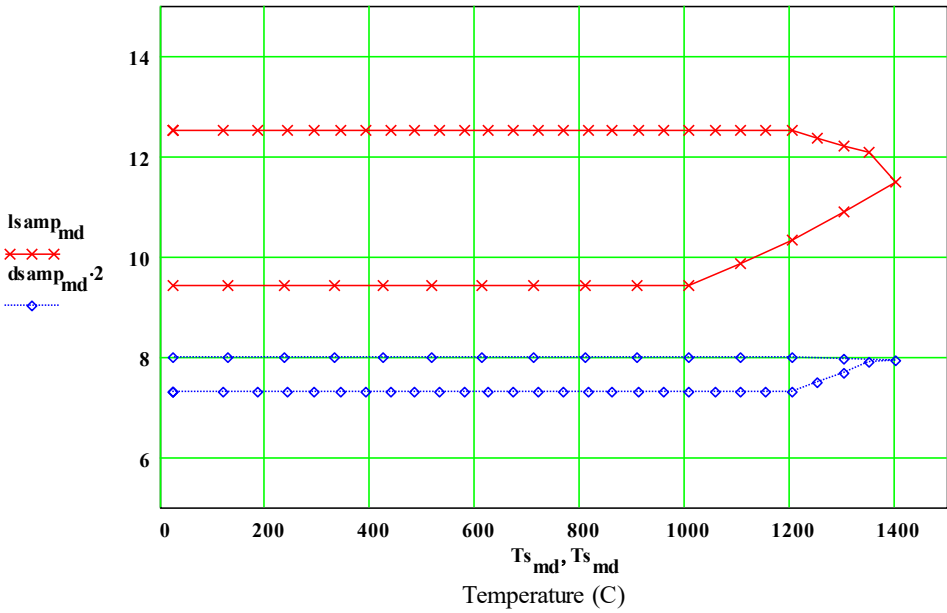
Interface between crucible wall and NU-LHT-4M after run to 1400C in argon.

# Appendix E. MPN Reports

Code Calculates Estimated Sample Dimensions & Volume and Plots Density As a Function of Temperature

Test = 2022071201                      MPN02284\_NU-LHT-4M.mcd                      AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN  
 Assumed Effective Dimensions (mm) and Density (gm/cc) as a Function of Temperature for Solid



# Appendix E. MPN Reports

Test = 2022071201

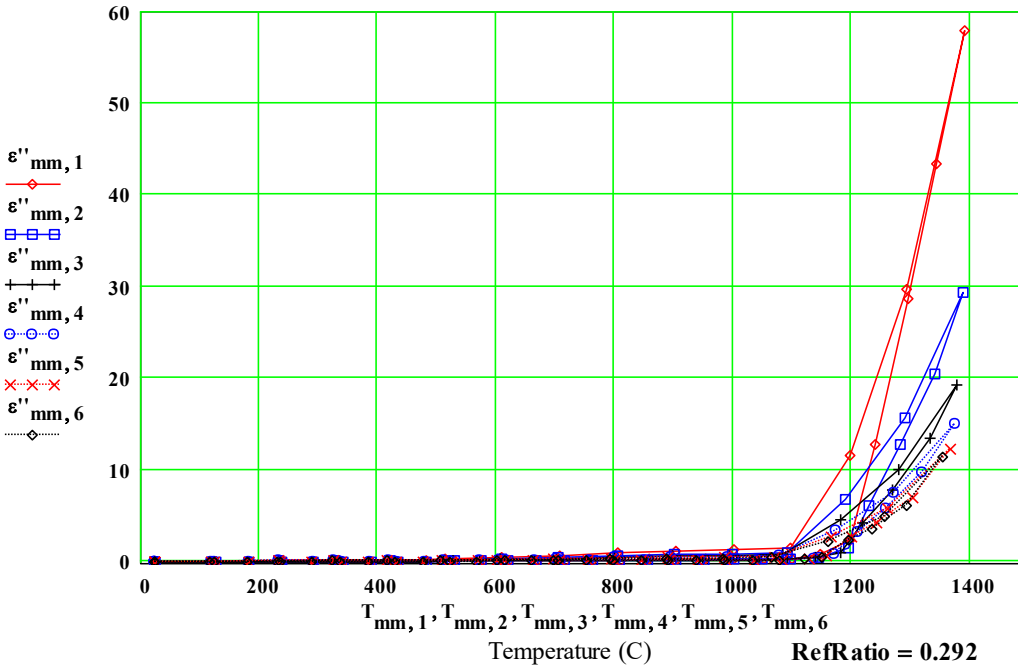
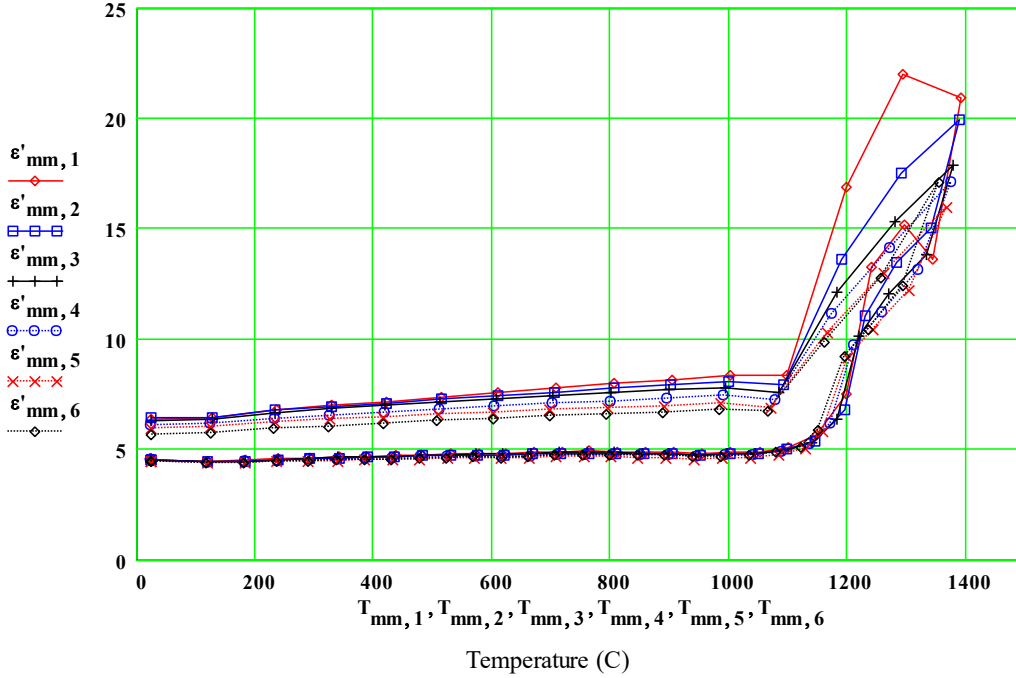
MPN02284\_NU-LHT-4Mmod.mcd

AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.35 \text{ gm/cc}$



The  $\epsilon'$  values during the ramp up in temperature go from  $\sim 4.5$  to  $5.0$  up to  $1100 \text{ C}$ , then increases rapidly!

This is usually an indication of melting ( of the glass component ?).

# Appendix E. MPN Reports

Test = 2022071201

MPN02284\_NU-LHT-4M.mcd

AnDat = 20191013

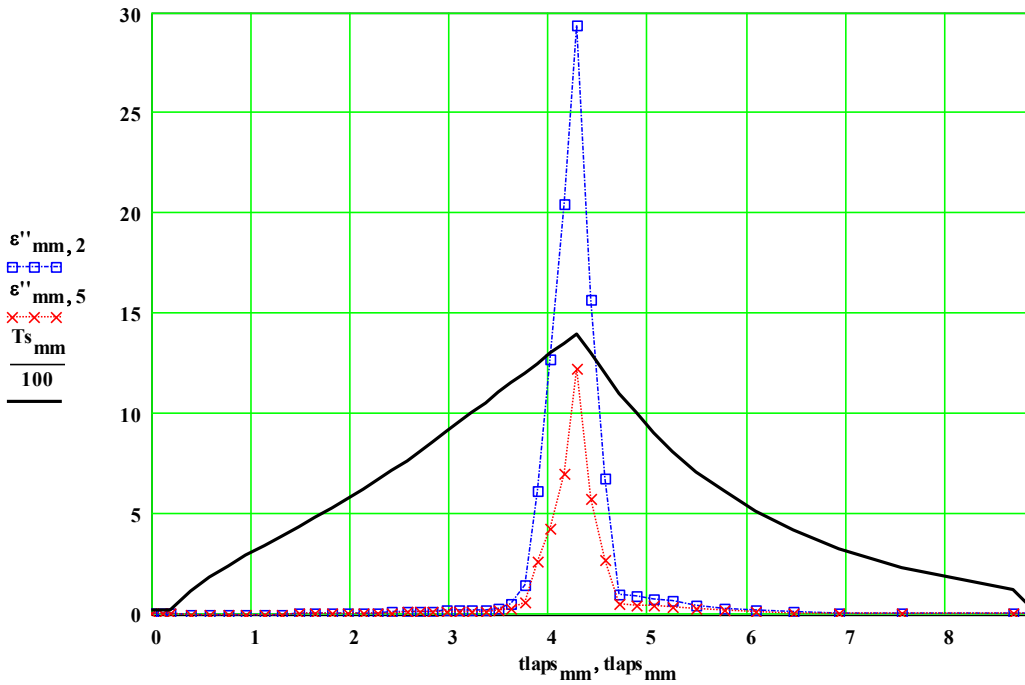
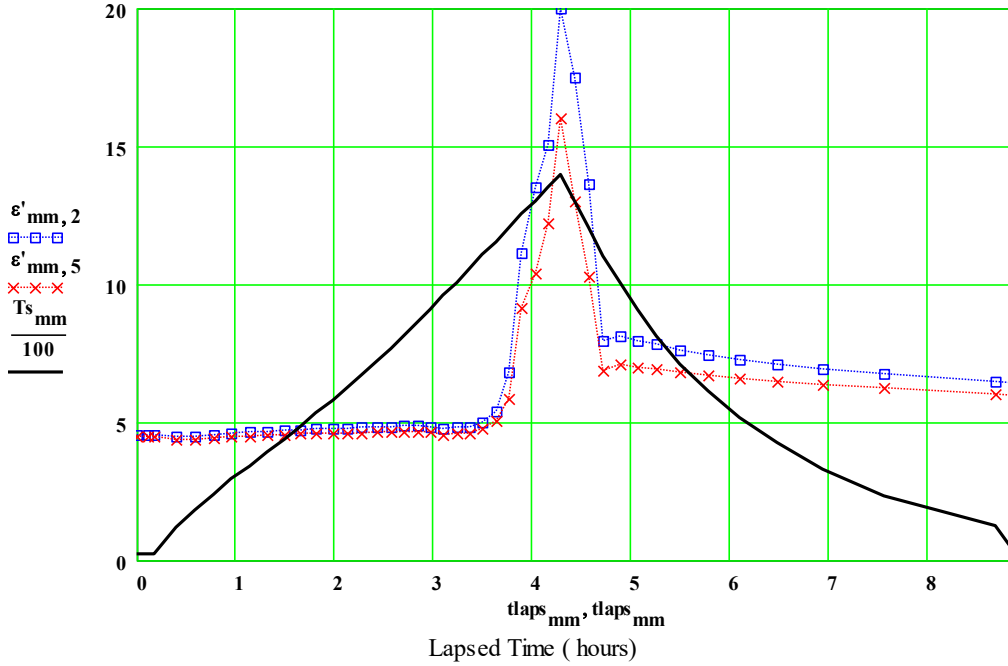
NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.35 \text{ gm/cc}$       **FracMassChange = 0.99**

$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2022071201

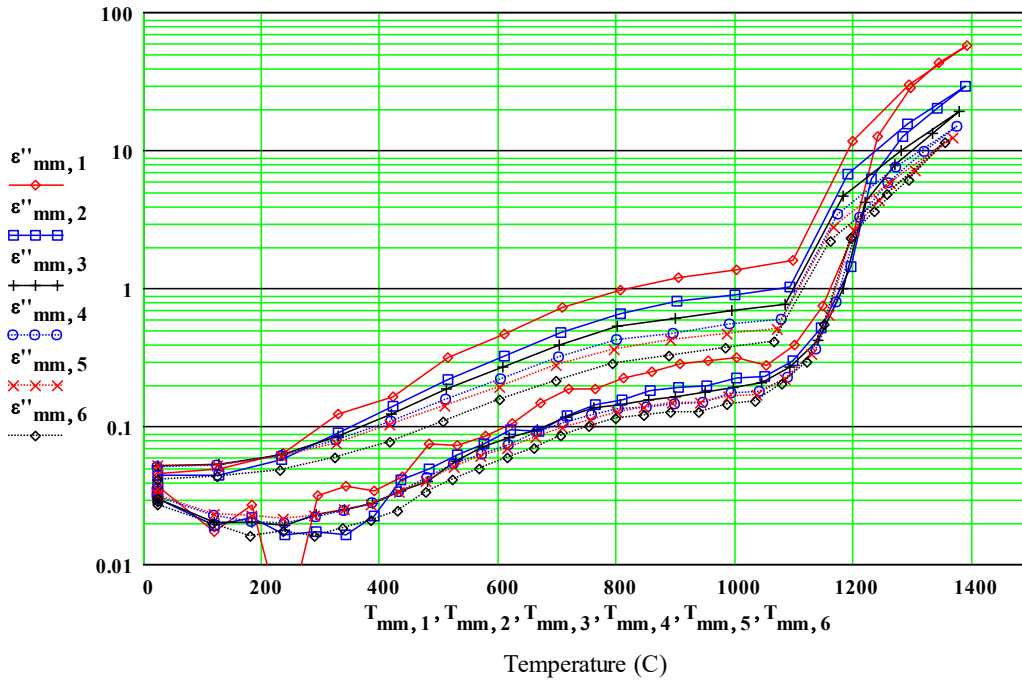
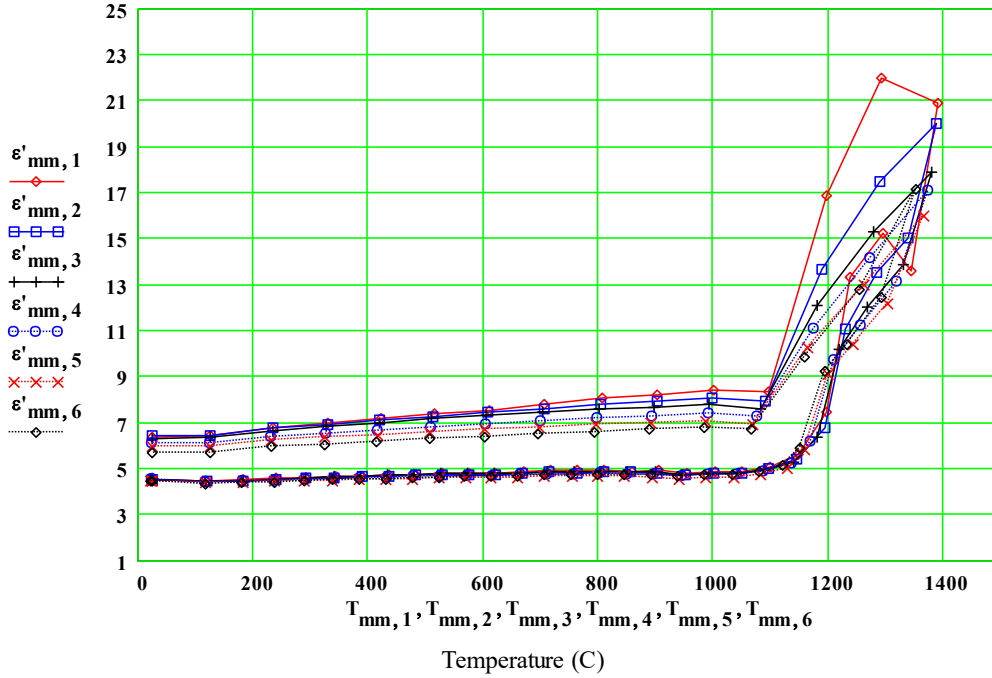
MPN02284\_NU-LHT-4M.med

AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.35 \text{ gm/cc}$

FracMassChange = 0.99       $\alpha_1 = 0$  /C       $\alpha_2 = 0$  /C



# Appendix E. MPN Reports

Test = 2022071201

MPN02284\_NU-LHT-4Mmod.mcd

AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2022071201

MPN02284\_NU-LHT-4M.mcd

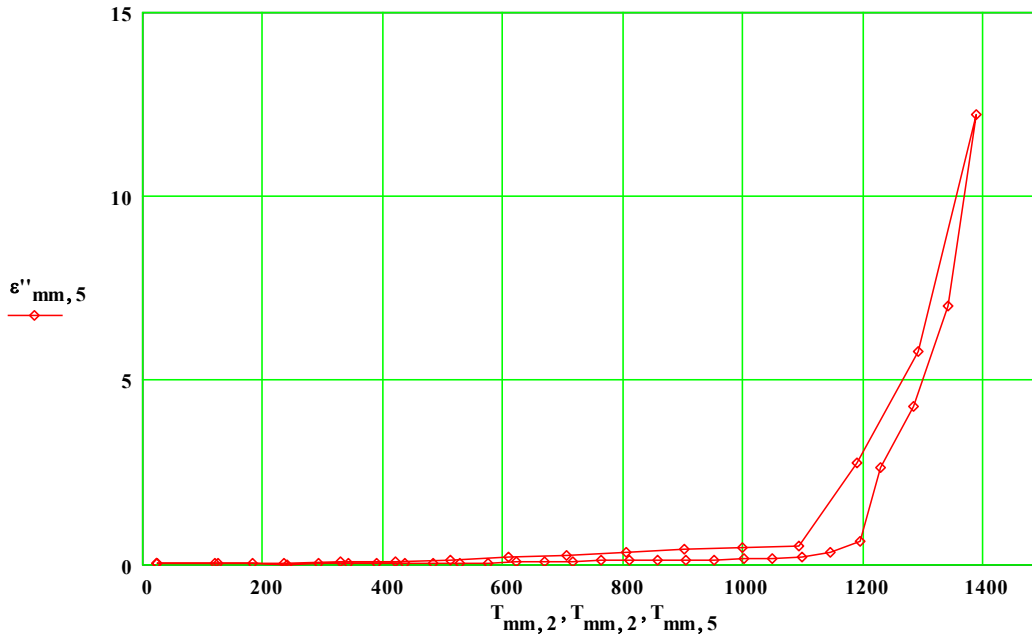
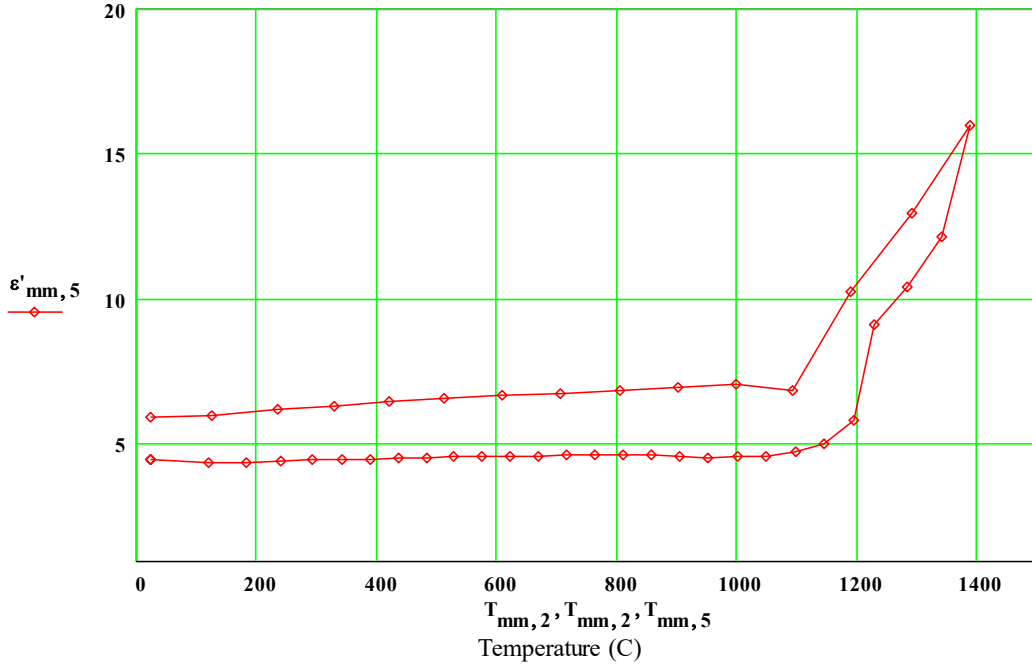
AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ , Thermal exp. coeff.  $\alpha_1 = 0$   $\alpha_2 = 0 \cdot 10^{-6}$

Final density(25C) =  $\text{dnsfinal} = 2.35 \text{ gm/cc}$

## Values for 2450 MHz



# Appendix E. MPN Reports

Test = 2022071201

MPN02284\_NU-LHT-4M.mcd

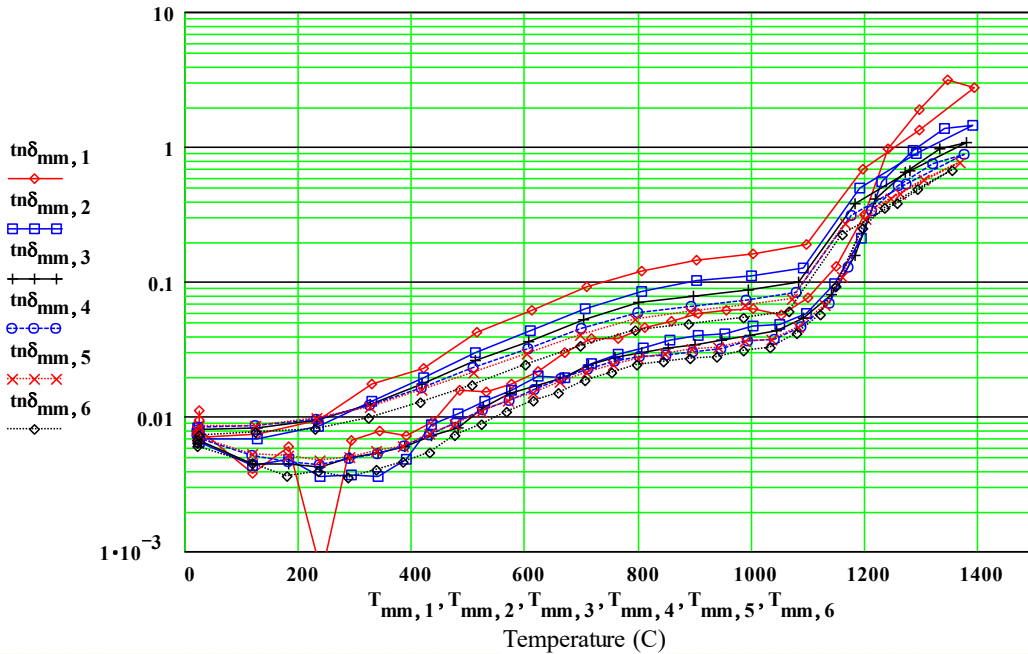
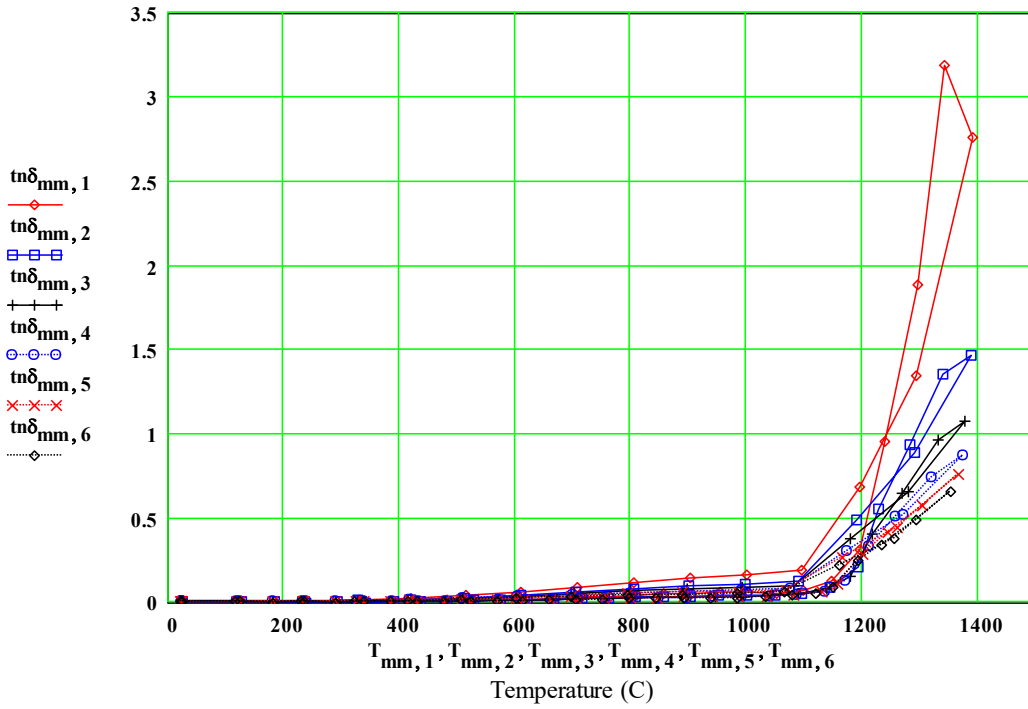
AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ ,

FracMassChange = 0.986

Final density(25C) =  $\text{dnsfinal} = 2.35 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2022071201

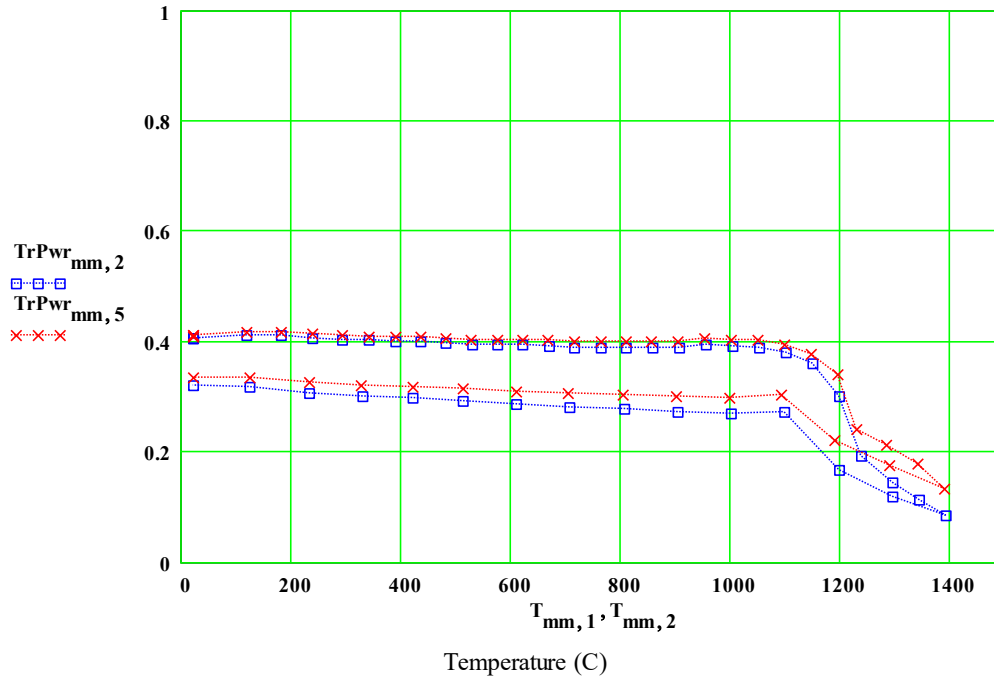
MPN02284\_NU-LHT-4M.mcd

AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Initial density =  $\text{sam} \text{dns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ , Final density(25C) =  $\text{dns}_{\text{final}} = 2.35 \text{ gm/cc}$

Ratio of the Power Transmitted through an interface to the Power Incident (Forward) onto the interface - for a Propagating TEM Wave (from Vacuum onto the sample material) at Normal Incidence to an Infinite Thickness of the Sample Material



# Appendix E. MPN Reports

Half-power Depth (millimeters)

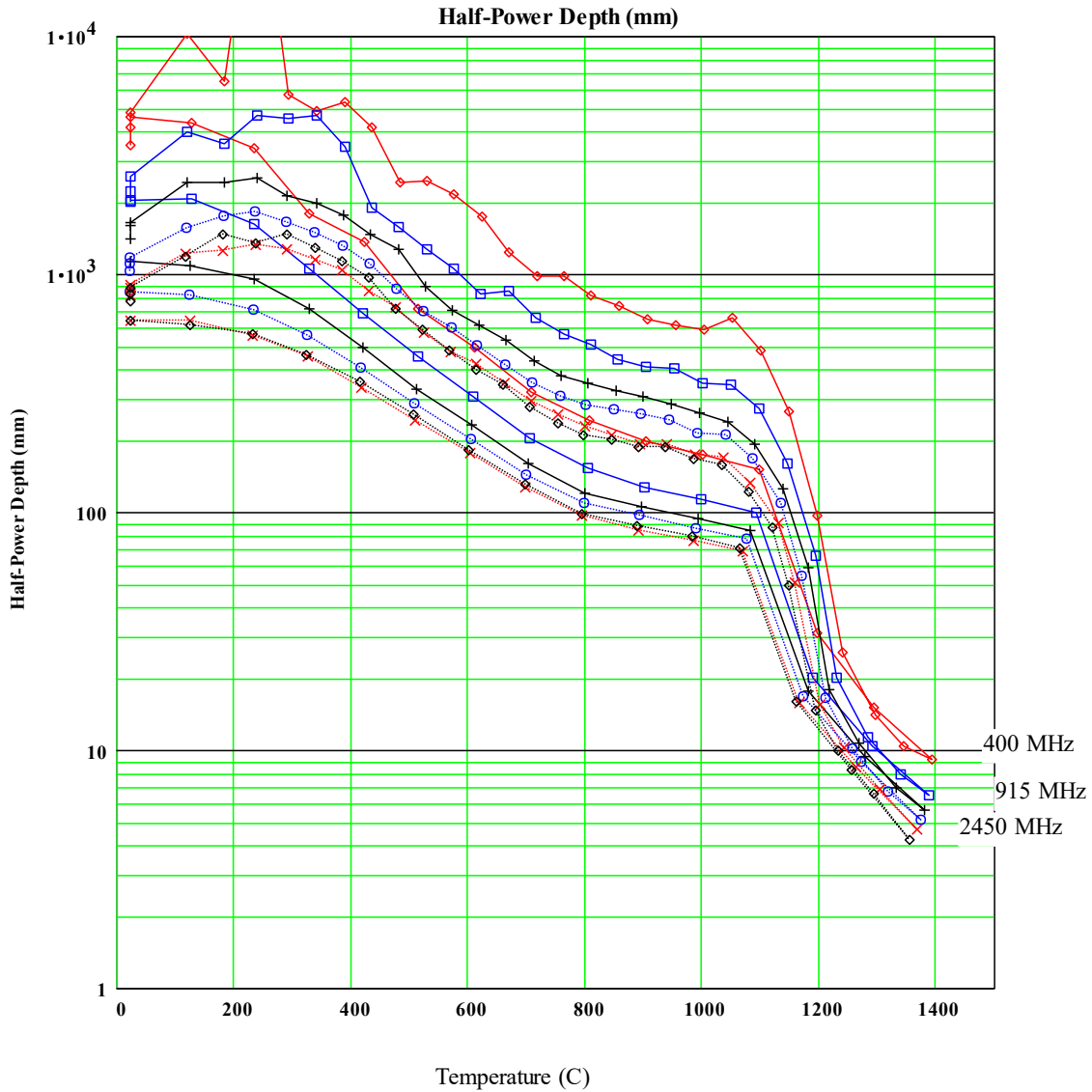
$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2022071201

MPN02284\_NU-LHT-4Mmod.mcd

AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN



This fit to the conductivity ( see below) suggests an activation energy (  $E_a = E_g/2$  ) of 4.0 eV above 1100C ---- which is patently ridiculous in a crystalline material --- and is the prime indicator of softening and melting of a glass ( in my experience) !

Calculate a theoretical  $e''$  , with two possible Arrhenious dependences,with activation energy , $E_g$

Operator: Chose the Functional Dependence, Input the Chosen Values for  $E_g$  and the Intrinsic Conductivity  $\sigma_{int}$

$$E_g := 8.0 \quad \text{eV}$$

$$\sigma_{int} := 150 \cdot 10^{11} \text{ Siemens/metre}$$

$$m_n := 1..16$$

$$k_B := 8.617 \cdot 10^{-5} \quad \text{eV/K}$$

$$\varepsilon_{ppth_{m_n, n}} := \left[ \frac{\sigma_{int}}{2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}} \cdot \exp \left[ \frac{-E_g}{2 \cdot k_B \cdot (T_{Q_{m_n}} + 273.)} \right] \right]$$

$$\sigma_{th_{m_n, n}} := \varepsilon_{ppth_{m_n, n}} \cdot 2 \cdot \pi \cdot f_{h_n} \cdot 8.85 \cdot 10^{-6}$$

# Appendix E. MPN Reports

Test = 2022071201

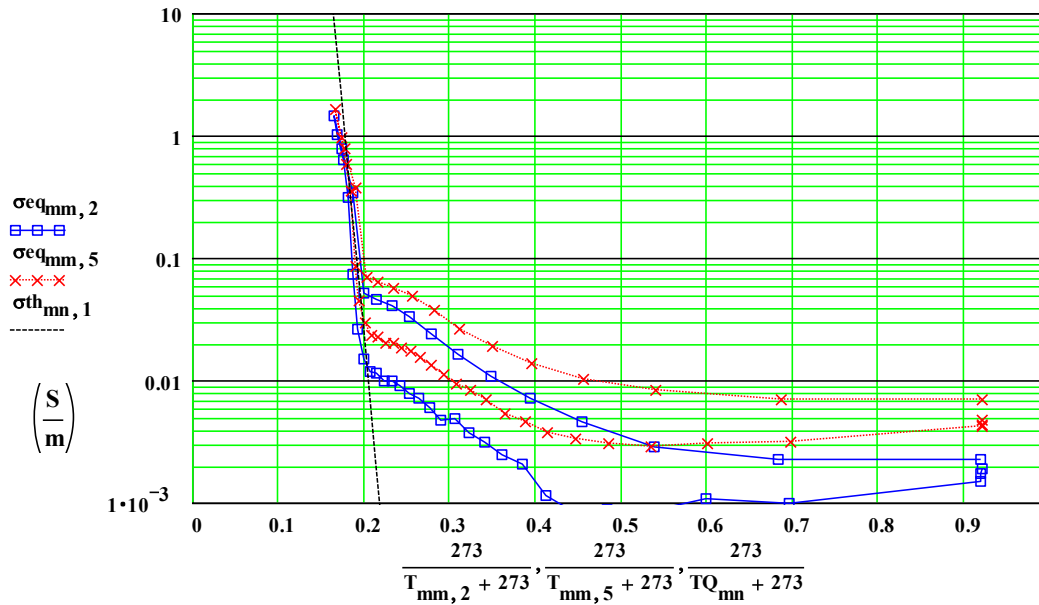
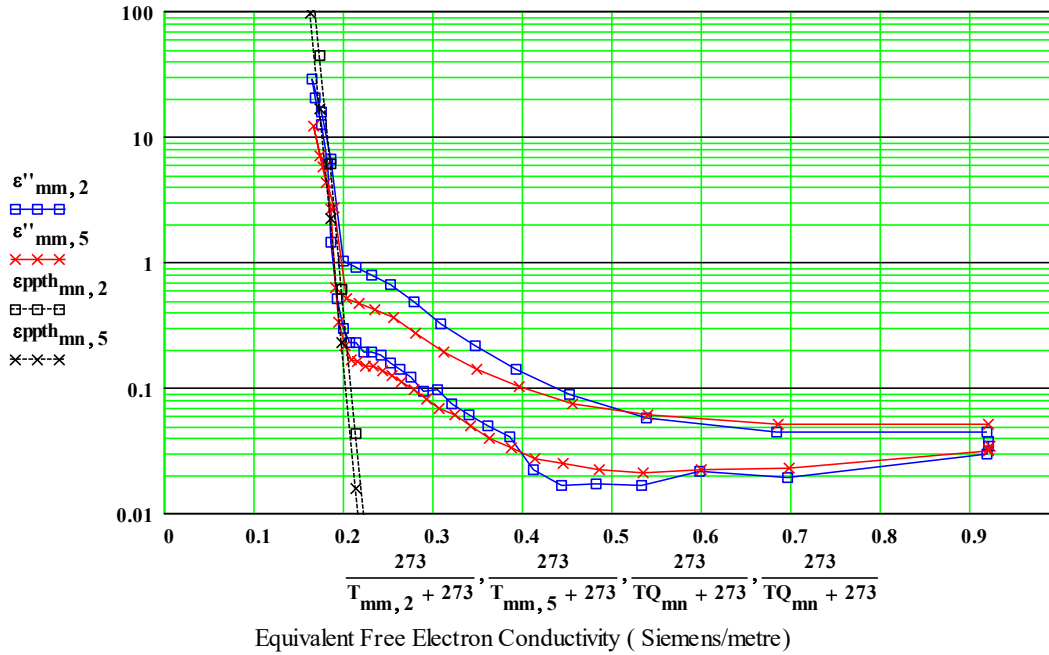
MPN02284\_NU-LHT-4M.mcd

AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.16 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.35 \text{ gm/cc}$

$E_g = 8 \text{ eV}$   $\sigma_{\text{int}} = 1.5 \cdot 10^{13} \text{ Siemens/metre}$



# Appendix E. MPN Reports

Test = 2022071201

MPN02284\_NU-LHT-4M.mcd

AnDat = 20191013

NU-LHT-4M, 8 mm Holder with Crucible, RT - 1400C, in flowing argon, Lunar Regolith run for MPN

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  and  $\tan\delta$  :  
 ~~~~~

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.159$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.352$  gm/cc  
 Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz 2466MHz 2986MHz      Time (hours)

| samdns | $r_{\text{mm}}$ | $T_{\text{mm}, 1}$ | $\epsilon'_{\text{mm}, 1}$ | $\epsilon'_{\text{mm}, 2}$ | $\epsilon'_{\text{mm}, 3}$ | $\epsilon'_{\text{mm}, 4}$ | $\epsilon'_{\text{mm}, 5}$ | $\epsilon'_{\text{mm}, 6}$ | tlaps <sub>mm</sub> | sammass <sub>mm</sub> |
|--------|-----------------|--------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|-----------------------|
| 2.159  | 12              | 24                 | 4.58                       | 4.57                       | 4.55                       | 4.54                       | 4.5                        | 4.48                       | 0                   | 0.283                 |
| 2.159  | 13              | 24                 | 4.57                       | 4.56                       | 4.54                       | 4.53                       | 4.49                       | 4.47                       | 0.11                | 0.283                 |
| 2.159  | 14              | 24                 | 4.56                       | 4.55                       | 4.53                       | 4.52                       | 4.49                       | 4.47                       | 0.18                | 0.283                 |
| 2.159  | 15              | 119                | 4.5                        | 4.47                       | 4.47                       | 4.42                       | 4.38                       | 4.37                       | 0.39                | 0.283                 |
| 2.159  | 16              | 183                | 4.53                       | 4.49                       | 4.51                       | 4.45                       | 4.4                        | 4.39                       | 0.59                | 0.283                 |
| 2.159  | 17              | 240                | 4.6                        | 4.55                       | 4.57                       | 4.5                        | 4.45                       | 4.44                       | 0.77                | 0.283                 |
| 2.159  | 18              | 293                | 4.65                       | 4.6                        | 4.62                       | 4.54                       | 4.48                       | 4.48                       | 0.96                | 0.283                 |
| 2.159  | 19              | 342                | 4.67                       | 4.64                       | 4.66                       | 4.57                       | 4.51                       | 4.51                       | 1.14                | 0.283                 |
| 2.158  | 20              | 390                | 4.7                        | 4.66                       | 4.69                       | 4.6                        | 4.52                       | 4.54                       | 1.32                | 0.283                 |
| 2.156  | 21              | 436                | 4.75                       | 4.69                       | 4.72                       | 4.62                       | 4.55                       | 4.57                       | 1.49                | 0.283                 |
| 2.153  | 22              | 483                | 4.77                       | 4.72                       | 4.75                       | 4.66                       | 4.58                       | 4.6                        | 1.65                | 0.282                 |
| 2.148  | 23              | 530                | 4.81                       | 4.76                       | 4.79                       | 4.69                       | 4.6                        | 4.64                       | 1.82                | 0.282                 |
| 2.143  | 24              | 577                | 4.85                       | 4.78                       | 4.81                       | 4.71                       | 4.62                       | 4.66                       | 1.98                | 0.281                 |
| 2.136  | 25              | 623                | 4.84                       | 4.77                       | 4.81                       | 4.71                       | 4.61                       | 4.65                       | 2.13                | 0.28                  |
| 2.136  | 26              | 670                | 4.87                       | 4.8                        | 4.82                       | 4.72                       | 4.62                       | 4.67                       | 2.28                | 0.28                  |
| 2.136  | 27              | 717                | 4.93                       | 4.86                       | 4.88                       | 4.78                       | 4.67                       | 4.73                       | 2.43                | 0.28                  |
| 2.136  | 28              | 765                | 4.94                       | 4.85                       | 4.87                       | 4.77                       | 4.66                       | 4.72                       | 2.57                | 0.28                  |
| 2.136  | 29              | 811                | 4.93                       | 4.86                       | 4.88                       | 4.78                       | 4.66                       | 4.74                       | 2.71                | 0.28                  |
| 2.136  | 30              | 858                | 4.92                       | 4.86                       | 4.86                       | 4.78                       | 4.65                       | 4.73                       | 2.84                | 0.28                  |
| 2.136  | 31              | 906                | 4.93                       | 4.85                       | 4.86                       | 4.77                       | 4.64                       | 4.73                       | 2.97                | 0.28                  |
| 2.136  | 32              | 954                | 4.84                       | 4.77                       | 4.77                       | 4.7                        | 4.56                       | 4.66                       | 3.1                 | 0.28                  |
| 2.134  | 33              | 1003               | 4.89                       | 4.83                       | 4.82                       | 4.75                       | 4.61                       | 4.72                       | 3.23                | 0.28                  |
| 2.133  | 34              | 1051               | 4.91                       | 4.85                       | 4.83                       | 4.78                       | 4.63                       | 4.75                       | 3.37                | 0.28                  |
| 2.132  | 35              | 1100               | 5.12                       | 5.02                       | 4.97                       | 4.92                       | 4.75                       | 4.88                       | 3.5                 | 0.28                  |
| 2.131  | 36              | 1149               | 5.65                       | 5.41                       | 5.31                       | 5.24                       | 5.05                       | 5.13                       | 3.63                | 0.279                 |
| 2.129  | 37              | 1197               | 7.49                       | 6.82                       | 6.4                        | 6.17                       | 5.83                       | 5.9                        | 3.76                | 0.279                 |
| 2.041  | 38              | 1239               | 13.31                      | 11.11                      | 10.18                      | 9.73                       | 9.14                       | 9.22                       | 3.89                | 0.279                 |
| 1.959  | 39              | 1295               | 15.22                      | 13.52                      | 12.06                      | 11.24                      | 10.42                      | 10.42                      | 4.03                | 0.279                 |
| 1.882  | 40              | 1344               | 13.61                      | 15.05                      | 13.87                      | 13.12                      | 12.2                       | 12.43                      | 4.16                | 0.279                 |
| 1.965  | 41              | 1392               | 20.92                      | 19.99                      | 17.92                      | 17.11                      | 16.01                      | 17.15                      | 4.29                | 0.279                 |
| 2.053  | 42              | 1294               | 22.03                      | 17.53                      | 15.31                      | 14.15                      | 13                         | 12.78                      | 4.43                | 0.279                 |
| 2.147  | 43              | 1197               | 16.87                      | 13.66                      | 12.11                      | 11.12                      | 10.3                       | 9.86                       | 4.57                | 0.279                 |
| 2.246  | 44              | 1097               | 8.39                       | 7.93                       | 7.61                       | 7.25                       | 6.9                        | 6.72                       | 4.72                | 0.279                 |
| 2.352  | 45              | 1002               | 8.41                       | 8.11                       | 7.84                       | 7.43                       | 7.09                       | 6.82                       | 4.89                | 0.279                 |
| 2.352  | 46              | 904                | 8.2                        | 7.94                       | 7.71                       | 7.3                        | 6.98                       | 6.71                       | 5.07                | 0.279                 |
| 2.352  | 47              | 806                | 8.06                       | 7.81                       | 7.61                       | 7.2                        | 6.91                       | 6.62                       | 5.26                | 0.279                 |
| 2.352  | 48              | 707                | 7.82                       | 7.63                       | 7.47                       | 7.07                       | 6.8                        | 6.51                       | 5.5                 | 0.279                 |
| 2.352  | 49              | 610                | 7.58                       | 7.47                       | 7.32                       | 6.94                       | 6.7                        | 6.41                       | 5.78                | 0.279                 |
| 2.352  | 50              | 514                | 7.38                       | 7.29                       | 7.18                       | 6.81                       | 6.59                       | 6.29                       | 6.1                 | 0.279                 |
| 2.352  | 51              | 422                | 7.2                        | 7.13                       | 7.03                       | 6.68                       | 6.48                       | 6.18                       | 6.48                | 0.279                 |
| 2.352  | 52              | 330                | 7                          | 6.96                       | 6.87                       | 6.55                       | 6.36                       | 6.07                       | 6.94                | 0.279                 |
| 2.352  | 53              | 235                | 6.79                       | 6.79                       | 6.69                       | 6.41                       | 6.24                       | 5.95                       | 7.57                | 0.279                 |
| 2.352  | 54              | 127                | 6.48                       | 6.48                       | 6.38                       | 6.14                       | 6                          | 5.73                       | 8.68                | 0.279                 |
| 2.352  | 55              | 24                 | 6.4                        | 6.43                       | 6.3                        | 6.12                       | 5.99                       | 5.7                        | 8.89                | 0.279                 |



MPN-285\_NUW-LHT-5M\_Rickman\_1mm

Aug. 12, 2023

Lunar Simulant NUW-LHT-5M, Heat Treated in Ar/4%H<sub>2</sub>  
Measurements of Complex Dielectric Constant of Pellets  
from Room Temperature to 1100°C, in < 1 milliTorr Vacuum

Dr. Doug Rickman ( NASA) requested that Microwave Properties North measure the complex dielectric properties of heat-treated NUW-LHT-5M lunar regolith simulant up to 1100C in vacuum. The powder sample material from Prof. H. Shulman arrived at MPN on June 6 / 2023. Dr. Shulman had already heat-treated the powder at 750 C in a 4% hydrogen/argon mixture.

For this measurement, MPN pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. However, the measurement run included an initial cycle to 200C and back to room temperature to record any measureable moisture loss. The sample holder was cycled ( and measured) to 1100C before the run to “clean” the holder and measure the “empty holder” values, which are subtracted during the later data analysis.

The initial sample parameters were:

- a) diameter 3.65 +- 0.02 mm
- b) length of 3 pellet stack: 12.36 +- 0.05 mm
- c) mass 0.272 +- 0.002 gm
- kk) room temperature density  $2.12 \pm 0.05$  gm/cc.
- ll) appearance - three (stacked) light grey pellets ( see photos)
- mm) magnetic response - The pellets had a very weak attraction to a strong magnet.

After the initial “drying” cycle to 200C, the dielectric properties measurements were performed at RT ( twice) and then the temperature was ramped up to 1000C in 50C steps, then to 1100C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets were easily removed, and their combined mass determined. Then the empty holder was run up to 1100C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) diameter  $3.68 \pm 0.05$  mm
- b) pellet stack length  $12.54 \pm 0.05$  mm
- c) mass  $0.270 \pm 0.002$  gm
- jj) room temperature density  $2.02 \pm 0.05$  gm/cc.
- kk) appearance - three light beige pellets ( see photos)
- ll) magnetic response - The pellets had a moderate attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

| # | <u>Frequency(MHz)</u> | <u>Symbol</u> |
|---|-----------------------|---------------|
|---|-----------------------|---------------|

## Appendix E. MPN Reports

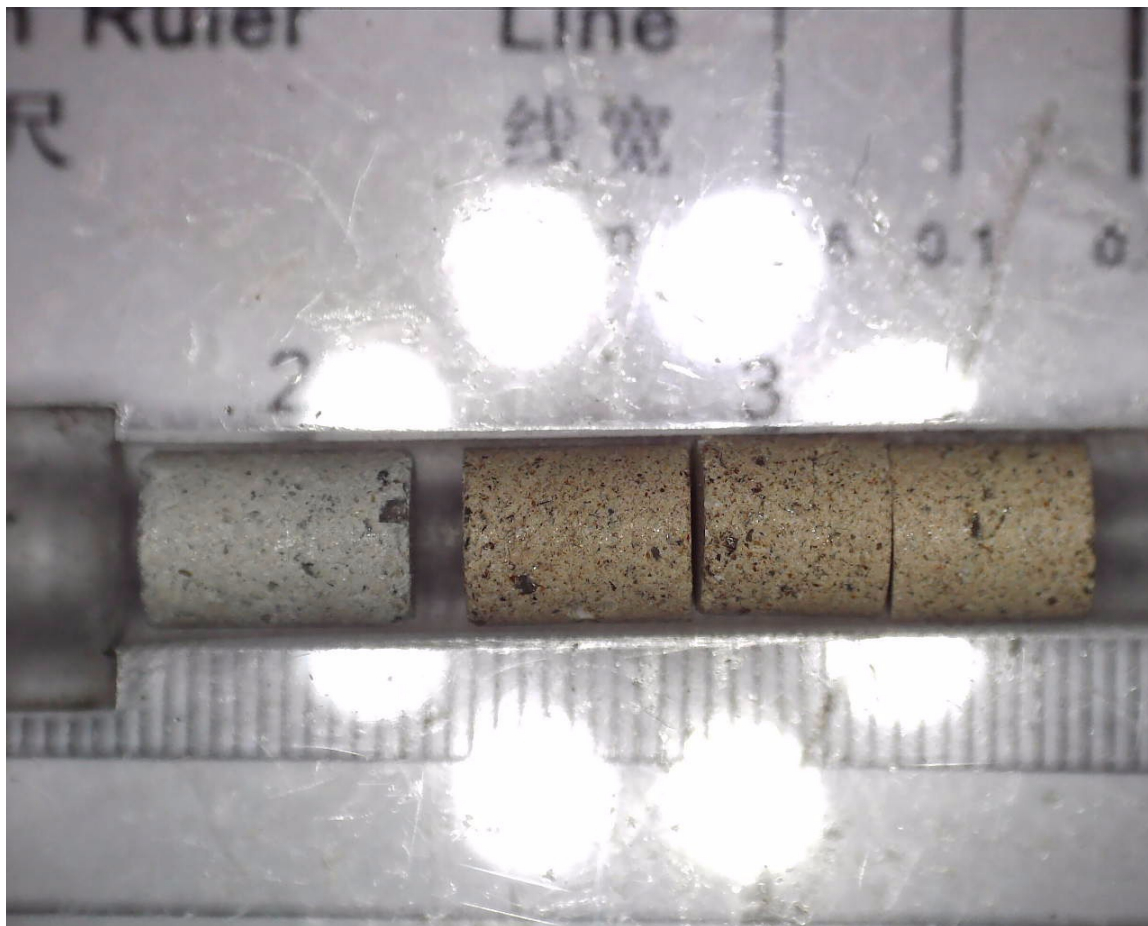
|   |      |                                                          |
|---|------|----------------------------------------------------------|
| 1 | 397  | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912  | blue square, solid line                                  |
| 3 | 1429 | black cross, solid line                                  |
| 4 | 1948 | blue circle, dotted line                                 |
| 5 | 2466 | red cross, dotted line                                   |
| 6 | 2986 | black diamond, dotted line                               |

### Comments on the data analysis:

A thermal expansion coefficient (CTE) of  $0.0 \cdot 10^{-6}/\text{C}$  was used.

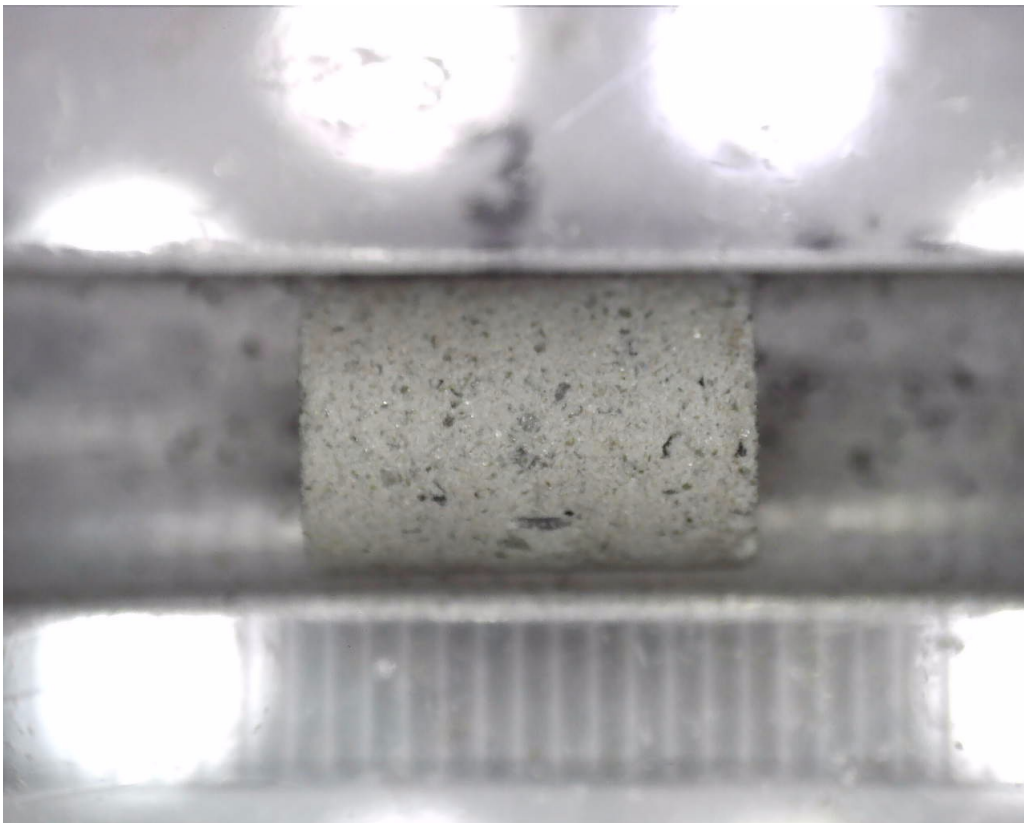
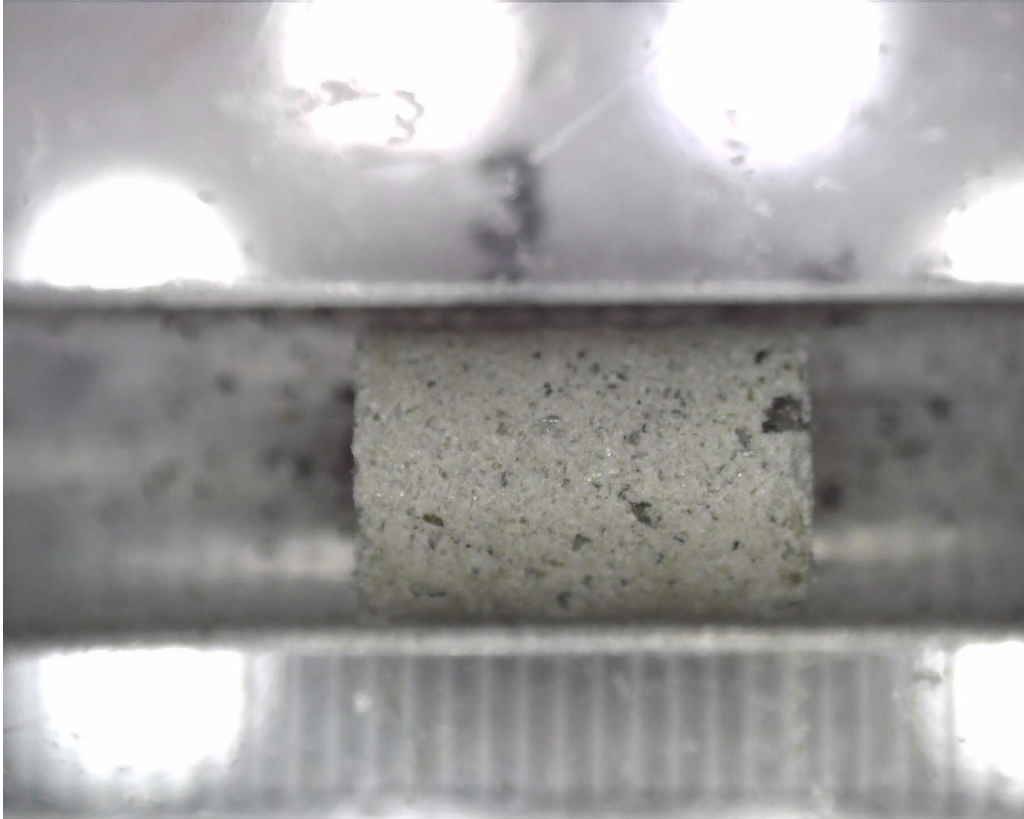
The final pellets appeared unchanged except for a beige colouring !.

The data for the ramp up to 1100C is interrupted by a slight decrease of the  $\epsilon'$  values which occurred between 850C and 950 C that resulted in a permanent change, suggesting a non-reversible phase change.



Left: Un-used initial pellet  
vacuum

Right: The 3 pellets after the run to 1100C in  $\sim 10^{-3}$  Torr



# Appendix E. MPN Reports

Two views of an un-used initial pellet ( 5.47 mm long, 3.64 mm diameter) – Pressed at ~ 33,000 psi

Code Calculates Estimated Sample Dimensions & Volume and Plots Density As a Function of Temperature

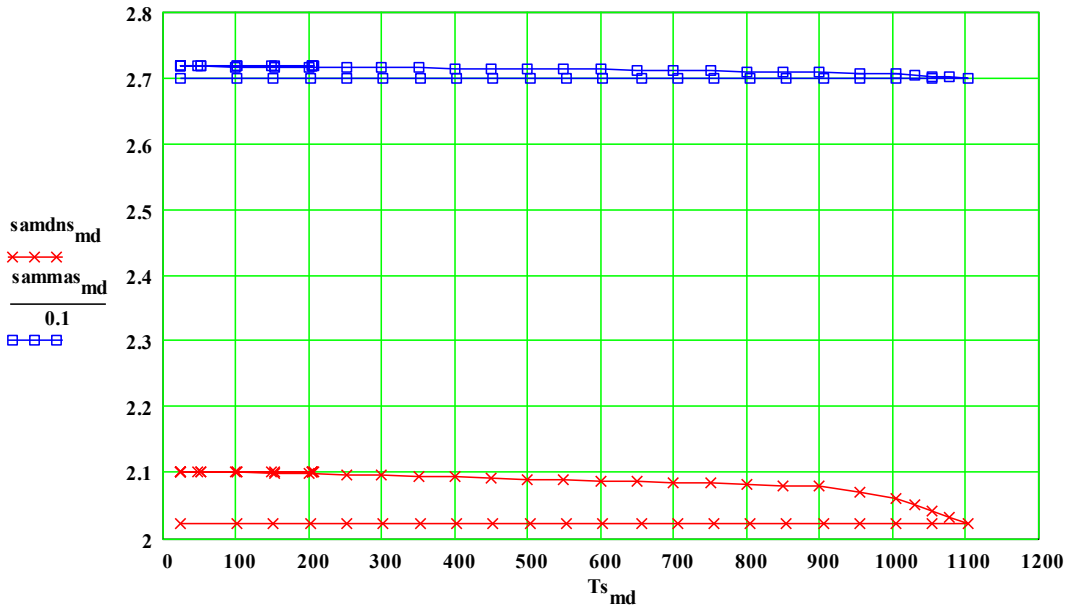
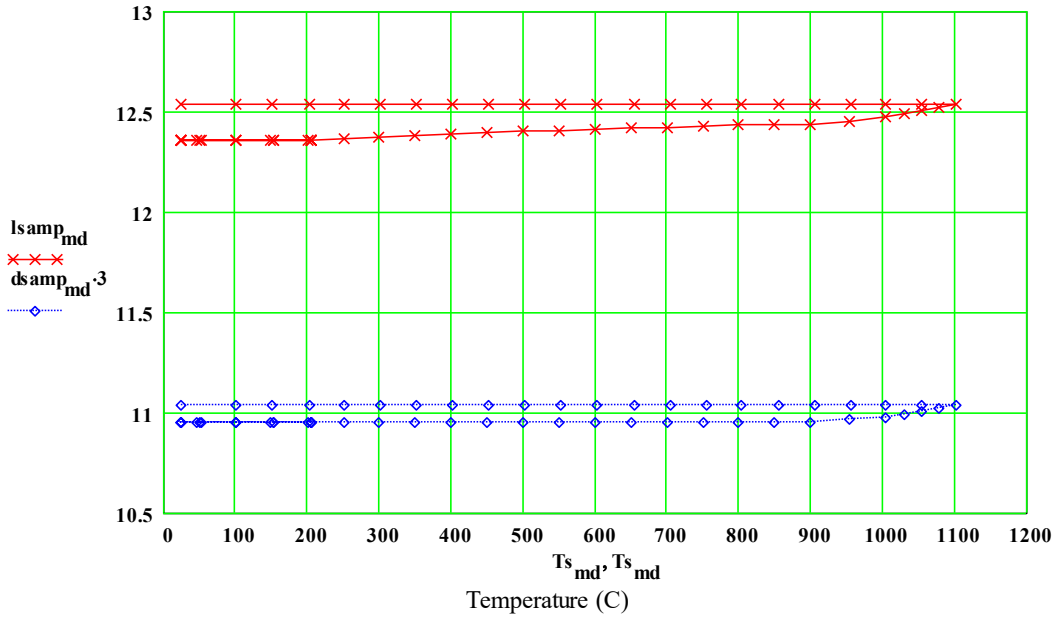
Test = 2023060601

NASA2358.mcd

AnDat = 20230609

1st Run: Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H , to 1100C, in vacuum ,for D. Rickman

Assumed Effective Dimensions (mm) and Density (gm/cc) as a Function of Temperature for Solid



# Appendix E. MPN Reports

Test = 2023060601

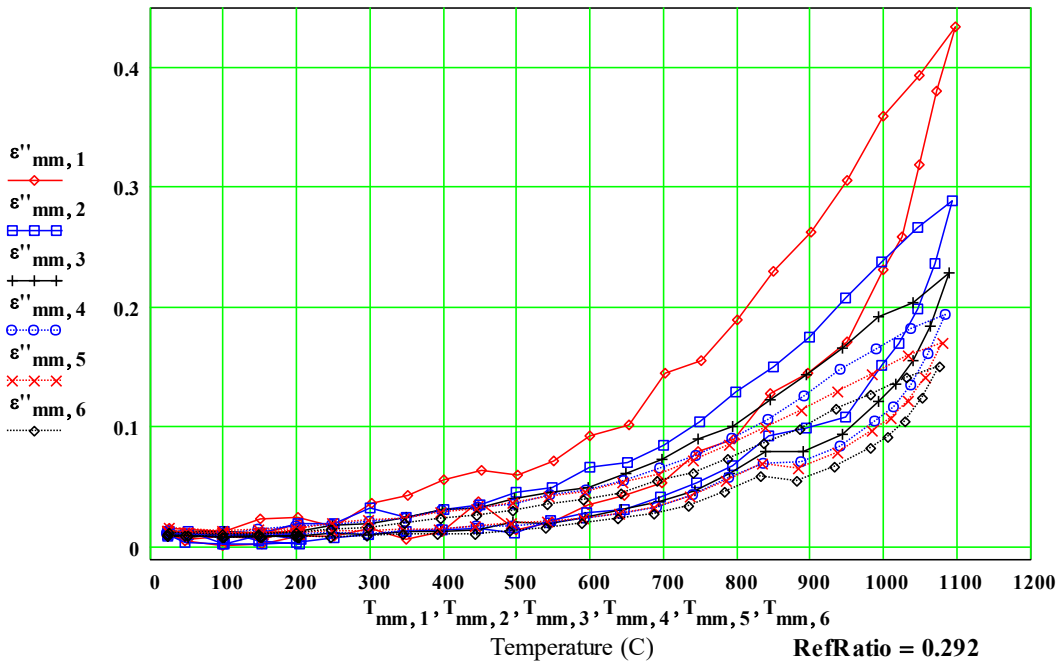
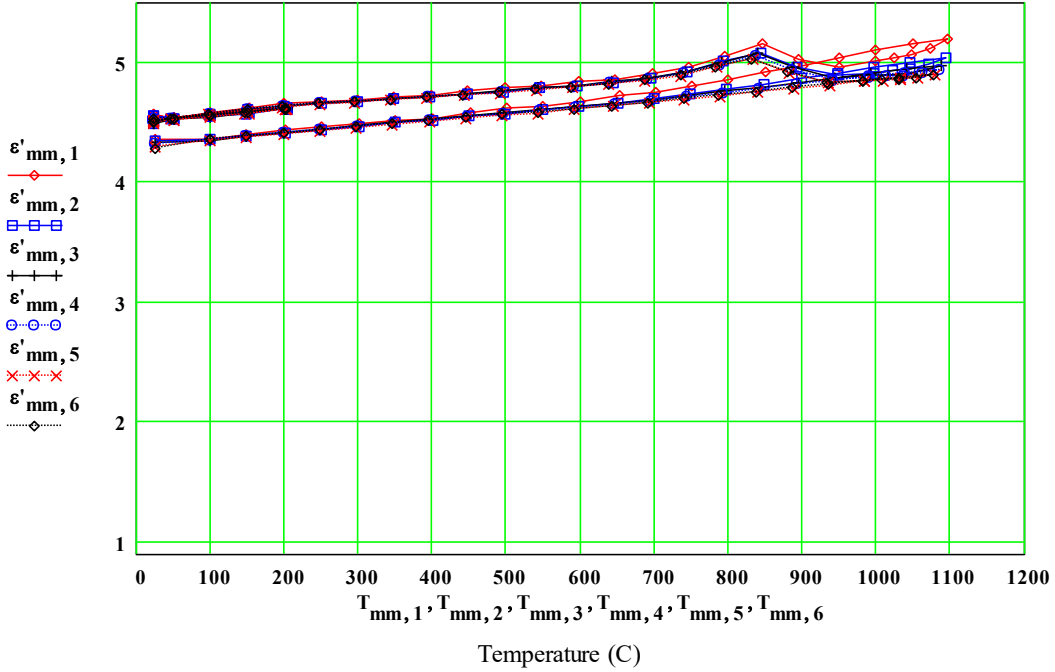
NASA2358.mcd

AnDat = 20230611

Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickme

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$

Final\_over\_Initial\_mass = 0.993



# Appendix E. MPN Reports

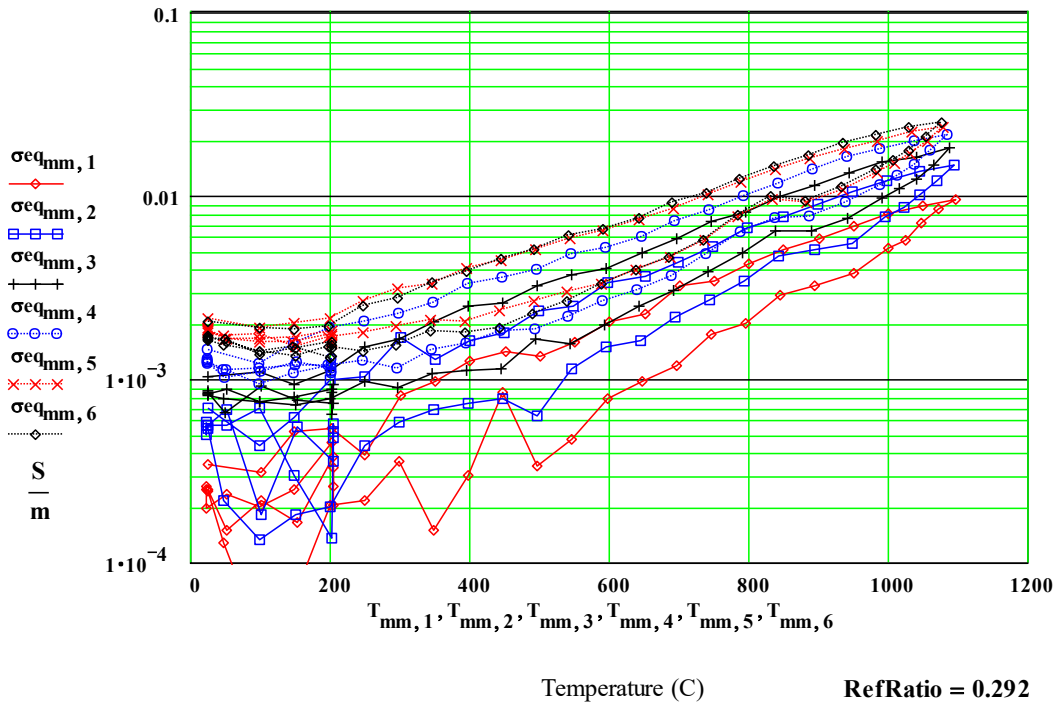
Test = 2023060601

NASA2358.mcd

AnDat = 20230611

Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickm

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2023060601

NASA2358.mcd

AnDat = 20230611

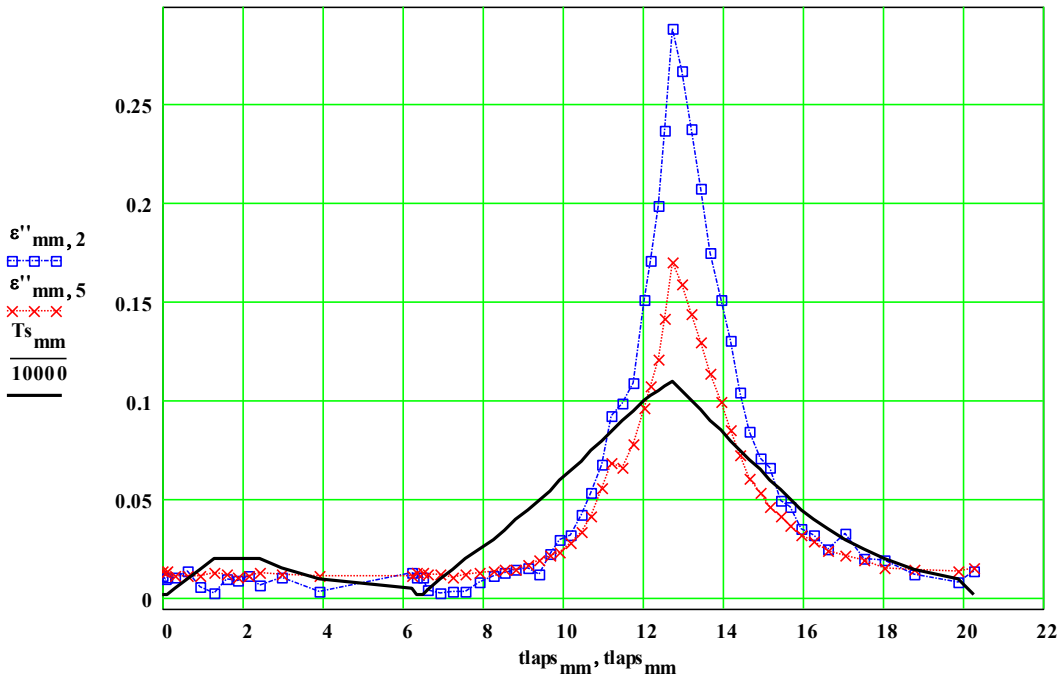
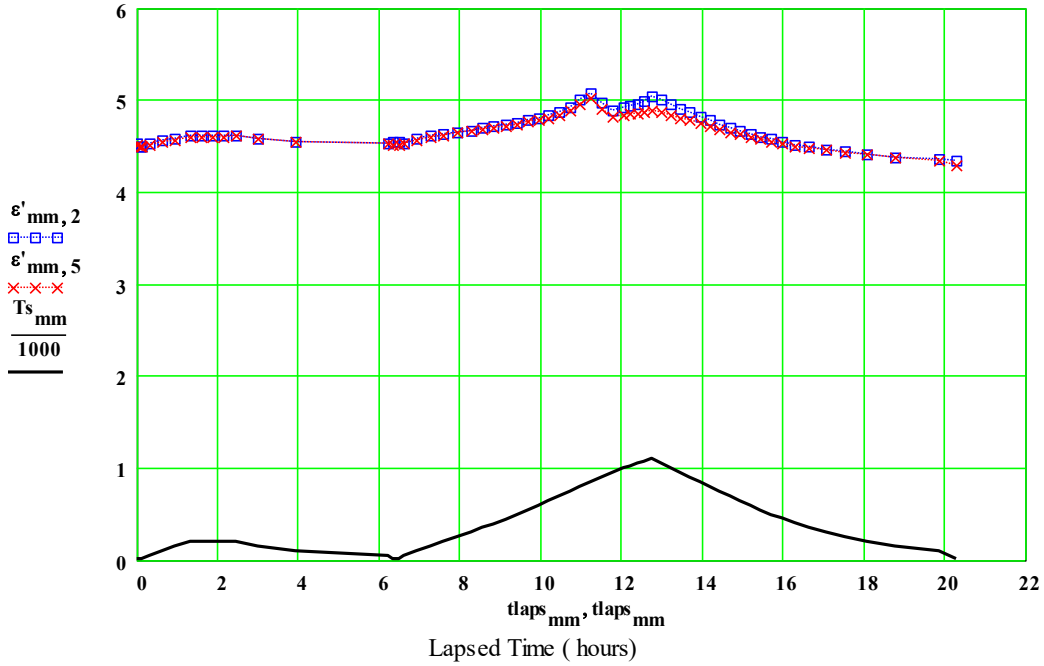
Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickman

Initial density =  $\text{sam dns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dns final} = 2.02 \text{ gm/cc}$        $\text{FracMassChange} = 0.99$

$\alpha_1 = 0$



# Appendix E. MPN Reports

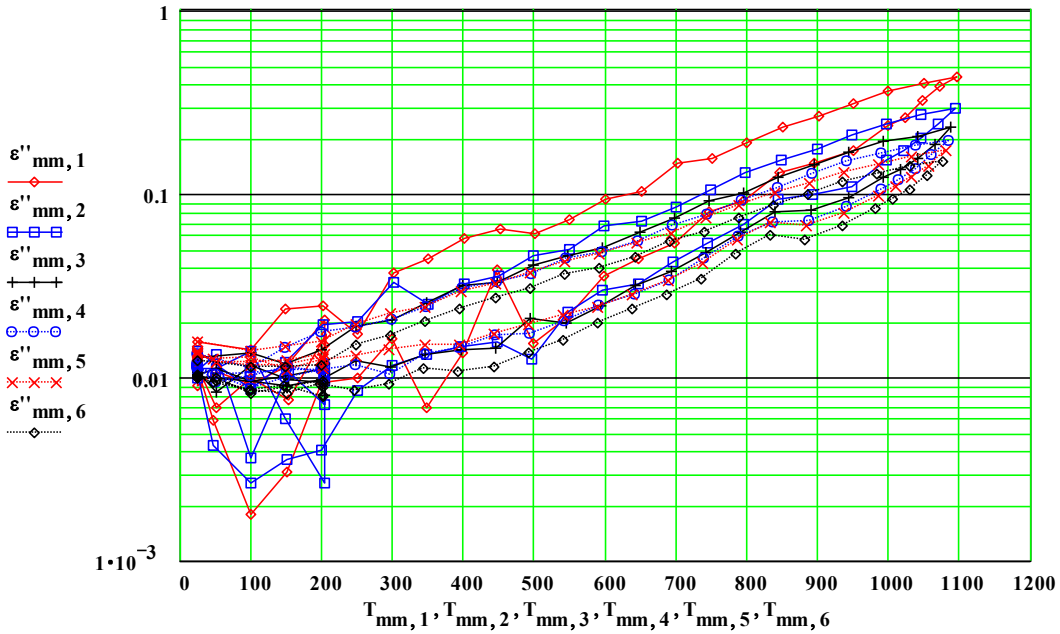
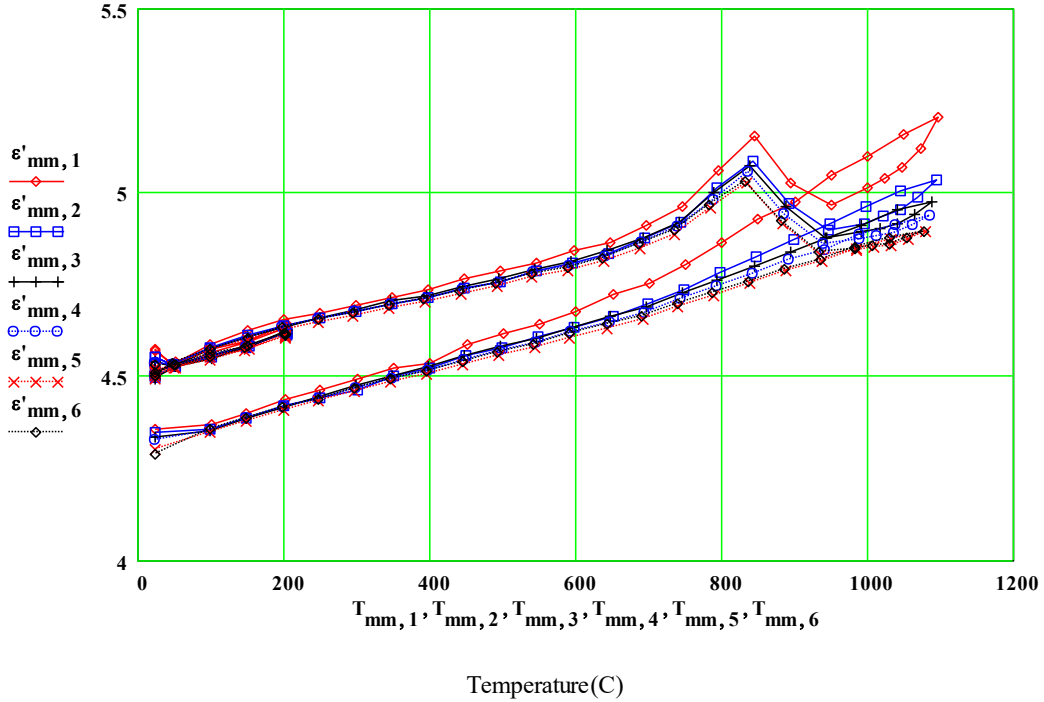
Test = 2023060601

NASA2358.mcd

AnDat = 20230611

Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023060601

NASA2358.mcd

AnDat = 20230611

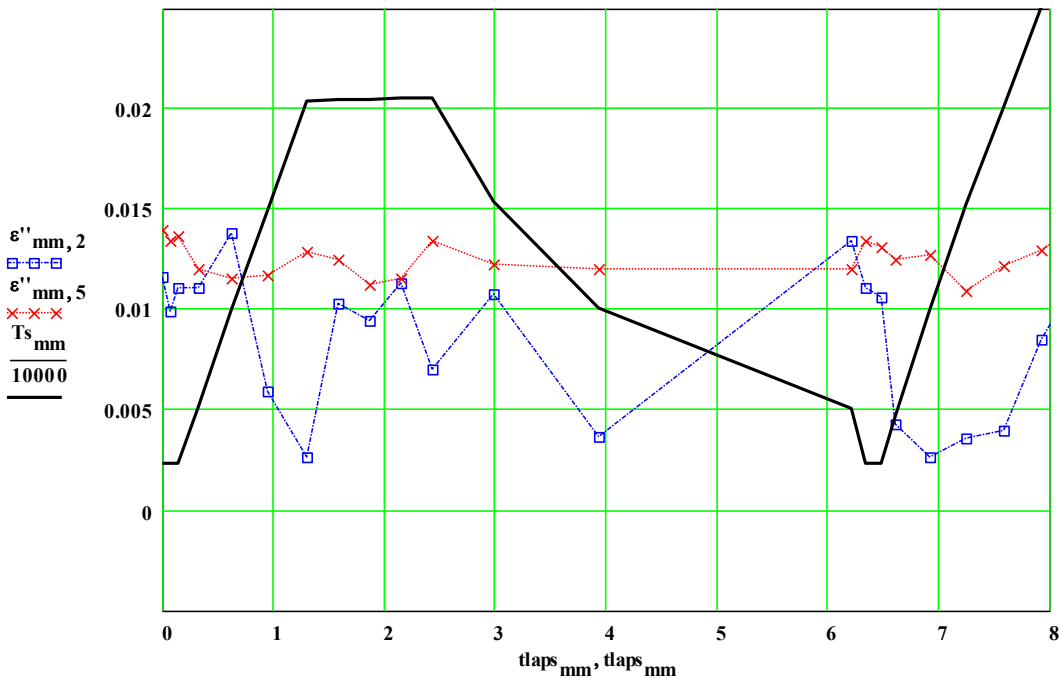
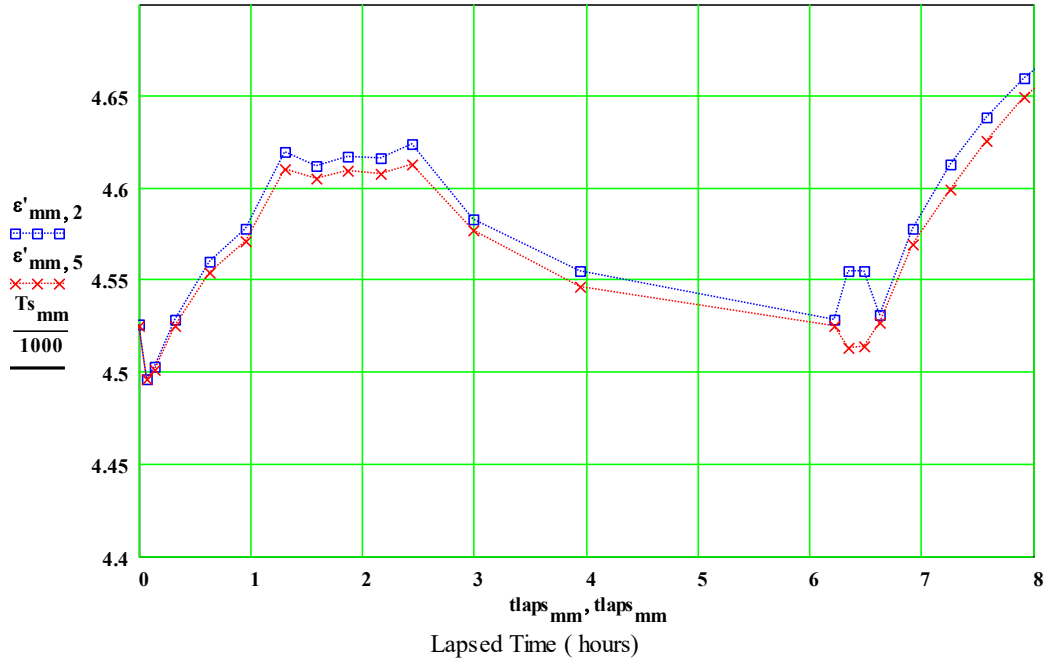
Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$        $\text{FracMassChange} = 0.99$

$\alpha_1 = 0$



Values for the initial cycle from RT to 200C and back to RT – then for the start of the ramp to 1100C.

The values demonstrate that within the error limits of  $\epsilon''$  ( $\pm 0.005$  at 915 MHz), there was no moisture loss during the cycle.

# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023060601

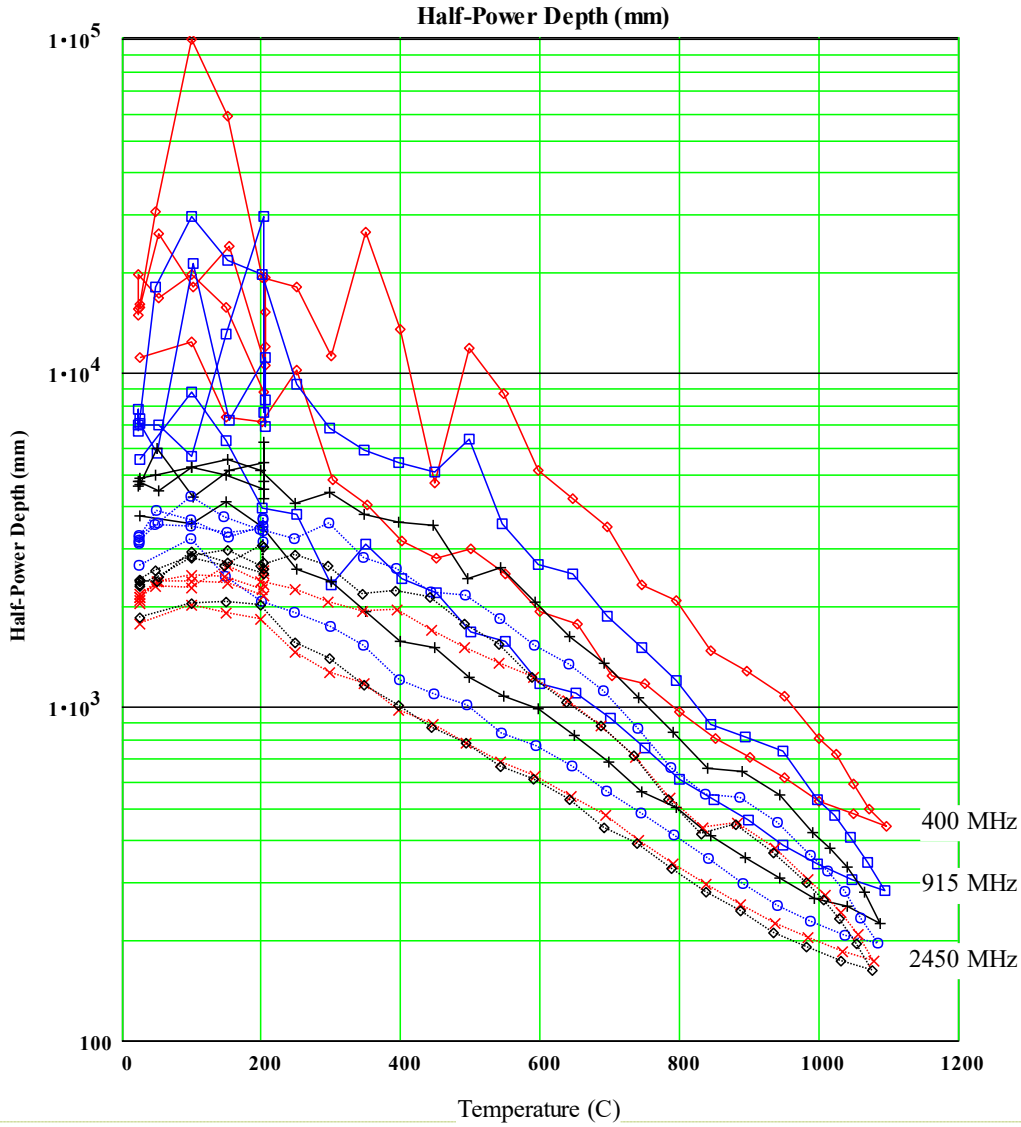
NASA2358.mcd

AnDat = 20230611

Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023060601

NASA2358.mcd

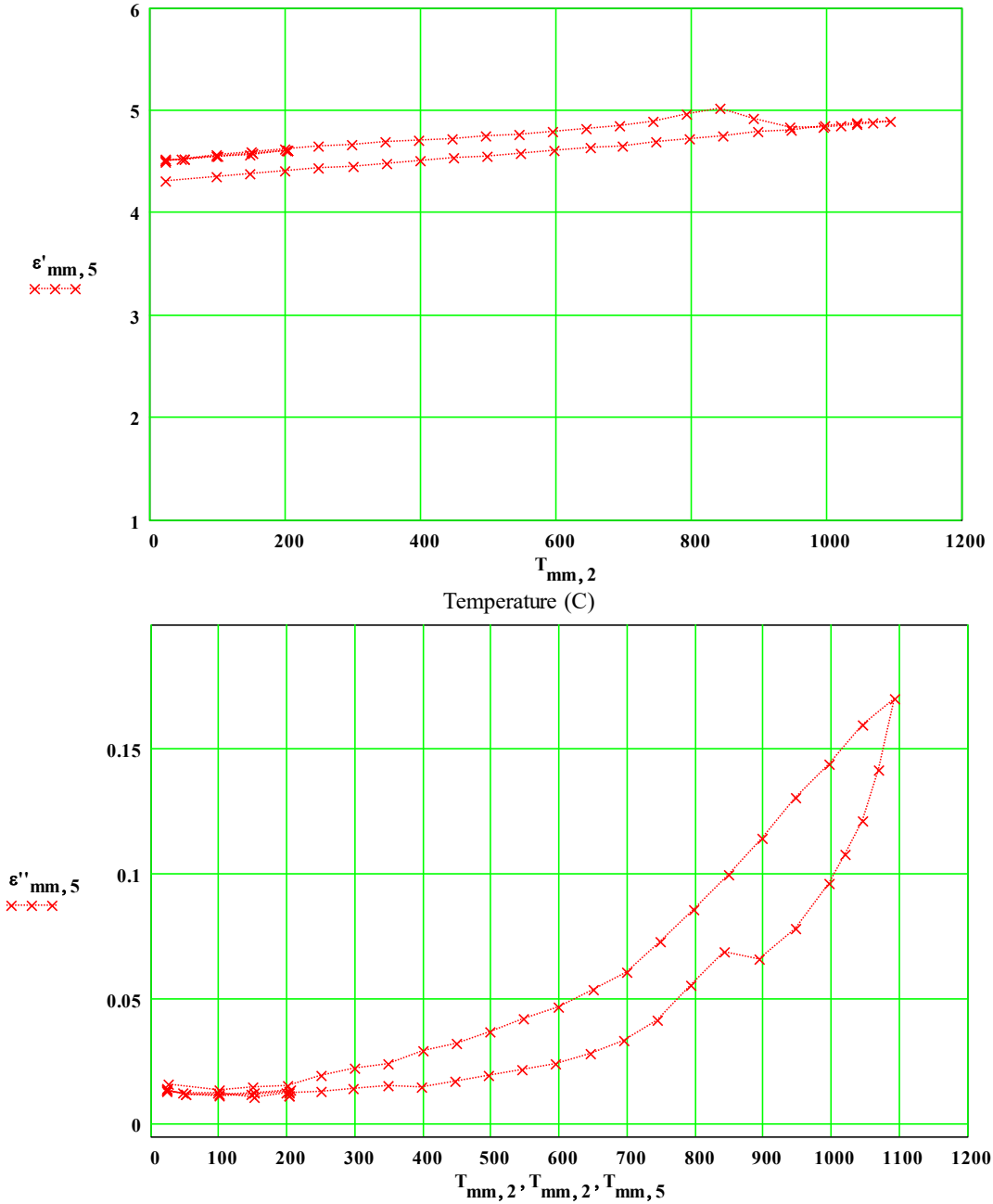
AnDat = 20230611

Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickman

Initial density =  $\text{sam dns}_{\text{NCal} + 1} = 2.1$  gm/cc, Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dns final} = 2.02$  gm/cc

## Values for 2450 MHz



# Appendix E. MPN Reports

Test = 2023060601

NASA2358.mcd

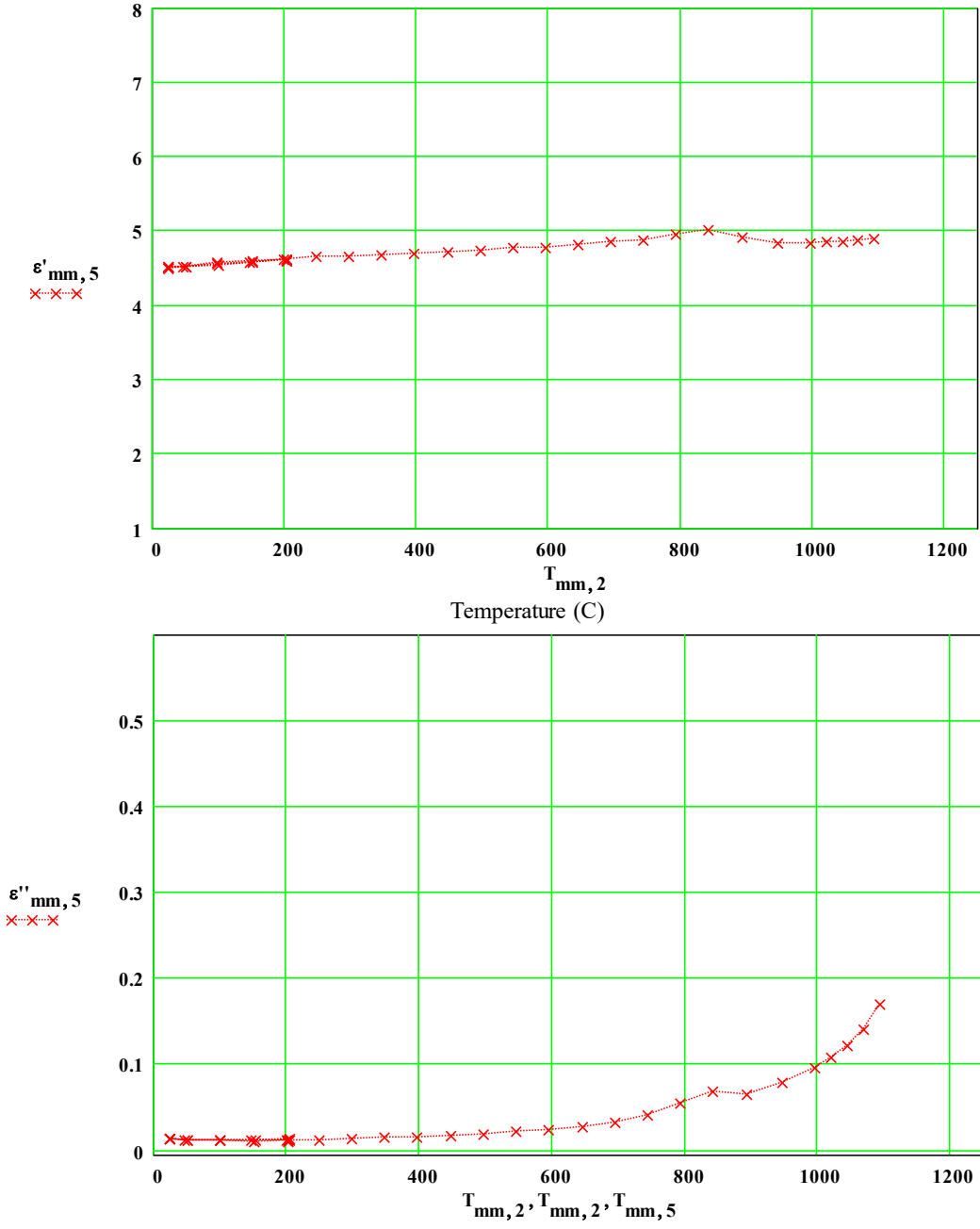
AnDat = 20230611

Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1$  gm/cc, Thermal exp. coeff  $\alpha_1 = 0$

Final density(25C) =  $\text{dnsfinal} = 2.02$  gm/cc

## Increasing Temperature Values for 2450 MHz



# Appendix E. MPN Reports

Test = 2023060601

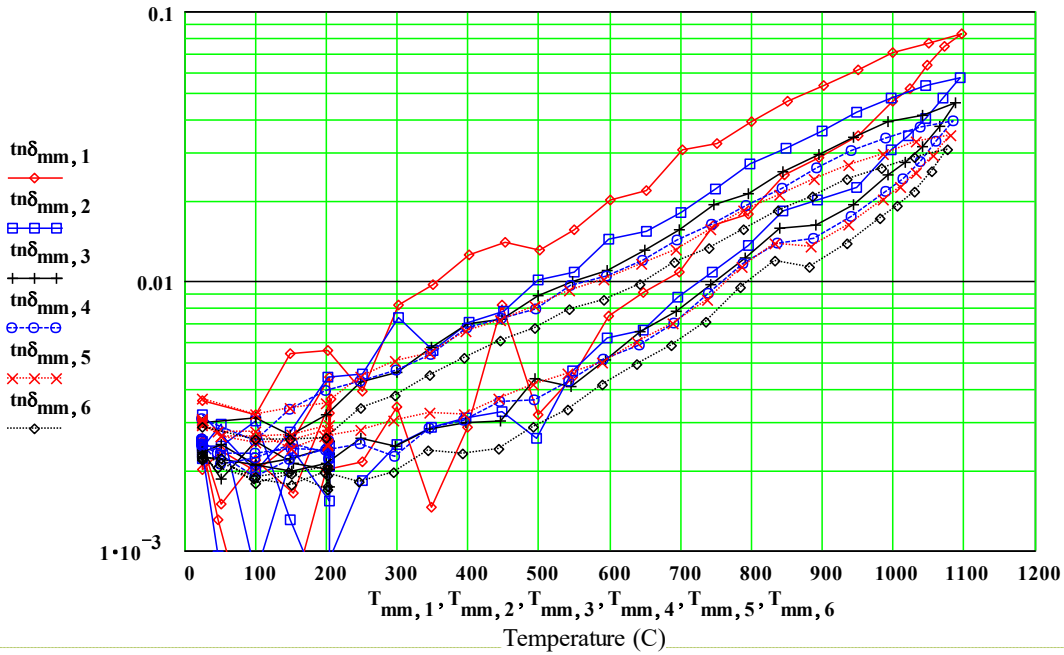
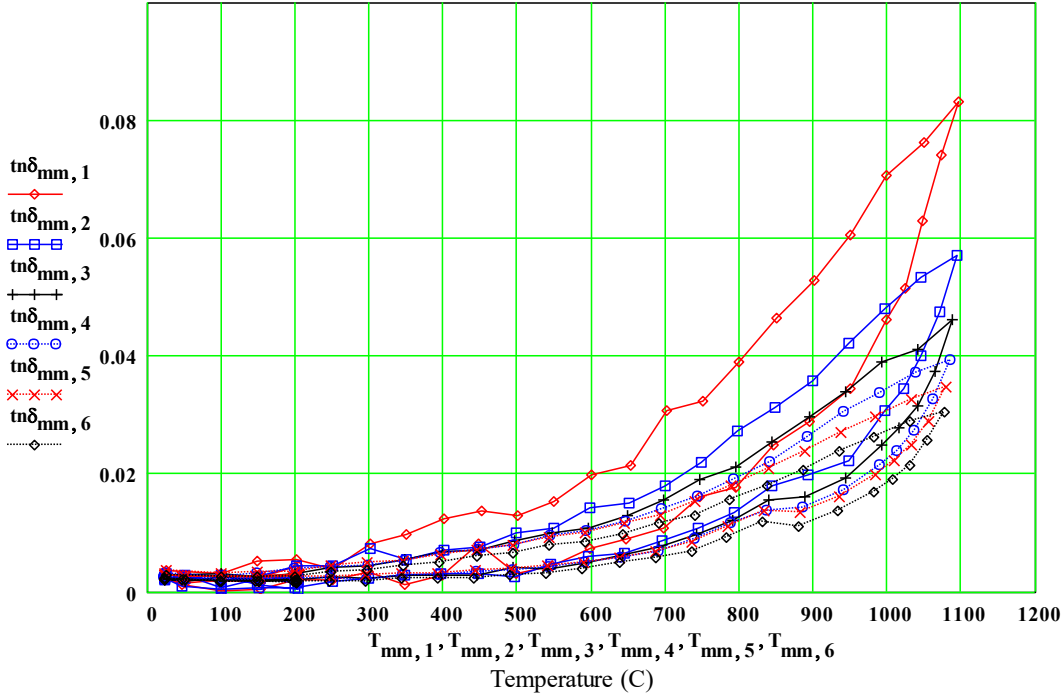
NASA2358.mcd

AnDat = 20230611

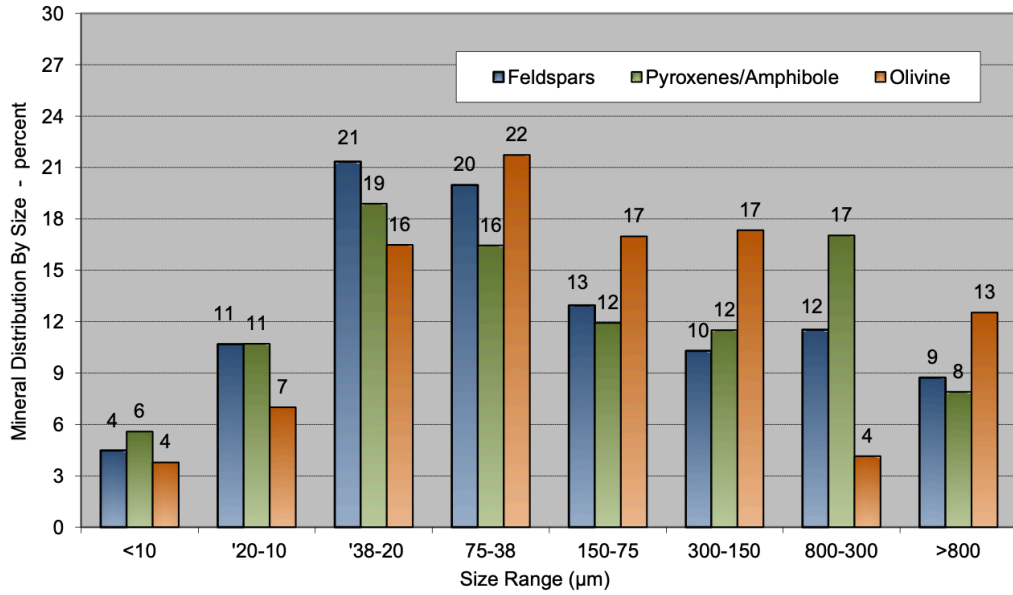
Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.1 \text{ gm/cc}$ ,

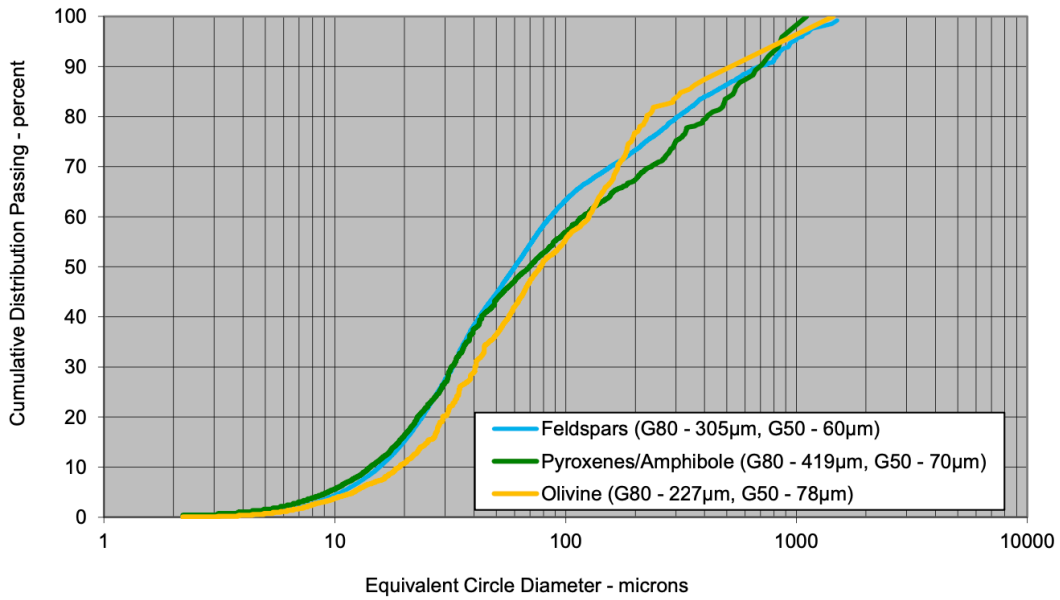
Final density(25C) =  $\text{dnsfinal} = 2.02 \text{ gm/cc}$



**FIGURE 3A**  
**MINERAL DISTRIBUTION BY THE MINERAL GRAIN SIZES**  
 NUW-LHT-5M Test 2 Jan 30, 2023, 222 $\mu$ m K<sub>80</sub>



**FIGURE 3B**  
**CUMULATIVE DISTRIBUTION BY THE MINERAL GRAIN SIZES**  
 NUW-LHT-5M Test 2 Jan 30, 2023, 222 $\mu$ m K<sub>80</sub>



Note: The sizing maybe overestimated due to coarse particle effects.

# Appendix E. MPN Reports

Test # = 2023060601      NASA2358.mcd      AnDat = 20230611  
 Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1100C, in vacuum (< 1 millitorr), for D. Rickm

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.103 \text{ gm/cc}$       Final density(25C) =  $\text{dnsfinal} = 2.024 \text{ gm/cc}$   
 Lapsed

| density | index | T(C)              | 397MHz                    | 912MHz                    | 1429MHz                   | 1948MHz                   | 2466MHz                   | 2986MHz                   | Time (hours)        | sammas               |
|---------|-------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------|----------------------|
| samdns  | mm    | T <sub>mm,1</sub> | $\epsilon'_{\text{mm},1}$ | $\epsilon'_{\text{mm},2}$ | $\epsilon'_{\text{mm},3}$ | $\epsilon'_{\text{mm},4}$ | $\epsilon'_{\text{mm},5}$ | $\epsilon'_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |
| 2.103   | 11    | 23                | 4.54                      | 4.53                      | 4.52                      | 4.53                      | 4.52                      | 4.53                      | 0                   | 0.272                |
| 2.103   | 12    | 24                | 4.5                       | 4.5                       | 4.49                      | 4.5                       | 4.5                       | 4.5                       | 0.08                | 0.272                |
| 2.103   | 13    | 24                | 4.51                      | 4.5                       | 4.5                       | 4.51                      | 4.5                       | 4.51                      | 0.13                | 0.272                |
| 2.103   | 14    | 52                | 4.54                      | 4.53                      | 4.53                      | 4.53                      | 4.53                      | 4.53                      | 0.33                | 0.272                |
| 2.103   | 15    | 100               | 4.58                      | 4.56                      | 4.56                      | 4.56                      | 4.55                      | 4.56                      | 0.62                | 0.272                |
| 2.103   | 16    | 148               | 4.6                       | 4.58                      | 4.58                      | 4.58                      | 4.57                      | 4.58                      | 0.95                | 0.272                |
| 2.103   | 17    | 203               | 4.64                      | 4.62                      | 4.62                      | 4.62                      | 4.61                      | 4.62                      | 1.31                | 0.272                |
| 2.103   | 18    | 204               | 4.63                      | 4.61                      | 4.61                      | 4.61                      | 4.61                      | 4.61                      | 1.59                | 0.272                |
| 2.103   | 19    | 204               | 4.64                      | 4.62                      | 4.62                      | 4.62                      | 4.61                      | 4.62                      | 1.87                | 0.272                |
| 2.103   | 20    | 205               | 4.62                      | 4.62                      | 4.62                      | 4.61                      | 4.61                      | 4.62                      | 2.15                | 0.272                |
| 2.103   | 21    | 205               | 4.64                      | 4.62                      | 4.63                      | 4.62                      | 4.61                      | 4.62                      | 2.44                | 0.272                |
| 2.103   | 22    | 153               | 4.6                       | 4.58                      | 4.58                      | 4.58                      | 4.58                      | 4.58                      | 2.98                | 0.272                |
| 2.102   | 23    | 101               | 4.57                      | 4.55                      | 4.55                      | 4.55                      | 4.55                      | 4.55                      | 3.94                | 0.272                |
| 2.102   | 24    | 51                | 4.53                      | 4.53                      | 4.53                      | 4.53                      | 4.53                      | 4.53                      | 6.22                | 0.272                |
| 2.102   | 25    | 24                | 4.57                      | 4.56                      | 4.54                      | 4.54                      | 4.51                      | 4.5                       | 6.35                | 0.272                |
| 2.102   | 26    | 24                | 4.58                      | 4.55                      | 4.54                      | 4.54                      | 4.51                      | 4.5                       | 6.49                | 0.272                |
| 2.102   | 27    | 47                | 4.53                      | 4.53                      | 4.53                      | 4.53                      | 4.53                      | 4.54                      | 6.62                | 0.272                |
| 2.101   | 28    | 99                | 4.59                      | 4.58                      | 4.57                      | 4.58                      | 4.57                      | 4.58                      | 6.92                | 0.272                |
| 2.101   | 29    | 152               | 4.62                      | 4.61                      | 4.61                      | 4.61                      | 4.6                       | 4.61                      | 7.25                | 0.272                |
| 2.101   | 30    | 200               | 4.66                      | 4.64                      | 4.64                      | 4.63                      | 4.63                      | 4.63                      | 7.59                | 0.272                |
| 2.099   | 31    | 250               | 4.67                      | 4.66                      | 4.66                      | 4.66                      | 4.65                      | 4.66                      | 7.92                | 0.272                |
| 2.097   | 32    | 299               | 4.69                      | 4.68                      | 4.68                      | 4.68                      | 4.67                      | 4.67                      | 8.26                | 0.272                |
| 2.096   | 33    | 348               | 4.71                      | 4.7                       | 4.71                      | 4.7                       | 4.69                      | 4.69                      | 8.55                | 0.272                |
| 2.094   | 34    | 398               | 4.74                      | 4.71                      | 4.72                      | 4.71                      | 4.7                       | 4.71                      | 8.83                | 0.272                |
| 2.093   | 35    | 448               | 4.77                      | 4.74                      | 4.74                      | 4.74                      | 4.72                      | 4.73                      | 9.13                | 0.271                |
| 2.091   | 36    | 498               | 4.79                      | 4.76                      | 4.77                      | 4.76                      | 4.74                      | 4.75                      | 9.42                | 0.271                |
| 2.09    | 37    | 547               | 4.81                      | 4.79                      | 4.79                      | 4.78                      | 4.77                      | 4.78                      | 9.68                | 0.271                |
| 2.089   | 38    | 597               | 4.84                      | 4.81                      | 4.81                      | 4.8                       | 4.79                      | 4.8                       | 9.94                | 0.271                |
| 2.087   | 39    | 647               | 4.87                      | 4.84                      | 4.84                      | 4.83                      | 4.81                      | 4.82                      | 10.2                | 0.271                |
| 2.086   | 40    | 697               | 4.91                      | 4.88                      | 4.88                      | 4.87                      | 4.85                      | 4.86                      | 10.46               | 0.271                |
| 2.085   | 41    | 746               | 4.96                      | 4.92                      | 4.92                      | 4.91                      | 4.89                      | 4.9                       | 10.71               | 0.271                |
| 2.083   | 42    | 796               | 5.06                      | 5.01                      | 5                         | 4.98                      | 4.96                      | 4.97                      | 10.97               | 0.271                |
| 2.082   | 43    | 845               | 5.15                      | 5.09                      | 5.08                      | 5.06                      | 5.03                      | 5.03                      | 11.23               | 0.271                |
| 2.082   | 44    | 895               | 5.03                      | 4.97                      | 4.96                      | 4.94                      | 4.91                      | 4.92                      | 11.5                | 0.271                |
| 2.072   | 45    | 950               | 4.97                      | 4.9                       | 4.88                      | 4.86                      | 4.83                      | 4.84                      | 11.77               | 0.271                |
| 2.063   | 46    | 999               | 5.01                      | 4.92                      | 4.89                      | 4.87                      | 4.84                      | 4.85                      | 12.03               | 0.271                |
| 2.053   | 47    | 1024              | 5.04                      | 4.94                      | 4.9                       | 4.88                      | 4.85                      | 4.86                      | 12.21               | 0.271                |
| 2.043   | 48    | 1048              | 5.07                      | 4.95                      | 4.92                      | 4.89                      | 4.86                      | 4.86                      | 12.39               | 0.27                 |
| 2.034   | 49    | 1072              | 5.12                      | 4.99                      | 4.94                      | 4.91                      | 4.87                      | 4.88                      | 12.56               | 0.27                 |
| 2.024   | 50    | 1096              | 5.2                       | 5.04                      | 4.98                      | 4.94                      | 4.89                      | 4.89                      | 12.74               | 0.27                 |
| 2.024   | 51    | 1048              | 5.16                      | 5                         | 4.95                      | 4.91                      | 4.88                      | 4.88                      | 12.97               | 0.27                 |
| 2.024   | 52    | 999               | 5.1                       | 4.96                      | 4.91                      | 4.88                      | 4.85                      | 4.85                      | 13.21               | 0.27                 |
| 2.024   | 53    | 950               | 5.05                      | 4.91                      | 4.88                      | 4.85                      | 4.81                      | 4.82                      | 13.45               | 0.27                 |
| 2.024   | 54    | 901               | 4.98                      | 4.87                      | 4.84                      | 4.82                      | 4.79                      | 4.79                      | 13.7                | 0.27                 |
| 2.024   | 55    | 850               | 4.93                      | 4.82                      | 4.8                       | 4.78                      | 4.75                      | 4.76                      | 13.94               | 0.27                 |
| 2.024   | 56    | 800               | 4.87                      | 4.78                      | 4.76                      | 4.74                      | 4.72                      | 4.73                      | 14.19               | 0.27                 |
| 2.024   | 57    | 751               | 4.81                      | 4.74                      | 4.73                      | 4.71                      | 4.69                      | 4.7                       | 14.44               | 0.27                 |
| 2.024   | 58    | 701               | 4.75                      | 4.7                       | 4.69                      | 4.67                      | 4.66                      | 4.67                      | 14.68               | 0.27                 |
| 2.024   | 59    | 652               | 4.72                      | 4.66                      | 4.67                      | 4.65                      | 4.63                      | 4.64                      | 14.93               | 0.27                 |
| 2.024   | 60    | 599               | 4.68                      | 4.64                      | 4.64                      | 4.62                      | 4.61                      | 4.62                      | 15.19               | 0.27                 |

mq = 61,62...nd - Nempties

| samdns | mmq | T <sub>mmq,1</sub> | $\epsilon'_{\text{mmq},1}$ | $\epsilon'_{\text{mmq},2}$ | $\epsilon'_{\text{mmq},3}$ | $\epsilon'_{\text{mmq},4}$ | $\epsilon'_{\text{mmq},5}$ | $\epsilon'_{\text{mmq},6}$ | tlaps <sub>mq</sub> | sammas <sub>mq</sub> |
|--------|-----|--------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|
| 2.024  | 61  | 550                | 4.64                       | 4.61                       | 4.61                       | 4.59                       | 4.58                       | 4.59                       | 15.43               | 0.27                 |
| 2.024  | 62  | 500                | 4.62                       | 4.58                       | 4.58                       | 4.57                       | 4.56                       | 4.57                       | 15.69               | 0.27                 |
| 2.024  | 63  | 451                | 4.59                       | 4.56                       | 4.56                       | 4.54                       | 4.53                       | 4.54                       | 15.98               | 0.27                 |
| 2.024  | 64  | 401                | 4.54                       | 4.53                       | 4.53                       | 4.52                       | 4.51                       | 4.52                       | 16.29               | 0.27                 |
| 2.024  | 65  | 350                | 4.52                       | 4.5                        | 4.5                        | 4.49                       | 4.48                       | 4.49                       | 16.64               | 0.27                 |
| 2.024  | 66  | 301                | 4.5                        | 4.46                       | 4.48                       | 4.47                       | 4.46                       | 4.47                       | 17.05               | 0.27                 |
| 2.024  | 67  | 250                | 4.46                       | 4.44                       | 4.45                       | 4.44                       | 4.43                       | 4.44                       | 17.51               | 0.27                 |
| 2.024  | 68  | 201                | 4.44                       | 4.42                       | 4.42                       | 4.42                       | 4.41                       | 4.42                       | 18.06               | 0.27                 |
| 2.024  | 69  | 149                | 4.4                        | 4.39                       | 4.39                       | 4.39                       | 4.38                       | 4.39                       | 18.79               | 0.27                 |
| 2.024  | 70  | 100                | 4.37                       | 4.36                       | 4.36                       | 4.36                       | 4.35                       | 4.36                       | 19.88               | 0.27                 |
| 2.024  | 71  | 25                 | 4.36                       | 4.35                       | 4.34                       | 4.33                       | 4.3                        | 4.29                       | 20.29               | 0.27                 |

# Appendix E. MPN Reports

Test = 2023060601      NASA2358.mcd      AnDat = 20230611  
 Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub> to 1100C, in vacuum (< 1 millitorr), for D. Rickm

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ~~~~~

Initial density =  $\text{samdns}_{\text{NCal}+1} = 2.103 \text{ gm/cc}$       Final density(25C) =  $\text{dnsfinal} = 2.024 \text{ gm/cc}$   
 Lapsed

density index T(C) 397MHz 912MHz 1429MHz 1948MHz2466MHz 2986MHz      Time (hours)

samdns	mm	T <sub>mm</sub>	$\epsilon''_{\text{mm},1}$	$\epsilon''_{\text{mm},2}$	$\epsilon''_{\text{mm},3}$	$\epsilon''_{\text{mm},4}$	$\epsilon''_{\text{mm},5}$	$\epsilon''_{\text{mm},6}$	tlaps <sub>mm</sub>	sammas <sub>mm</sub>
2.103	11	23	0.012	0.012	0.01	0.012	0.014	0.01	0	0.272
2.103	12	24	0.011	0.01	0.011	0.012	0.013	0.01	0.08	0.272
2.103	13	24	0.009	0.011	0.01	0.011	0.014	0.01	0.13	0.272
2.103	14	52	0.011	0.011	0.011	0.01	0.012	0.01	0.33	0.272
2.103	15	100	0.009	0.014	0.009	0.009	0.012	0.009	0.62	0.272
2.103	16	148	0.011	0.006	0.01	0.01	0.012	0.009	0.95	0.272
2.103	17	203	0.021	0.003	0.011	0.011	0.013	0.008	1.31	0.272
2.103	18	204	0.009	0.01	0.011	0.01	0.012	0.009	1.59	0.272
2.103	19	204	0.015	0.009	0.008	0.012	0.011	0.009	1.87	0.272
2.103	20	205	0.012	0.011	0.012	0.01	0.012	0.008	2.15	0.272
2.103	21	205	0.017	0.007	0.009	0.011	0.013	0.009	2.44	0.272
2.103	22	153	0.008	0.011	0.01	0.011	0.012	0.009	2.98	0.272
2.102	23	101	0.01	0.004	0.012	0.01	0.012	0.008	3.94	0.272
2.102	24	51	0.007	0.013	0.008	0.009	0.012	0.01	6.22	0.272
2.102	25	24	0.011	0.011	0.011	0.011	0.013	0.01	6.35	0.272
2.102	26	24	0.011	0.011	0.01	0.011	0.013	0.01	6.49	0.272
2.102	27	47	0.006	0.004	0.01	0.01	0.013	0.009	6.62	0.272
2.101	28	99	0.002	0.003	0.009	0.011	0.013	0.008	6.92	0.272
2.101	29	152	0.003	0.004	0.009	0.011	0.011	0.008	7.25	0.272
2.101	30	200	0.009	0.004	0.01	0.011	0.012	0.009	7.59	0.272
2.099	31	250	0.01	0.009	0.012	0.012	0.013	0.008	7.92	0.272
2.097	32	299	0.016	0.012	0.011	0.01	0.014	0.009	8.26	0.272
2.096	33	348	0.007	0.013	0.013	0.013	0.015	0.011	8.55	0.272
2.094	34	398	0.014	0.015	0.014	0.014	0.015	0.011	8.83	0.272
2.093	35	448	0.039	0.016	0.014	0.017	0.017	0.011	9.13	0.271
2.091	36	498	0.015	0.013	0.021	0.017	0.019	0.014	9.42	0.271
2.09	37	547	0.021	0.022	0.02	0.02	0.022	0.016	9.68	0.271
2.089	38	597	0.036	0.03	0.025	0.025	0.024	0.02	9.94	0.271
2.087	39	647	0.044	0.032	0.031	0.028	0.028	0.024	10.2	0.271
2.086	40	697	0.053	0.043	0.038	0.034	0.034	0.028	10.46	0.271
2.085	41	746	0.08	0.053	0.048	0.044	0.042	0.034	10.71	0.271
2.083	42	796	0.09	0.068	0.061	0.058	0.056	0.047	10.97	0.271
2.082	43	845	0.129	0.093	0.08	0.07	0.069	0.06	11.23	0.271
2.082	44	895	0.145	0.099	0.081	0.071	0.066	0.056	11.5	0.271
2.072	45	950	0.172	0.109	0.094	0.084	0.078	0.067	11.77	0.271
2.063	46	999	0.232	0.152	0.122	0.105	0.097	0.082	12.03	0.271
2.053	47	1024	0.26	0.171	0.136	0.117	0.108	0.093	12.21	0.271
2.043	48	1048	0.32	0.199	0.156	0.135	0.122	0.105	12.39	0.27
2.034	49	1072	0.38	0.238	0.185	0.161	0.142	0.125	12.56	0.27
2.024	50	1096	0.434	0.289	0.23	0.194	0.17	0.15	12.74	0.27
2.024	51	1048	0.394	0.268	0.204	0.183	0.16	0.141	12.97	0.27
2.024	52	999	0.36	0.238	0.192	0.165	0.144	0.128	13.21	0.27
2.024	53	950	0.306	0.208	0.167	0.148	0.13	0.115	13.45	0.27
2.024	54	901	0.264	0.175	0.144	0.126	0.114	0.099	13.7	0.27
2.024	55	850	0.23	0.151	0.123	0.106	0.1	0.087	13.94	0.27
2.024	56	800	0.19	0.13	0.101	0.09	0.086	0.074	14.19	0.27
2.024	57	751	0.155	0.105	0.091	0.077	0.073	0.062	14.44	0.27
2.024	58	701	0.146	0.085	0.073	0.066	0.061	0.055	14.68	0.27
2.024	59	652	0.102	0.071	0.061	0.055	0.054	0.045	14.93	0.27
2.024	60	599	0.093	0.067	0.051	0.048	0.047	0.039	15.19	0.27

m<sub>q</sub> := 61,62...nd - Neptunies

samdns	m <sub>q</sub>	T <sub>m<sub>q</sub></sub>	$\epsilon''_{\text{mq},1}$	$\epsilon''_{\text{mq},2}$	$\epsilon''_{\text{mq},3}$	$\epsilon''_{\text{mq},4}$	$\epsilon''_{\text{mq},5}$	$\epsilon''_{\text{mq},6}$	tlaps <sub>m<sub>q</sub></sub>	sammas <sub>m<sub>q</sub></sub>
2.024	61	550	0.072	0.05	0.046	0.044	0.042	0.036	15.43	0.27
2.024	62	500	0.06	0.046	0.041	0.036	0.037	0.03	15.69	0.27
2.024	63	451	0.064	0.035	0.033	0.033	0.032	0.027	15.98	0.27
2.024	64	401	0.057	0.032	0.031	0.03	0.029	0.023	16.29	0.27
2.024	65	350	0.044	0.025	0.026	0.024	0.024	0.02	16.64	0.27
2.024	66	301	0.037	0.033	0.021	0.021	0.022	0.017	17.05	0.27
2.024	67	250	0.017	0.02	0.019	0.019	0.02	0.015	17.51	0.27
2.024	68	201	0.025	0.019	0.014	0.017	0.015	0.012	18.06	0.27
2.024	69	149	0.024	0.012	0.012	0.015	0.015	0.011	18.79	0.27
2.024	70	100	0.014	0.009	0.014	0.011	0.014	0.011	19.88	0.27
2.024	71	25	0.016	0.014	0.013	0.013	0.016	0.012	20.29	0.27

MPN-285\_NUW-LHT-5M\_Rickman\_2m

July 24, 2023

Lunar Simulant NUW-LHT-5M, Heat Treated in Ar/4%H<sub>2</sub>  
Measurements of Complex Dielectric Constant of Pellets  
from Room Temperature to 1150°C, in flowing (10 sccm) UHP Argon

Dr. Doug Rickman ( NASA) had requested that Microwave Properties North measure the complex dielectric properties of heat-treated NUW-LHT-5M lunar regolith simulant up to a temperature of 1250C. The first run, in vacuum, up to 1100C, had an unfamiliar feature at ~ 850C . We decided to try a repeat run, but with a slight increase in maximum temperature ( 1150C ), and conditions changed as much as reasonable. Thus we decided to do the run in flowing ( 10 sccm) UHP argon, with more temperature steps starting just above 800C. This required a different sample holder, different background subtractions and new calibrations.

The powder sample material from Prof. H. Shulman arrived at MPN on June 6 / 2023. Dr. Shulman had already heat-treated the powder at 750 C in a 4% hydrogen/argon mixture.

For this measurement, MPN again pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. The first measurement run had included an initial cycle to 200C, which demonstrated no significant moisture up-take, so this run was a simple cycle to 1150C. The sample holder for this run was initially cycled ( and measured, empty) to 1100C before the run to “clean” the holder and measure the “empty holder” values, which were later used during the off-line data analysis.

The initial sample parameters were:

- a) diameter 3.63 +- 0.02 mm
- b) length of 3 pellet stack: 13.46 +- 0.05 mm
- c) mass 0.295 +- 0.002 gm
- nn) room temperature density  $2.12 \pm 0.05$  gm/cc.
- oo) appearance - three light grey pellets ( see photos)
- pp) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 800C in 50C steps, then to 1150C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets were easily removed, and their combined mass determined. Then the empty holder was run up to 1100C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) diameter  $3.66 \pm 0.02$  mm
- b) pellet stack length  $13.63 \pm 0.05$  mm
- c) mass  $0.295 \pm 0.002$  gm
- mm) room temperature density  $2.06 \pm 0.05$  gm/cc.
- nn) appearance - three light beige pellets ( see photos)
- oo) magnetic response - The pellets had a moderate attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

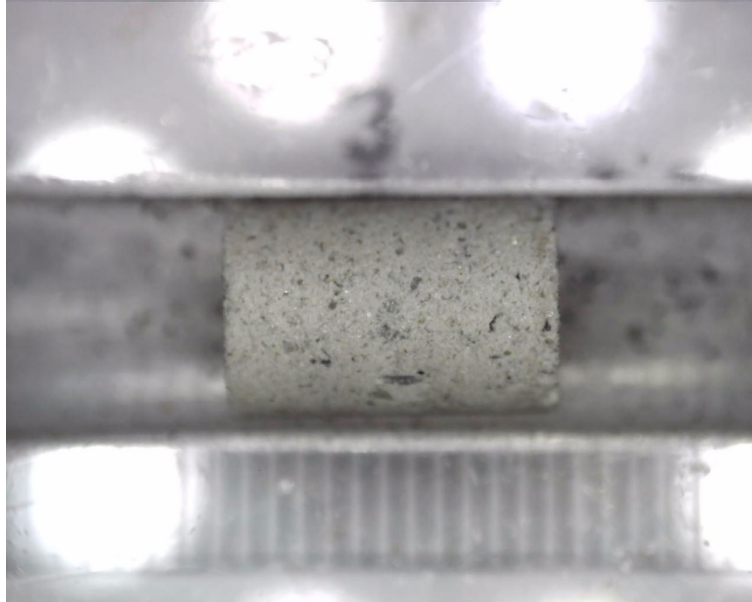
<u>#</u>	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line
6	2986	black diamond, dotted line

Comments on the data analysis:

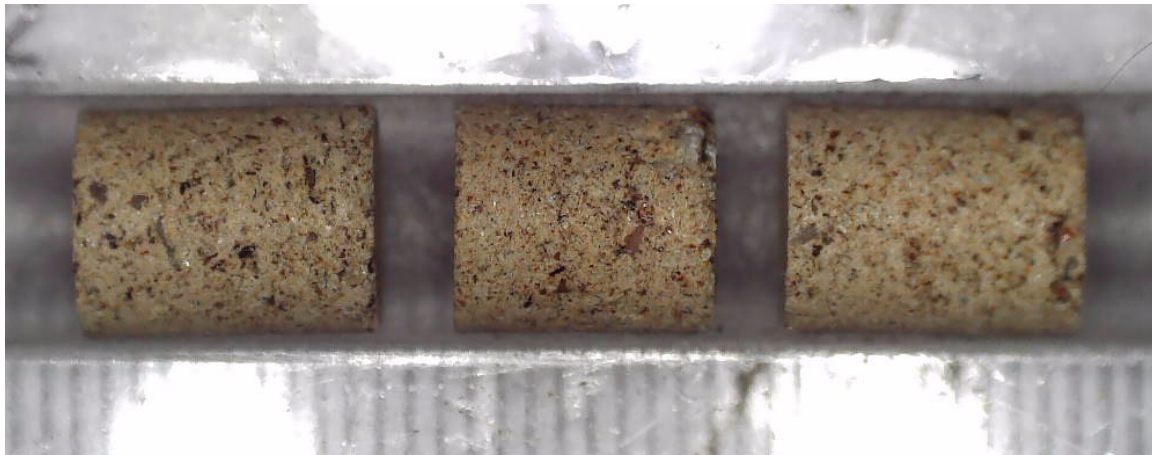
A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

The final pellets appeared unchanged except for a beige colouring !

The data for the ramp up to 1150C is interrupted by a slight decrease of the  $\epsilon'$  values which occurred between 850C and 950 C that resulted in a permanent change in  $\epsilon'$ , suggesting a non-reversible phase change.



Typical initial pellet -Pressed at ~ 33,000 psi



Three final pellets from 2<sup>nd</sup> run – ie., after the cycle to 1150C in UHP argon .



# Appendix E. MPN Reports

Test = 2023060901

NASA2360.mcd

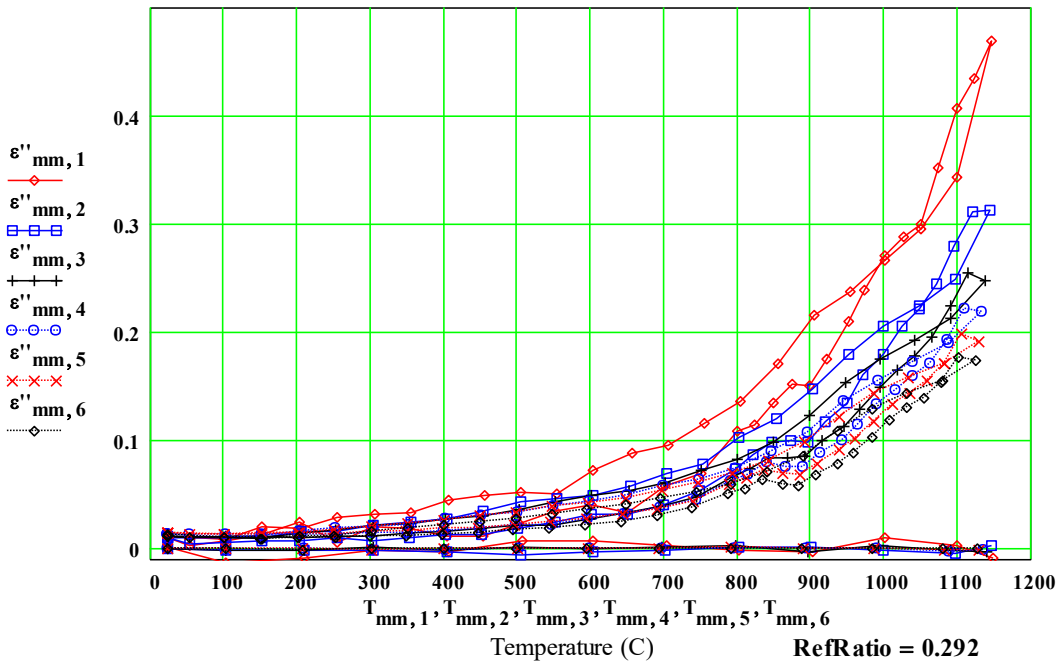
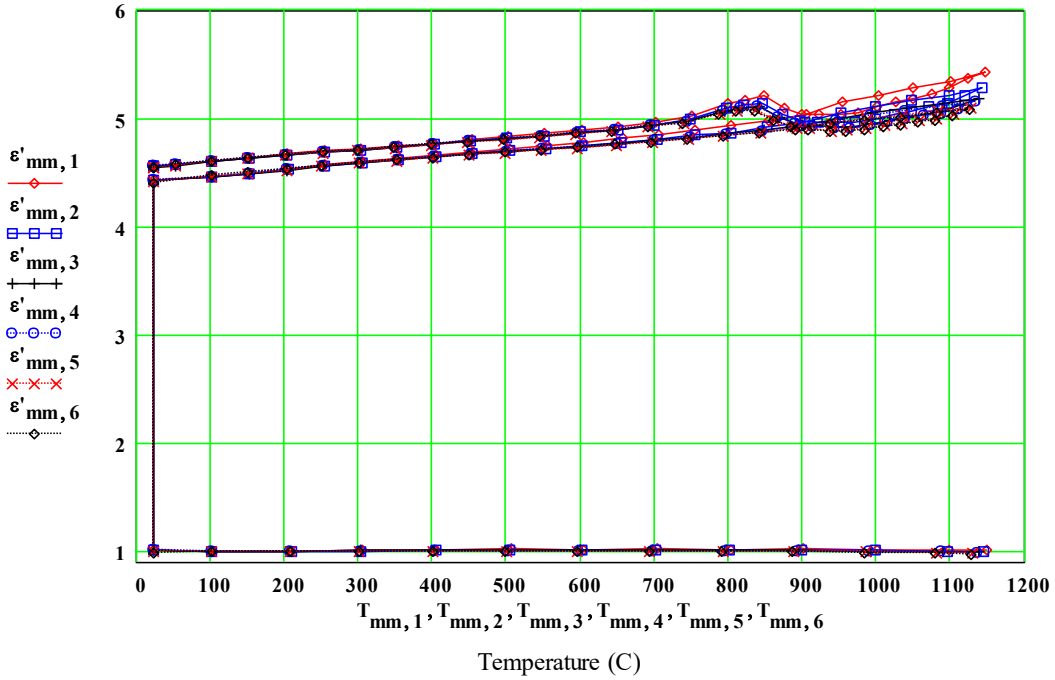
AnDat = 20230610

2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1150C, in flowing argon, for D.Rickmar

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



# Appendix E. MPN Reports

Test = 2023060901

NASA2360.mcd

AnDat = 20230610

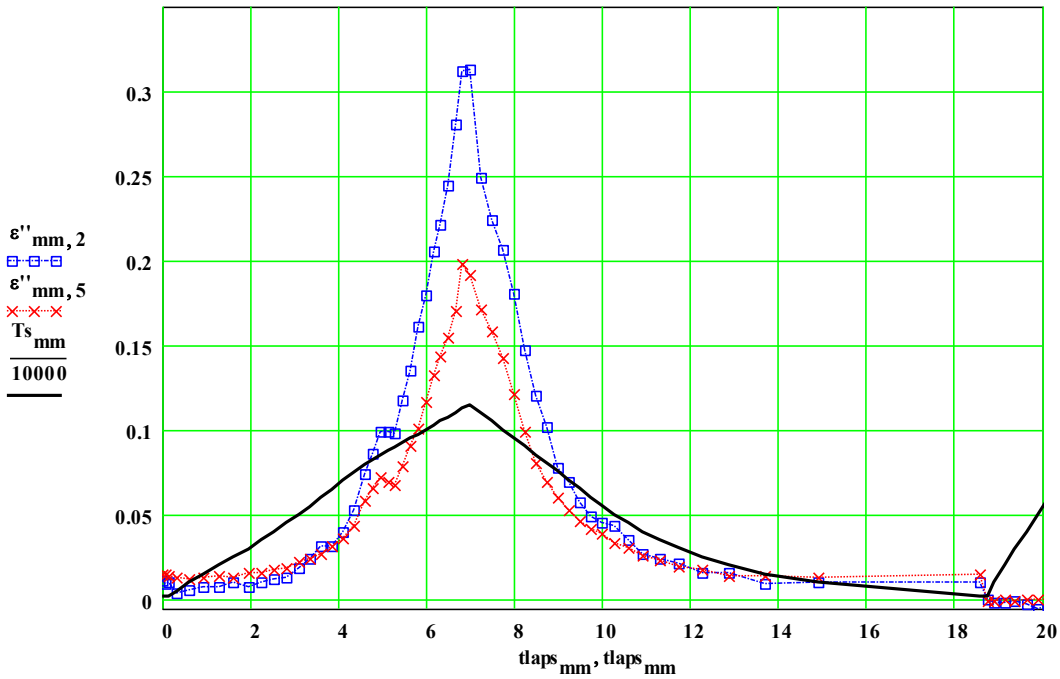
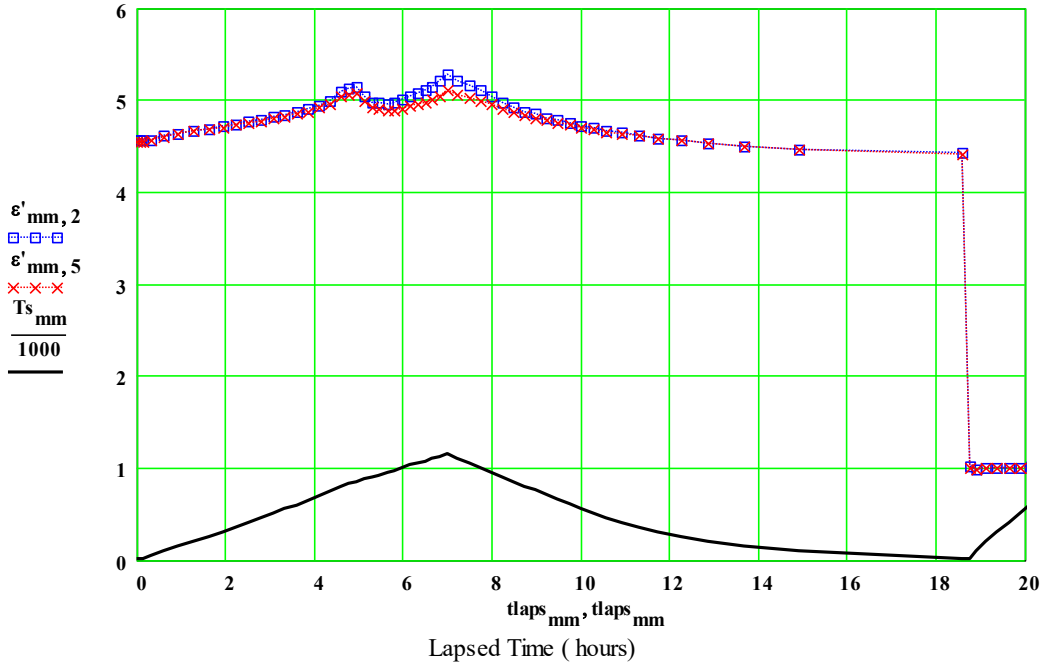
2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1150C, in flowing UHP argon, for Rickm

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$      $\text{FracMassChange} = 1$

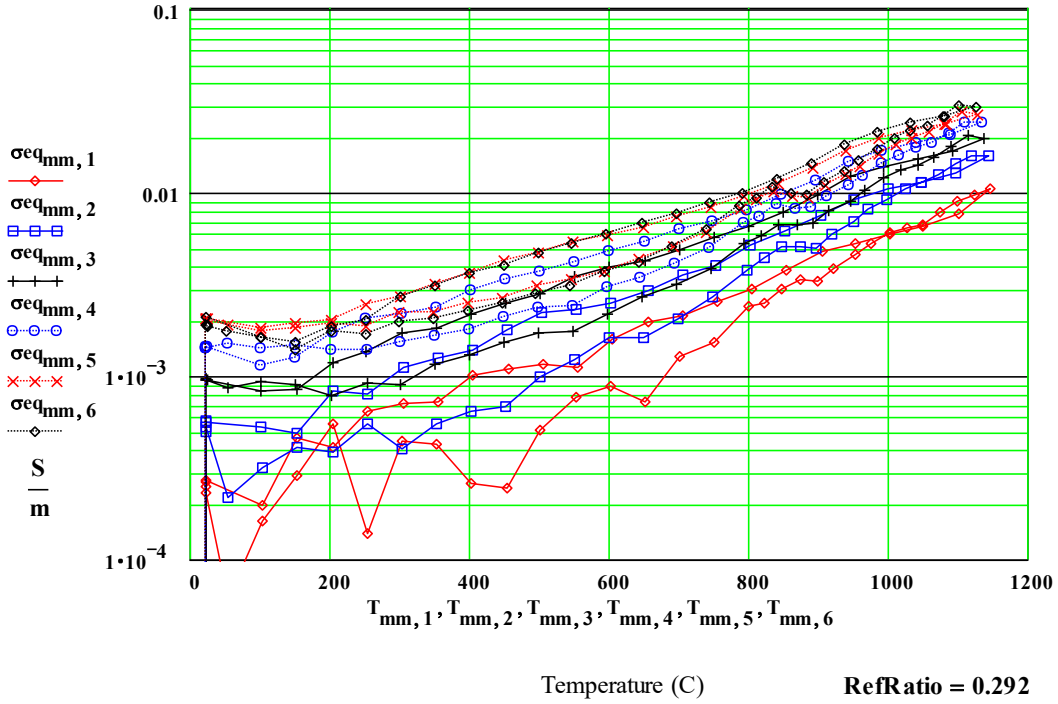
$\alpha_1 = 0$



# Appendix E. MPN Reports

Test = 2023060901                      NASA2360.mcd                      AnDat = 20230610  
2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1150C, in flowing argon, for D.Rickman

Equivalent Free Electron Conductivity ( Siemens/metre)





# Appendix E. MPN Reports

Test = 2023060901

NASA2360.mcd

AnDat = 20230610

T

2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1150C, in flowing argon, for D.Rickman

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$

It

FracMassChange = 1

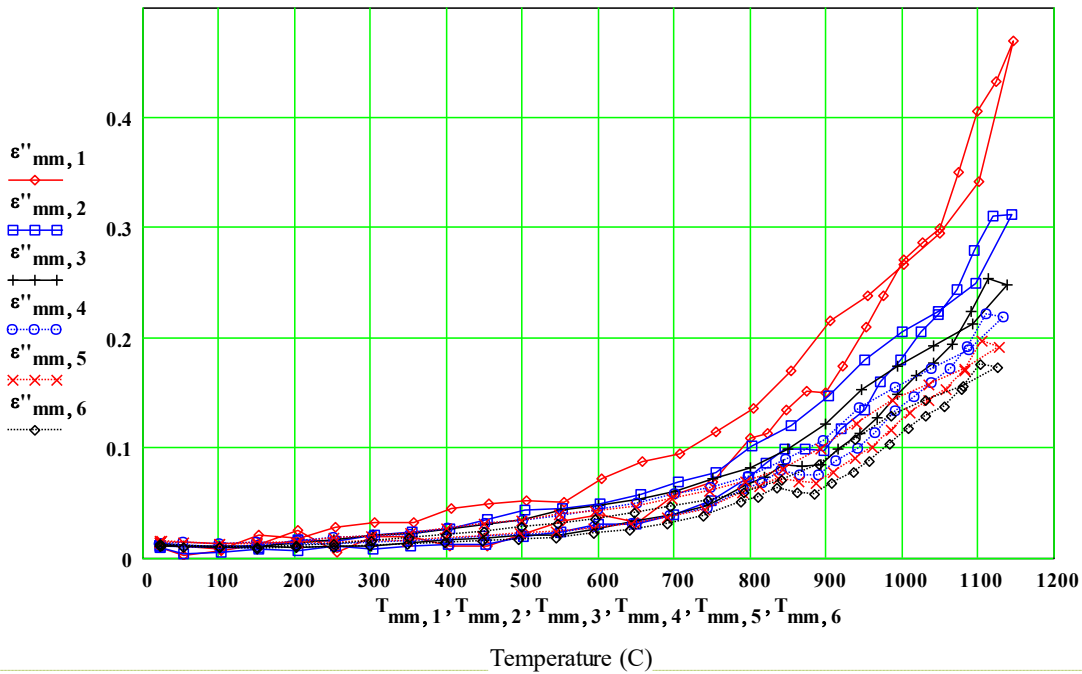
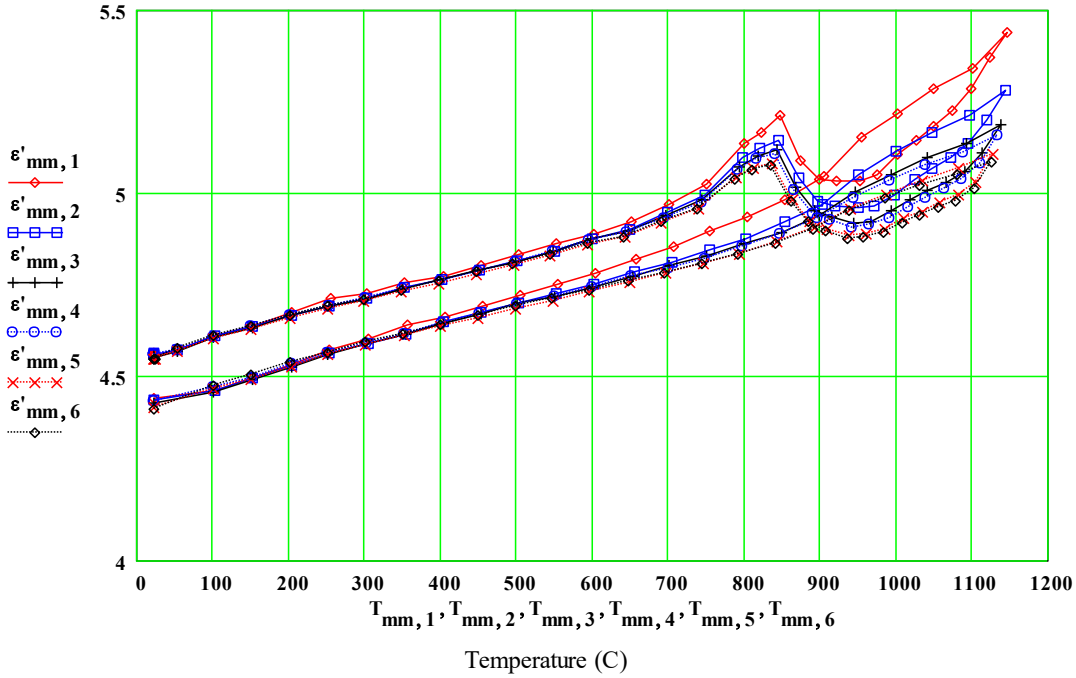
$\alpha_1 = 0$

/C

$\alpha_2 = 0$

/C

F



# Appendix E. MPN Reports

Test = 2023060901

NASA2360.mcd

AnDat = 20230610

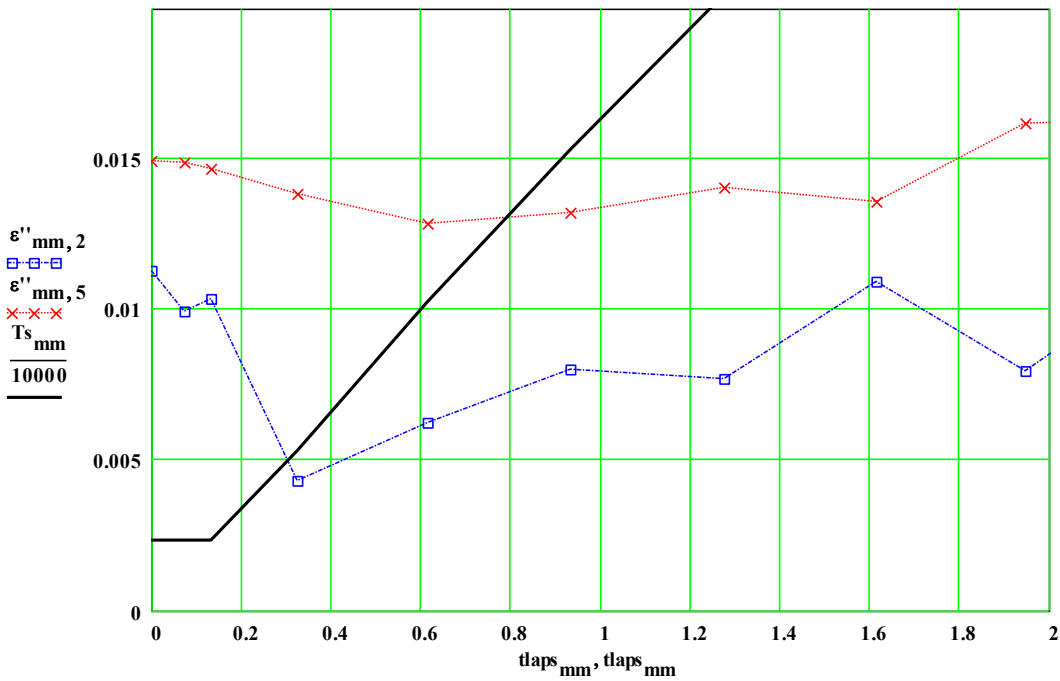
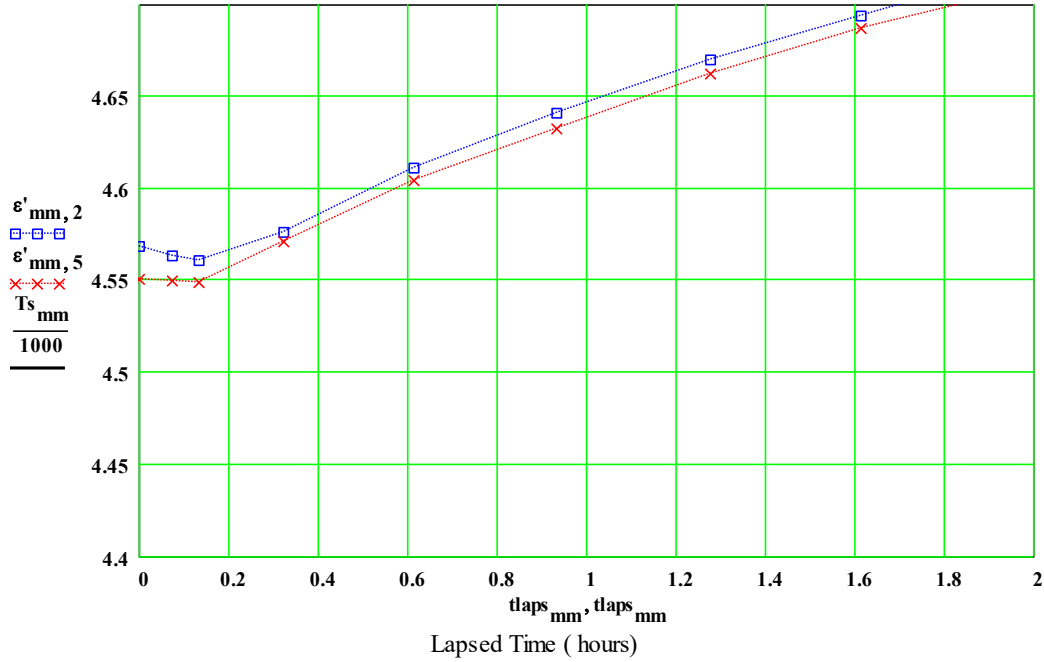
2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1150C, in flowing UHP argon, for Rickm

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$        $\text{FracMassChange} = 1$

$\alpha_1 = 0$



Values for the ramp up to 250C . The values demonstrate that within the error limits of  $\epsilon''$  (  $\pm 0.005$  at 915 MHz ), there was no moisture loss at the beginning of the cycle.

# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023060901

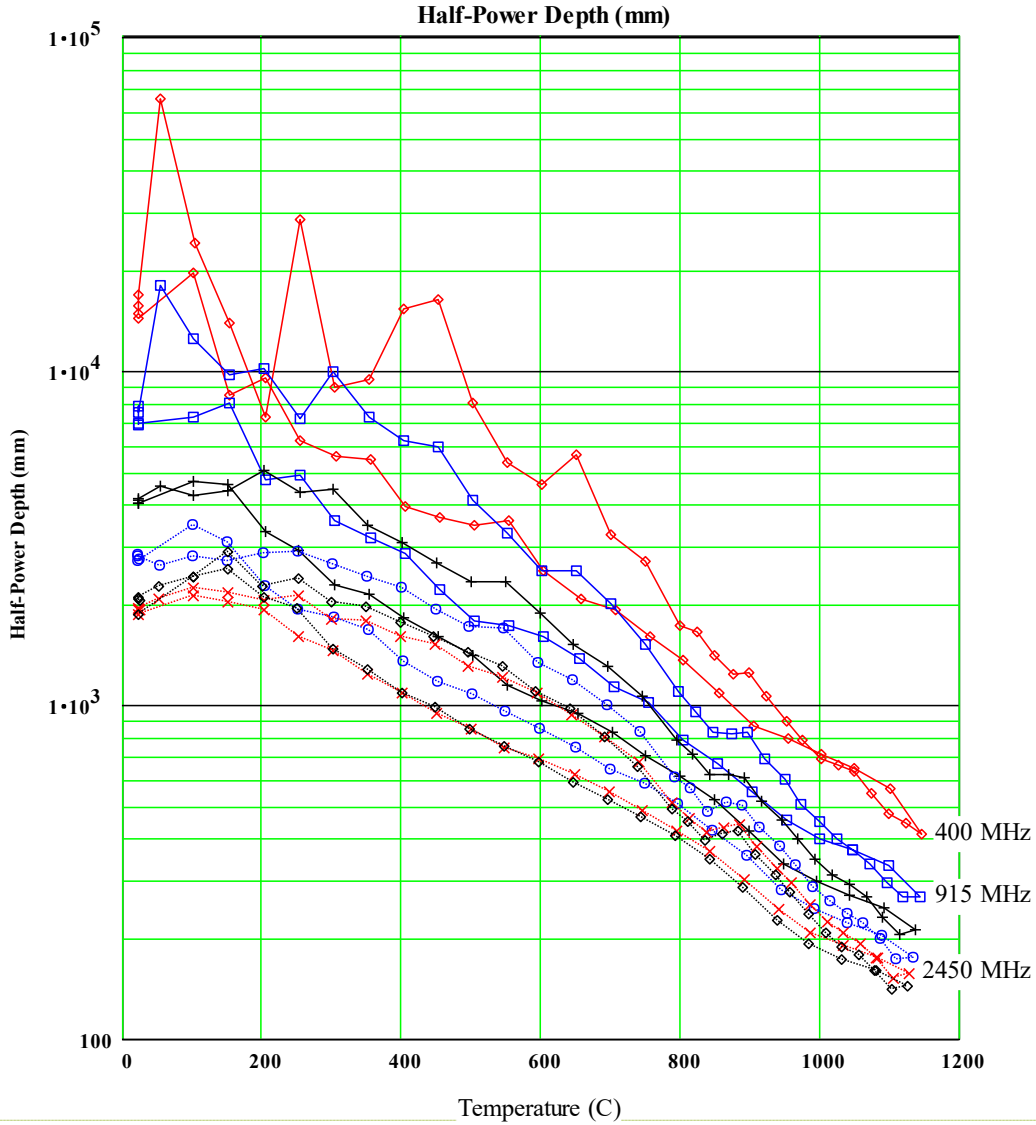
NASA2360.mcd

AnDat = 20230610

2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1150C, in flowing UHP argon, for Rickma

Initial density =  $\text{samdns}_{\text{NCal} + 1} =$  gm/cc,

Final density(25C) =  $\text{dnsfinal} =$  gm/cc



# Appendix E. MPN Reports

Test = 2023060901

NASA2360.mcd

AnDat = 20230611

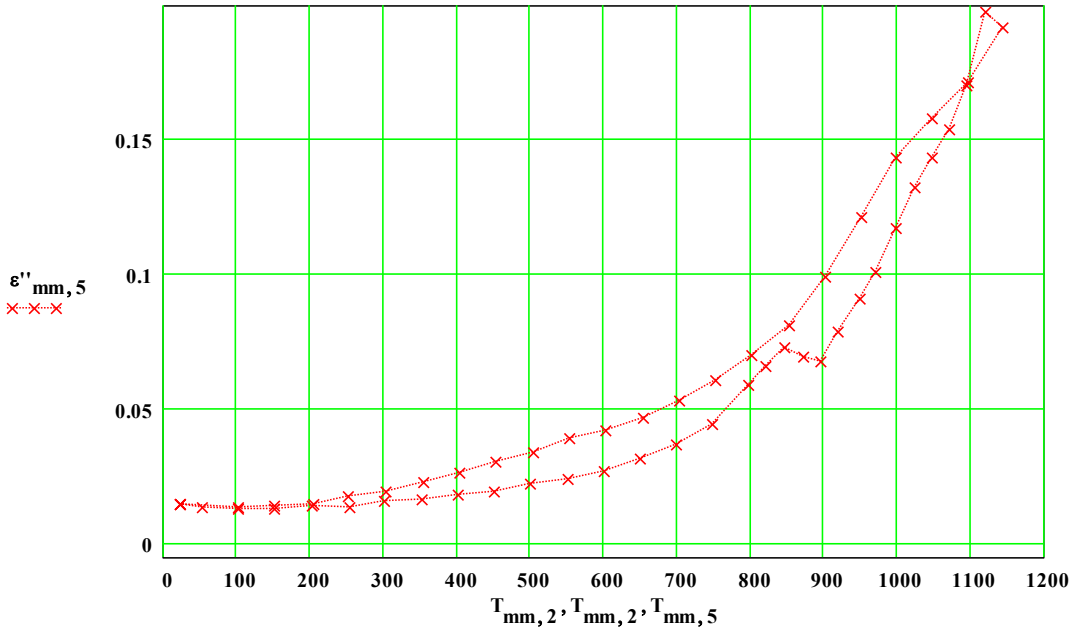
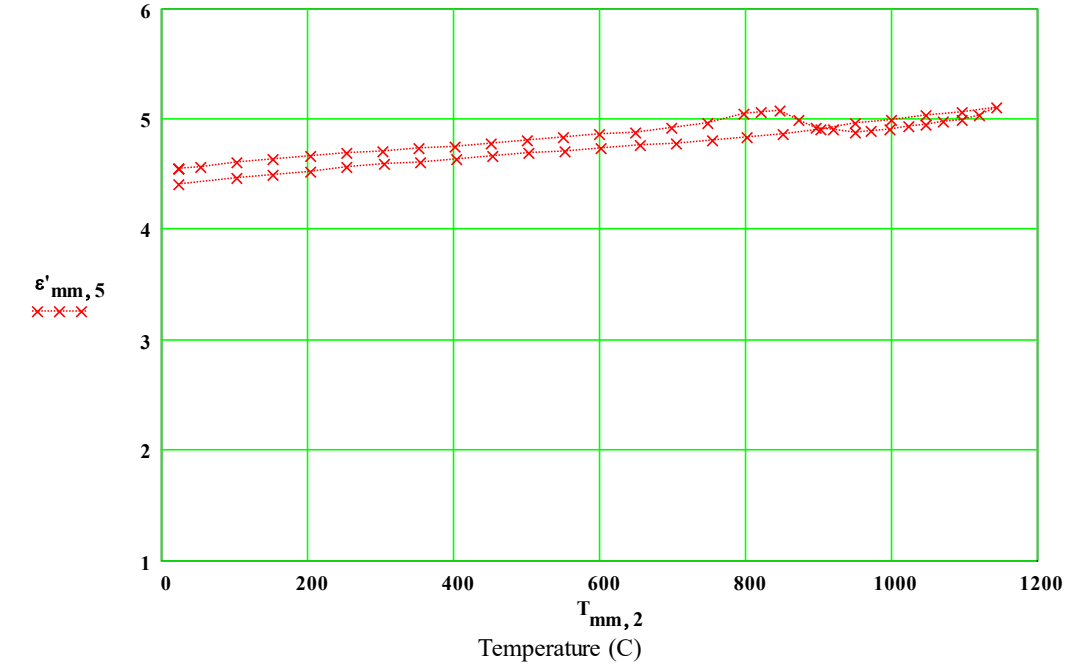
2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1150C, in flowing UHP argon, for Rickm

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$

Thermal exp. coeff.  $\alpha_1 = 0$

## Values for 2450 MHz



# Appendix E. MPN Reports

Test = 2023060901

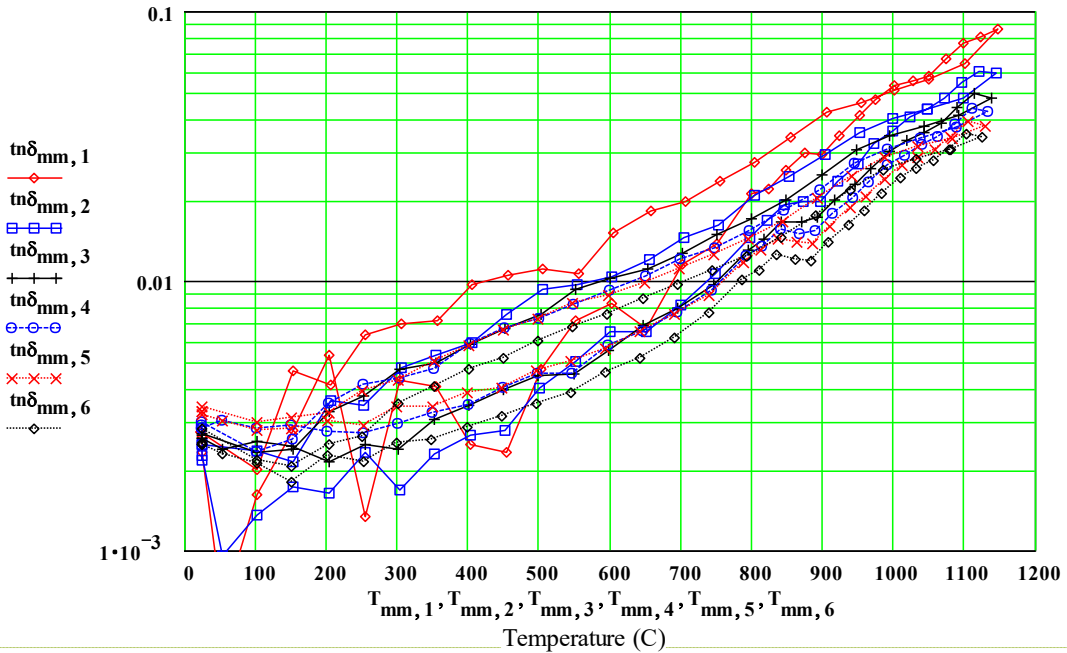
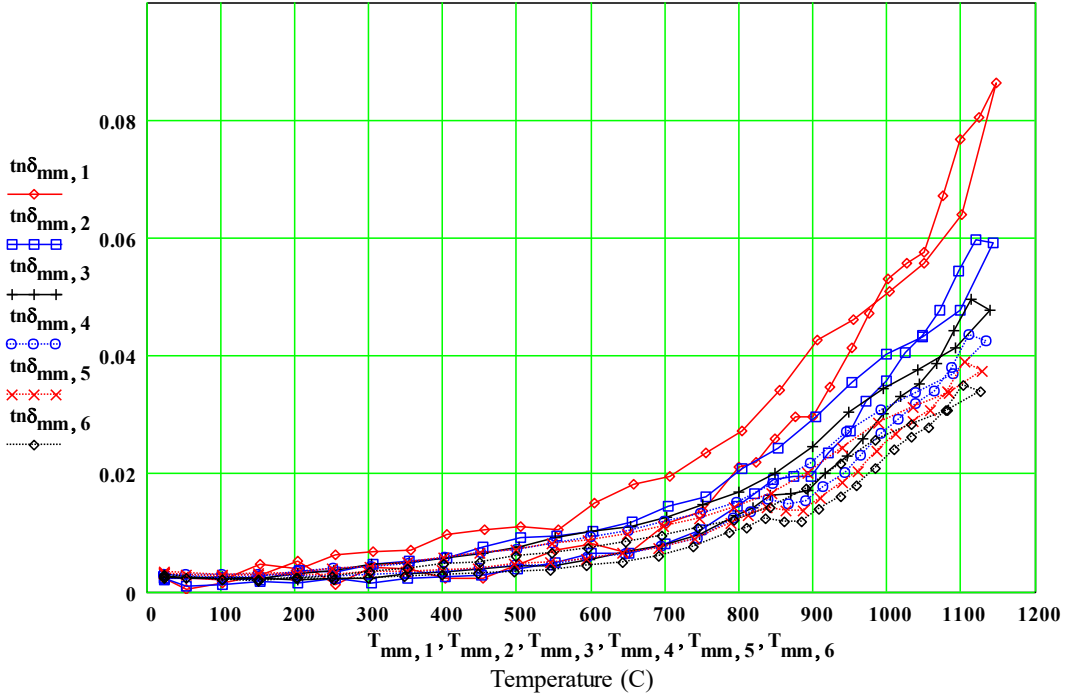
NASA2360.mcd

AnDat = 20230611

2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1150C, in flowing UHP argon, for Rickma

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.12 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023060901

NASA2360.mcd

AnDat = 20230611

2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1150C, in flowing UHP argon, for Rickm

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.118$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 2.057$  gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz      Lapsed Time (hours)

samdns <sub>mm</sub>	T <sub>mm,1</sub>	$\epsilon'_{\text{mm},1}$	$\epsilon'_{\text{mm},2}$	$\epsilon'_{\text{mm},3}$	$\epsilon'_{\text{mm},4}$	$\epsilon'_{\text{mm},5}$	$\epsilon'_{\text{mm},6}$	tlaps <sub>mm</sub>	sammas <sub>mm</sub>	
2.118	11	23	4.57	4.57	4.56	4.56	4.55	4.55	0	0.295
2.118	12	23	4.56	4.56	4.56	4.56	4.55	4.55	0.07	0.295
2.118	13	23	4.56	4.56	4.55	4.56	4.55	4.55	0.13	0.295
2.118	14	53	4.58	4.58	4.57	4.58	4.57	4.58	0.32	0.295
2.118	15	103	4.61	4.61	4.61	4.61	4.6	4.61	0.61	0.295
2.118	16	152	4.64	4.64	4.64	4.64	4.63	4.64	0.93	0.295
2.118	17	204	4.68	4.67	4.67	4.67	4.66	4.67	1.28	0.295
2.118	18	255	4.72	4.69	4.69	4.69	4.69	4.69	1.61	0.295
2.118	19	303	4.73	4.72	4.71	4.72	4.71	4.71	1.95	0.295
2.118	20	353	4.76	4.74	4.74	4.74	4.73	4.74	2.23	0.295
2.118	21	403	4.77	4.77	4.77	4.76	4.76	4.76	2.51	0.295
2.118	22	453	4.81	4.79	4.79	4.79	4.78	4.79	2.8	0.295
2.118	23	502	4.84	4.82	4.82	4.81	4.8	4.81	3.09	0.295
2.118	24	552	4.86	4.84	4.84	4.84	4.83	4.84	3.34	0.295
2.118	25	602	4.89	4.88	4.88	4.87	4.86	4.86	3.59	0.295
2.118	26	651	4.93	4.9	4.9	4.89	4.88	4.88	3.85	0.295
2.118	27	701	4.97	4.95	4.94	4.94	4.92	4.92	4.1	0.295
2.118	28	750	5.02	5	4.98	4.98	4.96	4.96	4.35	0.295
2.118	29	799	5.14	5.1	5.07	5.07	5.04	5.04	4.61	0.295
2.113	30	823	5.17	5.13	5.11	5.1	5.07	5.07	4.78	0.295
2.108	31	848	5.22	5.15	5.12	5.11	5.08	5.08	4.95	0.295
2.104	32	875	5.09	5.04	5.02	5.01	4.98	4.98	5.12	0.295
2.099	33	898	5.04	4.98	4.96	4.95	4.93	4.92	5.29	0.295
2.094	34	922	5.03	4.97	4.94	4.93	4.9	4.9	5.46	0.295
2.09	35	952	5.04	4.96	4.92	4.91	4.88	4.88	5.64	0.295
2.085	36	974	5.05	4.97	4.93	4.91	4.89	4.88	5.8	0.295
2.08	37	1001	5.11	5	4.95	4.93	4.91	4.9	5.98	0.295
2.076	38	1026	5.15	5.04	4.98	4.96	4.93	4.92	6.15	0.295
2.071	39	1050	5.18	5.07	5.01	4.99	4.95	4.94	6.32	0.295
2.066	40	1074	5.23	5.1	5.03	5.01	4.98	4.96	6.49	0.295
2.062	41	1099	5.29	5.14	5.06	5.04	5	4.98	6.65	0.295
2.057	42	1123	5.37	5.2	5.11	5.08	5.03	5.01	6.82	0.295
2.057	43	1147	5.44	5.28	5.19	5.16	5.11	5.09	6.99	0.295
2.057	44	1100	5.34	5.21	5.14	5.11	5.07	5.05	7.23	0.295
2.057	45	1050	5.29	5.17	5.1	5.08	5.04	5.02	7.48	0.295
2.057	46	1002	5.22	5.11	5.05	5.04	5	4.99	7.73	0.295
2.057	47	954	5.15	5.05	5.01	4.99	4.96	4.95	7.97	0.295
2.057	48	905	5.05	4.97	4.94	4.93	4.91	4.9	8.23	0.295
2.057	49	855	4.99	4.92	4.9	4.89	4.87	4.87	8.48	0.295
2.057	50	805	4.94	4.88	4.86	4.86	4.84	4.84	8.73	0.295
2.057	51	755	4.9	4.85	4.83	4.82	4.81	4.81	8.98	0.295
2.057	52	706	4.86	4.81	4.81	4.8	4.78	4.79	9.24	0.295
2.057	53	657	4.82	4.79	4.78	4.77	4.76	4.76	9.49	0.295
2.057	54	604	4.79	4.76	4.75	4.75	4.73	4.74	9.75	0.295
2.057	55	555	4.75	4.73	4.72	4.72	4.71	4.71	10	0.295
2.057	56	505	4.73	4.71	4.7	4.7	4.69	4.69	10.27	0.295
2.057	57	455	4.7	4.68	4.67	4.67	4.66	4.67	10.58	0.295
2.057	58	406	4.67	4.67	4.65	4.65	4.64	4.64	10.91	0.295
2.057	59	356	4.64	4.62	4.62	4.62	4.61	4.62	11.3	0.295
2.057	60	305	4.6	4.59	4.59	4.59	4.59	4.6	11.73	0.295

mq := 61,62..nd - Nempties

samdns <sub>mq</sub>	T <sub>mq,1</sub>	$\epsilon'_{\text{mq},1}$	$\epsilon'_{\text{mq},2}$	$\epsilon'_{\text{mq},3}$	$\epsilon'_{\text{mq},4}$	$\epsilon'_{\text{mq},5}$	$\epsilon'_{\text{mq},6}$	tlaps <sub>mq</sub>	sammas <sub>mq</sub>	
2.057	61	254	4.57	4.56	4.56	4.57	4.56	4.57	12.25	0.295
2.057	62	205	4.54	4.53	4.53	4.54	4.53	4.54	12.85	0.295
2.057	63	153	4.5	4.5	4.5	4.5	4.5	4.51	13.67	0.295
2.057	64	102	4.46	4.47	4.46	4.47	4.47	4.48	14.91	0.295
2.057	65	23	4.44	4.44	4.43	4.43	4.42	4.41	18.59	0.295



MPN-285\_NUW-LHT-5M\_Rickman\_3m

July 24, 2023

Lunar Simulant NUW-LHT-5M, Heat Treated in Ar/4% $H_2$   
Measurements of Complex Dielectric Constant of Pellets  
from Room Temperature to 1250°C, in flowing (10 sccm) UHP Argon

Dr. Doug Rickman (NASA) requested that Microwave Properties North measure the complex dielectric properties of heat-treated NUW-LHT-5M lunar regolith simulant up to a temperature of 1250C. The first run, in vacuum, up to 1100C, had an unfamiliar feature at ~ 850C. We decided to try to repeat the run, but with conditions changed as much as reasonable. Thus the second run was done in flowing (10 sccm) UHP argon, with more temperature steps starting just above 800C. This required a different sample holder, different background subtractions and new calibrations. The results were essentially the same as the first run.

This third run ( done again in flowing UHP argon) to 1250C used the same sample holder as the previous run, and was done to see if the maximum temperature could be slightly higher without interaction with the sample holder. This was successful!

The powder sample material from Prof. H. Shulman arrived at MPN on June 6 / 2023. Dr. Shulman had already heat-treated the powder at 750 C in a 4% hydrogen/argon mixture.

For this measurement, MPN again pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. The sample holder was the same one used on the previous ( 2<sup>nd</sup>) measurement . Thus the “empty holder” values were well established.

The initial sample parameters were:

- a) diameter 3.64 +- 0.02 mm
- b) length of 3 pellet stack: 12.99 +- 0.05 mm
- c) mass 0.283 +- 0.002 gm
- qq) room temperature density  $2.09 \pm 0.05$  gm/cc.
- rr) appearance - three light grey pellets
- ss) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 800C in 50C steps, then to 1250C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT. **It was noted at the end of the run that the plug had come out of the top of the holder at some point, possibly allowing a slight back-flow of air into the top of the holder.**

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets had “fused” into a rod, which was easily removed, and its mass determined ( no change!). Then the empty holder was run up to 1250 C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) diameter  $3.59 \pm 0.02$  mm
- b) pellet stack length  $12.7 \pm 0.1$  mm
- c) mass  $0.283 \pm 0.002$  gm
- pp) room temperature density  $2.20 \pm 0.05$  gm/cc.
- qq) appearance - single brown rod with coloured flecks ( see photos)
- rr) magnetic response - The rod had a very weak attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

#	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line
6	2986	black diamond, dotted line

Comments on the data analysis:

A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

The final sample looked as if the pellets had fused together, possibly with the assistance of the softening glass content. The colouring was somewhat darker than with the previous, lower temperature runs.

The data for the ramp up to 1250C is interrupted by a slight decrease of the  $\epsilon'$  values which occurred between 850C and 950 C that resulted in a permanent change in  $\epsilon'$ , suggesting a non-reversible phase change.

The slope of both  $\epsilon'$  and  $\epsilon''$  versus temperature increased dramatically at  $\sim 1180 \pm 15 C$ , suggesting softening of a glass component. The glass component may have diffused into the pores of the material, causing the slight decrease in sample volume.

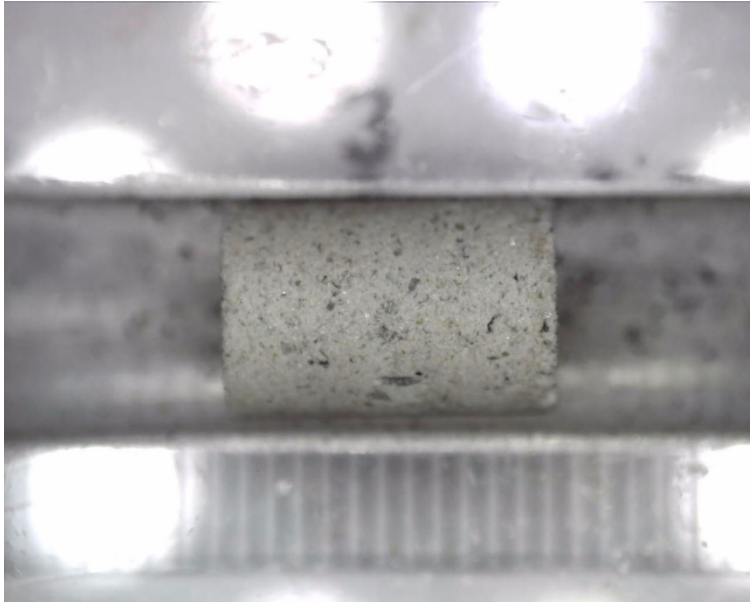
The final sample ( the three fused pellets) was sectioned ( split in half) using a thin ( 20 thou) diamond saw. Unfortunately, the pellets were not completely in line in the stack - and when Joe put it in a clamp to saw it, one pellet snapped off the end. He did "section" both pieces .

Several photos are shown below, and demonstrate my lack of experience with lighting and microscopy.

The interior did not have the "light brown" tinge that the outer surface had. My lighting makes the outer surface look dark brown – it was not!

At higher magnification, what had looked like black "blobs" in the first low magnification photo turned out to be cavities at higher magnification !

Also, the “line” between the two pellets shows that the gap had not filled in completely – suggesting the glass had not completely flowed – even at 1250 C !



Typical initial pellet - Pressed at ~ 33,000 psi



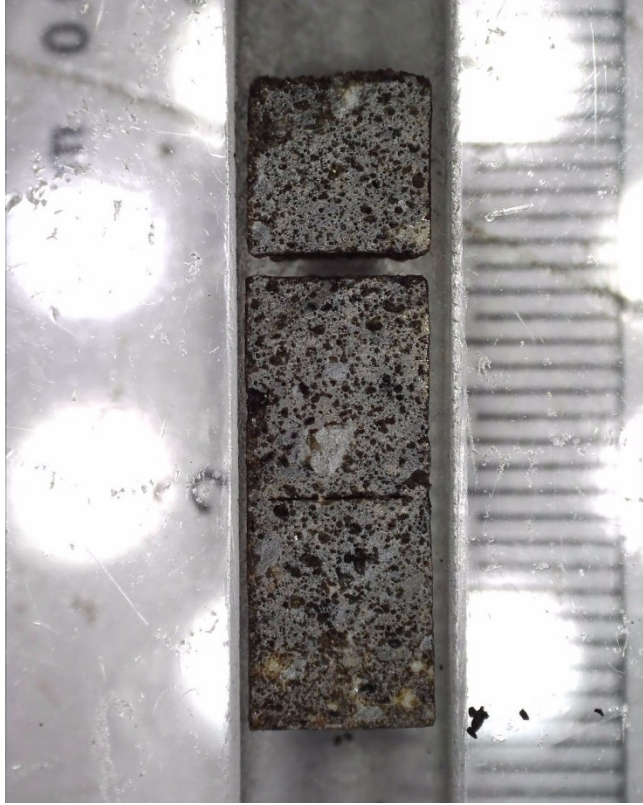
Final sample, after cycle to 1250 C in UHP argon.

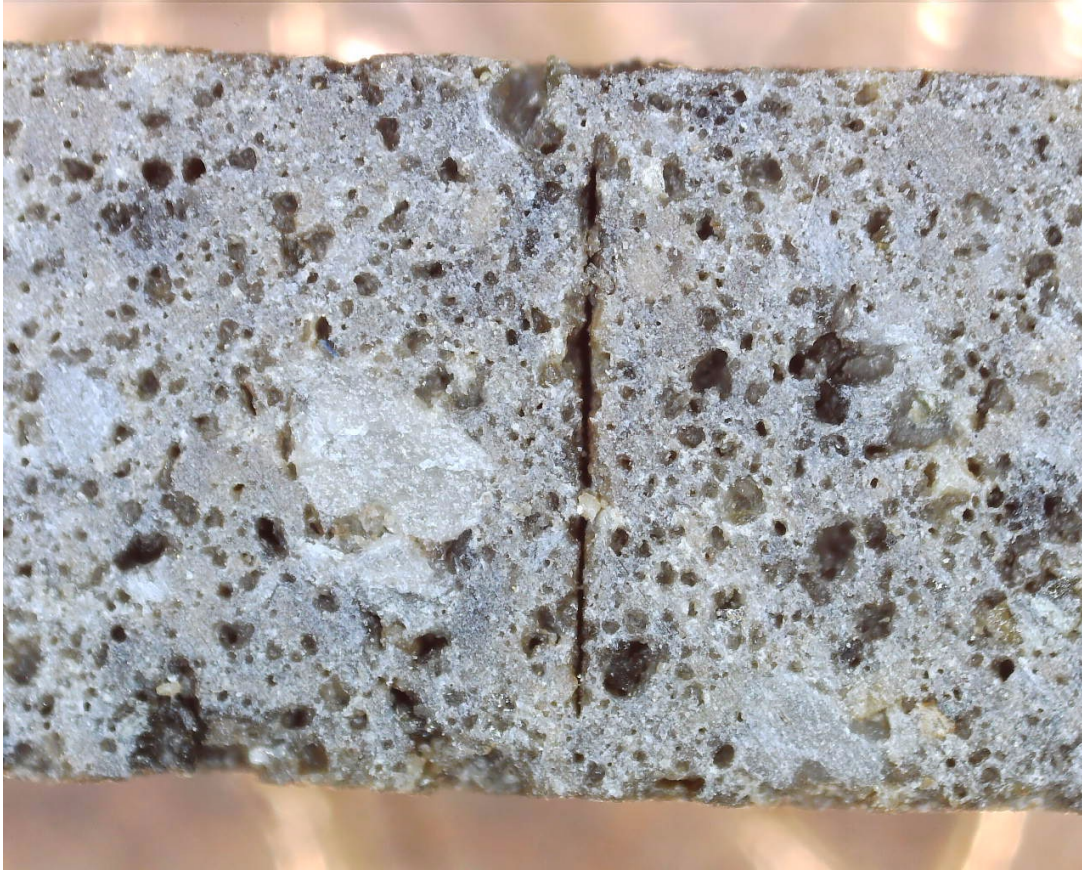


Three final pellets ( a “sintered” rod) from 3<sup>rd</sup> run – ie., after the cycle to 1250C in UHP argon .



The diametrically sectioned final sample. The outer surface ( left photo) was not as dark as this .....  
I though I was looking a “dark” blobs of material in the interior ( right hand photo), but when I increased the magnification, they were clearly voids!





With increased magnification and better illumination, the voids are clearly seen. The fusing of the two pellets was not complete, as seen by the line between the partially joined pellets.





Test = 2023061101

NASA2361.mcd

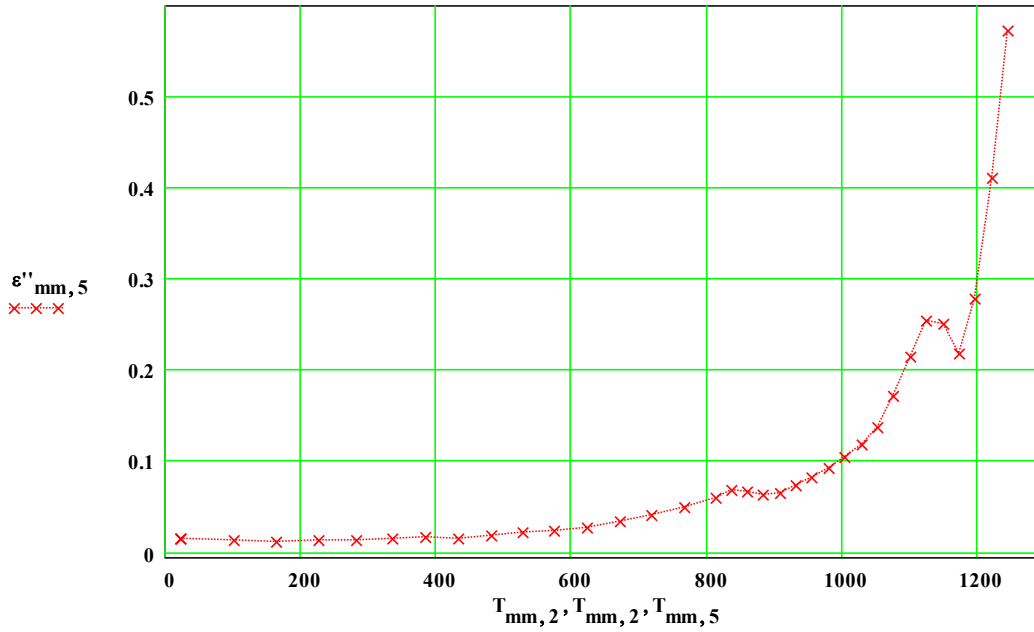
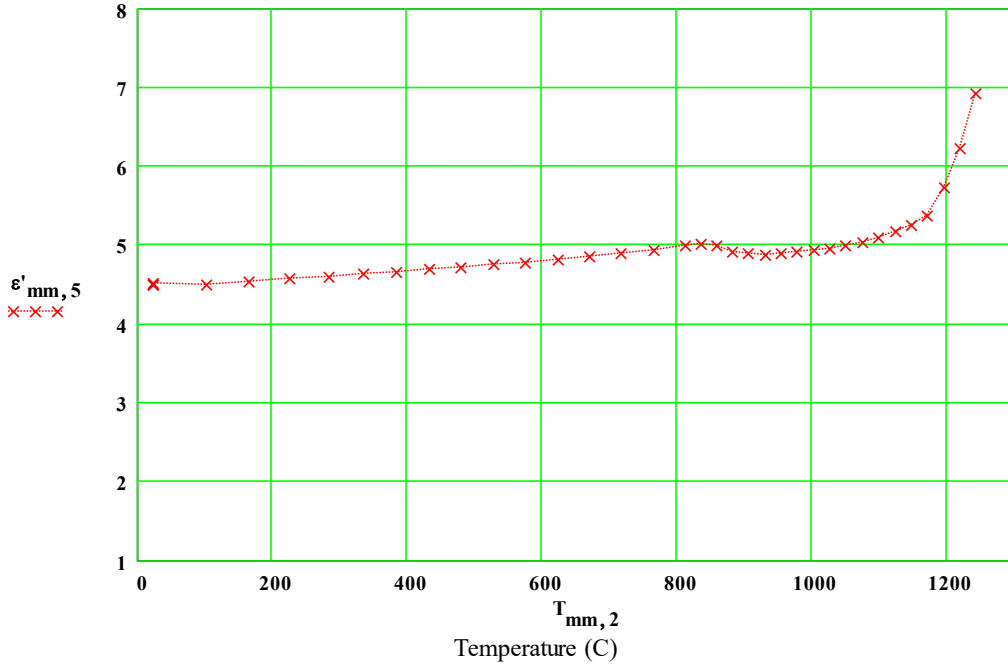
AnDat = 20230612

3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1250C, in flowing UHP argon, for Rickma

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.2 \text{ gm/cc}$

Values for 2450 MHz - Increasing Temperature



# Appendix E. MPN Reports

Test = 2023061101

NASA2361.mcd

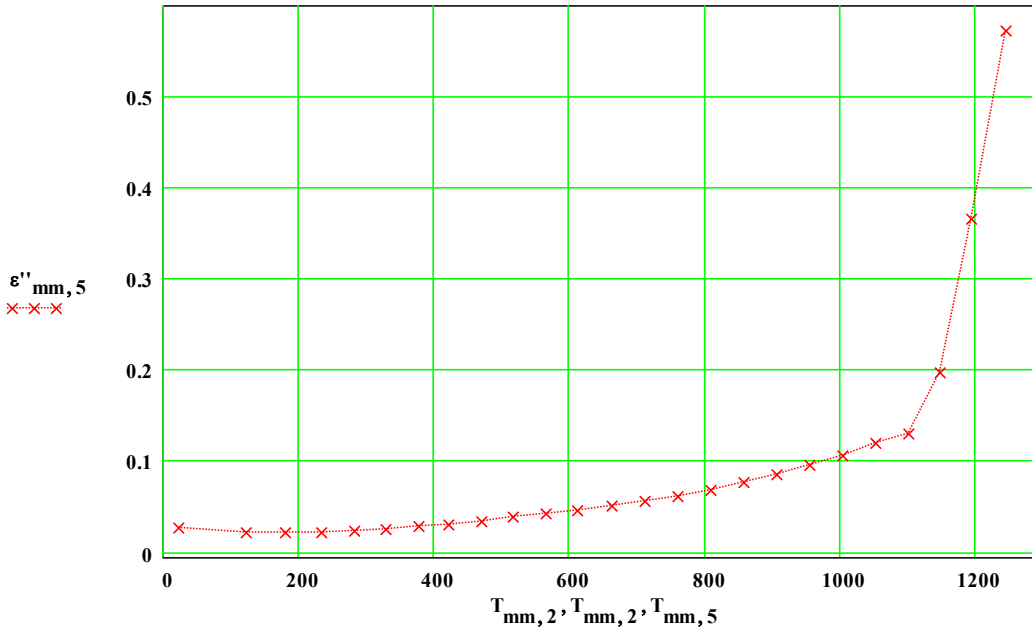
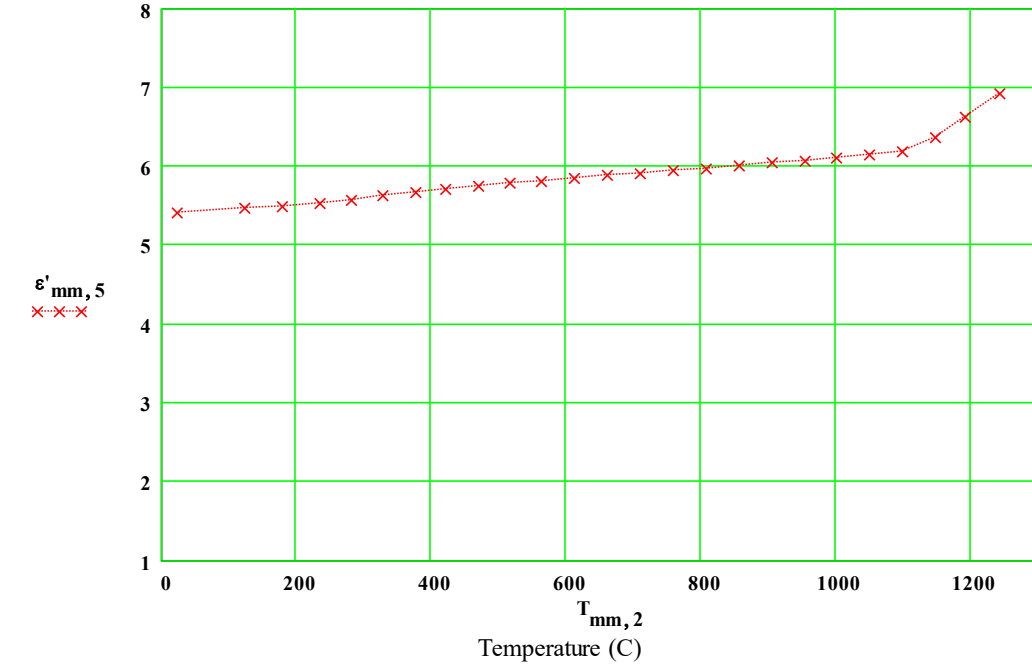
AnDat = 20230612

3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1250C, in flowing UHP argon, for Rickma

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.2 \text{ gm/cc}$

## Values for 2450 MHz - Decreasing Temperature



# Appendix E. MPN Reports

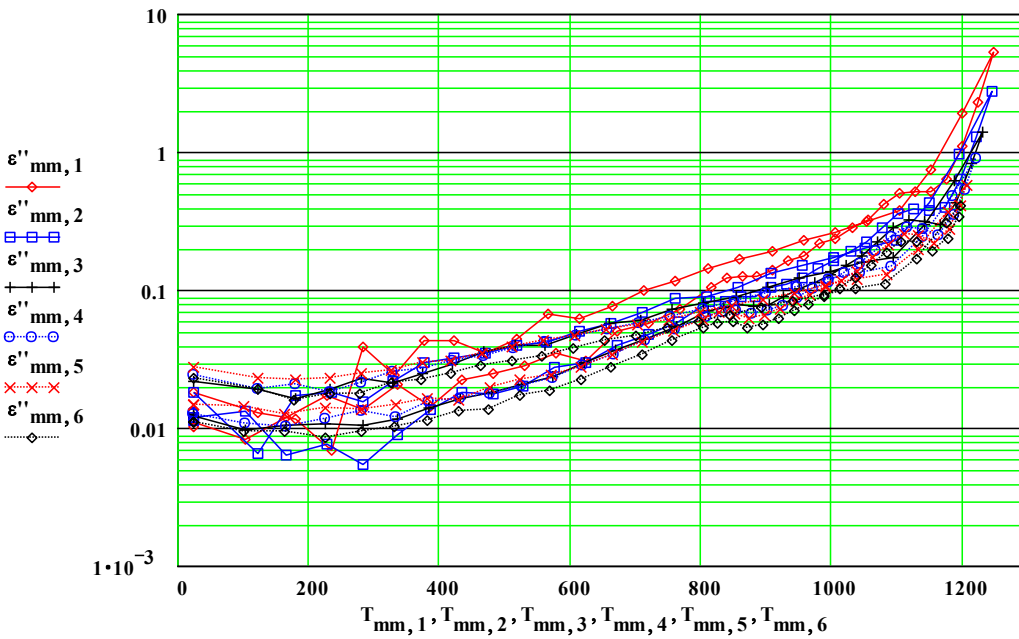
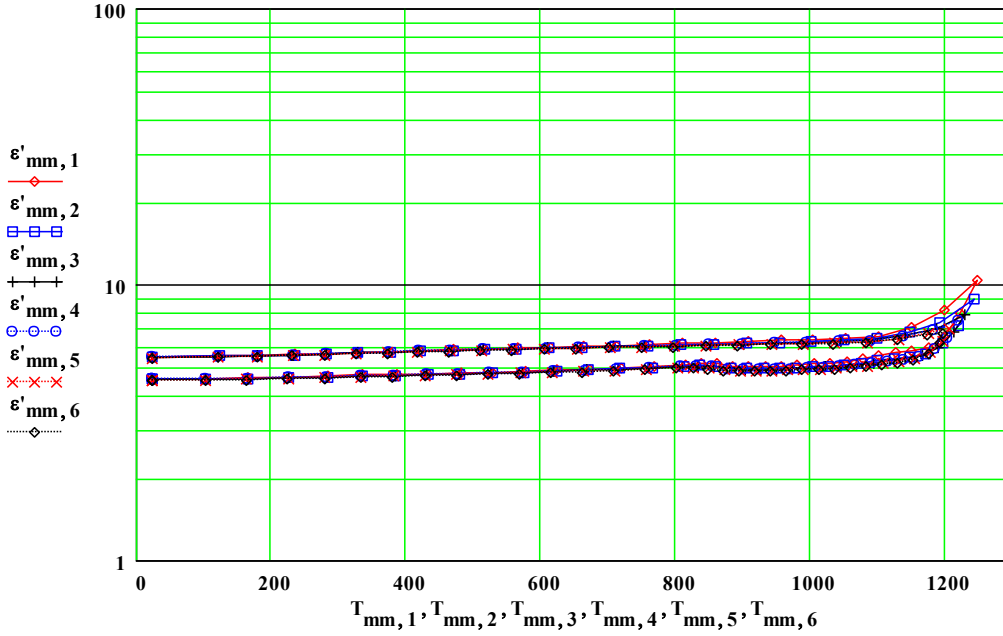
Test = 2023061101

NASA2361.mcd

AnDat = 20230612

3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1250C, in flowing UHP argon, for Rickm

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.2 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023061101

NASA2361.mcd

AnDat = 20230612

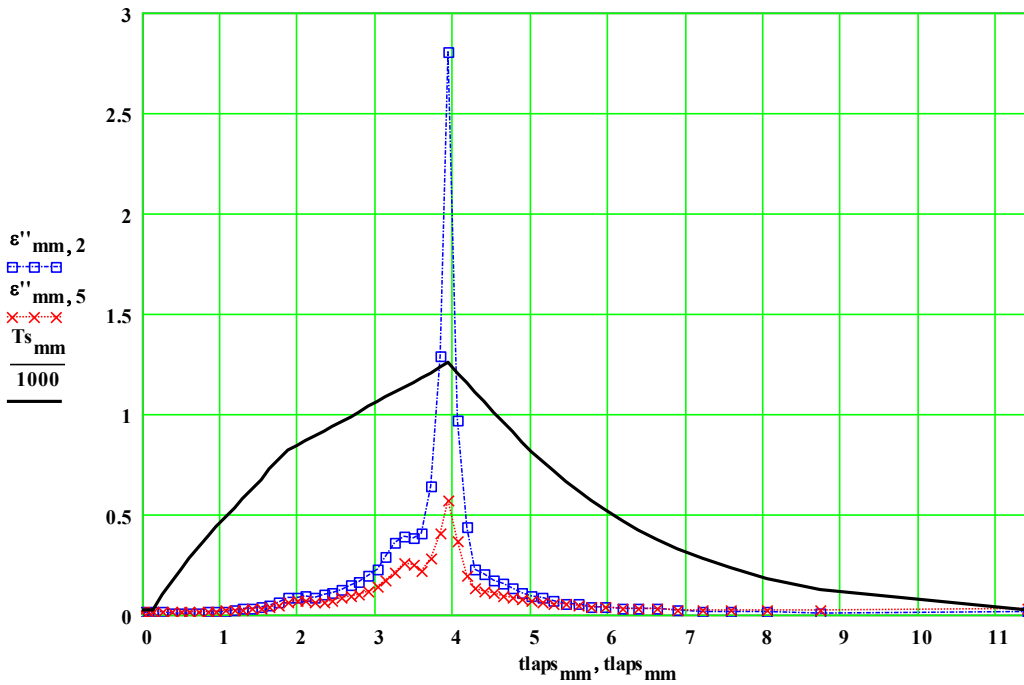
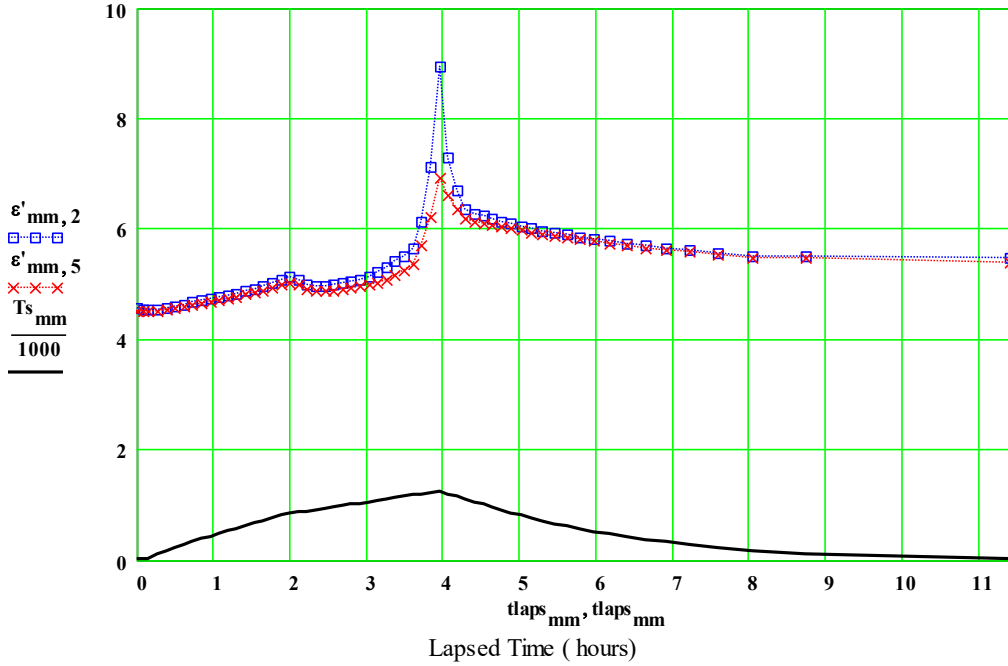
3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1250C, in flowing UHP argon, for Rickm

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.2 \text{ gm/cc}$        $\text{FracMassChange} = 1$

$\alpha_1 = 0$



# Appendix E. MPN Reports

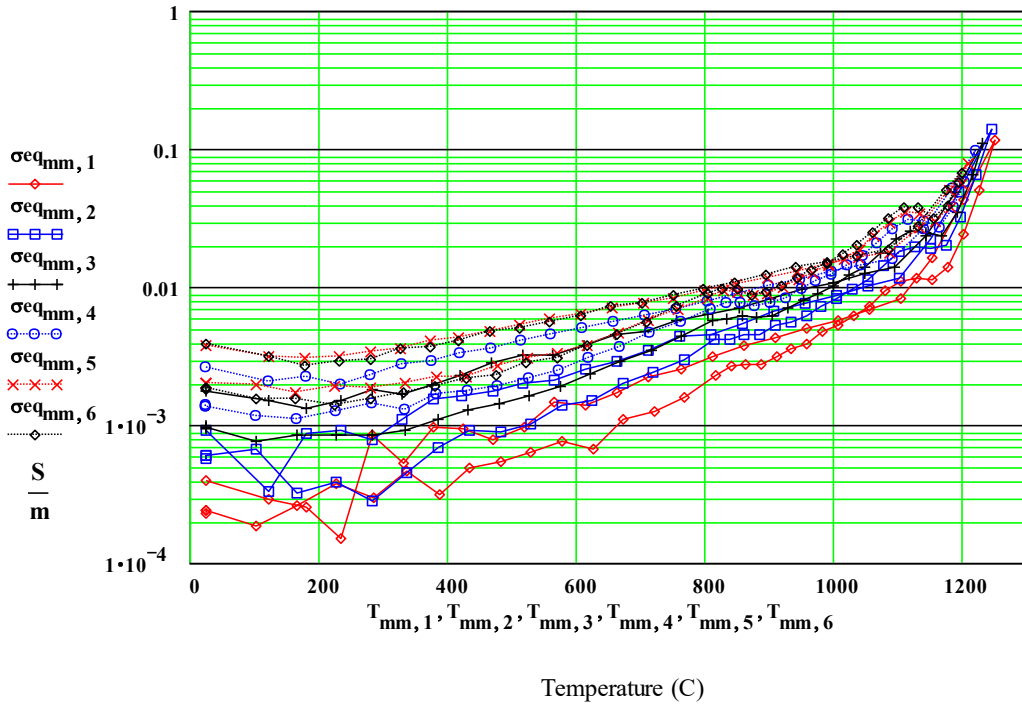
Test = 2023061101

NASA2361.mcd

AnDat = 20230612

3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1250C, in flowing argon, for D.Rickman

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2023061101

NASA2361.mcd

AnDat = 20230612

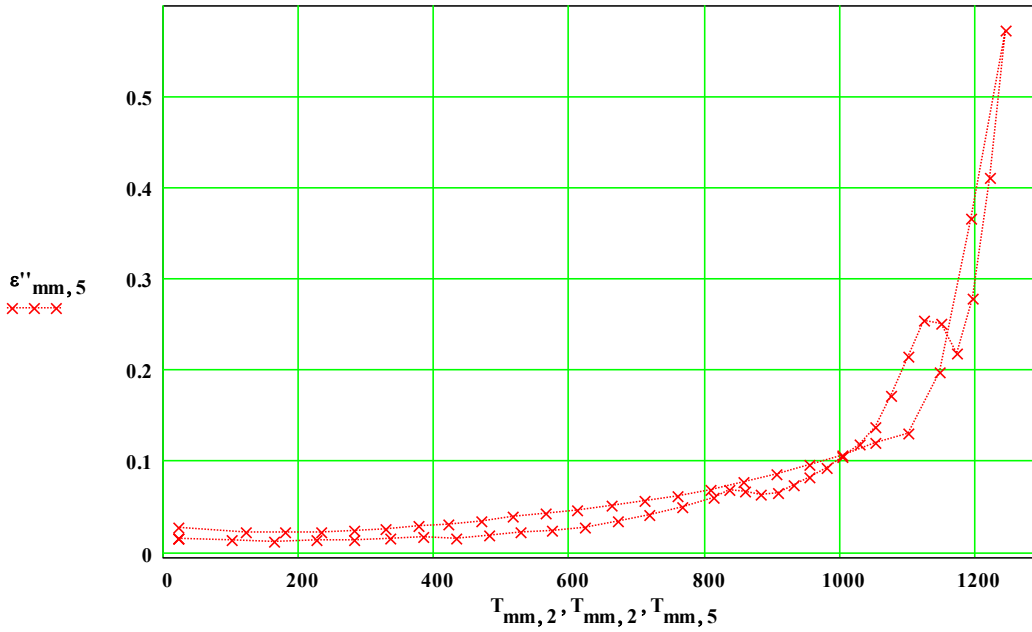
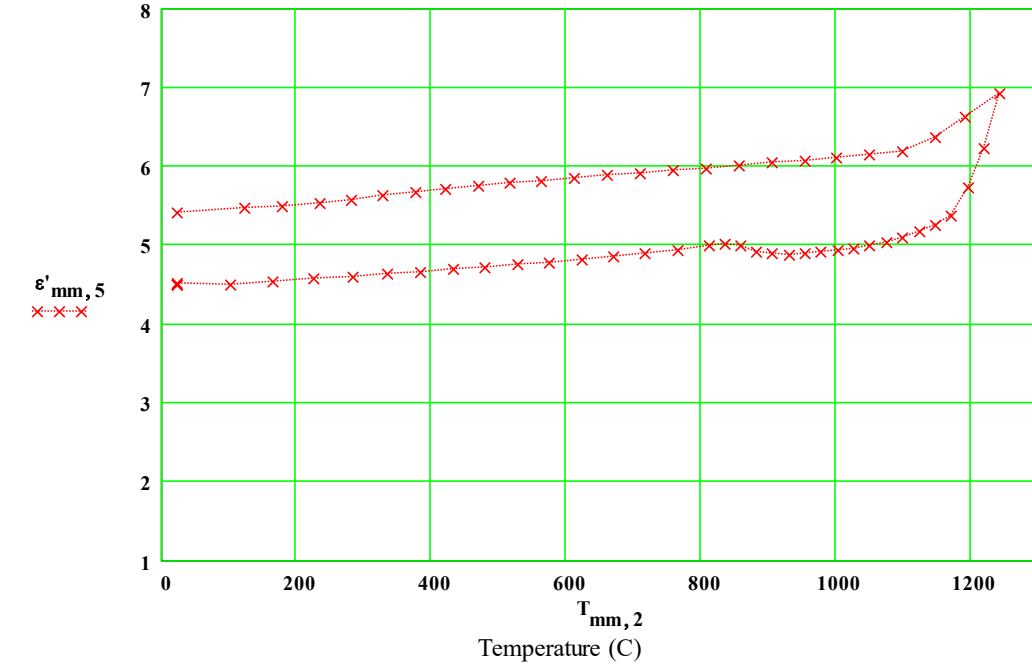
3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1250C, in flowing UHP argon, for Rickma

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.2 \text{ gm/cc}$

Thermal exp. coeff.  $\alpha_1 = 0$

## Values for 2450 MHz



# Appendix E. MPN Reports

Test = 2023061101

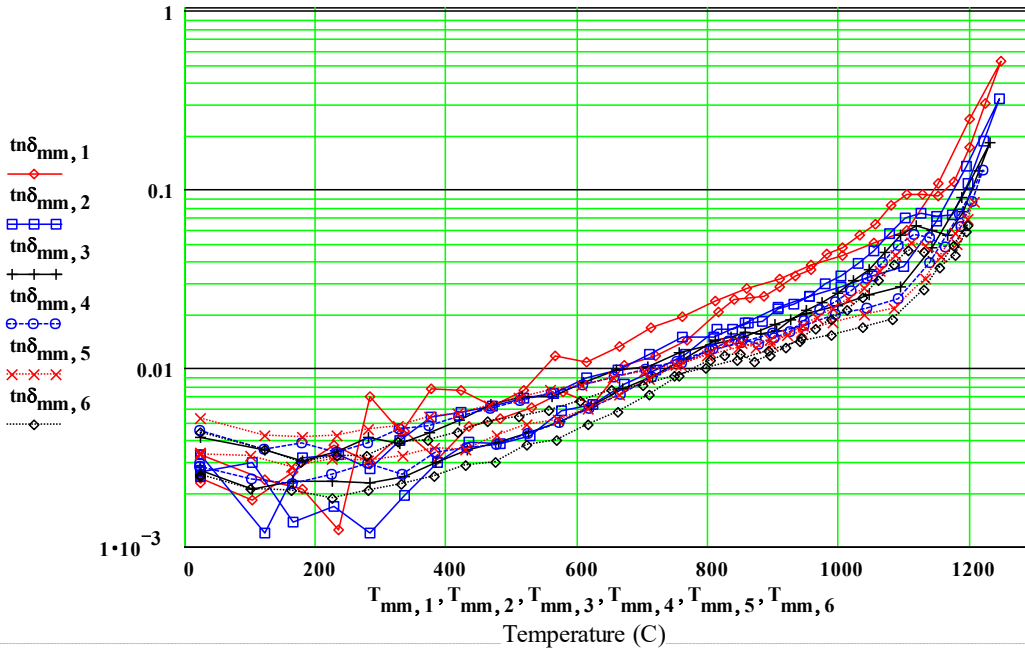
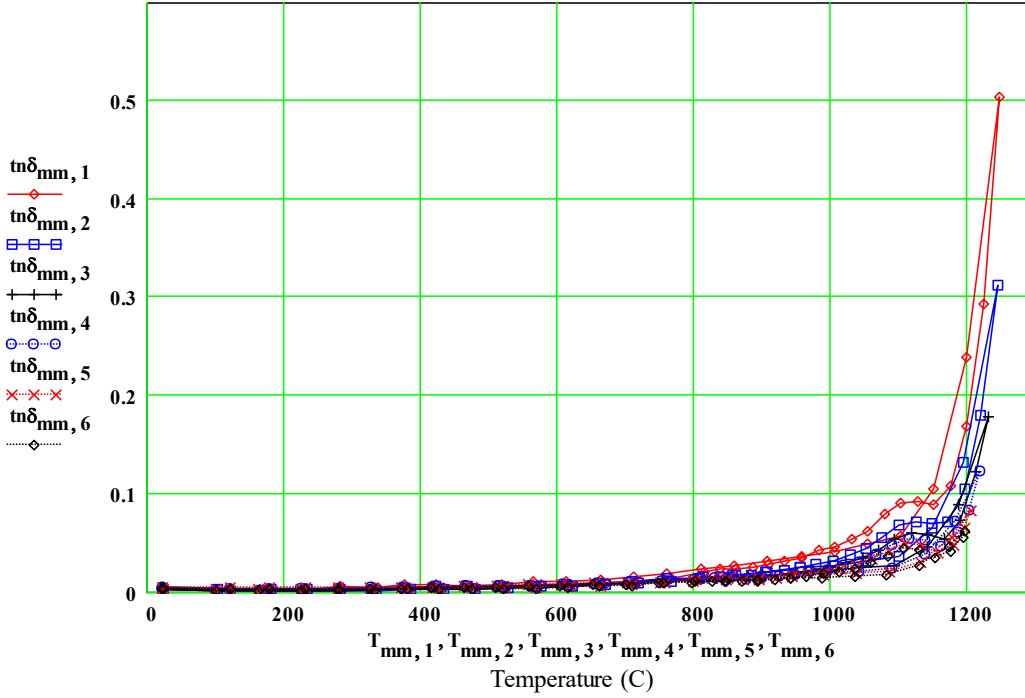
NASA2361.mcd

AnDat = 20230612

3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1250C, in flowing UHP argon, for Rickmai

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.2 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023061101

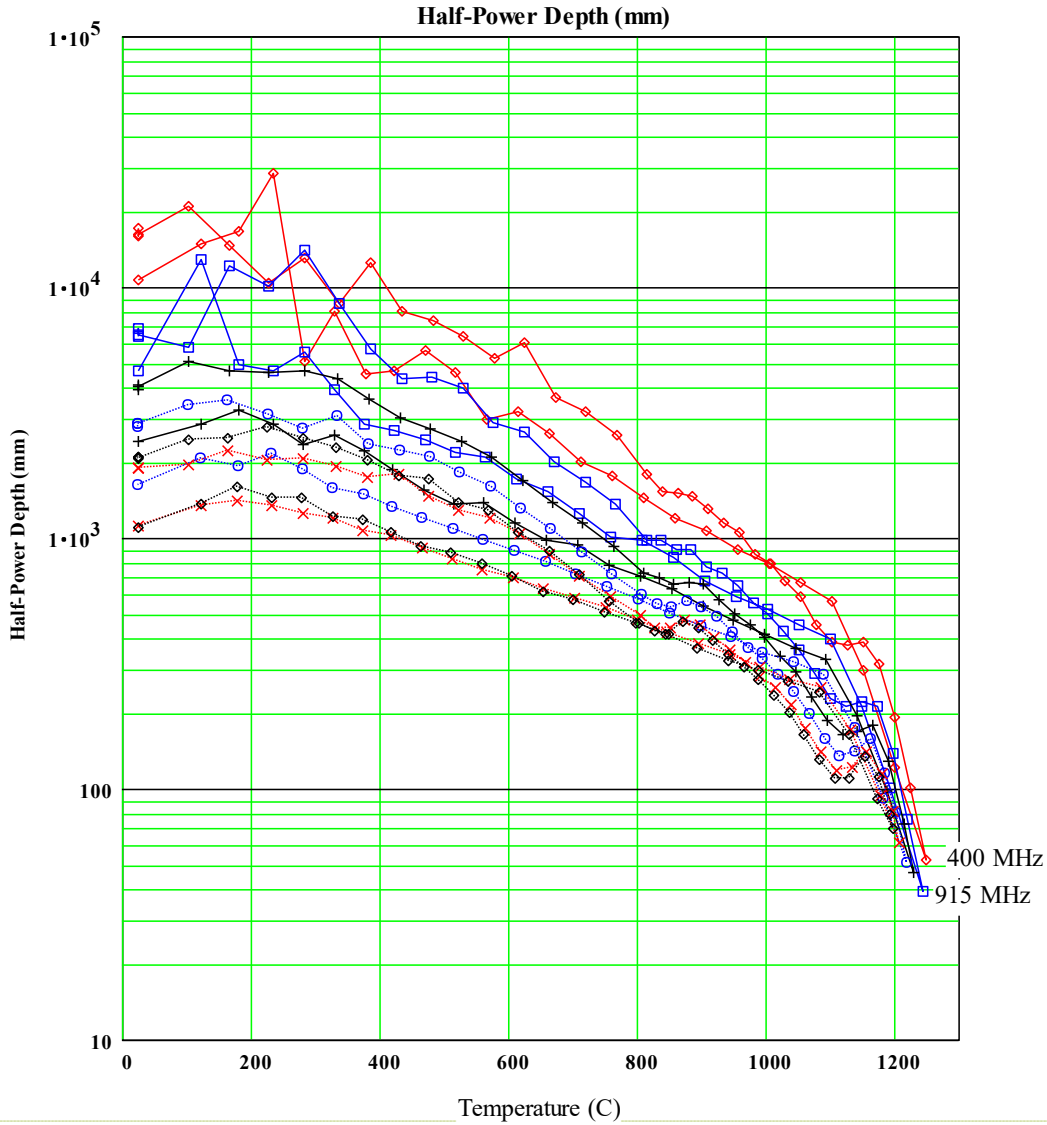
NASA2361.mcd

AnDat = 20230612

3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub>, to 1250C, in flowing UHP argon, for Rickma

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.09 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.2 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023061101

NASA2361.mcd

AnDat = 20230612

3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1250C, in flowing argon, for D.Rickn

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCat} + 1} = 2.094 \text{ gm/cc}$       Final density(25C) =  $\text{dnsfinal} = 2.201 \text{ gm/cc}$

density index T(C) 397MHz 912MHz 1429MHz 1948MHz 2466MHz 2986MHz  
Lapsed Time (hours)

samdns	mm	T <sub>mm,1</sub>	$\epsilon'_{\text{mm},1}$	$\epsilon'_{\text{mm},2}$	$\epsilon'_{\text{mm},3}$	$\epsilon'_{\text{mm},4}$	$\epsilon'_{\text{mm},5}$	$\epsilon'_{\text{mm},6}$	tlaps <sub>mm</sub>	sammass <sub>mm</sub>
2.094	11	24	4.58	4.56	4.55	4.54	4.51	4.48	0	0.283
2.094	12	24	4.57	4.55	4.54	4.54	4.51	4.49	0.08	0.283
2.094	13	24	4.57	4.56	4.55	4.54	4.51	4.49	0.14	0.283
2.094	14	103	4.57	4.55	4.54	4.54	4.51	4.49	0.27	0.283
2.094	15	166	4.6	4.58	4.57	4.56	4.54	4.52	0.38	0.283
2.094	16	227	4.64	4.61	4.61	4.6	4.57	4.55	0.5	0.283
2.094	17	284	4.67	4.64	4.64	4.63	4.6	4.58	0.61	0.283
2.094	18	337	4.71	4.68	4.68	4.66	4.64	4.62	0.73	0.283
2.094	19	386	4.73	4.71	4.71	4.69	4.66	4.65	0.84	0.283
2.094	20	434	4.76	4.74	4.74	4.72	4.69	4.68	0.96	0.283
2.094	21	482	4.79	4.77	4.77	4.75	4.72	4.71	1.07	0.283
2.094	22	529	4.83	4.8	4.8	4.78	4.75	4.73	1.19	0.283
2.094	23	577	4.87	4.84	4.84	4.82	4.79	4.77	1.3	0.283
2.094	24	625	4.92	4.87	4.87	4.85	4.82	4.8	1.42	0.283
2.094	25	672	4.96	4.91	4.91	4.89	4.86	4.84	1.53	0.283
2.094	26	720	5.02	4.97	4.95	4.93	4.9	4.87	1.65	0.283
2.084	27	768	5.07	5.02	5	4.98	4.94	4.91	1.76	0.283
2.077	28	815	5.16	5.09	5.07	5.04	5	4.97	1.88	0.283
2.077	29	839	5.2	5.13	5.1	5.07	5.03	5	1.99	0.283
2.077	30	862	5.17	5.09	5.06	5.04	4.99	4.96	2.11	0.283
2.077	31	886	5.08	5.01	4.98	4.96	4.92	4.89	2.22	0.283
2.077	32	910	5.06	4.98	4.96	4.94	4.9	4.87	2.34	0.283
2.077	33	934	5.06	4.98	4.95	4.93	4.88	4.86	2.45	0.283
2.077	34	958	5.09	4.99	4.96	4.94	4.89	4.86	2.57	0.283
2.077	35	982	5.12	5.02	4.98	4.96	4.91	4.88	2.68	0.283
2.077	36	1006	5.18	5.06	5.01	4.99	4.93	4.9	2.8	0.283
2.077	37	1030	5.22	5.09	5.05	5.01	4.96	4.93	2.91	0.283
2.077	38	1054	5.29	5.14	5.08	5.05	5	4.96	3.03	0.283
2.077	39	1079	5.39	5.21	5.14	5.1	5.04	5	3.14	0.283
2.077	40	1103	5.54	5.31	5.22	5.17	5.1	5.05	3.26	0.283
2.077	41	1127	5.68	5.43	5.32	5.25	5.17	5.12	3.37	0.283
2.077	42	1152	5.75	5.51	5.4	5.34	5.25	5.2	3.49	0.283
2.097	43	1176	5.89	5.66	5.53	5.48	5.38	5.33	3.61	0.283
2.118	44	1200	6.53	6.15	5.94	5.86	5.72	5.65	3.72	0.283
2.138	45	1224	7.88	7.13	6.73	6.4	6.23	6.13	3.84	0.283
2.159	46	1248	10.44	8.94	7.84	7.36	6.92	6.68	3.95	0.283
2.18	47	1200	8.14	7.31	6.97	6.83	6.63	6.54	4.07	0.283
2.201	48	1151	7.01	6.71	6.55	6.48	6.37	6.31	4.18	0.283
2.201	49	1102	6.53	6.37	6.3	6.26	6.2	6.16	4.3	0.283
2.201	50	1054	6.42	6.29	6.23	6.21	6.15	6.12	4.41	0.283
2.201	51	1005	6.36	6.24	6.19	6.16	6.11	6.08	4.53	0.283
2.201	52	957	6.29	6.19	6.15	6.13	6.08	6.05	4.65	0.283
2.201	53	908	6.24	6.14	6.12	6.09	6.05	6.02	4.77	0.283
2.201	54	859	6.18	6.09	6.07	6.05	6.01	5.99	4.89	0.283
2.201	55	810	6.13	6.06	6.04	6.02	5.98	5.96	5.02	0.283
2.201	56	761	6.08	6.02	6.01	5.98	5.95	5.93	5.16	0.283
2.201	57	712	6.04	5.98	5.97	5.95	5.92	5.9	5.3	0.283
2.201	58	663	5.99	5.94	5.94	5.92	5.88	5.87	5.45	0.283
2.201	59	614	5.95	5.9	5.9	5.88	5.85	5.84	5.62	0.283
2.201	60	565	5.91	5.86	5.87	5.85	5.82	5.81	5.79	0.283

mq := 61,62...nd - Nempties

samdns	mmq	T <sub>mq,1</sub>	$\epsilon'_{\text{mq},1}$	$\epsilon'_{\text{mq},2}$	$\epsilon'_{\text{mq},3}$	$\epsilon'_{\text{mq},4}$	$\epsilon'_{\text{mq},5}$	$\epsilon'_{\text{mq},6}$	tlaps <sub>mq</sub>	sammass <sub>mq</sub>
2.201	61	518	5.87	5.83	5.83	5.81	5.78	5.77	5.98	0.283
2.201	62	471	5.83	5.78	5.79	5.77	5.75	5.73	6.18	0.283
2.201	63	422	5.79	5.75	5.75	5.74	5.72	5.7	6.4	0.283
2.201	64	377	5.73	5.7	5.7	5.69	5.67	5.66	6.64	0.283
2.201	65	330	5.68	5.67	5.67	5.66	5.63	5.62	6.91	0.283
2.201	66	283	5.64	5.62	5.62	5.61	5.58	5.57	7.21	0.283
2.201	67	235	5.59	5.57	5.57	5.56	5.54	5.53	7.59	0.283
2.201	68	181	5.54	5.52	5.52	5.51	5.49	5.48	8.05	0.283
2.201	69	123	5.53	5.52	5.51	5.51	5.48	5.47	8.74	0.283
2.201	70	24	5.5	5.49	5.47	5.45	5.41	5.38	11.41	0.283

# Appendix E. MPN Reports

Test = 2023061101                      NASA2361.mcd                      AnDat = 20230612  
 3rd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1250C, in flowing argon, for D.Rickn

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal}+1} = 2.094 \text{ gm/cc}$                       Final density(25C) =  $\text{dns}_{\text{final}} = 2.201 \text{ gm/cc}$   
 density index T(C) 397MHz 912MHz 1429MHz 1948MHz2466MHz 2986MHz                      Lapsed Time (hours)

samdns	mm	T	$\epsilon''_{\text{mm},1}$	$\epsilon''_{\text{mm},2}$	$\epsilon''_{\text{mm},3}$	$\epsilon''_{\text{mm},4}$	$\epsilon''_{\text{mm},5}$	$\epsilon''_{\text{mm},6}$	daps	sammas
2.094	11	24	0.01	0.012	0.013	0.013	0.015	0.011	0	0.283
2.094	12	24	0.011	0.011	0.012	0.013	0.015	0.011	0.08	0.283
2.094	13	24	0.011	0.012	0.012	0.013	0.015	0.011	0.14	0.283
2.094	14	103	0.008	0.013	0.01	0.011	0.014	0.01	0.27	0.283
2.094	15	166	0.012	0.006	0.011	0.01	0.013	0.009	0.38	0.283
2.094	16	227	0.017	0.008	0.011	0.012	0.014	0.009	0.5	0.283
2.094	17	284	0.014	0.006	0.011	0.013	0.014	0.009	0.61	0.283
2.094	18	337	0.021	0.009	0.012	0.012	0.015	0.01	0.73	0.283
2.094	19	386	0.014	0.014	0.014	0.016	0.017	0.012	0.84	0.283
2.094	20	434	0.022	0.018	0.017	0.017	0.016	0.013	0.96	0.283
2.094	21	482	0.025	0.018	0.018	0.018	0.02	0.014	1.07	0.283
2.094	22	529	0.029	0.02	0.021	0.02	0.023	0.017	1.19	0.283
2.094	23	577	0.035	0.028	0.024	0.023	0.024	0.019	1.3	0.283
2.094	24	625	0.031	0.03	0.03	0.029	0.028	0.023	1.42	0.283
2.094	25	672	0.051	0.04	0.037	0.034	0.034	0.027	1.53	0.283
2.094	26	720	0.058	0.048	0.045	0.043	0.042	0.034	1.65	0.283
2.084	27	768	0.072	0.059	0.055	0.052	0.051	0.043	1.76	0.283
2.077	28	815	0.104	0.084	0.072	0.064	0.061	0.054	1.88	0.283
2.077	29	839	0.124	0.084	0.075	0.07	0.069	0.058	1.99	0.283
2.077	30	862	0.125	0.09	0.079	0.071	0.068	0.059	2.11	0.283
2.077	31	886	0.127	0.09	0.077	0.067	0.063	0.053	2.22	0.283
2.077	32	910	0.142	0.105	0.079	0.071	0.066	0.056	2.34	0.283
2.077	33	934	0.163	0.111	0.09	0.078	0.073	0.062	2.45	0.283
2.077	34	958	0.178	0.125	0.103	0.089	0.083	0.071	2.57	0.283
2.077	35	982	0.218	0.146	0.114	0.103	0.092	0.08	2.68	0.283
2.077	36	1006	0.24	0.164	0.129	0.115	0.105	0.09	2.8	0.283
2.077	37	1030	0.282	0.192	0.153	0.133	0.118	0.103	2.91	0.283
2.077	38	1054	0.329	0.228	0.178	0.156	0.138	0.122	3.03	0.283
2.077	39	1079	0.426	0.288	0.225	0.194	0.172	0.151	3.14	0.283
2.077	40	1103	0.509	0.362	0.282	0.244	0.215	0.189	3.26	0.283
2.077	41	1127	0.526	0.394	0.325	0.286	0.255	0.226	3.37	0.283
2.077	42	1152	0.518	0.383	0.315	0.279	0.251	0.227	3.49	0.283
2.097	43	1176	0.636	0.404	0.301	0.252	0.219	0.19	3.61	0.283
2.118	44	1200	1.099	0.643	0.438	0.354	0.278	0.236	3.72	0.283
2.138	45	1224	2.315	1.287	0.829	0.534	0.41	0.344	3.84	0.283
2.159	46	1248	5.27	2.803	1.403	0.906	0.572	0.411	3.95	0.283
2.18	47	1200	1.946	0.97	0.618	0.486	0.366	0.307	4.07	0.283
2.201	48	1151	0.742	0.438	0.302	0.245	0.197	0.169	4.18	0.283
2.201	49	1102	0.38	0.23	0.175	0.148	0.13	0.112	4.3	0.283
2.201	50	1054	0.318	0.201	0.158	0.133	0.121	0.102	4.41	0.283
2.201	51	1005	0.264	0.174	0.138	0.121	0.108	0.092	4.53	0.283
2.201	52	957	0.232	0.153	0.122	0.104	0.096	0.084	4.65	0.283
2.201	53	908	0.195	0.132	0.106	0.094	0.086	0.074	4.77	0.283
2.201	54	859	0.171	0.107	0.09	0.083	0.078	0.065	4.89	0.283
2.201	55	810	0.143	0.09	0.081	0.074	0.069	0.059	5.02	0.283
2.201	56	761	0.116	0.088	0.072	0.065	0.061	0.053	5.16	0.283
2.201	57	712	0.101	0.07	0.06	0.057	0.056	0.047	5.3	0.283
2.201	58	663	0.078	0.057	0.057	0.051	0.052	0.044	5.45	0.283
2.201	59	614	0.063	0.051	0.048	0.046	0.047	0.038	5.62	0.283
2.201	60	565	0.068	0.042	0.04	0.042	0.043	0.034	5.79	0.283

mj = 61,62..nd - Nempties

samdns	mm	T	$\epsilon''_{\text{mj},1}$	$\epsilon''_{\text{mj},2}$	$\epsilon''_{\text{mj},3}$	$\epsilon''_{\text{mj},4}$	$\epsilon''_{\text{mj},5}$	$\epsilon''_{\text{mj},6}$	daps	sammas
2.201	61	518	0.044	0.04	0.04	0.038	0.039	0.03	5.98	0.283
2.201	62	471	0.036	0.035	0.036	0.034	0.035	0.029	6.18	0.283
2.201	63	422	0.043	0.032	0.029	0.031	0.031	0.025	6.4	0.283
2.201	64	377	0.044	0.03	0.025	0.027	0.03	0.022	6.64	0.283
2.201	65	330	0.024	0.022	0.021	0.026	0.027	0.021	6.91	0.283
2.201	66	283	0.039	0.015	0.023	0.021	0.025	0.018	7.21	0.283
2.201	67	235	0.007	0.018	0.019	0.018	0.023	0.018	7.59	0.283
2.201	68	181	0.012	0.017	0.017	0.021	0.022	0.016	8.05	0.283
2.201	69	123	0.013	0.007	0.019	0.019	0.023	0.019	8.74	0.283
2.201	70	24	0.018	0.018	0.022	0.024	0.028	0.023	11.41	0.283

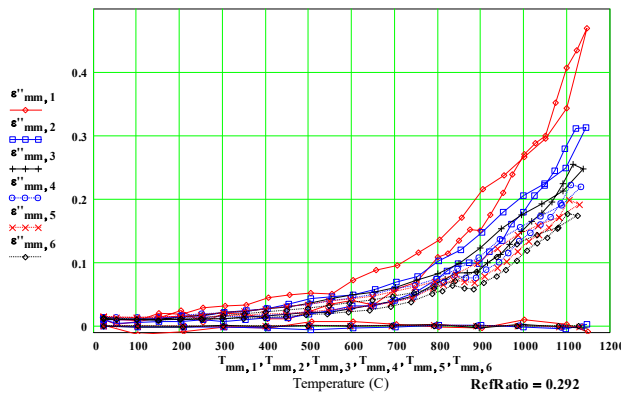
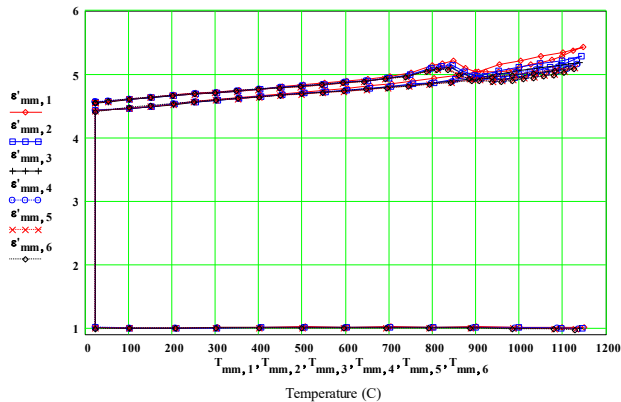
MPN-292\_MPN\_Glass for 5M Simulant\_Creedon\_Washington Mills Sept. 11, 2023

Glass Used in NUW-LHT-5M Lunar Simulant , from Washington Mills,  
Measurements of Complex Dielectric Constant of Pressed Pellets  
Room Temperature to 1150°C to RT, in flowing (10 sccm) UHP Argon

Dr. Doug Rickman ( NASA) was interested in knowing the dielectric properties of the special glass that was manufactured by Washington Mills, and used in the making of the NUW-LHT-5M simulant. Dr. Matt Creedon of Washington Mills sent a sample of the 5M simulant glass powder to MPN, who had offered to measure its microwave dielectric properties.

Microwave Properties North had already done three complex dielectric properties measurement runs on heat-treated NUW-LHT-5M lunar regolith simulant up to temperatures of 1100C, 1150C and 1250C under a NASA contract. The first dielectric measurement run on the full NUW-LHT-5M simulant, in vacuum, up to 1100C, had an unfamiliar feature at ~ 850C . The second full simulant run was done up to 1150C in flowing ( 10 sccm) UHP argon. This required a different sample holder, different background subtractions and new calibrations. However, the same feature was noted in the dielectric constant, shown in the following plots.

Test = 2023060901                      NASA2360.mcd                      AnDat = 20230610  
 2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H<sub>2</sub> to 1150C, in flowing argon, for D.Rickman  
 Initial density =  $\text{samdns}_{\text{NCat} + 1} = 2.12 \text{ gm/cc}$ ,                      Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$   
 Final\_over\_Initial\_mass = 1



The top line of the  $\epsilon'$  plot ( initial value  $\epsilon' \sim 4.7$  ) is the values measured during the ramp up to 1150°C .

The bottom line in the plots is the empty holder measurement done immediately after the sample measurement. Only the initial and final sample dimensions were actually measured.

The NUW-LHT-5M lunar simulant has ~ 40 wt% of a relatively unique ( on earth at least) glass, largely composed of the same elements as the crystalline content of the simulant. It seemed useful to measure the properties of the glass alone, but under similar conditions.

For this 5M glass measurement, MPN again pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. This run was a simple cycle to 1150C and back to room temperature. The sample holder for this run was initially cycled ( and measured, empty) to 1150C before the run to “clean” the holder and measure the “empty holder” values, which were later used during the off-line data analysis.

**For this measurement, a holder with a small hole in the base was used, so UHP argon gas could flow up, past the sample pellets, at ~ 10 sccm regulated flow rate.**

The initial sample parameters were:

- a) diameter 3.63 +- 0.02 mm
- b) length of 3 pellet stack: 13.54 +- 0.05 mm
- c) mass 0.280 +- 0.002 gm
- tt) room temperature density  $1.90 \pm 0.05$  gm/cc.
- uu) appearance - three light grey pellets ( see photos)
- vv) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 800C in 50C steps, then to 1150C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets were easily removed, and their combined mass determined. Then the empty holder was run up to 1100C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

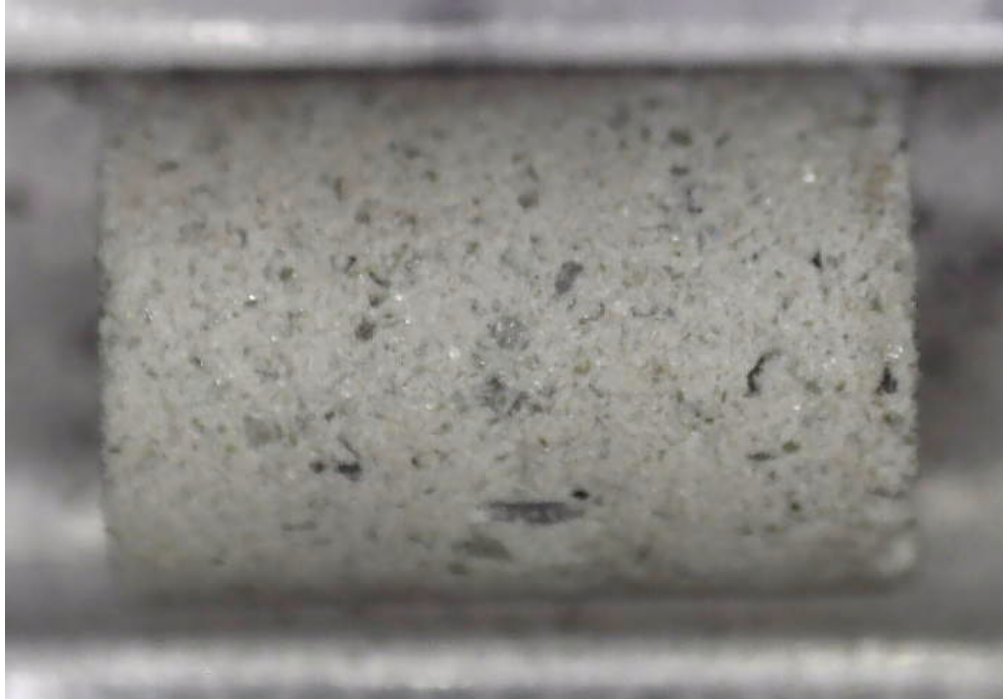
- a) diameter  $3.60 \pm 0.03$  mm
- b) pellet stack length  $13.52 \pm 0.05$  mm
- c) mass  $0.280 \pm 0.002$  gm
- ss) room temperature density  $1.81 \pm 0.05$  gm/cc.
- tt) appearance - three very light beige pellets ( see photos)
- uu) magnetic response - The pellets had a very weak attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

Legend for Data Plots :

#	<u>Frequency(MHz)</u>	<u>Symbol</u>
1	397	red diamond, solid line – sometimes the line is omitted!
2	912	blue square, solid line
3	1429	black cross, solid line
4	1948	blue circle, dotted line
5	2466	red cross, dotted line
6	2986	black diamond, dotted line



Typical initial NUW-LHT-5M pellet -Pressed at ~ 33,000 psi



Initial 5M Glass ( Washington Mills) pellet - Pressed at ~ 33,000 psi



Three final NUW-LHT-5M pellets after a cycle to 1150C in UHP argon .



Three final 5M Glass pellets after the cycle to 1150C in UHP argon

# Appendix E. MPN Reports

Test = 2023090501

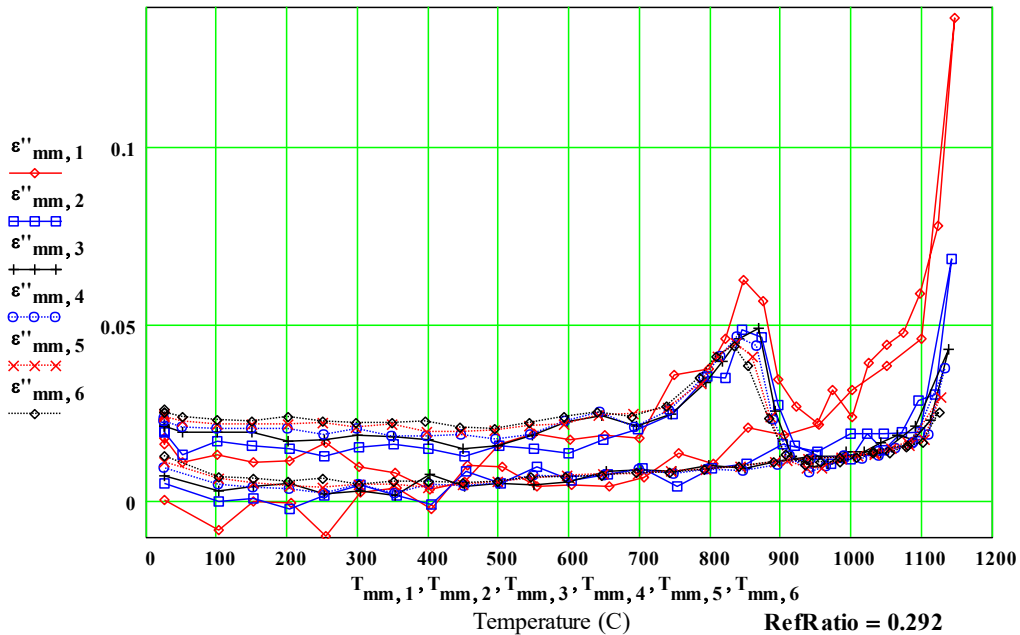
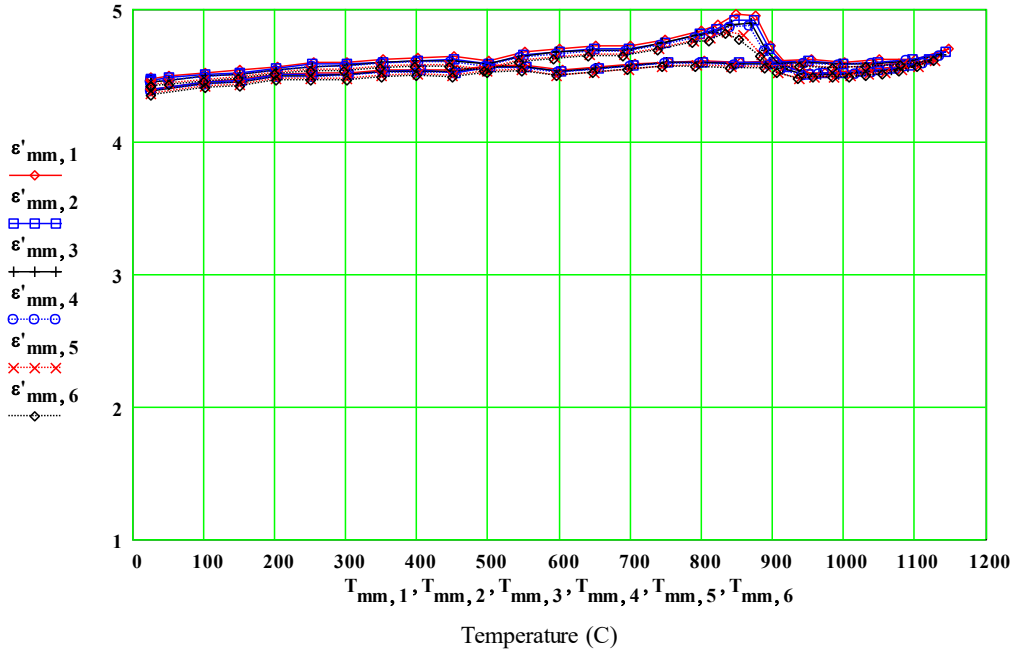
MPN023100.mcd

AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.98 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



Note the very rapid increase in  $\epsilon''$  values above 1100 °C. This is indicative of approaching the melting point. The thermal activation energy is large – very approximately 400 Kjoule/mole ( $\sim 4.2 \text{ eV}$ ) by fitting the points between 1100C and 1150 C. The feature at 850 C seen in the simulant runs is evident in this glass 5M run.

The two data points at 850C and 875C in the “ramp-up” have been changed throughout this report to match the values measured in a second run and shown in Appendix 1. This was done to improve the usefulness and accuracy of the plots for the reader.

Comments on the data run :

A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6} / C$  was used.

The final pellets appeared unchanged except for a very slight beige colouring of some components !

The smooth ramp up of the values to 1150C was interrupted only by a slight drop of the  $\epsilon'$  values at 850C and 875 C (plot below). This was very difficult to understand, so another run was done to 1000C ( MPN023101) on a new set of pellets in a solid-bottom holder, with the argon gas flowing down onto the top of the test sample. In this configuration, expansion of the pellet diametrically cannot result in vertical movement of the test sample caused by the cover gas flow! This second run demonstrated that, in fact, a transformation ( re-crystallization ? ) was occurring between 700C and 925C, which resulted in small increases in both  $\epsilon'$  and  $\epsilon''$  , with a maxima at ~ 860 C. The details of this run are presented in Appendix 1 at the end of this report.

The explanation for the dip in the first run to 1150C ( MPN023100, plot below ) would seem to be that the pellets expanded in diameter during this transformation ( which actually started at ~ 600C ) , and at 850C the expansion blocked the vertical flow of argon and increased the pressure sufficiently to lift the pellet(s?) into a region of the cavity that had a slightly lower electric field ( The equivalent of shortening the sample). By changing the “effective” pellet length ( and thus the volume ) slightly for only the two temperatures ( 850C and 875 C ) during the data analysis, the peak shape was made to match that seen in the second run to 1000C ( shown in Appendix 1 ).

This feature, although interesting, is small and probably not very significant in the high temperature properties of the 5M simulant.

# Appendix E. MPN Reports

Test = 2023090501

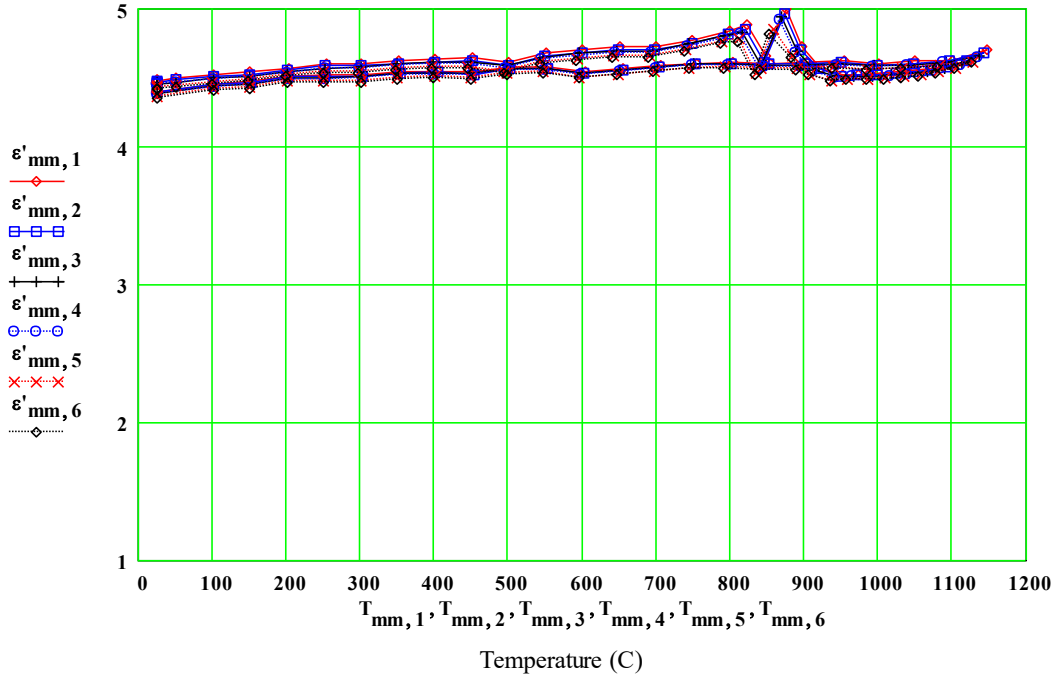
MPN023100.mcd

AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.98 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



# Appendix E. MPN Reports

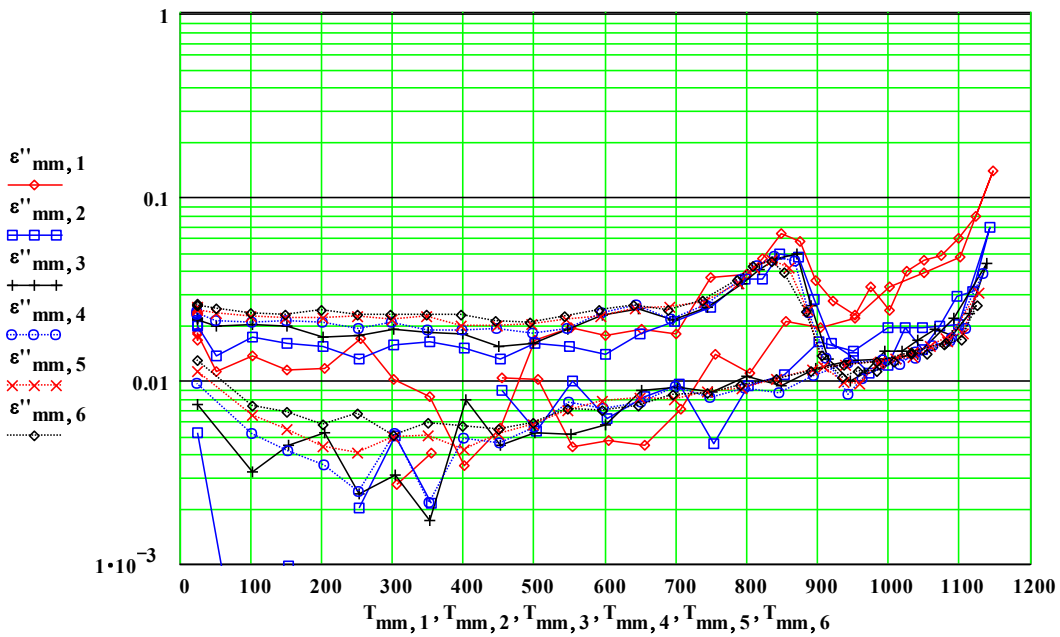
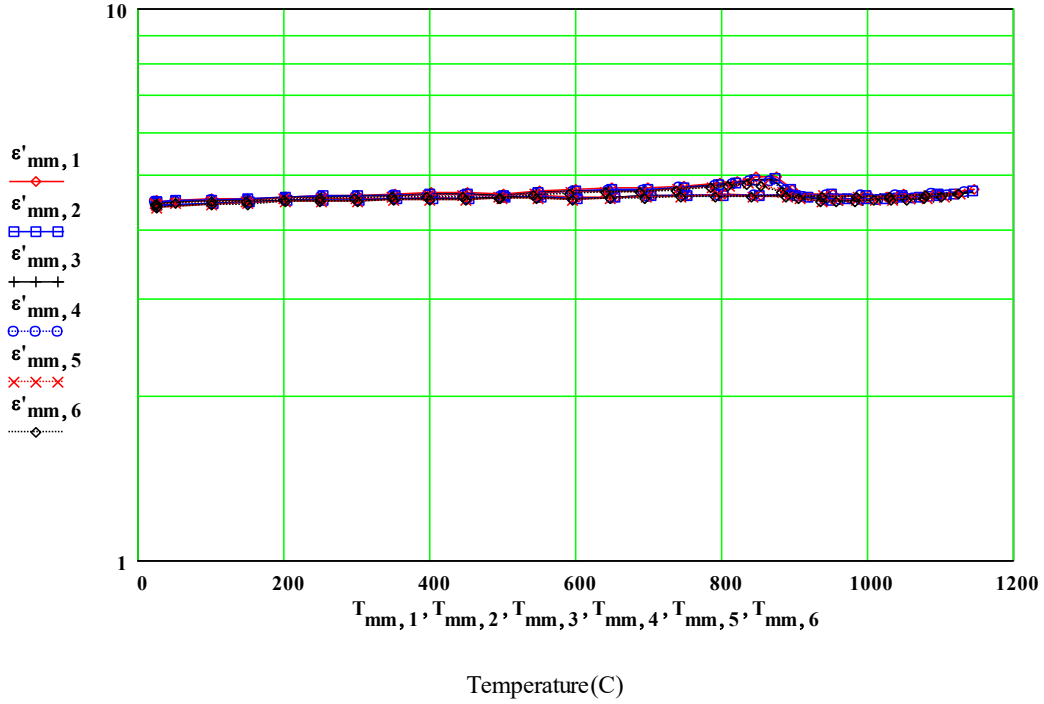
Test = 2023090501

MPN023100.med

AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.98 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023090501

MPN023100.mcd

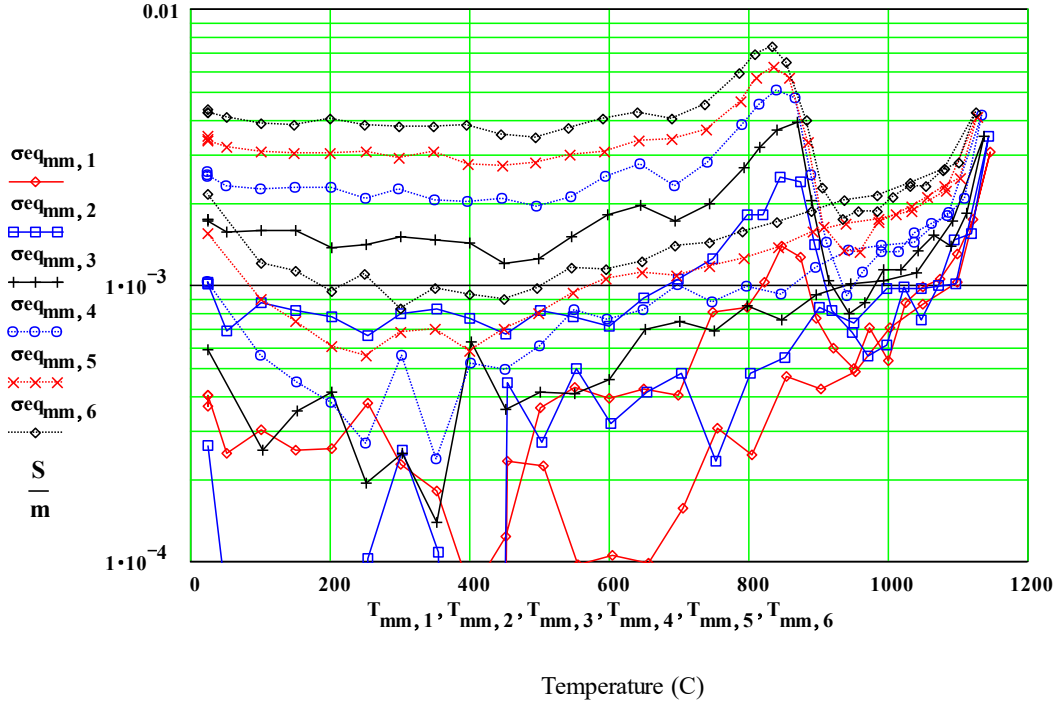
AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{14} = 2 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.98 \text{ gm/cc}$

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2023090501

MPN023100.mcd

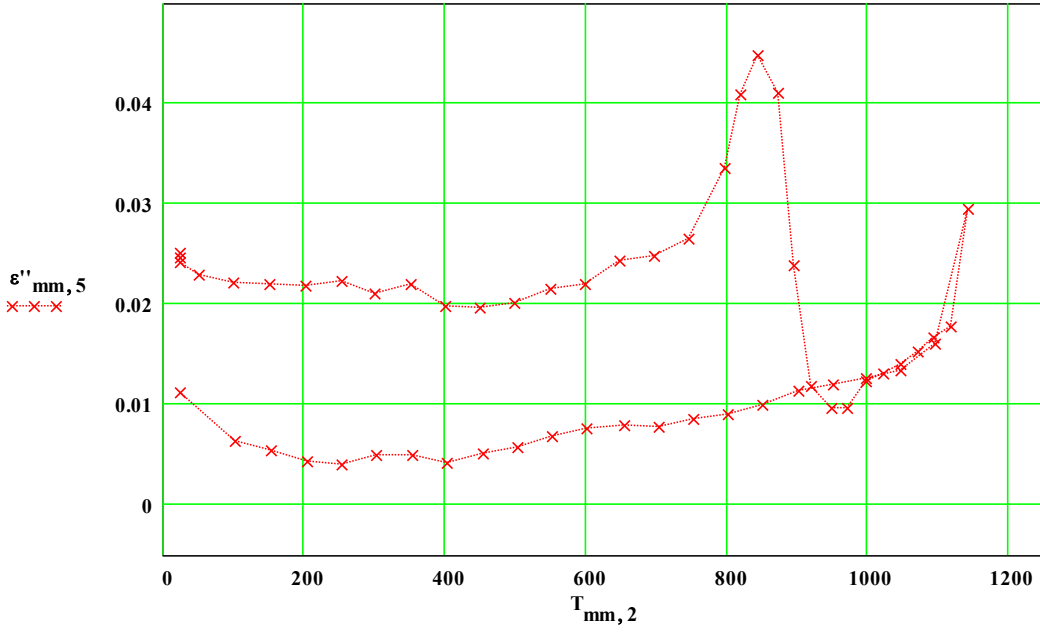
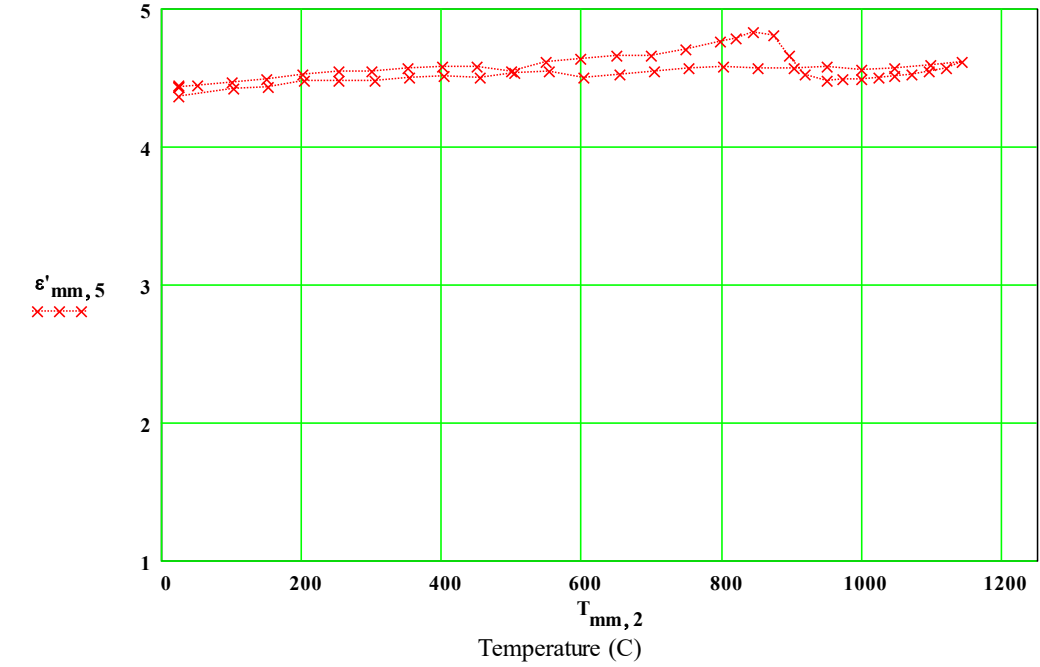
AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2$  gm/cc, Final density(25C) =  $\text{dnsfinal} = 1.98$  gm/cc

Thermal exp. coeff.  $\alpha_1 = 0$

## Values for 2450 MHz



# Appendix E. MPN Reports

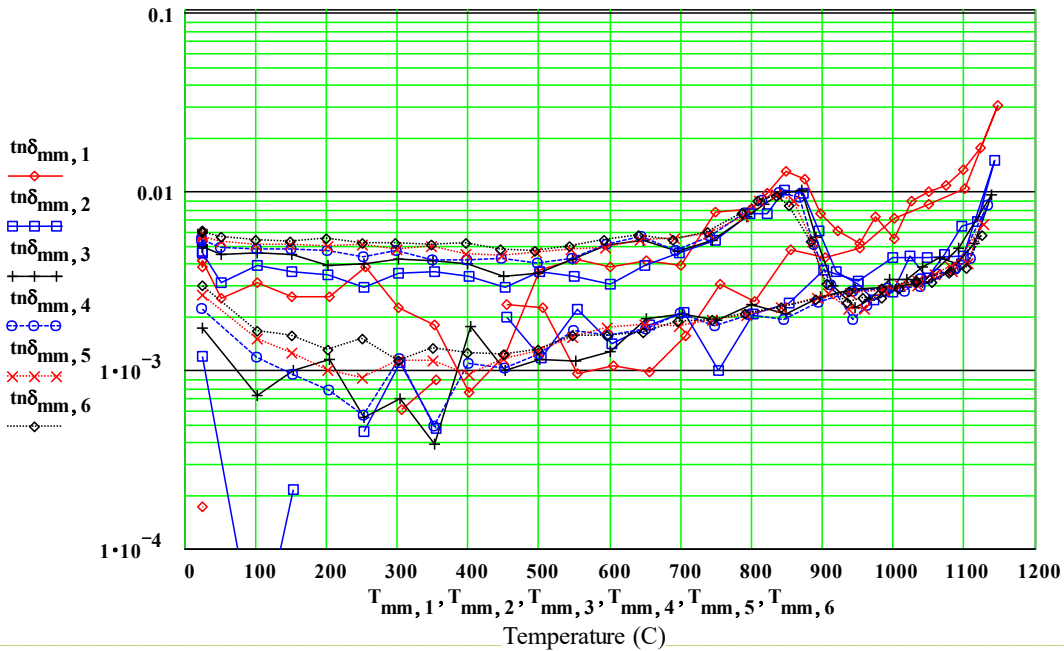
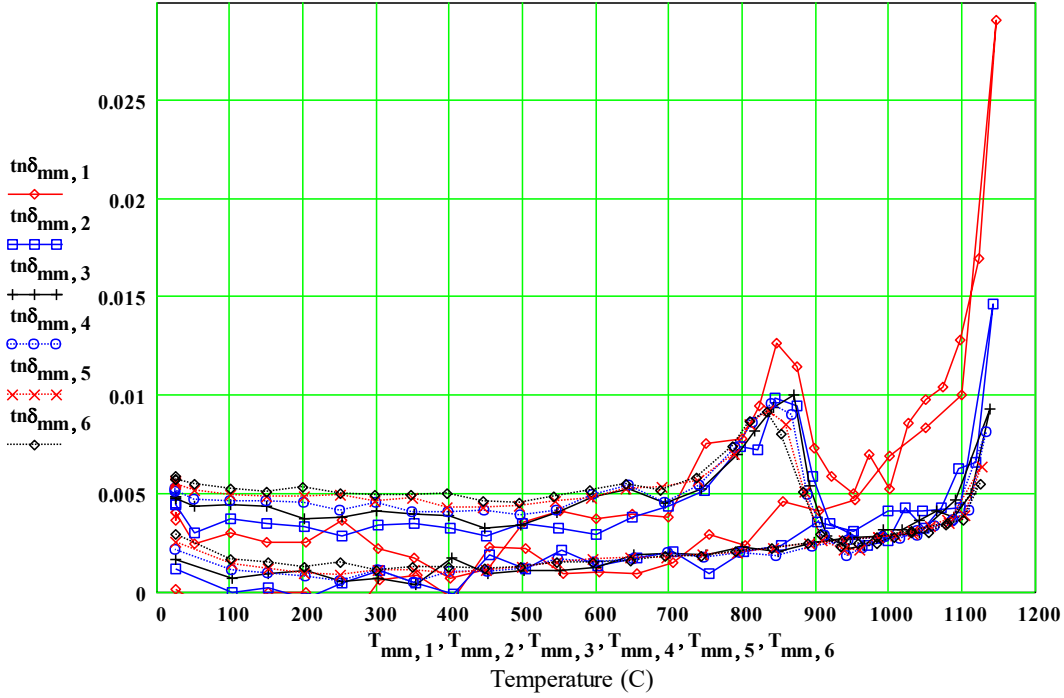
Test = 2023090501

MPN023100.mcd

AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.98 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023090501

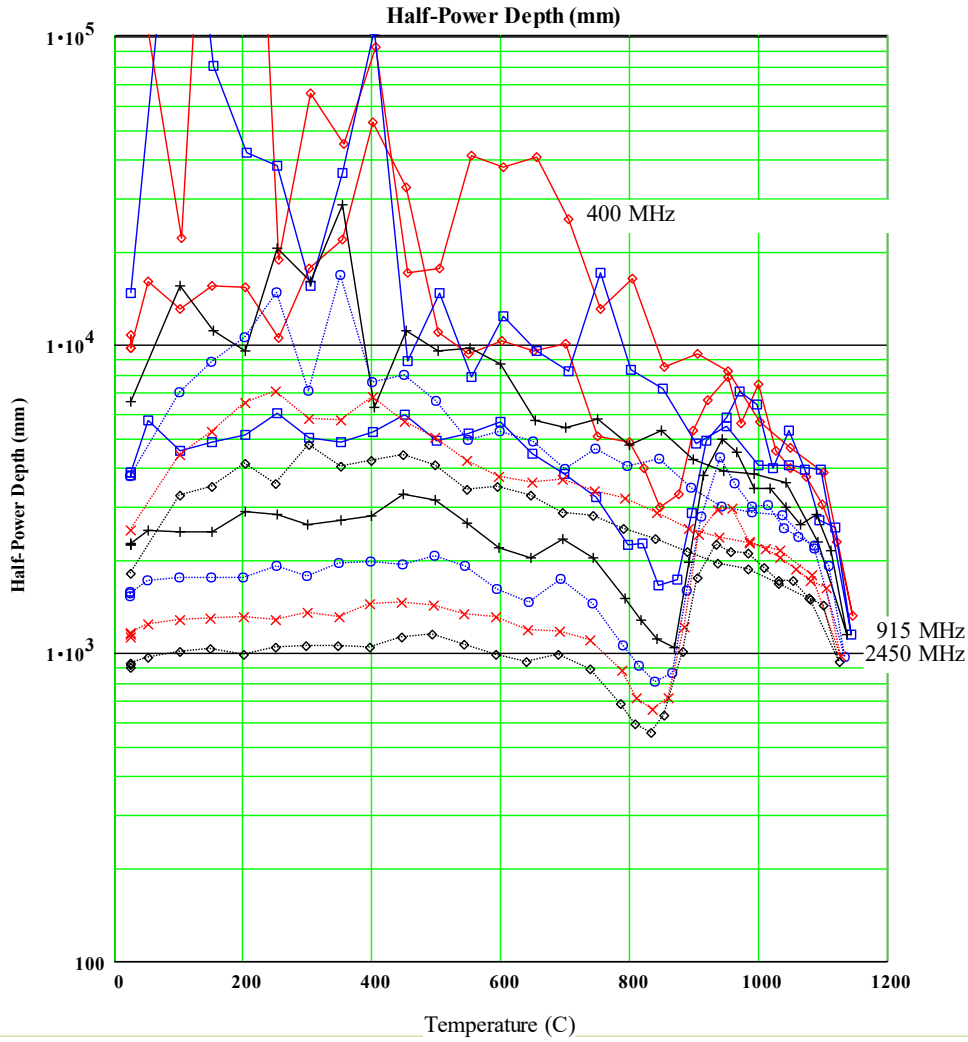
MPN023100.mcd

AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.98 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023090501                      MPN023100.mcd                      AnDat = 20230907  
 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :  
 ~~~~~~

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.998$  gm/cc                      Final density(25C) =  $\text{dnsfinal} = 1.979$  gm/cc  
 Lapsed

| density                     | index             | T(C)                      | 397MHz                    | 912MHz                    | 1429MHz                   | 1948MHz                   | 2466MHz                   | 2986MHz | Time (hours) | $\text{tlaps}_{\text{mm}}$ | $\text{sammas}_{\text{mm}}$ |
|-----------------------------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------|--------------|----------------------------|-----------------------------|
| $\text{samdns}_{\text{mm}}$ | $T_{\text{mm},1}$ | $\epsilon'_{\text{mm},1}$ | $\epsilon'_{\text{mm},2}$ | $\epsilon'_{\text{mm},3}$ | $\epsilon'_{\text{mm},4}$ | $\epsilon'_{\text{mm},5}$ | $\epsilon'_{\text{mm},6}$ |         |              |                            |                             |
| 1.998                       | 11                | 25                        | 4.49                      | 4.48                      | 4.47                      | 4.46                      | 4.44                      | 4.43    | 0            | 0.28                       |                             |
| 1.998                       | 12                | 25                        | 4.48                      | 4.47                      | 4.45                      | 4.45                      | 4.43                      | 4.41    | 0.15         | 0.28                       |                             |
| 1.998                       | 13                | 25                        | 4.48                      | 4.47                      | 4.45                      | 4.45                      | 4.43                      | 4.42    | 0.22         | 0.28                       |                             |
| 1.998                       | 14                | 52                        | 4.5                       | 4.49                      | 4.47                      | 4.46                      | 4.44                      | 4.43    | 0.4          | 0.28                       |                             |
| 1.998                       | 15                | 101                       | 4.52                      | 4.51                      | 4.5                       | 4.49                      | 4.47                      | 4.46    | 0.7          | 0.28                       |                             |
| 1.998                       | 16                | 151                       | 4.55                      | 4.53                      | 4.51                      | 4.51                      | 4.49                      | 4.47    | 1.01         | 0.28                       |                             |
| 1.998                       | 17                | 203                       | 4.57                      | 4.56                      | 4.55                      | 4.54                      | 4.52                      | 4.51    | 1.36         | 0.28                       |                             |
| 1.998                       | 18                | 254                       | 4.6                       | 4.59                      | 4.57                      | 4.56                      | 4.54                      | 4.53    | 1.7          | 0.28                       |                             |
| 1.998                       | 19                | 302                       | 4.6                       | 4.59                      | 4.58                      | 4.57                      | 4.55                      | 4.54    | 2.03         | 0.28                       |                             |
| 1.998                       | 20                | 352                       | 4.63                      | 4.61                      | 4.6                       | 4.59                      | 4.57                      | 4.56    | 2.32         | 0.28                       |                             |
| 1.998                       | 21                | 402                       | 4.64                      | 4.62                      | 4.61                      | 4.6                       | 4.58                      | 4.57    | 2.6          | 0.28                       |                             |
| 1.998                       | 22                | 452                       | 4.65                      | 4.63                      | 4.62                      | 4.6                       | 4.58                      | 4.57    | 2.89         | 0.28                       |                             |
| 1.998                       | 23                | 501                       | 4.61                      | 4.59                      | 4.59                      | 4.57                      | 4.55                      | 4.54    | 3.18         | 0.28                       |                             |
| 1.998                       | 24                | 550                       | 4.68                      | 4.66                      | 4.65                      | 4.64                      | 4.61                      | 4.6     | 3.43         | 0.28                       |                             |
| 1.998                       | 25                | 600                       | 4.7                       | 4.68                      | 4.68                      | 4.66                      | 4.64                      | 4.63    | 3.68         | 0.28                       |                             |
| 1.998                       | 26                | 650                       | 4.73                      | 4.7                       | 4.7                       | 4.68                      | 4.66                      | 4.64    | 3.94         | 0.28                       |                             |
| 1.998                       | 27                | 699                       | 4.73                      | 4.7                       | 4.7                       | 4.68                      | 4.66                      | 4.65    | 4.19         | 0.28                       |                             |
| 1.998                       | 28                | 749                       | 4.78                      | 4.75                      | 4.75                      | 4.73                      | 4.71                      | 4.7     | 4.44         | 0.28                       |                             |
| 1.98                        | 29                | 799                       | 4.84                      | 4.82                      | 4.8                       | 4.79                      | 4.76                      | 4.74    | 4.7          | 0.28                       |                             |
| 1.961                       | 30                | 822                       | 4.88                      | 4.85                      | 4.83                      | 4.81                      | 4.78                      | 4.77    | 4.86         | 0.28                       |                             |
| 2.063                       | 31                | 847                       | 4.96                      | 4.91                      | 4.89                      | 4.86                      | 4.83                      | 4.81    | 5.04         | 0.28                       |                             |
| 1.909                       | 32                | 875                       | 4.96                      | 4.93                      | 4.9                       | 4.87                      | 4.81                      | 4.77    | 5.21         | 0.28                       |                             |
| 1.907                       | 33                | 897                       | 4.73                      | 4.7                       | 4.69                      | 4.68                      | 4.66                      | 4.65    | 5.38         | 0.28                       |                             |
| 1.89                        | 34                | 921                       | 4.57                      | 4.56                      | 4.56                      | 4.55                      | 4.53                      | 4.52    | 5.54         | 0.28                       |                             |
| 1.872                       | 35                | 951                       | 4.52                      | 4.51                      | 4.51                      | 4.5                       | 4.48                      | 4.47    | 5.73         | 0.28                       |                             |
| 1.872                       | 36                | 974                       | 4.53                      | 4.52                      | 4.51                      | 4.51                      | 4.49                      | 4.49    | 5.89         | 0.28                       |                             |
| 1.872                       | 37                | 1000                      | 4.54                      | 4.53                      | 4.52                      | 4.51                      | 4.49                      | 4.49    | 6.07         | 0.28                       |                             |
| 1.872                       | 38                | 1026                      | 4.55                      | 4.53                      | 4.52                      | 4.51                      | 4.49                      | 4.49    | 6.24         | 0.28                       |                             |
| 1.872                       | 39                | 1050                      | 4.56                      | 4.55                      | 4.53                      | 4.53                      | 4.51                      | 4.5     | 6.41         | 0.28                       |                             |
| 1.872                       | 40                | 1074                      | 4.57                      | 4.56                      | 4.55                      | 4.54                      | 4.52                      | 4.51    | 6.58         | 0.28                       |                             |
| 1.877                       | 41                | 1098                      | 4.59                      | 4.58                      | 4.57                      | 4.56                      | 4.54                      | 4.54    | 6.74         | 0.28                       |                             |
| 1.881                       | 42                | 1122                      | 4.62                      | 4.62                      | 4.6                       | 4.6                       | 4.57                      | 4.56    | 6.91         | 0.28                       |                             |
| 1.886                       | 43                | 1146                      | 4.7                       | 4.68                      | 4.66                      | 4.65                      | 4.62                      | 4.61    | 7.08         | 0.28                       |                             |
| 1.89                        | 44                | 1100                      | 4.63                      | 4.63                      | 4.61                      | 4.61                      | 4.59                      | 4.58    | 7.31         | 0.28                       |                             |
| 1.895                       | 45                | 1049                      | 4.62                      | 4.61                      | 4.6                       | 4.59                      | 4.57                      | 4.56    | 7.57         | 0.28                       |                             |
| 1.899                       | 46                | 1001                      | 4.6                       | 4.59                      | 4.59                      | 4.58                      | 4.56                      | 4.55    | 7.82         | 0.28                       |                             |
| 1.904                       | 47                | 953                       | 4.62                      | 4.61                      | 4.6                       | 4.6                       | 4.58                      | 4.57    | 8.06         | 0.28                       |                             |
| 1.909                       | 48                | 904                       | 4.61                      | 4.6                       | 4.59                      | 4.58                      | 4.57                      | 4.56    | 8.31         | 0.28                       |                             |
| 1.913                       | 49                | 854                       | 4.61                      | 4.6                       | 4.59                      | 4.58                      | 4.57                      | 4.56    | 8.57         | 0.28                       |                             |
| 1.918                       | 50                | 804                       | 4.62                      | 4.6                       | 4.61                      | 4.6                       | 4.58                      | 4.57    | 8.82         | 0.28                       |                             |
| 1.922                       | 51                | 755                       | 4.6                       | 4.6                       | 4.6                       | 4.59                      | 4.57                      | 4.56    | 9.07         | 0.28                       |                             |
| 1.927                       | 52                | 706                       | 4.59                      | 4.58                      | 4.58                      | 4.57                      | 4.55                      | 4.54    | 9.32         | 0.28                       |                             |
| 1.932                       | 53                | 656                       | 4.57                      | 4.56                      | 4.56                      | 4.55                      | 4.53                      | 4.52    | 9.57         | 0.28                       |                             |
| 1.936                       | 54                | 604                       | 4.55                      | 4.54                      | 4.54                      | 4.53                      | 4.51                      | 4.5     | 9.84         | 0.28                       |                             |
| 1.941                       | 55                | 554                       | 4.58                      | 4.57                      | 4.57                      | 4.56                      | 4.54                      | 4.53    | 10.09        | 0.28                       |                             |
| 1.946                       | 56                | 504                       | 4.58                      | 4.56                      | 4.56                      | 4.55                      | 4.54                      | 4.53    | 10.36        | 0.28                       |                             |
| 1.951                       | 57                | 455                       | 4.54                      | 4.53                      | 4.53                      | 4.52                      | 4.5                       | 4.49    | 10.66        | 0.28                       |                             |
| 1.955                       | 58                | 405                       | 4.55                      | 4.54                      | 4.54                      | 4.53                      | 4.51                      | 4.5     | 11           | 0.28                       |                             |
| 1.96                        | 59                | 355                       | 4.55                      | 4.53                      | 4.53                      | 4.52                      | 4.5                       | 4.49    | 11.39        | 0.28                       |                             |
| 1.965                       | 60                | 305                       | 4.52                      | 4.51                      | 4.51                      | 4.5                       | 4.48                      | 4.47    | 11.83        | 0.28                       |                             |

mq := 61,62..nd - Nempties

| $\text{samdns}_{\text{mq}}$ | $T_{\text{mq},1}$ | $\epsilon'_{\text{mq},1}$ | $\epsilon'_{\text{mq},2}$ | $\epsilon'_{\text{mq},3}$ | $\epsilon'_{\text{mq},4}$ | $\epsilon'_{\text{mq},5}$ | $\epsilon'_{\text{mq},6}$ | $\text{tlaps}_{\text{mq}}$ | $\text{sammas}_{\text{mq}}$ |      |
|-----------------------------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|----------------------------|-----------------------------|------|
| 1.97                        | 61                | 254                       | 4.52                      | 4.51                      | 4.5                       | 4.49                      | 4.47                      | 4.46                       | 12.35                       | 0.28 |
| 1.974                       | 62                | 204                       | 4.51                      | 4.51                      | 4.5                       | 4.49                      | 4.47                      | 4.46                       | 12.96                       | 0.28 |
| 1.979                       | 63                | 153                       | 4.48                      | 4.47                      | 4.46                      | 4.45                      | 4.43                      | 4.43                       | 13.8                        | 0.28 |
| 1.979                       | 64                | 103                       | 4.46                      | 4.45                      | 4.44                      | 4.44                      | 4.42                      | 4.41                       | 15.06                       | 0.28 |
| 1.979                       | 65                | 25                        | 4.4                       | 4.4                       | 4.39                      | 4.39                      | 4.37                      | 4.35                       | 21.46                       | 0.28 |

# Appendix E. MPN Reports

Test = 2023090501                      MPN023100.mcd                      AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.998$  gm/cc                      Final density(25C) =  $\text{dnsfinal} = 1.979$  gm/cc  
Lapsed

density index T(C) 397MHz 912MHz 1429MHz 1948MHz2466MHz 2986MHz                      Time (hours)

| samdns | mm | T <sub>mm,1</sub> | $\epsilon''_{\text{mm},1}$ | $\epsilon''_{\text{mm},2}$ | $\epsilon''_{\text{mm},3}$ | $\epsilon''_{\text{mm},4}$ | $\epsilon''_{\text{mm},5}$ | $\epsilon''_{\text{mm},6}$ | flaps <sub>mm</sub> | sammas <sub>mm</sub> |
|--------|----|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|
| 1.998  | 11 | 25                | 0.018                      | 0.02                       | 0.022                      | 0.024                      | 0.025                      | 0.026                      | 0                   | 0.28                 |
| 1.998  | 12 | 25                | 0.016                      | 0.02                       | 0.022                      | 0.023                      | 0.025                      | 0.026                      | 0.15                | 0.28                 |
| 1.998  | 13 | 25                | 0.018                      | 0.02                       | 0.021                      | 0.023                      | 0.024                      | 0.025                      | 0.22                | 0.28                 |
| 1.998  | 14 | 52                | 0.011                      | 0.014                      | 0.02                       | 0.021                      | 0.023                      | 0.024                      | 0.4                 | 0.28                 |
| 1.998  | 15 | 101               | 0.014                      | 0.017                      | 0.02                       | 0.021                      | 0.022                      | 0.023                      | 0.7                 | 0.28                 |
| 1.998  | 16 | 151               | 0.011                      | 0.016                      | 0.02                       | 0.021                      | 0.022                      | 0.023                      | 1.01                | 0.28                 |
| 1.998  | 17 | 203               | 0.012                      | 0.015                      | 0.017                      | 0.021                      | 0.022                      | 0.024                      | 1.36                | 0.28                 |
| 1.998  | 18 | 254               | 0.017                      | 0.013                      | 0.018                      | 0.019                      | 0.022                      | 0.023                      | 1.7                 | 0.28                 |
| 1.998  | 19 | 302               | 0.01                       | 0.016                      | 0.019                      | 0.021                      | 0.021                      | 0.023                      | 2.03                | 0.28                 |
| 1.998  | 20 | 352               | 0.008                      | 0.016                      | 0.018                      | 0.019                      | 0.022                      | 0.023                      | 2.32                | 0.28                 |
| 1.998  | 21 | 402               | 0.003                      | 0.015                      | 0.018                      | 0.019                      | 0.02                       | 0.023                      | 2.6                 | 0.28                 |
| 1.998  | 22 | 452               | 0.006                      | 0.013                      | 0.015                      | 0.019                      | 0.02                       | 0.021                      | 2.89                | 0.28                 |
| 1.998  | 23 | 501               | 0.016                      | 0.016                      | 0.016                      | 0.018                      | 0.02                       | 0.021                      | 3.18                | 0.28                 |
| 1.998  | 24 | 550               | 0.019                      | 0.015                      | 0.019                      | 0.019                      | 0.021                      | 0.022                      | 3.43                | 0.28                 |
| 1.998  | 25 | 600               | 0.018                      | 0.014                      | 0.023                      | 0.023                      | 0.022                      | 0.024                      | 3.68                | 0.28                 |
| 1.998  | 26 | 650               | 0.019                      | 0.018                      | 0.025                      | 0.025                      | 0.024                      | 0.026                      | 3.94                | 0.28                 |
| 1.998  | 27 | 699               | 0.018                      | 0.021                      | 0.021                      | 0.021                      | 0.025                      | 0.024                      | 4.19                | 0.28                 |
| 1.998  | 28 | 749               | 0.036                      | 0.025                      | 0.025                      | 0.026                      | 0.027                      | 0.027                      | 4.44                | 0.28                 |
| 1.98   | 29 | 799               | 0.038                      | 0.036                      | 0.034                      | 0.035                      | 0.034                      | 0.035                      | 4.7                 | 0.28                 |
| 1.961  | 30 | 822               | 0.046                      | 0.035                      | 0.04                       | 0.041                      | 0.041                      | 0.041                      | 4.86                | 0.28                 |
| 2.063  | 31 | 847               | 0.063                      | 0.049                      | 0.046                      | 0.047                      | 0.045                      | 0.044                      | 5.04                | 0.28                 |
| 1.909  | 32 | 875               | 0.057                      | 0.047                      | 0.049                      | 0.044                      | 0.041                      | 0.039                      | 5.21                | 0.28                 |
| 1.907  | 33 | 897               | 0.035                      | 0.028                      | 0.026                      | 0.023                      | 0.024                      | 0.024                      | 5.38                | 0.28                 |
| 1.89   | 34 | 921               | 0.027                      | 0.016                      | 0.013                      | 0.013                      | 0.012                      | 0.013                      | 5.54                | 0.28                 |
| 1.872  | 35 | 951               | 0.023                      | 0.013                      | 0.01                       | 0.008                      | 0.01                       | 0.01                       | 5.73                | 0.28                 |
| 1.872  | 36 | 974               | 0.032                      | 0.011                      | 0.011                      | 0.01                       | 0.01                       | 0.011                      | 5.89                | 0.28                 |
| 1.872  | 37 | 1000              | 0.024                      | 0.012                      | 0.014                      | 0.012                      | 0.012                      | 0.011                      | 6.07                | 0.28                 |
| 1.872  | 38 | 1026              | 0.039                      | 0.019                      | 0.014                      | 0.012                      | 0.013                      | 0.012                      | 6.24                | 0.28                 |
| 1.872  | 39 | 1050              | 0.045                      | 0.015                      | 0.017                      | 0.014                      | 0.014                      | 0.014                      | 6.41                | 0.28                 |
| 1.872  | 40 | 1074              | 0.048                      | 0.02                       | 0.019                      | 0.015                      | 0.015                      | 0.014                      | 6.58                | 0.28                 |
| 1.877  | 41 | 1098              | 0.059                      | 0.029                      | 0.018                      | 0.016                      | 0.017                      | 0.016                      | 6.74                | 0.28                 |
| 1.881  | 42 | 1122              | 0.078                      | 0.03                       | 0.023                      | 0.019                      | 0.018                      | 0.017                      | 6.91                | 0.28                 |
| 1.886  | 43 | 1146              | 0.137                      | 0.069                      | 0.043                      | 0.038                      | 0.03                       | 0.025                      | 7.08                | 0.28                 |
| 1.89   | 44 | 1100              | 0.046                      | 0.02                       | 0.022                      | 0.017                      | 0.016                      | 0.016                      | 7.31                | 0.28                 |
| 1.895  | 45 | 1049              | 0.039                      | 0.019                      | 0.014                      | 0.013                      | 0.013                      | 0.014                      | 7.57                | 0.28                 |
| 1.899  | 46 | 1001              | 0.032                      | 0.019                      | 0.013                      | 0.013                      | 0.013                      | 0.013                      | 7.82                | 0.28                 |
| 1.904  | 47 | 953               | 0.022                      | 0.014                      | 0.013                      | 0.012                      | 0.012                      | 0.012                      | 8.06                | 0.28                 |
| 1.909  | 48 | 904               | 0.019                      | 0.016                      | 0.012                      | 0.011                      | 0.011                      | 0.011                      | 8.31                | 0.28                 |
| 1.913  | 49 | 854               | 0.021                      | 0.011                      | 0.009                      | 0.009                      | 0.01                       | 0.01                       | 8.57                | 0.28                 |
| 1.918  | 50 | 804               | 0.011                      | 0.009                      | 0.011                      | 0.009                      | 0.009                      | 0.009                      | 8.82                | 0.28                 |
| 1.922  | 51 | 755               | 0.014                      | 0.005                      | 0.009                      | 0.008                      | 0.009                      | 0.009                      | 9.07                | 0.28                 |
| 1.927  | 52 | 706               | 0.007                      | 0.009                      | 0.009                      | 0.009                      | 0.008                      | 0.008                      | 9.32                | 0.28                 |
| 1.932  | 53 | 656               | 0.004                      | 0.008                      | 0.009                      | 0.008                      | 0.008                      | 0.007                      | 9.57                | 0.28                 |
| 1.936  | 54 | 604               | 0.005                      | 0.006                      | 0.006                      | 0.007                      | 0.008                      | 0.007                      | 9.84                | 0.28                 |
| 1.941  | 55 | 554               | 0.004                      | 0.01                       | 0.005                      | 0.007                      | 0.007                      | 0.007                      | 10.09               | 0.28                 |
| 1.946  | 56 | 504               | 0.01                       | 0.005                      | 0.005                      | 0.006                      | 0.006                      | 0.006                      | 10.36               | 0.28                 |
| 1.951  | 57 | 455               | 0.01                       | 0.009                      | 0.004                      | 0.005                      | 0.005                      | 0.005                      | 10.66               | 0.28                 |
| 1.955  | 58 | 405               | -0.002                     | -0.001                     | 0.008                      | 0.005                      | 0.004                      | 0.006                      | 11                  | 0.28                 |
| 1.96   | 59 | 355               | 0.004                      | 0.002                      | 0.002                      | 0.002                      | 0.005                      | 0.006                      | 11.39               | 0.28                 |
| 1.965  | 60 | 305               | 0.003                      | 0.005                      | 0.003                      | 0.005                      | 0.005                      | 0.005                      | 11.83               | 0.28                 |

mq := 61,62..nd - Nempties

| samdns | mq | T <sub>mq,1</sub> | $\epsilon''_{\text{mq},1}$ | $\epsilon''_{\text{mq},2}$ | $\epsilon''_{\text{mq},3}$ | $\epsilon''_{\text{mq},4}$ | $\epsilon''_{\text{mq},5}$ | $\epsilon''_{\text{mq},6}$ | flaps <sub>mq</sub> | sammas <sub>mq</sub> |
|--------|----|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|
| 1.97   | 61 | 254               | -0.009                     | 0.002                      | 0.002                      | 0.002                      | 0.004                      | 0.007                      | 12.35               | 0.28                 |
| 1.974  | 62 | 204               | -                          | -0.002                     | 0.005                      | 0.003                      | 0.004                      | 0.006                      | 12.96               | 0.28                 |
| 1.979  | 63 | 153               | 0                          | 0.001                      | 0.004                      | 0.004                      | 0.005                      | 0.007                      | 13.8                | 0.28                 |
| 1.979  | 64 | 103               | -0.008                     | 0                          | 0.003                      | 0.005                      | 0.006                      | 0.007                      | 15.06               | 0.28                 |
| 1.979  | 65 | 25                | 0.001                      | 0.005                      | 0.007                      | 0.01                       | 0.011                      | 0.013                      | 21.46               | 0.28                 |

**APPENDIX 1 : Second Run to 1000 °C on 5M Simulant Glass**  
Glass Used in NUW-LHT-5M Lunar Simulant , from Washington Mills,  
Measurements of Complex Dielectric Constant of Pressed Pellets  
RT to 1000°C to RT, in downward- flowing (30 sccm) UHP Argon

For this 5M glass measurement, MPN again pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. This run was a simple cycle to 1000C and back to room temperature. A steel tube was inserted into the top of the holder and its bottom end positioned 5 cm above the top of the pellet stack, bathing the pellets in UHP argon.

The initial sample parameters were:

- a) effective diameter 3.65 +- 0.02 mm
- b) length of 3 pellet stack: 14.89 +- 0.05 mm
- c) mass 0.295 +- 0.002 gm
- ww) room temperature density  $1.90 \pm 0.05$  gm/cc.
- xx) appearance - three light grey pellets
- yy) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 500C in 50C steps, then to 1000C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets were easily removed, and their combined mass determined. Then the empty holder was run up to 1000C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) effective diameter  $3.74 \pm 0.03$  mm
- b) pellet stack length  $14.89 \pm 0.05$  mm
- c) mass  $0.296 \pm 0.002$  gm
- vv) room temperature density  $1.81 \pm 0.05$  gm/cc.
- ww) appearance - three light grey pellets
- xx) magnetic response - The pellets had a very weak attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

# Appendix E. MPN Reports

Test = 2023090801

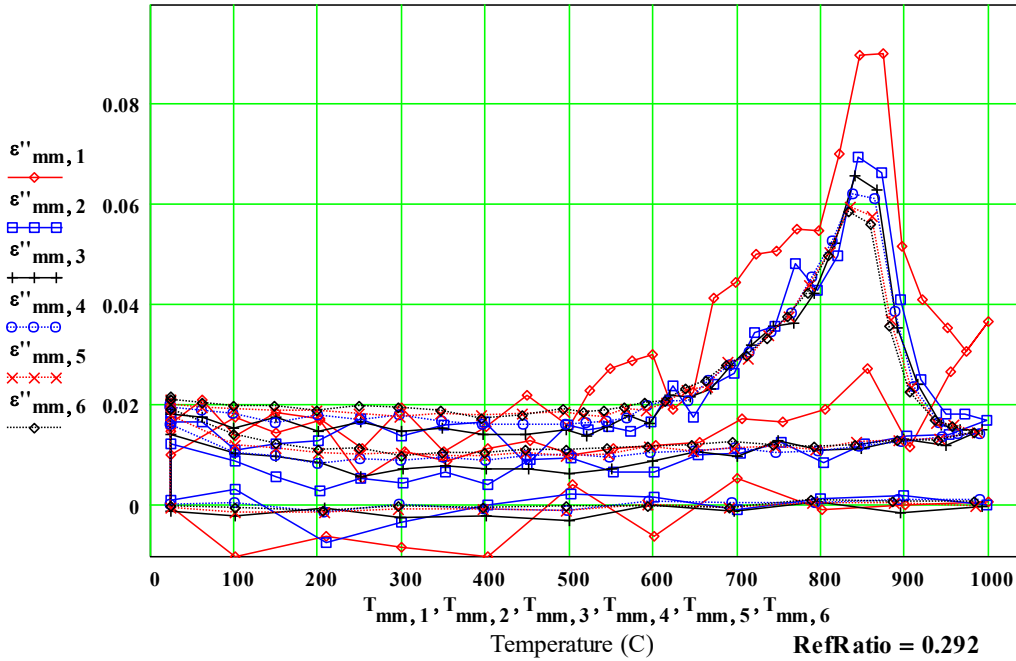
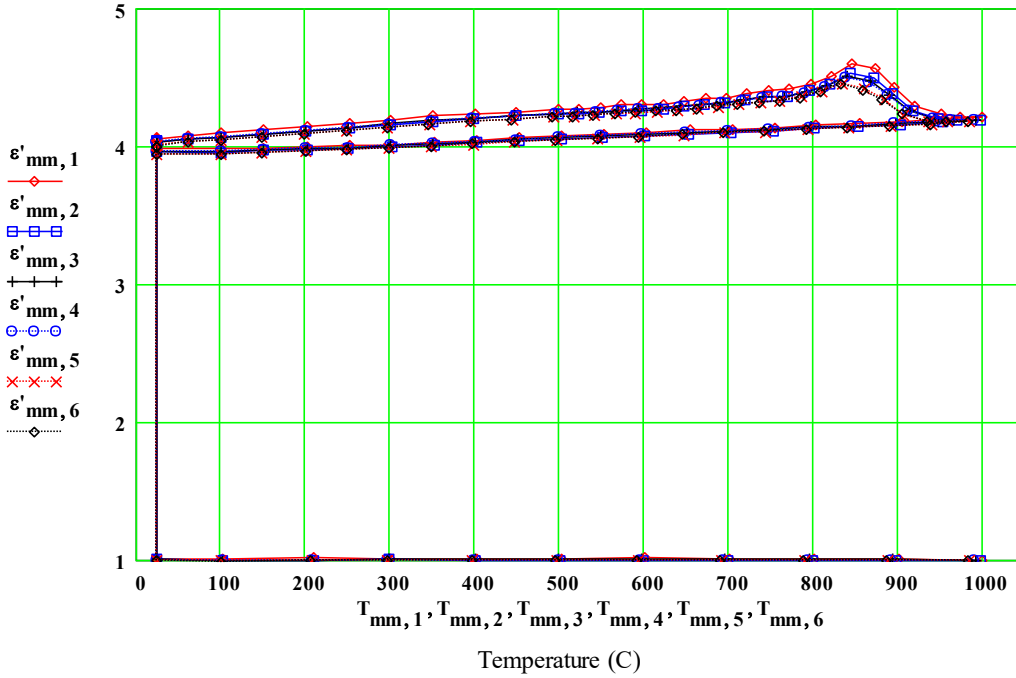
MPN023101.mcd

AnDat = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1.003



# Appendix E. MPN Reports

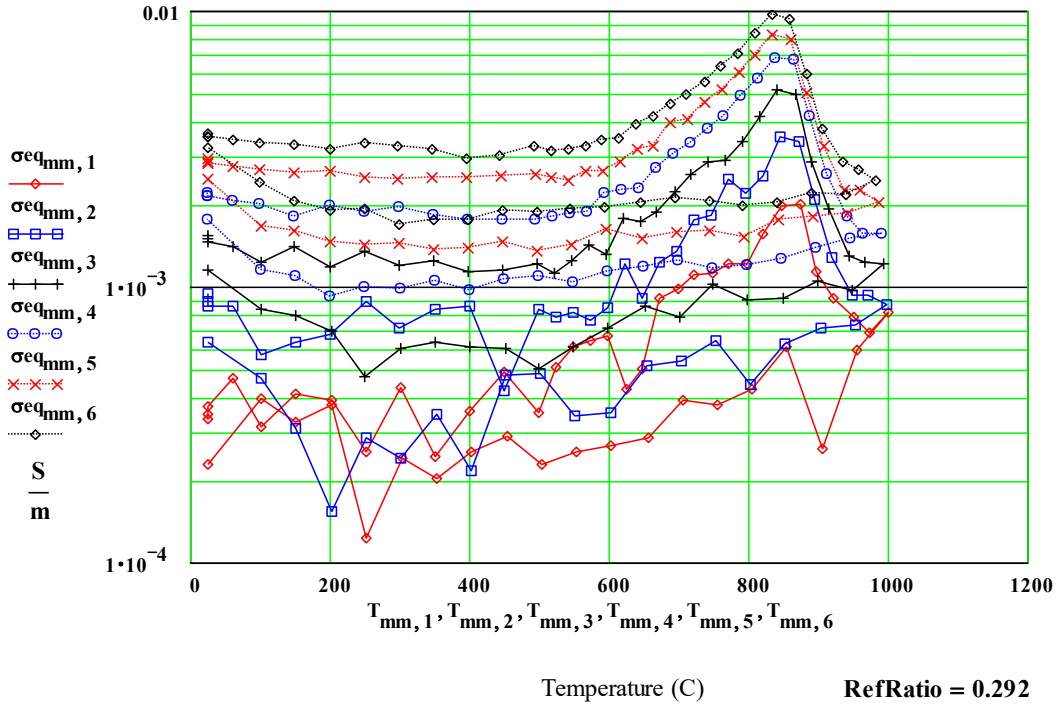
Test = 2023090801

MPN023101.mcd

AnDat = 20230910

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

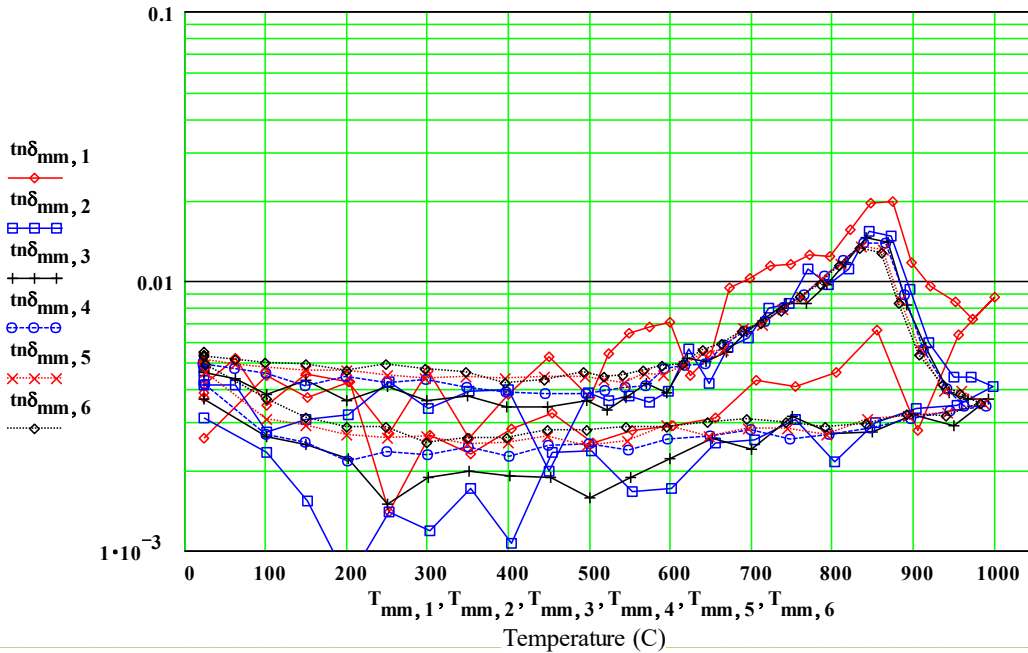
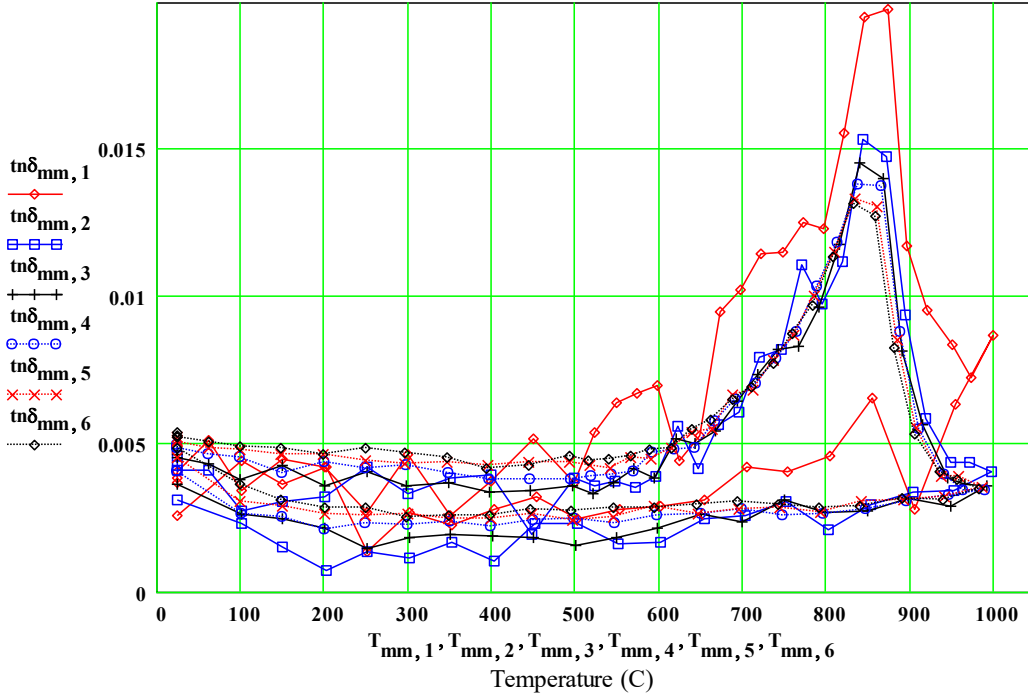
Test = 2023090801

MPN023101.med

AnDat = 20230910

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023090801

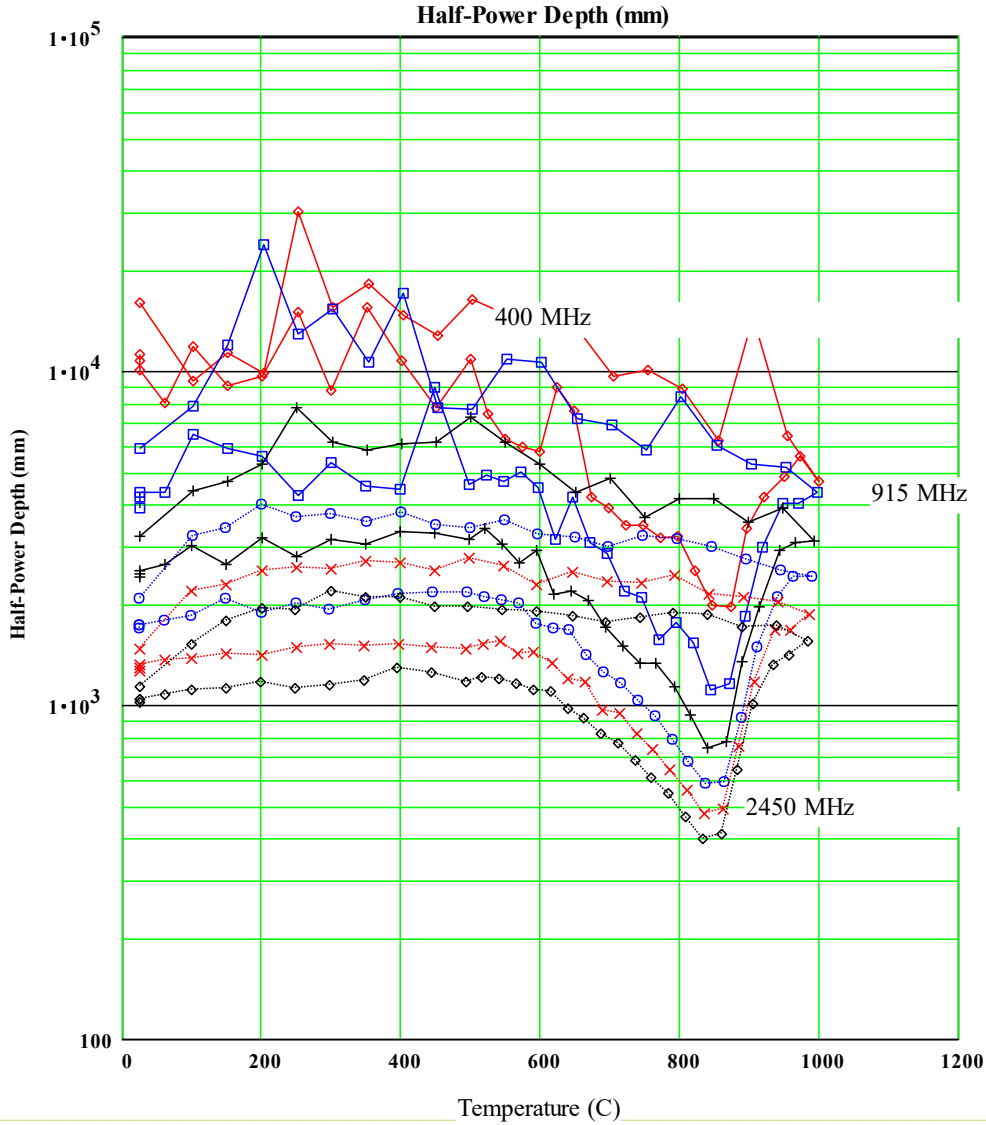
MPN023101.mcd

AnD at = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023090801

MPN023101.mcd

AnDat = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP arg

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.898$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 1.81$  gm/cc  
Lapsed

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz      Time (hours)

| samdns | $\epsilon''_{\text{mm}}$ | $T_{\text{mm},1}$ | $\epsilon'_{\text{mm},1}$ | $\epsilon'_{\text{mm},2}$ | $\epsilon'_{\text{mm},3}$ | $\epsilon'_{\text{mm},4}$ | $\epsilon'_{\text{mm},5}$ | $\epsilon'_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |
|--------|--------------------------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------|----------------------|
| 1.898  | 3                        | 24                | 4.07                      | 4.05                      | 4.04                      | 4.04                      | 4.01                      | 4                         | 0                   | 0.295                |
| 1.898  | 4                        | 24                | 4.06                      | 4.04                      | 4.04                      | 4.04                      | 4.01                      | 4                         | 0.19                | 0.295                |
| 1.898  | 5                        | 24                | 4.06                      | 4.04                      | 4.03                      | 4.04                      | 4.01                      | 4.01                      | 0.25                | 0.295                |
| 1.898  | 6                        | 62                | 4.08                      | 4.06                      | 4.05                      | 4.06                      | 4.03                      | 4.03                      | 0.51                | 0.295                |
| 1.898  | 7                        | 101               | 4.1                       | 4.07                      | 4.07                      | 4.07                      | 4.05                      | 4.04                      | 0.76                | 0.295                |
| 1.898  | 8                        | 150               | 4.12                      | 4.09                      | 4.09                      | 4.09                      | 4.06                      | 4.06                      | 1.08                | 0.295                |
| 1.898  | 9                        | 201               | 4.15                      | 4.12                      | 4.11                      | 4.11                      | 4.09                      | 4.09                      | 1.43                | 0.295                |
| 1.898  | 10                       | 252               | 4.17                      | 4.14                      | 4.14                      | 4.14                      | 4.11                      | 4.11                      | 1.77                | 0.295                |
| 1.898  | 11                       | 300               | 4.19                      | 4.16                      | 4.17                      | 4.16                      | 4.14                      | 4.14                      | 2.1                 | 0.295                |
| 1.898  | 12                       | 351               | 4.23                      | 4.19                      | 4.19                      | 4.19                      | 4.16                      | 4.16                      | 2.39                | 0.295                |
| 1.898  | 13                       | 400               | 4.24                      | 4.2                       | 4.21                      | 4.2                       | 4.18                      | 4.18                      | 2.68                | 0.295                |
| 1.898  | 14                       | 450               | 4.25                      | 4.22                      | 4.23                      | 4.22                      | 4.2                       | 4.2                       | 2.97                | 0.295                |
| 1.898  | 15                       | 499               | 4.27                      | 4.24                      | 4.24                      | 4.24                      | 4.21                      | 4.21                      | 3.26                | 0.295                |
| 1.898  | 16                       | 524               | 4.28                      | 4.24                      | 4.25                      | 4.24                      | 4.22                      | 4.22                      | 3.45                | 0.295                |
| 1.898  | 17                       | 549               | 4.29                      | 4.25                      | 4.25                      | 4.25                      | 4.23                      | 4.23                      | 3.62                | 0.295                |
| 1.898  | 18                       | 574               | 4.3                       | 4.26                      | 4.26                      | 4.26                      | 4.23                      | 4.24                      | 3.8                 | 0.295                |
| 1.898  | 19                       | 598               | 4.3                       | 4.27                      | 4.27                      | 4.27                      | 4.24                      | 4.25                      | 3.97                | 0.295                |
| 1.898  | 20                       | 624               | 4.31                      | 4.28                      | 4.28                      | 4.28                      | 4.25                      | 4.26                      | 4.15                | 0.295                |
| 1.898  | 21                       | 648               | 4.32                      | 4.29                      | 4.29                      | 4.29                      | 4.26                      | 4.26                      | 4.32                | 0.295                |
| 1.898  | 22                       | 673               | 4.35                      | 4.3                       | 4.3                       | 4.3                       | 4.27                      | 4.28                      | 4.49                | 0.295                |
| 1.899  | 23                       | 698               | 4.36                      | 4.32                      | 4.32                      | 4.31                      | 4.29                      | 4.29                      | 4.67                | 0.295                |
| 1.9    | 24                       | 722               | 4.38                      | 4.34                      | 4.34                      | 4.33                      | 4.3                       | 4.3                       | 4.85                | 0.295                |
| 1.901  | 25                       | 747               | 4.41                      | 4.36                      | 4.36                      | 4.35                      | 4.32                      | 4.32                      | 5.02                | 0.295                |
| 1.889  | 26                       | 772               | 4.42                      | 4.36                      | 4.37                      | 4.36                      | 4.33                      | 4.33                      | 5.2                 | 0.296                |
| 1.878  | 27                       | 797               | 4.46                      | 4.41                      | 4.4                       | 4.39                      | 4.36                      | 4.36                      | 5.38                | 0.296                |
| 1.867  | 28                       | 821               | 4.51                      | 4.46                      | 4.45                      | 4.43                      | 4.4                       | 4.39                      | 5.56                | 0.296                |
| 1.856  | 29                       | 846               | 4.61                      | 4.53                      | 4.51                      | 4.5                       | 4.46                      | 4.45                      | 5.74                | 0.296                |
| 1.844  | 30                       | 874               | 4.56                      | 4.5                       | 4.48                      | 4.46                      | 4.42                      | 4.41                      | 5.92                | 0.296                |
| 1.833  | 31                       | 897               | 4.43                      | 4.39                      | 4.38                      | 4.37                      | 4.34                      | 4.34                      | 6.1                 | 0.296                |
| 1.821  | 32                       | 921               | 4.3                       | 4.26                      | 4.26                      | 4.26                      | 4.23                      | 4.23                      | 6.28                | 0.296                |
| 1.81   | 33                       | 951               | 4.23                      | 4.2                       | 4.2                       | 4.2                       | 4.18                      | 4.18                      | 6.48                | 0.296                |
| 1.81   | 34                       | 973               | 4.22                      | 4.19                      | 4.2                       | 4.2                       | 4.18                      | 4.18                      | 6.65                | 0.296                |
| 1.81   | 35                       | 1000              | 4.22                      | 4.2                       | 4.2                       | 4.2                       | 4.18                      | 4.18                      | 6.84                | 0.296                |
| 1.81   | 36                       | 955               | 4.21                      | 4.18                      | 4.18                      | 4.18                      | 4.16                      | 4.16                      | 7.06                | 0.296                |
| 1.81   | 37                       | 905               | 4.18                      | 4.16                      | 4.17                      | 4.17                      | 4.15                      | 4.15                      | 7.3                 | 0.296                |
| 1.81   | 38                       | 854               | 4.17                      | 4.15                      | 4.15                      | 4.15                      | 4.13                      | 4.14                      | 7.54                | 0.296                |
| 1.81   | 39                       | 804               | 4.16                      | 4.13                      | 4.14                      | 4.14                      | 4.12                      | 4.13                      | 7.78                | 0.296                |
| 1.81   | 40                       | 754               | 4.14                      | 4.12                      | 4.13                      | 4.13                      | 4.11                      | 4.11                      | 8.02                | 0.296                |
| 1.81   | 41                       | 705               | 4.13                      | 4.11                      | 4.12                      | 4.12                      | 4.1                       | 4.1                       | 8.27                | 0.296                |
| 1.81   | 42                       | 655               | 4.12                      | 4.1                       | 4.1                       | 4.1                       | 4.08                      | 4.09                      | 8.51                | 0.296                |
| 1.81   | 43                       | 603               | 4.11                      | 4.08                      | 4.09                      | 4.09                      | 4.07                      | 4.07                      | 8.76                | 0.296                |
| 1.81   | 44                       | 553               | 4.1                       | 4.07                      | 4.08                      | 4.07                      | 4.06                      | 4.06                      | 9.01                | 0.296                |
| 1.81   | 45                       | 503               | 4.08                      | 4.06                      | 4.07                      | 4.07                      | 4.05                      | 4.05                      | 9.27                | 0.296                |
| 1.81   | 46                       | 453               | 4.07                      | 4.04                      | 4.05                      | 4.05                      | 4.03                      | 4.04                      | 9.57                | 0.296                |
| 1.81   | 47                       | 403               | 4.05                      | 4.03                      | 4.04                      | 4.03                      | 4.02                      | 4.02                      | 9.89                | 0.296                |
| 1.81   | 48                       | 353               | 4.04                      | 4.01                      | 4.02                      | 4.02                      | 4                         | 4.01                      | 10.26               | 0.296                |
| 1.81   | 49                       | 303               | 4.02                      | 4                         | 4.01                      | 4.01                      | 3.99                      | 3.99                      | 10.67               | 0.296                |
| 1.81   | 50                       | 252               | 4.01                      | 3.99                      | 3.99                      | 3.99                      | 3.97                      | 3.98                      | 11.16               | 0.296                |
| 1.81   | 51                       | 203               | 4                         | 3.98                      | 3.98                      | 3.98                      | 3.97                      | 3.97                      | 11.73               | 0.296                |
| 1.81   | 52                       | 151               | 3.99                      | 3.97                      | 3.97                      | 3.97                      | 3.95                      | 3.96                      | 12.5                | 0.296                |

mq := 53,54..nd - Nempties

| samdns | $\epsilon''_{\text{mq}}$ | $T_{\text{mq},1}$ | $\epsilon'_{\text{mq},1}$ | $\epsilon'_{\text{mq},2}$ | $\epsilon'_{\text{mq},3}$ | $\epsilon'_{\text{mq},4}$ | $\epsilon'_{\text{mq},5}$ | $\epsilon'_{\text{mq},6}$ | tlaps <sub>mq</sub> | sammas <sub>mq</sub> |
|--------|--------------------------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------|----------------------|
| 1.81   | 53                       | 101               | 3.98                      | 3.96                      | 3.96                      | 3.96                      | 3.95                      | 3.95                      | 13.64               | 0.296                |
| 1.81   | 54                       | 24                | 3.99                      | 3.97                      | 3.97                      | 3.97                      | 3.94                      | 3.94                      | 17.15               | 0.296                |



MPN-292\_MPN\_Glass for Corrected 5M Simulant\_Creedon\_Washington Mills

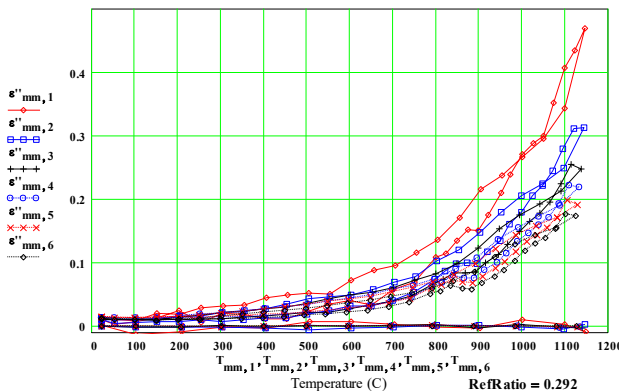
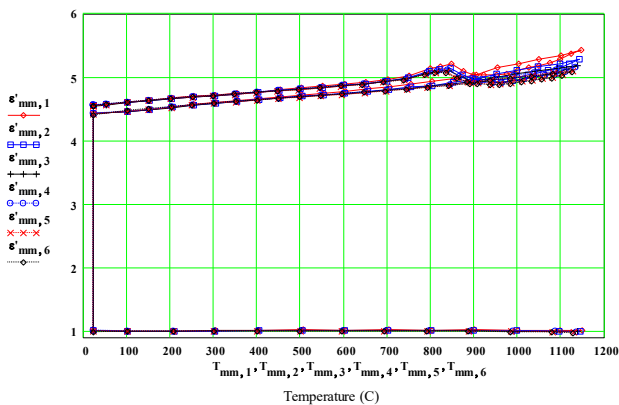
# 1. Aug. 9, 2025

## Glass Used in NUW-LHT-5M Lunar Simulant , from Washington Mills, Measurements of Complex Dielectric Constant of Pressed Pellets Room Temperature to 1150°C to RT, in flowing (10 sccm) UHP Argon

Dr. Doug Rickman ( NASA) was interested in knowing the dielectric properties of the special glass that was manufactured by Washington Mills, and used in the making of the NUW-LHT-5M simulant. Dr. Matt Creedon of Washington Mills sent a sample of the 5M simulant glass powder to MPN, who had offered to measure its microwave dielectric properties.

Microwave Properties North had already done three complex dielectric properties measurement runs on heat-treated NUW-LHT-5M lunar regolith simulant up to temperatures of 1100C, 1150C and 1250C under a NASA contract. The first dielectric measurement run on the full NUW-LHT-5M simulant, in vacuum, up to 1100C, had an unfamiliar feature at ~ 850C . The second full simulant run was done up to 1150C in flowing ( 10 sccm) UHP argon. This required a different sample holder, different background subtractions and new calibrations. However, the same feature was noted in the dielectric constant, shown in the following plots.

Test = 2023060901                      NASA2360.mcd                      AnDat = 20230610  
 2nd Run, Lunar Simulant NUW-LHT-5M, pre-baked at 750C in Ar/H, to 1150C, in flowing argon, for D.Rickman  
 Initial density =  $\text{samdns}_{\text{NCat} + 1} = 2.12 \text{ gm/cc}$ ,                      Final density(25C) =  $\text{dnsfinal} = 2.06 \text{ gm/cc}$   
 Final\_over\_Initial\_mass = 1



The top line of the  $\epsilon'$  plot ( initial value  $\epsilon' \sim 4.7$  ) is the values measured during the ramp up to 1150°C .

The bottom line in the plots is the empty holder measurement done immediately after the sample measurement. Only the initial and final sample dimensions were actually measured.

The NUW-LHT-5M lunar simulant has  $\sim 40$  wt% of a relatively unique ( on earth at least) glass, largely composed of the same elements as the crystalline content of the simulant. It seemed useful to measure the properties of the glass alone, but under similar conditions.

For this 5M glass measurement, MPN again pressed pellets of the powder material in a uniaxial press at  $\sim 33,000$  psi. The pellets were not initially baked by MPN to ensure dryness. This run was a simple cycle to 1150C and back to room temperature. The sample holder for this run was initially cycled ( and measured, empty) to 1150C before the run to “clean” the holder and measure the “empty holder” values, which were later used during the off-line data analysis.

For this measurement, a holder with a small hole in the base was used, so UHP argon gas could flow up, past the sample pellets, at  $\sim 10$  sccm regulated flow rate.

For : MPN23100.prn :

The initial sample parameters were:

- a) diameter 3.63 +- 0.02 mm
- b) length of 3 pellet stack: 13.54 +- 0.05 mm
- c) mass 0.280 +- 0.002 gm
- zz) room temperature density  $2.00 \pm 0.05$  gm/cc.
- aaa) appearance - three light grey pellets ( see photos)
- bbb) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 800C in 50C steps, then to 1150C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets were easily removed, and their combined mass determined. Then the empty holder was run up to 1100C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) diameter  $3.60 \pm 0.03$  mm
- b) pellet stack length  $13.52 \pm 0.05$  mm
- c) mass  $0.280 \pm 0.002$  gm
- yy) room temperature density  $2.03 \pm 0.06$  gm/cc.
- zz) appearance - three very light beige pellets ( see photos)
- aaa) magnetic response - The pellets had a very weak attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

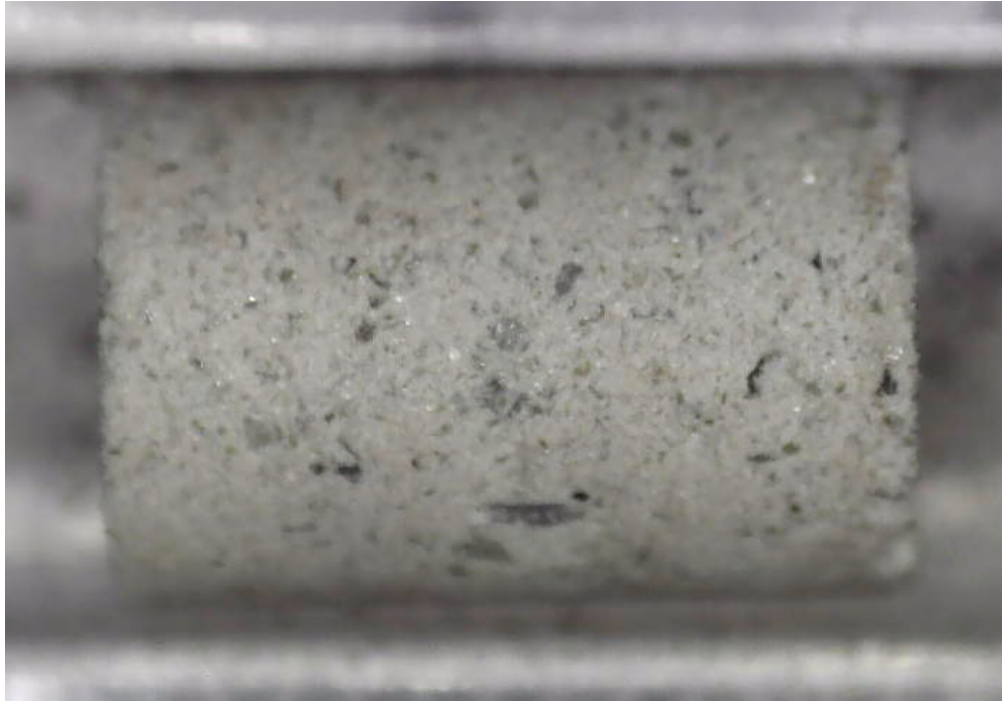
The frequency coding is :

Legend for Data Plots :

| # | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|---|-----------------------|----------------------------------------------------------|
| 1 | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2 | 912                   | blue square, solid line                                  |
| 3 | 1429                  | black cross, solid line                                  |
| 4 | 1948                  | blue circle, dotted line                                 |

Appendix E. MPN Reports

|   |      |                            |
|---|------|----------------------------|
| 5 | 2466 | red cross, dotted line     |
| 6 | 2986 | black diamond, dotted line |



Typical initial NUW-LHT-5M pellet -Pressed at ~ 33,000 psi



Initial 5M Glass ( Washington Mills) pellet - Pressed at ~ 30,000 psi



Three final NUW-LHT-5M pellets after a cycle to 1150C in UHP argon .



Three final 5M Glass pellets after the cycle to 1150C in UHP argon, non-adhering.

# Appendix E. MPN Reports

Test = 2023090501

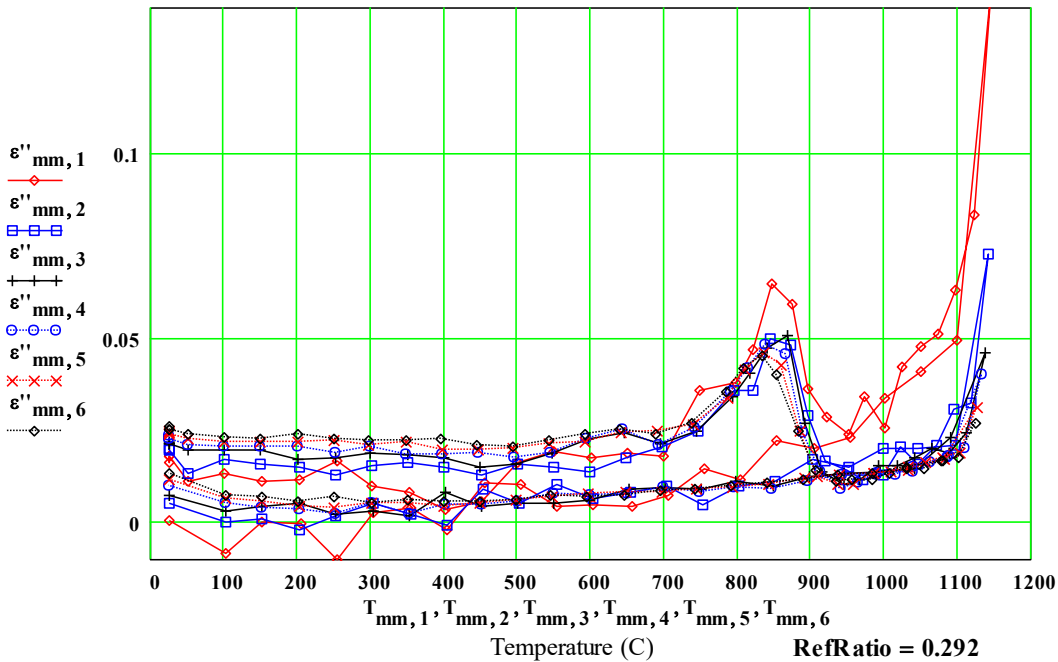
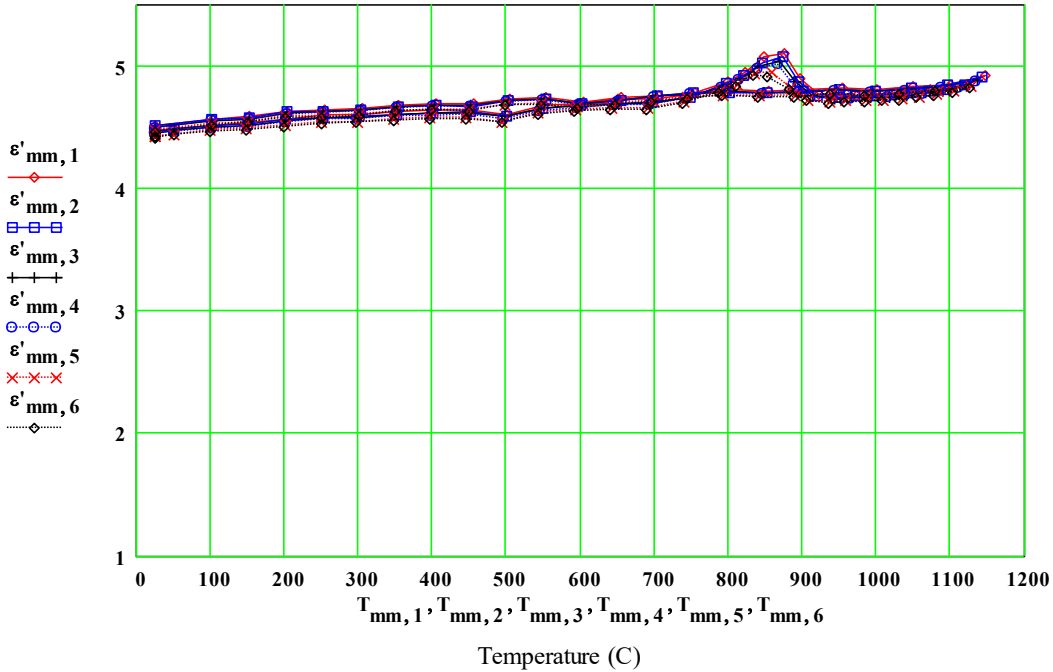
MPN023100corrected.mcd

AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.03 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



Note the very rapid increase in  $\epsilon''$  values above 1100 °C. This is indicative of approaching the melting/ fluid conditions above  $T_g$ . The thermal activation energy is large – very approximately 400 Kjoule/mole ( $\sim 4.2 \text{ eV}$ ) by fitting the points between 1100C and 1150 C. The feature at 850 C seen in the simulant runs is evident in this glass 5M run.

The two data points at 850C and 875C in the “ramp-up” have been changed throughout this report to match the values measured in a second run and shown in Appendix 1. This was done to improve the usefulness and accuracy of the plots for the reader.

Comments on the data run :

A thermal expansion coefficient ( CTE) of  $0.0 * 10^{-6}/C$  was used.

The final pellets appeared unchanged except for a very slight beige colouring of some components !

The smooth ramp up of the values to 1150C is now obvious, except for the “bump” at Tg ?

Another run was done to 1000C ( MPN023101) on a new set of pellets in a solid-bottom holder, with the argon gas flowing down onto the top of the test sample. In this configuration, expansion of the pellet diametrically cannot result in vertical movement of the test sample caused by the cover gas flow!

This second run demonstrated that, in fact, a transformation ( re-crystallization ? ) was occurring between 700C and 925C, which resulted in small increases in both  $\epsilon'$  and  $\epsilon''$  , with a maxima at  $\sim 860$  C. The details of this run are presented in Appendix 1 at the end of this report.

By changing the “effective” pellet length ( and thus the volume ) slightly for only the two temperatures ( 850C and 875 C ) during the data analysis, the peak shape was made to match that seen in the second run to 1000C ( shown in Appendix 1 ).

This feature, although interesting, is small and probably not very significant in the high temperature properties of the 5M simulant.

The following plot is the old original plot before the adjustment of the two points ( mentioned above) .

# Appendix E. MPN Reports

Test = 2023090501

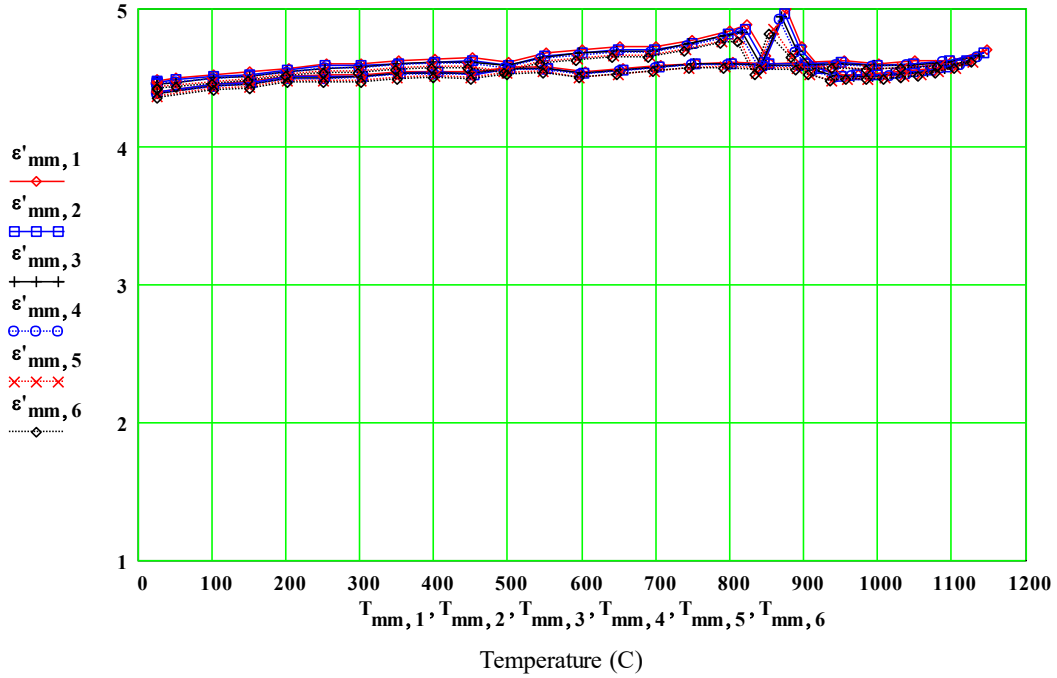
MPN023100.mcd

AnDat = 20230907

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.98 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



# Appendix E. MPN Reports

Test = 2023090501

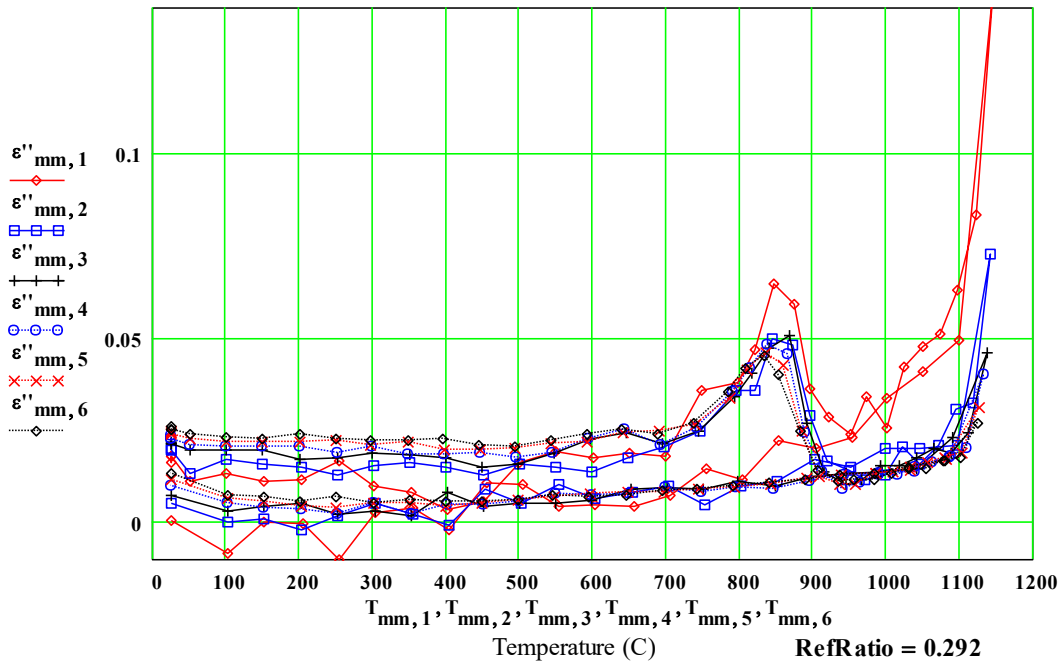
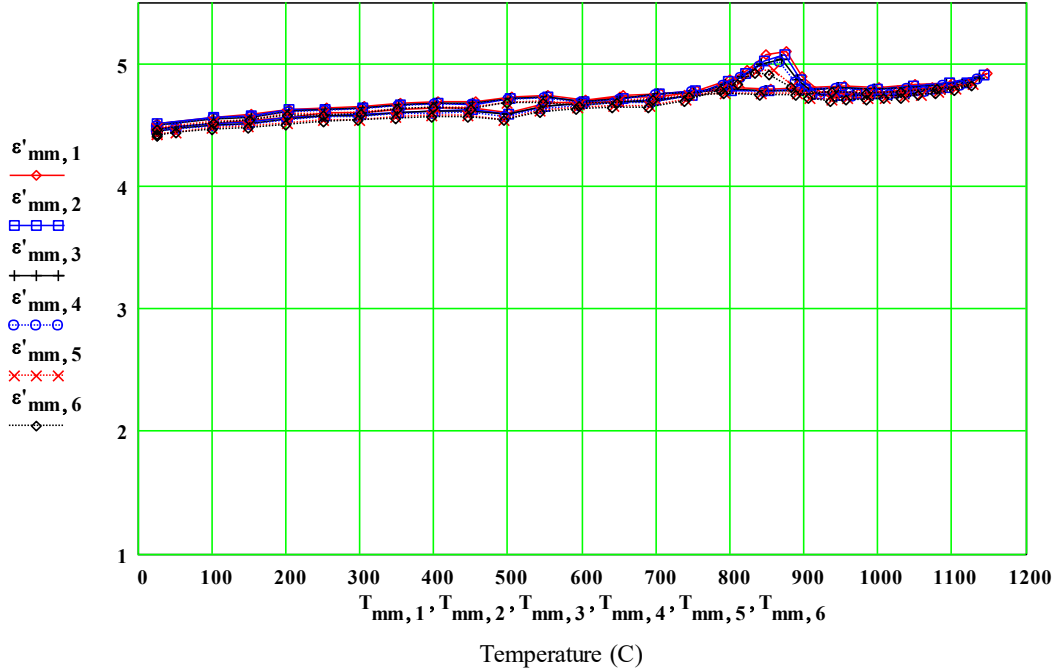
MPN023100corrected.mcd

AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.03 \text{ gm/cc}$

Final\_over\_Initial\_mass = 1



# Appendix E. MPN Reports

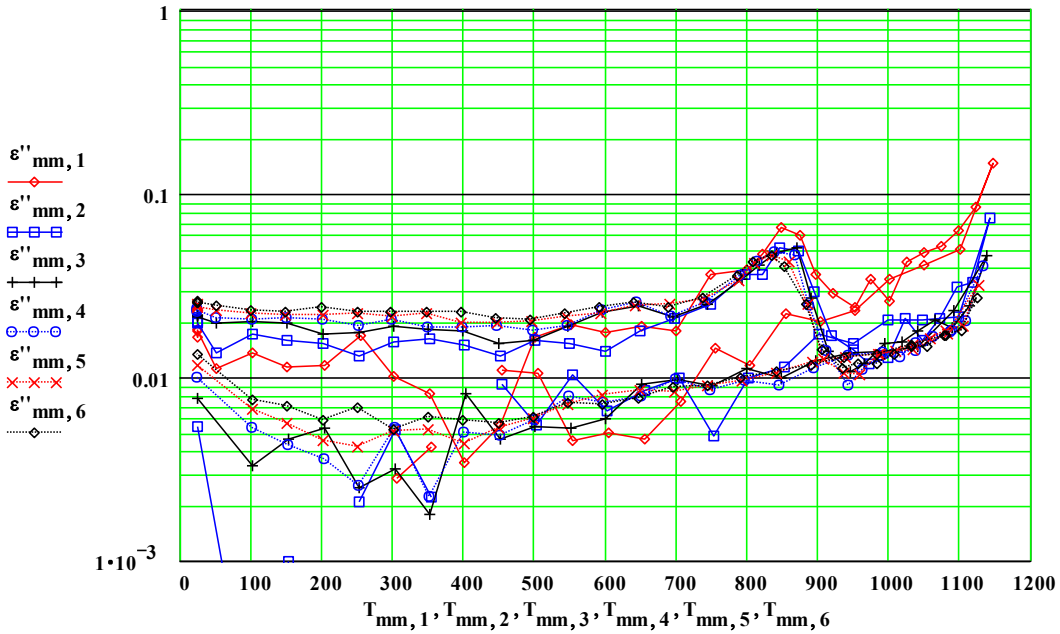
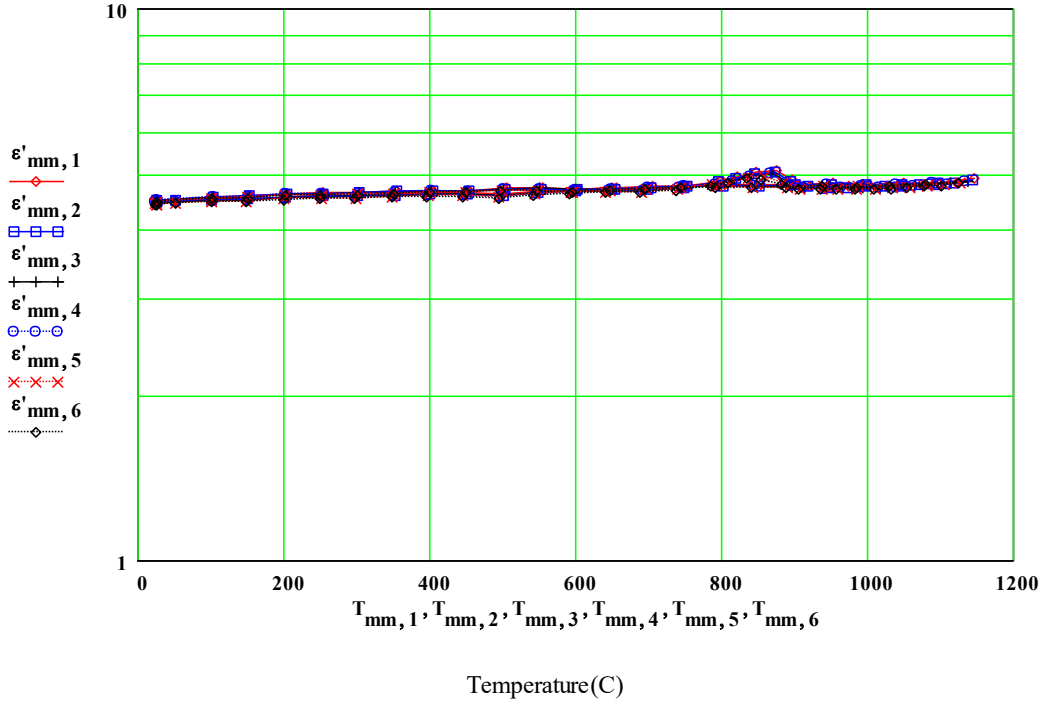
Test = 2023090501

MPN023100.med

AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.03 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023090501

MPN023100.mcd

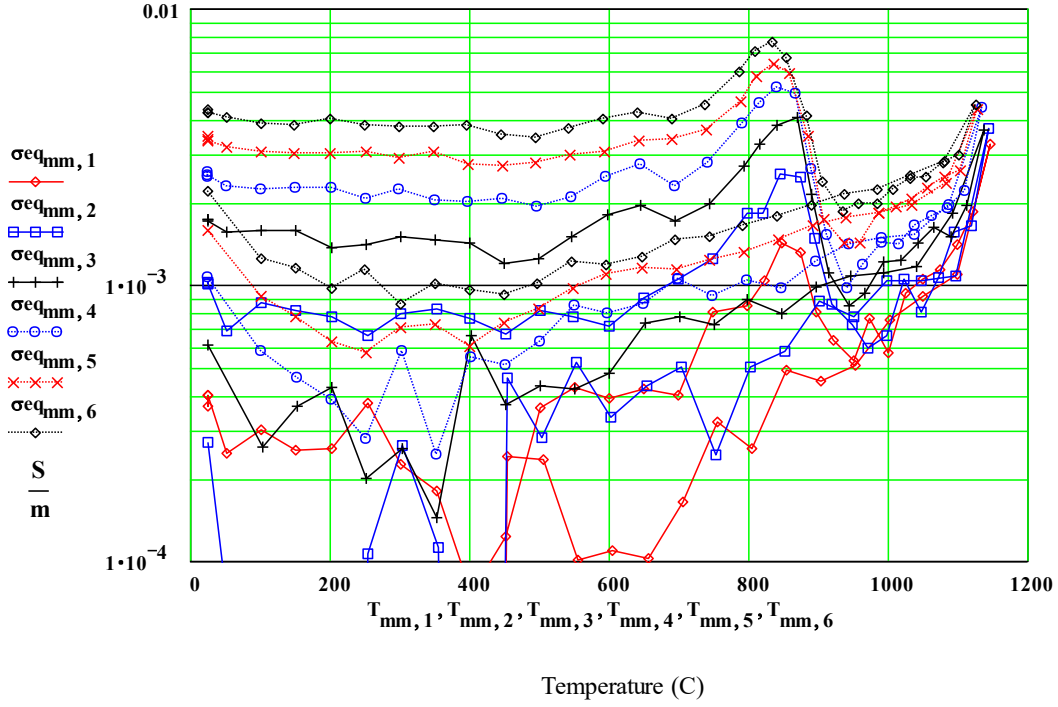
AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{14} = 2 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.03 \text{ gm/cc}$

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2023090501

MPN023100.mcd

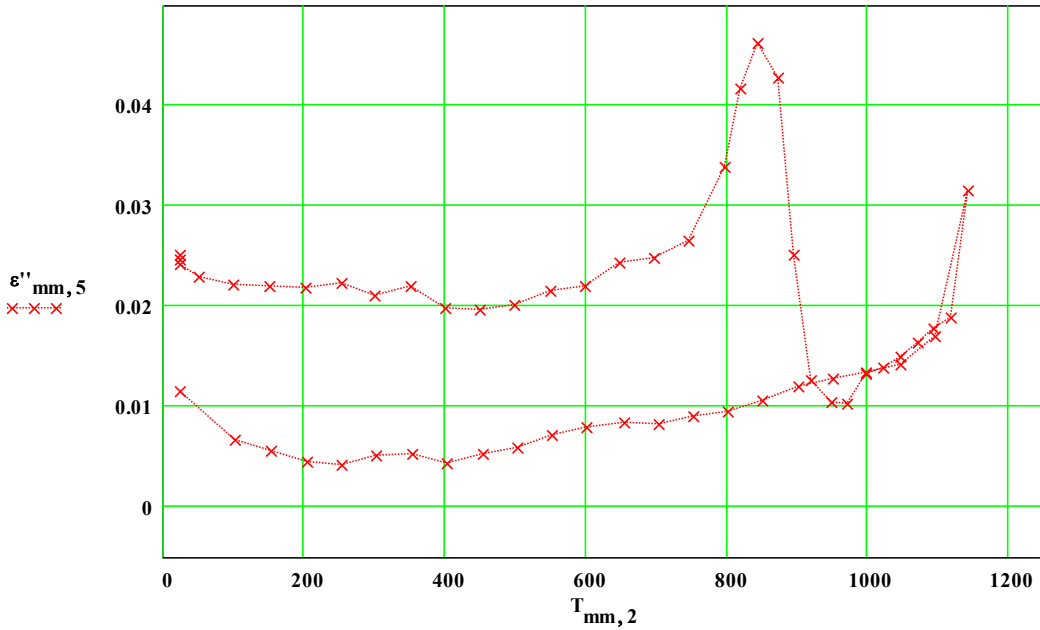
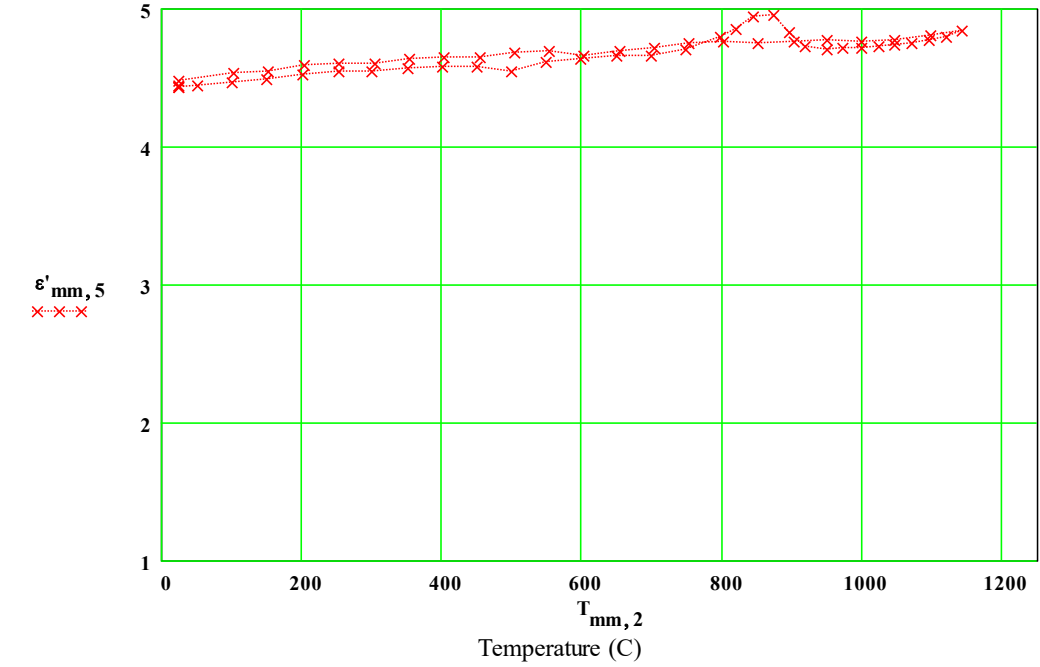
AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2$  gm/cc, Final density(25C) =  $\text{dnsfinal} = 2.03$  gm/cc

Thermal exp. coeff.  $\alpha_1 = 0$

## Values for 2450 MHz



# Appendix E. MPN Reports

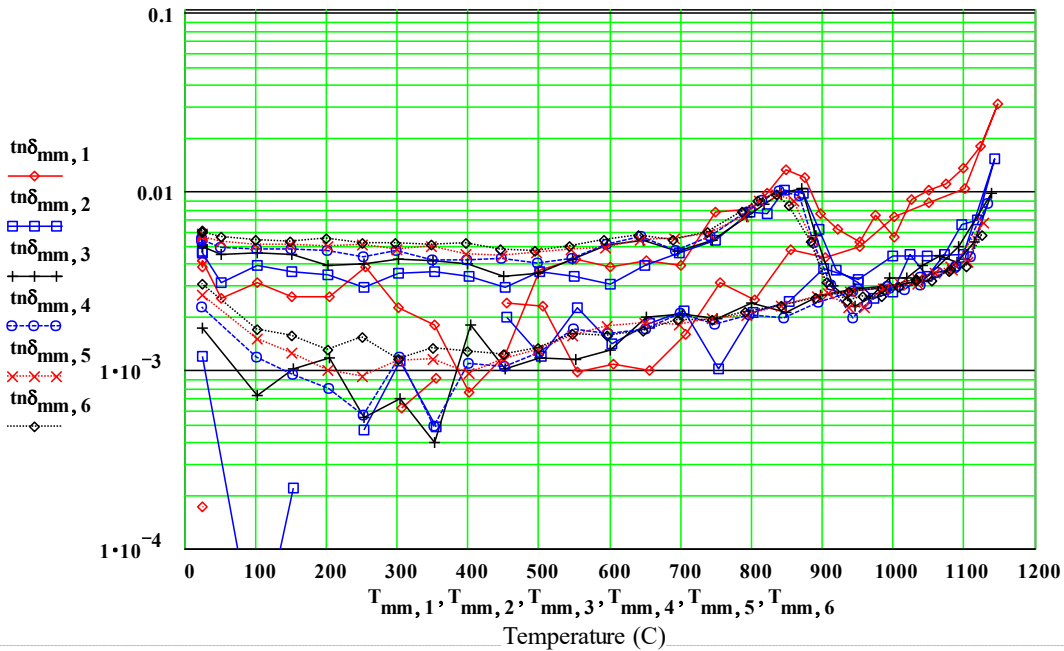
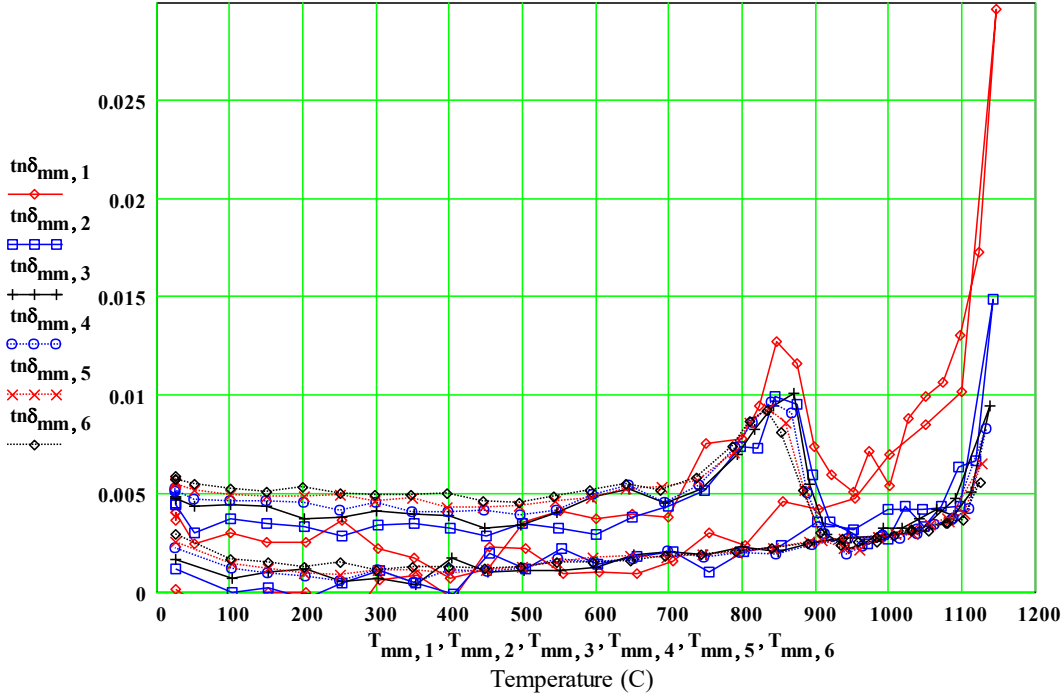
Test = 2023090501

MPN023100.mcd

AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.03 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023090501

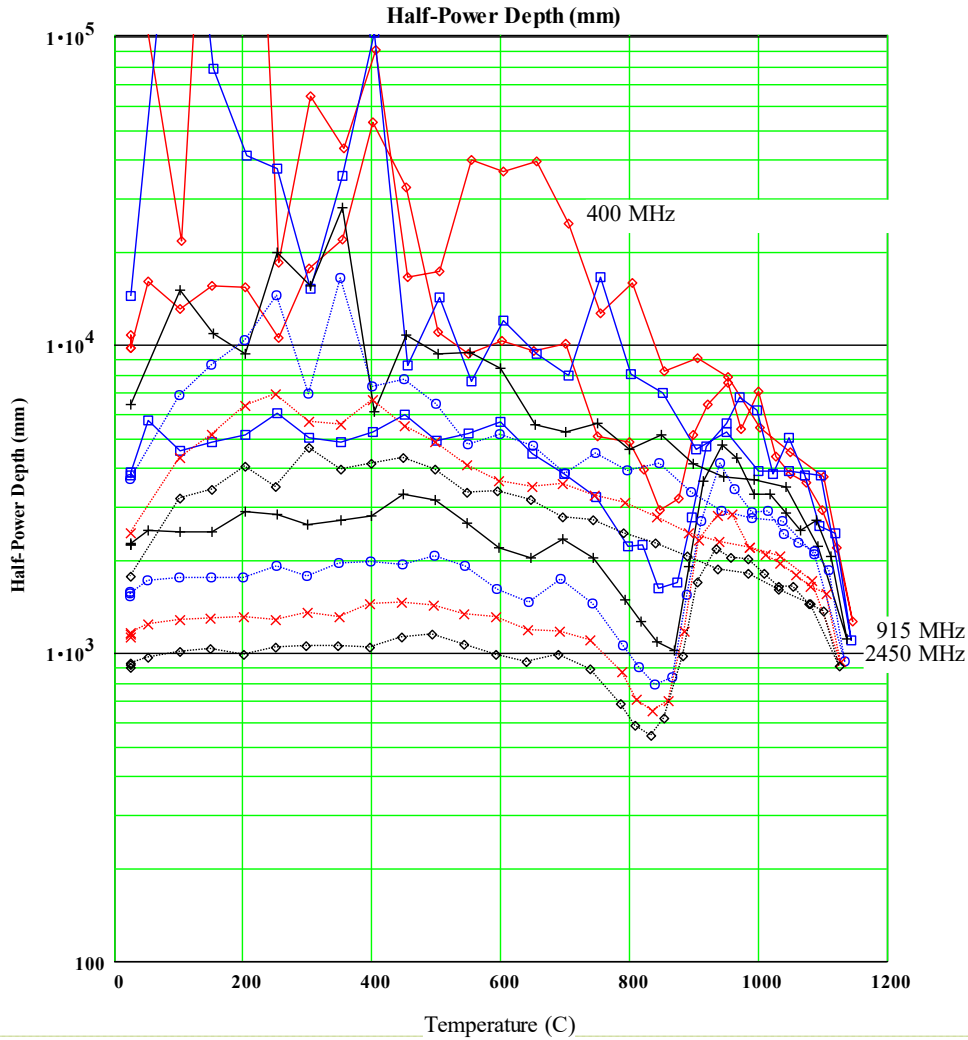
MPN023100.mcd

AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 2.03 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023090501                      MPN023100.mcd                      AnDat = 20250809  
 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.998 \text{ gm/cc}$                       Final density(25C) =  $\text{dnsfinal} = 2.035 \text{ gm/cc}$

density index T(C) 397MHz 912MHz 1429MHz 1948MHz 2466MHz 2986MHz  
 Lapsed Time (hours)

| samdns | $n_{\text{mm}}$ | $T_{\text{mm},1}$ | $\epsilon'_{\text{mm},1}$ | $\epsilon'_{\text{mm},2}$ | $\epsilon'_{\text{mm},3}$ | $\epsilon'_{\text{mm},4}$ | $\epsilon'_{\text{mm},5}$ | $\epsilon'_{\text{mm},6}$ | $t_{\text{laps}}_{\text{mm}}$ | $s_{\text{ammas}}_{\text{mm}}$ |
|--------|-----------------|-------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|-------------------------------|--------------------------------|
| 1.998  | 11              | 25                | 4.49                      | 4.48                      | 4.47                      | 4.46                      | 4.44                      | 4.43                      | 0                             | 0.28                           |
| 1.998  | 12              | 25                | 4.48                      | 4.47                      | 4.45                      | 4.45                      | 4.43                      | 4.41                      | 0.15                          | 0.28                           |
| 1.998  | 13              | 25                | 4.48                      | 4.47                      | 4.45                      | 4.45                      | 4.43                      | 4.42                      | 0.22                          | 0.28                           |
| 1.998  | 14              | 52                | 4.5                       | 4.49                      | 4.47                      | 4.46                      | 4.44                      | 4.43                      | 0.4                           | 0.28                           |
| 1.998  | 15              | 101               | 4.52                      | 4.51                      | 4.5                       | 4.49                      | 4.47                      | 4.46                      | 0.7                           | 0.28                           |
| 1.998  | 16              | 151               | 4.55                      | 4.53                      | 4.51                      | 4.51                      | 4.49                      | 4.47                      | 1.01                          | 0.28                           |
| 1.998  | 17              | 203               | 4.57                      | 4.56                      | 4.55                      | 4.54                      | 4.52                      | 4.51                      | 1.36                          | 0.28                           |
| 1.998  | 18              | 254               | 4.6                       | 4.59                      | 4.57                      | 4.56                      | 4.54                      | 4.53                      | 1.7                           | 0.28                           |
| 1.998  | 19              | 302               | 4.6                       | 4.59                      | 4.58                      | 4.57                      | 4.55                      | 4.54                      | 2.03                          | 0.28                           |
| 1.998  | 20              | 352               | 4.63                      | 4.61                      | 4.6                       | 4.59                      | 4.57                      | 4.56                      | 2.32                          | 0.28                           |
| 1.998  | 21              | 402               | 4.64                      | 4.62                      | 4.61                      | 4.6                       | 4.58                      | 4.57                      | 2.6                           | 0.28                           |
| 1.998  | 22              | 452               | 4.65                      | 4.63                      | 4.62                      | 4.6                       | 4.58                      | 4.57                      | 2.89                          | 0.28                           |
| 1.998  | 23              | 501               | 4.61                      | 4.59                      | 4.59                      | 4.57                      | 4.55                      | 4.54                      | 3.18                          | 0.28                           |
| 1.998  | 24              | 550               | 4.68                      | 4.66                      | 4.65                      | 4.64                      | 4.61                      | 4.6                       | 3.43                          | 0.28                           |
| 1.998  | 25              | 600               | 4.7                       | 4.68                      | 4.68                      | 4.66                      | 4.64                      | 4.63                      | 3.68                          | 0.28                           |
| 1.998  | 26              | 650               | 4.73                      | 4.7                       | 4.7                       | 4.68                      | 4.66                      | 4.64                      | 3.94                          | 0.28                           |
| 1.998  | 27              | 699               | 4.73                      | 4.7                       | 4.7                       | 4.68                      | 4.66                      | 4.65                      | 4.19                          | 0.28                           |
| 1.998  | 28              | 749               | 4.78                      | 4.75                      | 4.75                      | 4.73                      | 4.71                      | 4.7                       | 4.44                          | 0.28                           |
| 1.995  | 29              | 799               | 4.88                      | 4.85                      | 4.84                      | 4.82                      | 4.79                      | 4.78                      | 4.7                           | 0.28                           |
| 1.992  | 30              | 822               | 4.95                      | 4.92                      | 4.9                       | 4.88                      | 4.85                      | 4.83                      | 4.86                          | 0.28                           |
| 2.112  | 31              | 847               | 5.07                      | 5.03                      | 5                         | 4.97                      | 4.94                      | 4.92                      | 5.04                          | 0.28                           |
| 1.97   | 32              | 875               | 5.1                       | 5.07                      | 5.04                      | 5.02                      | 4.95                      | 4.91                      | 5.21                          | 0.28                           |
| 1.983  | 33              | 897               | 4.9                       | 4.88                      | 4.87                      | 4.85                      | 4.83                      | 4.81                      | 5.38                          | 0.28                           |
| 1.979  | 34              | 921               | 4.77                      | 4.76                      | 4.76                      | 4.75                      | 4.72                      | 4.72                      | 5.54                          | 0.28                           |
| 1.976  | 35              | 951               | 4.75                      | 4.74                      | 4.74                      | 4.73                      | 4.71                      | 4.7                       | 5.73                          | 0.28                           |
| 1.976  | 36              | 974               | 4.76                      | 4.75                      | 4.75                      | 4.74                      | 4.72                      | 4.71                      | 5.89                          | 0.28                           |
| 1.976  | 37              | 1000              | 4.77                      | 4.76                      | 4.75                      | 4.74                      | 4.72                      | 4.71                      | 6.07                          | 0.28                           |
| 1.976  | 38              | 1026              | 4.79                      | 4.77                      | 4.75                      | 4.74                      | 4.72                      | 4.71                      | 6.24                          | 0.28                           |
| 1.976  | 39              | 1050              | 4.79                      | 4.78                      | 4.76                      | 4.76                      | 4.73                      | 4.72                      | 6.41                          | 0.28                           |
| 1.976  | 40              | 1074              | 4.81                      | 4.8                       | 4.78                      | 4.77                      | 4.75                      | 4.74                      | 6.58                          | 0.28                           |
| 1.979  | 41              | 1098              | 4.82                      | 4.81                      | 4.8                       | 4.79                      | 4.77                      | 4.76                      | 6.74                          | 0.28                           |
| 1.981  | 42              | 1122              | 4.85                      | 4.85                      | 4.83                      | 4.82                      | 4.8                       | 4.78                      | 6.91                          | 0.28                           |
| 1.984  | 43              | 1146              | 4.93                      | 4.91                      | 4.88                      | 4.87                      | 4.84                      | 4.83                      | 7.08                          | 0.28                           |
| 1.986  | 44              | 1100              | 4.84                      | 4.85                      | 4.83                      | 4.83                      | 4.8                       | 4.79                      | 7.31                          | 0.28                           |
| 1.989  | 45              | 1049              | 4.84                      | 4.82                      | 4.81                      | 4.8                       | 4.78                      | 4.77                      | 7.57                          | 0.28                           |
| 1.991  | 46              | 1001              | 4.81                      | 4.8                       | 4.79                      | 4.78                      | 4.76                      | 4.75                      | 7.82                          | 0.28                           |
| 1.994  | 47              | 953               | 4.82                      | 4.81                      | 4.8                       | 4.8                       | 4.78                      | 4.77                      | 8.06                          | 0.28                           |
| 1.996  | 48              | 904               | 4.81                      | 4.79                      | 4.79                      | 4.78                      | 4.76                      | 4.75                      | 8.31                          | 0.28                           |
| 1.999  | 49              | 854               | 4.8                       | 4.79                      | 4.78                      | 4.77                      | 4.75                      | 4.75                      | 8.57                          | 0.28                           |
| 2.001  | 50              | 804               | 4.81                      | 4.79                      | 4.79                      | 4.78                      | 4.76                      | 4.76                      | 8.82                          | 0.28                           |
| 2.004  | 51              | 755               | 4.79                      | 4.78                      | 4.78                      | 4.77                      | 4.75                      | 4.74                      | 9.07                          | 0.28                           |
| 2.006  | 52              | 706               | 4.76                      | 4.75                      | 4.75                      | 4.74                      | 4.72                      | 4.71                      | 9.32                          | 0.28                           |
| 2.009  | 53              | 656               | 4.74                      | 4.72                      | 4.73                      | 4.71                      | 4.69                      | 4.69                      | 9.57                          | 0.28                           |
| 2.012  | 54              | 604               | 4.71                      | 4.7                       | 4.7                       | 4.69                      | 4.66                      | 4.66                      | 9.84                          | 0.28                           |
| 2.014  | 55              | 554               | 4.74                      | 4.73                      | 4.73                      | 4.72                      | 4.7                       | 4.69                      | 10.09                         | 0.28                           |
| 2.017  | 56              | 504               | 4.73                      | 4.72                      | 4.72                      | 4.7                       | 4.69                      | 4.68                      | 10.36                         | 0.28                           |
| 2.019  | 57              | 455               | 4.69                      | 4.67                      | 4.68                      | 4.66                      | 4.64                      | 4.64                      | 10.66                         | 0.28                           |
| 2.022  | 58              | 405               | 4.69                      | 4.68                      | 4.68                      | 4.67                      | 4.65                      | 4.64                      | 11                            | 0.28                           |
| 2.024  | 59              | 355               | 4.68                      | 4.67                      | 4.67                      | 4.65                      | 4.64                      | 4.63                      | 11.39                         | 0.28                           |
| 2.027  | 60              | 305               | 4.65                      | 4.64                      | 4.64                      | 4.62                      | 4.61                      | 4.6                       | 11.83                         | 0.28                           |

$m_q := 61, 62, \dots, nd$  - Nempties

| samdns | $m_{mq}$ | $T_{mq,1}$ | $\epsilon'_{mq,1}$ | $\epsilon'_{mq,2}$ | $\epsilon'_{mq,3}$ | $\epsilon'_{mq,4}$ | $\epsilon'_{mq,5}$ | $\epsilon'_{mq,6}$ | $t_{laps}_{mq}$ | $s_{ammas}_{mq}$ |
|--------|----------|------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|-----------------|------------------|
| 2.029  | 61       | 254        | 4.65               | 4.63               | 4.63               | 4.62               | 4.6                | 4.59               | 12.35           | 0.28             |
| 2.032  | 62       | 204        | 4.63               | 4.63               | 4.62               | 4.61               | 4.59               | 4.58               | 12.96           | 0.28             |
| 2.035  | 63       | 153        | 4.59               | 4.58               | 4.57               | 4.57               | 4.55               | 4.54               | 13.8            | 0.28             |
| 2.035  | 64       | 103        | 4.57               | 4.57               | 4.56               | 4.55               | 4.53               | 4.52               | 15.06           | 0.28             |
| 2.035  | 65       | 25         | 4.51               | 4.51               | 4.5                | 4.5                | 4.47               | 4.46               | 21.46           | 0.28             |

# Appendix E. MPN Reports

Test = 2023090501                      MPN023100.mcd                      AnDat = 20250809

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C, in flowing UHP argon

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.998 \text{ gm/cc}$                       Final density(25C) =  $\text{dnsfinal} = 2.035 \text{ gm/cc}$

density index T(C) 397MHz 912MHz 1429MH 1948MHz2466MHz 2986MHz                      Lapsed Time (hours)

| samdns | mm | T <sub>mm,1</sub> | $\epsilon''_{\text{mm},1}$ | $\epsilon''_{\text{mm},2}$ | $\epsilon''_{\text{mm},3}$ | $\epsilon''_{\text{mm},4}$ | $\epsilon''_{\text{mm},5}$ | $\epsilon''_{\text{mm},6}$ | tlaps <sub>mm</sub> | sammas <sub>mm</sub> |
|--------|----|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|
| 1.998  | 11 | 25                | 0.018                      | 0.02                       | 0.022                      | 0.024                      | 0.025                      | 0.026                      | 0                   | 0.28                 |
| 1.998  | 12 | 25                | 0.016                      | 0.02                       | 0.022                      | 0.023                      | 0.025                      | 0.026                      | 0.15                | 0.28                 |
| 1.998  | 13 | 25                | 0.018                      | 0.02                       | 0.021                      | 0.023                      | 0.024                      | 0.025                      | 0.22                | 0.28                 |
| 1.998  | 14 | 52                | 0.011                      | 0.014                      | 0.02                       | 0.021                      | 0.023                      | 0.024                      | 0.4                 | 0.28                 |
| 1.998  | 15 | 101               | 0.014                      | 0.017                      | 0.02                       | 0.021                      | 0.022                      | 0.023                      | 0.7                 | 0.28                 |
| 1.998  | 16 | 151               | 0.011                      | 0.016                      | 0.02                       | 0.021                      | 0.022                      | 0.023                      | 1.01                | 0.28                 |
| 1.998  | 17 | 203               | 0.012                      | 0.015                      | 0.017                      | 0.021                      | 0.022                      | 0.024                      | 1.36                | 0.28                 |
| 1.998  | 18 | 254               | 0.017                      | 0.013                      | 0.018                      | 0.019                      | 0.022                      | 0.023                      | 1.7                 | 0.28                 |
| 1.998  | 19 | 302               | 0.01                       | 0.016                      | 0.019                      | 0.021                      | 0.021                      | 0.023                      | 2.03                | 0.28                 |
| 1.998  | 20 | 352               | 0.008                      | 0.016                      | 0.018                      | 0.019                      | 0.022                      | 0.023                      | 2.32                | 0.28                 |
| 1.998  | 21 | 402               | 0.003                      | 0.015                      | 0.018                      | 0.019                      | 0.02                       | 0.023                      | 2.6                 | 0.28                 |
| 1.998  | 22 | 452               | 0.006                      | 0.013                      | 0.015                      | 0.019                      | 0.02                       | 0.021                      | 2.89                | 0.28                 |
| 1.998  | 23 | 501               | 0.016                      | 0.016                      | 0.016                      | 0.018                      | 0.02                       | 0.021                      | 3.18                | 0.28                 |
| 1.998  | 24 | 550               | 0.019                      | 0.015                      | 0.019                      | 0.019                      | 0.021                      | 0.022                      | 3.43                | 0.28                 |
| 1.998  | 25 | 600               | 0.018                      | 0.014                      | 0.023                      | 0.023                      | 0.022                      | 0.024                      | 3.68                | 0.28                 |
| 1.998  | 26 | 650               | 0.019                      | 0.018                      | 0.025                      | 0.025                      | 0.024                      | 0.026                      | 3.94                | 0.28                 |
| 1.998  | 27 | 699               | 0.018                      | 0.021                      | 0.021                      | 0.021                      | 0.025                      | 0.024                      | 4.19                | 0.28                 |
| 1.998  | 28 | 749               | 0.036                      | 0.025                      | 0.025                      | 0.026                      | 0.027                      | 0.027                      | 4.44                | 0.28                 |
| 1.995  | 29 | 799               | 0.038                      | 0.036                      | 0.034                      | 0.036                      | 0.034                      | 0.036                      | 4.7                 | 0.28                 |
| 1.992  | 30 | 822               | 0.047                      | 0.036                      | 0.041                      | 0.042                      | 0.042                      | 0.042                      | 4.86                | 0.28                 |
| 2.112  | 31 | 847               | 0.065                      | 0.05                       | 0.048                      | 0.048                      | 0.046                      | 0.046                      | 5.04                | 0.28                 |
| 1.97   | 32 | 875               | 0.059                      | 0.049                      | 0.051                      | 0.046                      | 0.043                      | 0.04                       | 5.21                | 0.28                 |
| 1.983  | 33 | 897               | 0.036                      | 0.029                      | 0.027                      | 0.024                      | 0.025                      | 0.025                      | 5.38                | 0.28                 |
| 1.979  | 34 | 921               | 0.029                      | 0.017                      | 0.014                      | 0.014                      | 0.013                      | 0.014                      | 5.54                | 0.28                 |
| 1.976  | 35 | 951               | 0.024                      | 0.014                      | 0.011                      | 0.009                      | 0.01                       | 0.011                      | 5.73                | 0.28                 |
| 1.976  | 36 | 974               | 0.034                      | 0.012                      | 0.012                      | 0.011                      | 0.01                       | 0.012                      | 5.89                | 0.28                 |
| 1.976  | 37 | 1000              | 0.026                      | 0.013                      | 0.015                      | 0.013                      | 0.013                      | 0.012                      | 6.07                | 0.28                 |
| 1.976  | 38 | 1026              | 0.042                      | 0.021                      | 0.015                      | 0.013                      | 0.014                      | 0.013                      | 6.24                | 0.28                 |
| 1.976  | 39 | 1050              | 0.048                      | 0.016                      | 0.018                      | 0.015                      | 0.015                      | 0.015                      | 6.41                | 0.28                 |
| 1.976  | 40 | 1074              | 0.051                      | 0.021                      | 0.02                       | 0.016                      | 0.016                      | 0.015                      | 6.58                | 0.28                 |
| 1.979  | 41 | 1098              | 0.063                      | 0.031                      | 0.019                      | 0.018                      | 0.018                      | 0.017                      | 6.74                | 0.28                 |
| 1.981  | 42 | 1122              | 0.084                      | 0.033                      | 0.025                      | 0.02                       | 0.019                      | 0.018                      | 6.91                | 0.28                 |
| 1.984  | 43 | 1146              | 0.146                      | 0.073                      | 0.046                      | 0.04                       | 0.032                      | 0.027                      | 7.08                | 0.28                 |
| 1.986  | 44 | 1100              | 0.049                      | 0.021                      | 0.023                      | 0.018                      | 0.017                      | 0.017                      | 7.31                | 0.28                 |
| 1.989  | 45 | 1049              | 0.041                      | 0.02                       | 0.015                      | 0.014                      | 0.014                      | 0.015                      | 7.57                | 0.28                 |
| 1.991  | 46 | 1001              | 0.034                      | 0.02                       | 0.014                      | 0.014                      | 0.013                      | 0.013                      | 7.82                | 0.28                 |
| 1.994  | 47 | 953               | 0.023                      | 0.015                      | 0.014                      | 0.013                      | 0.013                      | 0.013                      | 8.06                | 0.28                 |
| 1.996  | 48 | 904               | 0.02                       | 0.017                      | 0.012                      | 0.011                      | 0.012                      | 0.012                      | 8.31                | 0.28                 |
| 1.999  | 49 | 854               | 0.022                      | 0.011                      | 0.01                       | 0.009                      | 0.011                      | 0.011                      | 8.57                | 0.28                 |
| 2.001  | 50 | 804               | 0.012                      | 0.01                       | 0.011                      | 0.01                       | 0.01                       | 0.01                       | 8.82                | 0.28                 |
| 2.004  | 51 | 755               | 0.015                      | 0.005                      | 0.009                      | 0.008                      | 0.009                      | 0.009                      | 9.07                | 0.28                 |
| 2.006  | 52 | 706               | 0.007                      | 0.01                       | 0.01                       | 0.01                       | 0.008                      | 0.009                      | 9.32                | 0.28                 |
| 2.009  | 53 | 656               | 0.005                      | 0.009                      | 0.009                      | 0.008                      | 0.008                      | 0.008                      | 9.57                | 0.28                 |
| 2.012  | 54 | 604               | 0.005                      | 0.007                      | 0.006                      | 0.007                      | 0.008                      | 0.007                      | 9.84                | 0.28                 |
| 2.014  | 55 | 554               | 0.005                      | 0.01                       | 0.005                      | 0.008                      | 0.007                      | 0.007                      | 10.09               | 0.28                 |
| 2.017  | 56 | 504               | 0.011                      | 0.006                      | 0.005                      | 0.006                      | 0.006                      | 0.006                      | 10.36               | 0.28                 |
| 2.019  | 57 | 455               | 0.011                      | 0.009                      | 0.005                      | 0.005                      | 0.005                      | 0.006                      | 10.66               | 0.28                 |
| 2.022  | 58 | 405               | -0.002                     | -0.001                     | 0.008                      | 0.005                      | 0.004                      | 0.006                      | 11                  | 0.28                 |
| 2.024  | 59 | 355               | 0.004                      | 0.002                      | 0.002                      | 0.002                      | 0.005                      | 0.006                      | 11.39               | 0.28                 |
| 2.027  | 60 | 305               | 0.003                      | 0.005                      | 0.003                      | 0.005                      | 0.005                      | 0.005                      | 11.83               | 0.28                 |

mq := 61,62..nd - Nempties

| samdns | mm | T <sub>mq,1</sub> | $\epsilon''_{\text{mq},1}$ | $\epsilon''_{\text{mq},2}$ | $\epsilon''_{\text{mq},3}$ | $\epsilon''_{\text{mq},4}$ | $\epsilon''_{\text{mq},5}$ | $\epsilon''_{\text{mq},6}$ | tlaps <sub>mq</sub> | sammas <sub>mq</sub> |
|--------|----|-------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|
| 2.029  | 61 | 254               | -0.01                      | 0.002                      | 0.003                      | 0.003                      | 0.004                      | 0.007                      | 12.35               | 0.28                 |
| 2.032  | 62 | 204               | 0                          | -0.002                     | 0.005                      | 0.004                      | 0.005                      | 0.006                      | 12.96               | 0.28                 |
| 2.035  | 63 | 153               | 0                          | 0.001                      | 0.005                      | 0.004                      | 0.006                      | 0.007                      | 13.8                | 0.28                 |
| 2.035  | 64 | 103               | -0.008                     | 0                          | 0.003                      | 0.005                      | 0.007                      | 0.007                      | 15.06               | 0.28                 |
| 2.035  | 65 | 25                | 0.001                      | 0.005                      | 0.008                      | 0.01                       | 0.012                      | 0.013                      | 21.46               | 0.28                 |

**APPENDIX 1 : Run #2 --RT to 1000 °C on 5M Simulant Glass**  
Glass Used in NUW-LHT-5M Lunar Simulant , from Washington Mills,  
Measurements of Complex Dielectric Constant of Pressed Pellets  
RT to 1000°C to RT, in downward- flowing (30 sccm) UHP Argon

For this 5M glass measurement, MPN again pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. This run was a simple cycle to 1000C and back to room temperature. A steel tube was inserted into the top of the holder and its bottom end positioned 5 cm above the top of the pellet stack, bathing the pellets in UHP argon.

The initial sample parameters were:

- a) effective diameter 3.65 +- 0.02 mm
- b) length of 3 pellet stack: 14.89 +- 0.05 mm
- c) mass 0.295 +- 0.002 gm
- ccc) room temperature density  $1.90 \pm 0.05$  gm/cc.
- ddd) appearance - three light grey pellets
- eee) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 500C in 50C steps, then to 1000C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets were easily removed, and their combined mass determined. Then the empty holder was run up to 1000C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) effective diameter  $3.74 \pm 0.03$  mm
- b) pellet stack length  $14.89 \pm 0.05$  mm
- c) mass  $0.296 \pm 0.002$  gm
- bbb) room temperature density  $1.81 \pm 0.05$  gm/cc.
- ccc) appearance - three light grey pellets
- ddd) magnetic response - The pellets had a very weak attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

# Appendix E. MPN Reports

Test = 2023090801

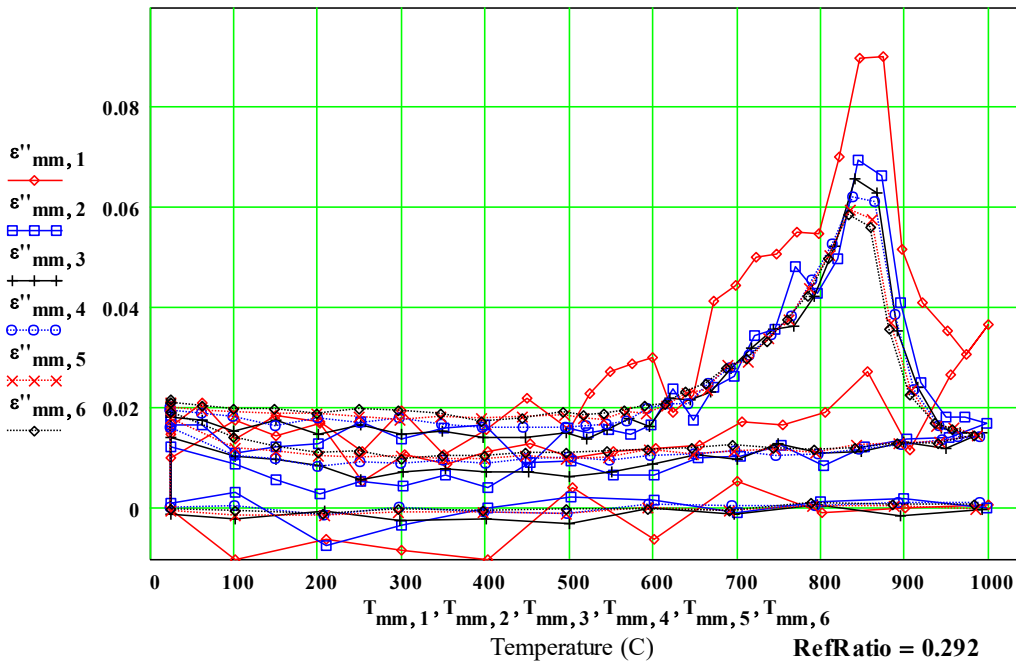
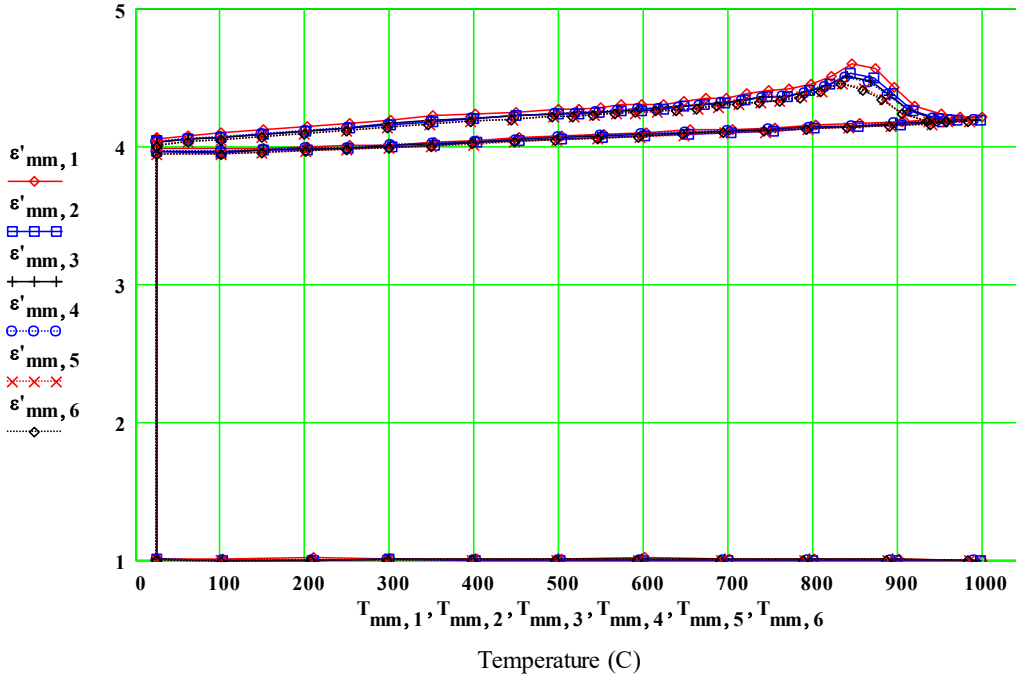
MPN023101.mcd

AnDat = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$

**Final\_over\_Initial\_mass = 1.003**



# Appendix E. MPN Reports

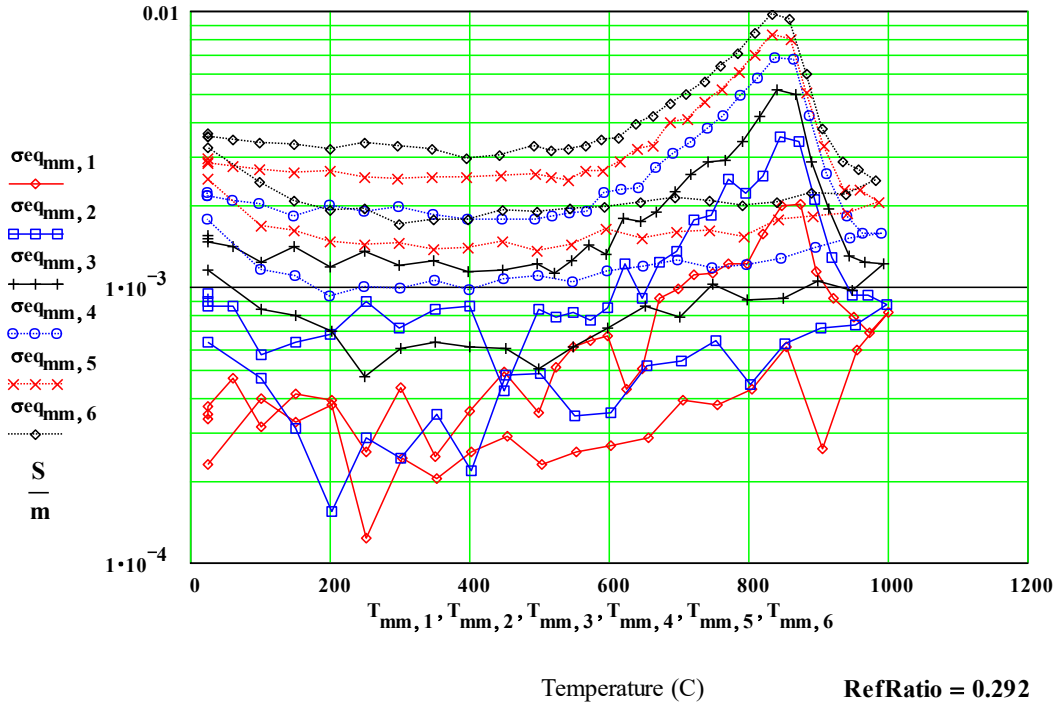
Test = 2023090801

MPN023101.mcd

AnDat = 20230910

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Equivalent Free Electron Conductivity ( Siemens/metre)



Final pellets after the run to 1000C in UHP argon on 5M Glass pellets from Matt Creedon

# Appendix E. MPN Reports

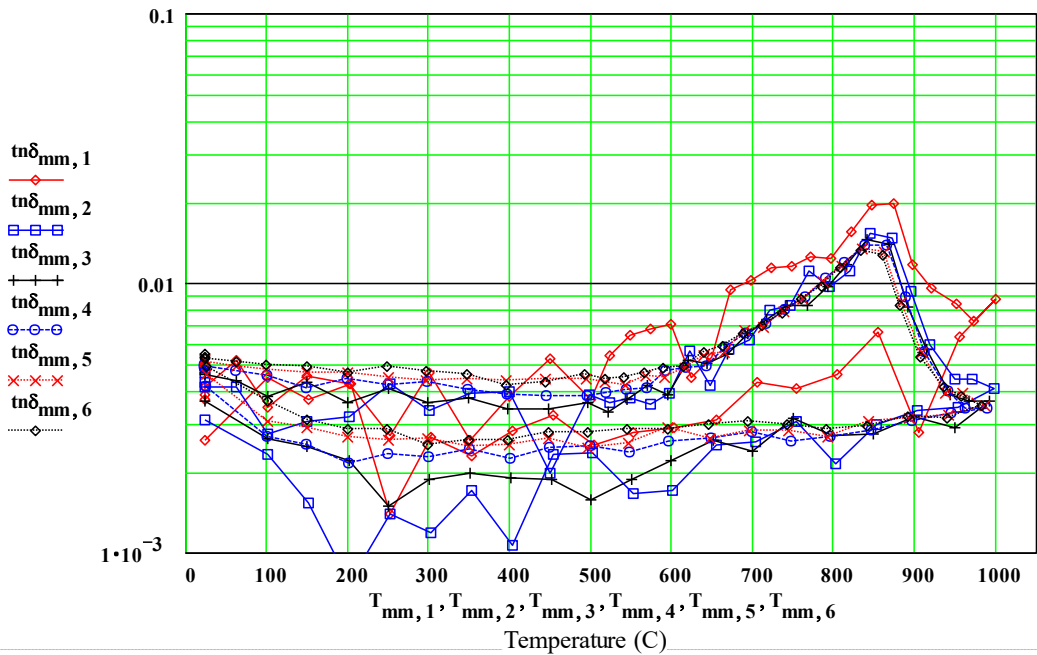
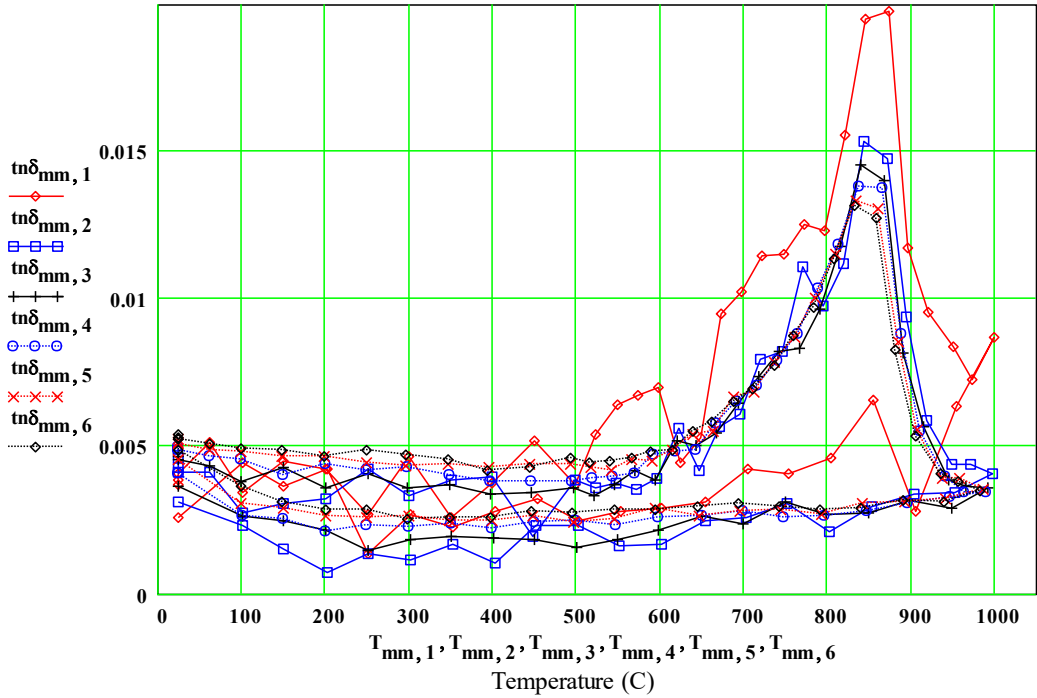
Test = 2023090801

MPN023101.med

AnDat = 20230910

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023090801

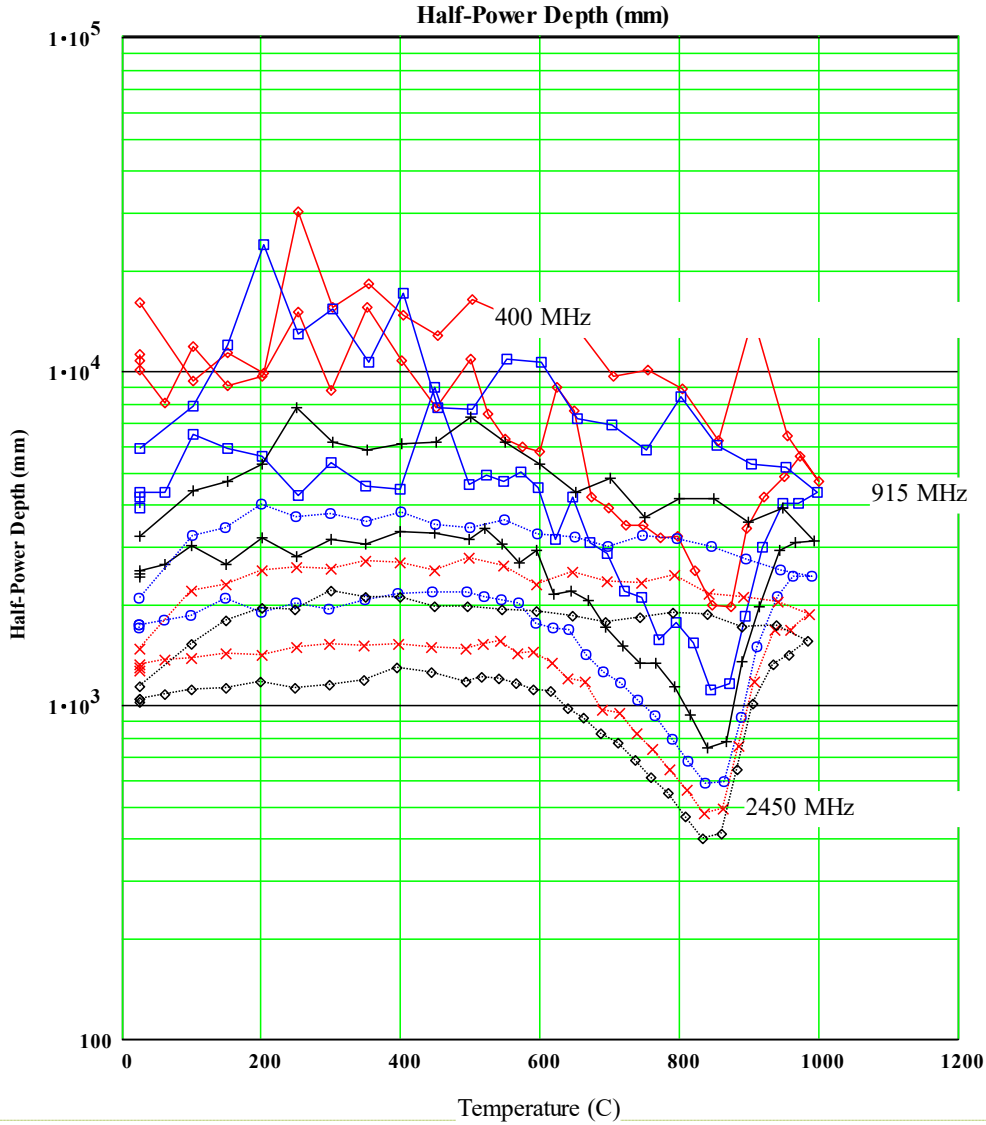
MPN023101.mcd

AnDat = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$



# Appendix E. MPN Reports

Test = 2023090801

MPN023101.mcd

AnDat = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP arg

List of Measured Values of  $\epsilon'$  and  $\epsilon''$  :

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.898$  gm/cc      Final density(25C) =  $\text{dnsfinal} = 1.81$  gm/cc

density index T(C) 397MHz 912MHz 1429MH 1948MHz 2466MHz 2986MHz      Time (hours)

| 1.898 | 3  | 24   | 4.07 | 4.05 | 4.04 | 4.04 | 4.01 | 4    | 0     | 0.295 |
|-------|----|------|------|------|------|------|------|------|-------|-------|
| 1.898 | 4  | 24   | 4.06 | 4.04 | 4.04 | 4.04 | 4.01 | 4    | 0.19  | 0.295 |
| 1.898 | 5  | 24   | 4.06 | 4.04 | 4.03 | 4.04 | 4.01 | 4.01 | 0.25  | 0.295 |
| 1.898 | 6  | 62   | 4.08 | 4.06 | 4.05 | 4.06 | 4.03 | 4.03 | 0.51  | 0.295 |
| 1.898 | 7  | 101  | 4.1  | 4.07 | 4.07 | 4.07 | 4.05 | 4.04 | 0.76  | 0.295 |
| 1.898 | 8  | 150  | 4.12 | 4.09 | 4.09 | 4.09 | 4.06 | 4.06 | 1.08  | 0.295 |
| 1.898 | 9  | 201  | 4.15 | 4.12 | 4.11 | 4.11 | 4.09 | 4.09 | 1.43  | 0.295 |
| 1.898 | 10 | 252  | 4.17 | 4.14 | 4.14 | 4.14 | 4.11 | 4.11 | 1.77  | 0.295 |
| 1.898 | 11 | 300  | 4.19 | 4.16 | 4.17 | 4.16 | 4.14 | 4.14 | 2.1   | 0.295 |
| 1.898 | 12 | 351  | 4.23 | 4.19 | 4.19 | 4.19 | 4.16 | 4.16 | 2.39  | 0.295 |
| 1.898 | 13 | 400  | 4.24 | 4.2  | 4.21 | 4.2  | 4.18 | 4.18 | 2.68  | 0.295 |
| 1.898 | 14 | 450  | 4.25 | 4.22 | 4.23 | 4.22 | 4.2  | 4.2  | 2.97  | 0.295 |
| 1.898 | 15 | 499  | 4.27 | 4.24 | 4.24 | 4.24 | 4.21 | 4.21 | 3.26  | 0.295 |
| 1.898 | 16 | 524  | 4.28 | 4.24 | 4.25 | 4.24 | 4.22 | 4.22 | 3.45  | 0.295 |
| 1.898 | 17 | 549  | 4.29 | 4.25 | 4.25 | 4.25 | 4.23 | 4.23 | 3.62  | 0.295 |
| 1.898 | 18 | 574  | 4.3  | 4.26 | 4.26 | 4.26 | 4.23 | 4.24 | 3.8   | 0.295 |
| 1.898 | 19 | 598  | 4.3  | 4.27 | 4.27 | 4.27 | 4.24 | 4.25 | 3.97  | 0.295 |
| 1.898 | 20 | 624  | 4.31 | 4.28 | 4.28 | 4.28 | 4.25 | 4.26 | 4.15  | 0.295 |
| 1.898 | 21 | 648  | 4.32 | 4.29 | 4.29 | 4.29 | 4.26 | 4.26 | 4.32  | 0.295 |
| 1.898 | 22 | 673  | 4.35 | 4.3  | 4.3  | 4.3  | 4.27 | 4.28 | 4.49  | 0.295 |
| 1.899 | 23 | 698  | 4.36 | 4.32 | 4.32 | 4.31 | 4.29 | 4.29 | 4.67  | 0.295 |
| 1.9   | 24 | 722  | 4.38 | 4.34 | 4.34 | 4.33 | 4.3  | 4.3  | 4.85  | 0.295 |
| 1.901 | 25 | 747  | 4.41 | 4.36 | 4.36 | 4.35 | 4.32 | 4.32 | 5.02  | 0.295 |
| 1.889 | 26 | 772  | 4.42 | 4.36 | 4.37 | 4.36 | 4.33 | 4.33 | 5.2   | 0.296 |
| 1.878 | 27 | 797  | 4.46 | 4.41 | 4.4  | 4.39 | 4.36 | 4.36 | 5.38  | 0.296 |
| 1.867 | 28 | 821  | 4.51 | 4.46 | 4.45 | 4.43 | 4.4  | 4.39 | 5.56  | 0.296 |
| 1.856 | 29 | 846  | 4.61 | 4.53 | 4.51 | 4.5  | 4.46 | 4.45 | 5.74  | 0.296 |
| 1.844 | 30 | 874  | 4.56 | 4.5  | 4.48 | 4.46 | 4.42 | 4.41 | 5.92  | 0.296 |
| 1.833 | 31 | 897  | 4.43 | 4.39 | 4.38 | 4.37 | 4.34 | 4.34 | 6.1   | 0.296 |
| 1.821 | 32 | 921  | 4.3  | 4.26 | 4.26 | 4.26 | 4.23 | 4.23 | 6.28  | 0.296 |
| 1.81  | 33 | 951  | 4.23 | 4.2  | 4.2  | 4.2  | 4.18 | 4.18 | 6.48  | 0.296 |
| 1.81  | 34 | 973  | 4.22 | 4.19 | 4.2  | 4.2  | 4.18 | 4.18 | 6.65  | 0.296 |
| 1.81  | 35 | 1000 | 4.22 | 4.2  | 4.2  | 4.2  | 4.18 | 4.18 | 6.84  | 0.296 |
| 1.81  | 36 | 955  | 4.21 | 4.18 | 4.18 | 4.18 | 4.16 | 4.16 | 7.06  | 0.296 |
| 1.81  | 37 | 905  | 4.18 | 4.16 | 4.17 | 4.17 | 4.15 | 4.15 | 7.3   | 0.296 |
| 1.81  | 38 | 854  | 4.17 | 4.15 | 4.15 | 4.15 | 4.13 | 4.14 | 7.54  | 0.296 |
| 1.81  | 39 | 804  | 4.16 | 4.13 | 4.14 | 4.14 | 4.12 | 4.13 | 7.78  | 0.296 |
| 1.81  | 40 | 754  | 4.14 | 4.12 | 4.13 | 4.13 | 4.11 | 4.11 | 8.02  | 0.296 |
| 1.81  | 41 | 705  | 4.13 | 4.11 | 4.12 | 4.12 | 4.1  | 4.1  | 8.27  | 0.296 |
| 1.81  | 42 | 655  | 4.12 | 4.1  | 4.1  | 4.1  | 4.08 | 4.09 | 8.51  | 0.296 |
| 1.81  | 43 | 603  | 4.11 | 4.08 | 4.09 | 4.09 | 4.07 | 4.07 | 8.76  | 0.296 |
| 1.81  | 44 | 553  | 4.1  | 4.07 | 4.08 | 4.07 | 4.06 | 4.06 | 9.01  | 0.296 |
| 1.81  | 45 | 503  | 4.08 | 4.06 | 4.07 | 4.07 | 4.05 | 4.05 | 9.27  | 0.296 |
| 1.81  | 46 | 453  | 4.07 | 4.04 | 4.05 | 4.05 | 4.03 | 4.04 | 9.57  | 0.296 |
| 1.81  | 47 | 403  | 4.05 | 4.03 | 4.04 | 4.03 | 4.02 | 4.02 | 9.89  | 0.296 |
| 1.81  | 48 | 353  | 4.04 | 4.01 | 4.02 | 4.02 | 4    | 4.01 | 10.26 | 0.296 |
| 1.81  | 49 | 303  | 4.02 | 4    | 4.01 | 4.01 | 3.99 | 3.99 | 10.67 | 0.296 |
| 1.81  | 50 | 252  | 4.01 | 3.99 | 3.99 | 3.99 | 3.97 | 3.98 | 11.16 | 0.296 |
| 1.81  | 51 | 203  | 4    | 3.98 | 3.98 | 3.98 | 3.97 | 3.97 | 11.73 | 0.296 |
| 1.81  | 52 | 151  | 3.99 | 3.97 | 3.97 | 3.97 | 3.95 | 3.96 | 12.5  | 0.296 |

mq := 53,54..nd - Nempties

| 1.81 | 53 | 101 | 3.98 | 3.96 | 3.96 | 3.96 | 3.95 | 3.95 | 13.64 | 0.296 |
|------|----|-----|------|------|------|------|------|------|-------|-------|
| 1.81 | 54 | 24  | 3.99 | 3.97 | 3.97 | 3.97 | 3.94 | 3.94 | 17.15 | 0.296 |



MPN-294\_MPN\_5M Glass to 1300C\_Creedon\_Washington Mills

Sept. 28, 2023

Measurements of the Complex Dielectric Constant of  
Pressed Pellets of the 5M Glass, used in the NUW-LHT-5M Lunar Simulant  
from Washington Mills,  
RT to 1300°C to RT, in upward-flowing (10 sccm) UHP Argon

Dr. Doug Rickman ( NASA) was interested in knowing the dielectric properties of the special glass that was manufactured by Washington Mills, and used in the making of the NUW-LHT-5M highlands simulant. Dr. Matt Creedon of Washington Mills sent a sample of the 5M simulant glass powder to MPN, who had offered to measure its microwave dielectric properties. The first measurements went to 1150C, but higher temperatures appeared to be required for engineering of “consolidated” material . The DSC measurements of Austin Patridge and Alan Whittington suggested that at higher temperatures, approaching the melt zone, the viscosity might be high enough to allow measurements in standard pellet form, with reasonably well defined density !

For this 1300°C 5M glass measurement, MPN again pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. This run was a simple cycle to 1300C and back to room temperature. The sample holder for this run was an 8 mm OD, 6 mm ID fused silica holder, but to reduce possible reaction of the sample with the holder material, a 5.7 mm OD, 4.15 mm ID, 15.1 mm long, high purity, alumina crucible was fitted inside the silica holder ( see photo) . UHP argon gas was flowed up past the crucible during the run. The holder and crucible were initially cycled ( and measured, empty) to 1300C before the run, both to “clean” the holder and measure the “empty holder” values, which were later used during the off-line data analysis.

The initial sample parameters were:

- a) diameter 3.63 +- 0.02 mm
- b) length of 3 pellet stack: 13.29 +- 0.05 mm
- c) mass 0.280 +- 0.002 gm
- fff) room temperature density  $2.04 \pm 0.05$  gm/cc.
- ggg) appearance - three light grey pellets ( see photos)
- hhh) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 600C in 50C steps, then to 1300C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample and crucible were weighed together. The pellets were easily broken out of the crucible ( there was slight adherence only to the crucible base) ( see photo).

The final sample properties, at room temperature were :

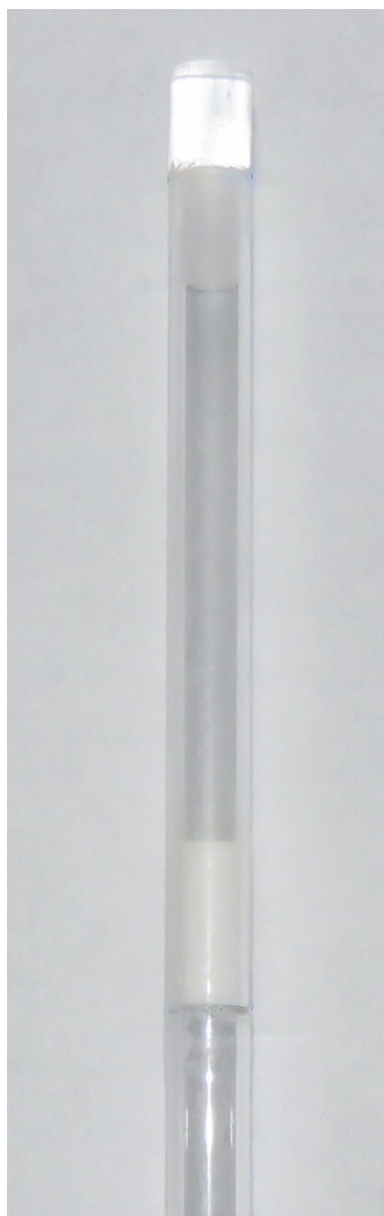
- a) diameter  $3.49 \pm 0.03$  mm
- b) pellet stack length  $12.52 \pm 0.05$  mm
- c) mass  $0.280 \pm 0.002$  gm
- eee) room temperature density  $2.34 \pm 0.05$  gm/cc.
- fff) appearance - three very light beige pellets with dark reaction/melting spots ( see photos)
- ggg) magnetic response - The pellets had a very weak attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

The frequency coding is :

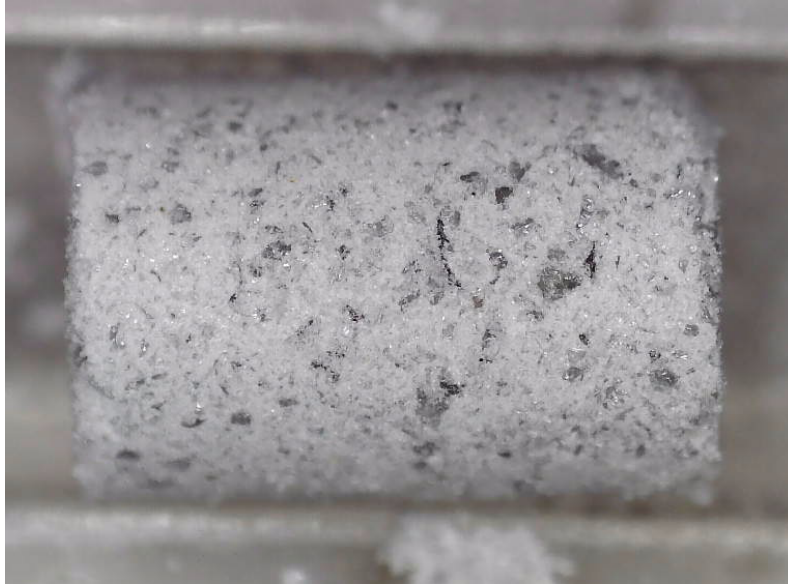
Legend for Data Plots :

| <u>#</u> | <u>Frequency(MHz)</u> | <u>Symbol</u>                                            |
|----------|-----------------------|----------------------------------------------------------|
| 1        | 397                   | red diamond, solid line – sometimes the line is omitted! |
| 2        | 912                   | blue square, solid line                                  |
| 3        | 1429                  | black cross, solid line                                  |
| 4        | 1948                  | blue circle, dotted line                                 |
| 5        | 2466                  | red cross, dotted line                                   |
| 6        | 2986                  | black diamond, dotted line                               |

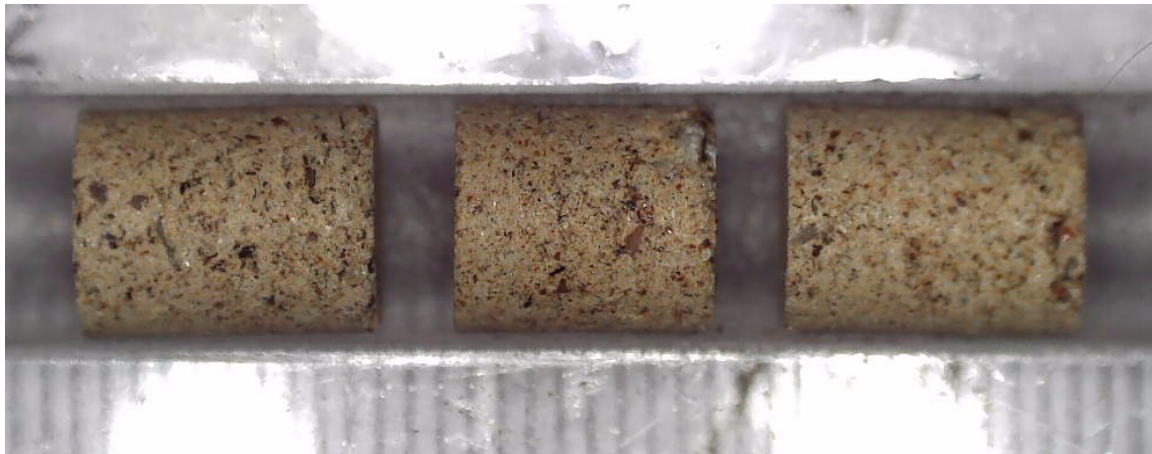


The 8 mm OD high purity fused silica ( GE-214) holder with a 5.7 mm OD, 15.1 mm long, high purity alumina crucible inside, in location. The pellets are inside the crucible. A loose plug of

fused silica is inserted at the top to stop backflow of air, but allows the UHP argon to flow up past the crucible and out.



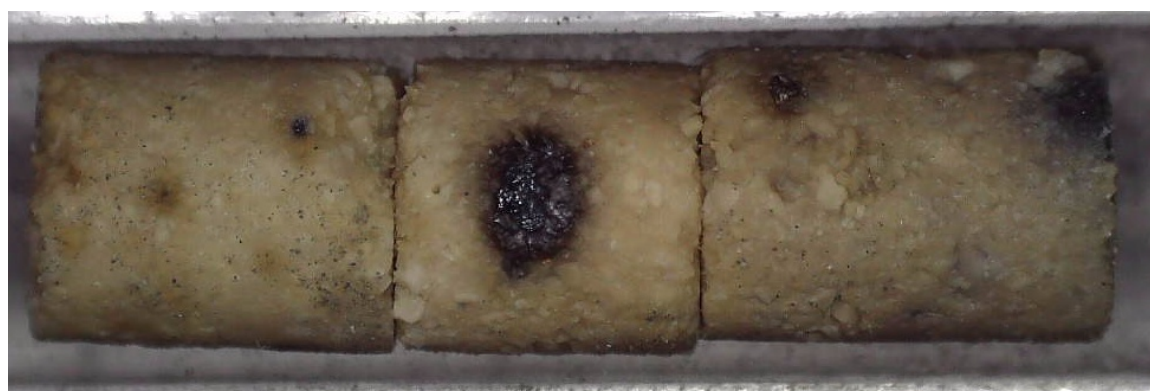
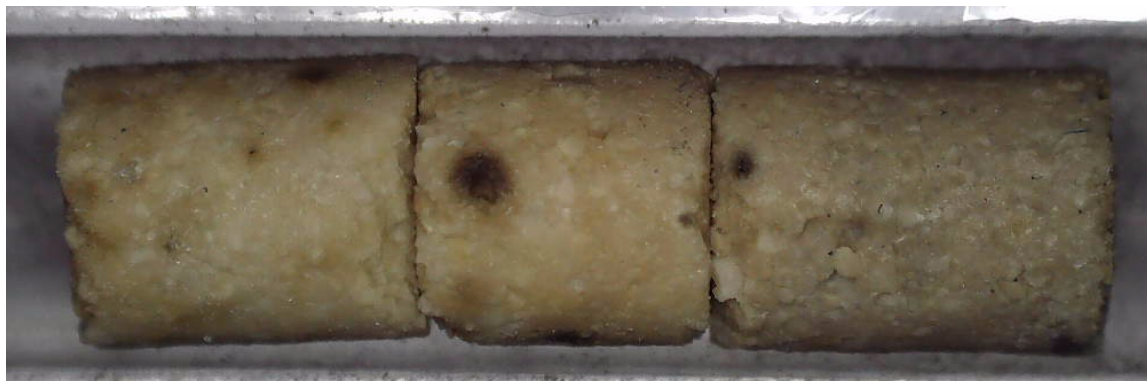
Initial 5M Glass ( Washington Mills) pellet - Pressed at ~ 33,000 psi



Three final NUW-LHT-5M stimulant pellets after a cycle to 1150C in UHP argon .



Three 5M Glass pellets after a cycle to 1150C in UHP argon (a previous run)



Three views of the final stack of three 5M Glass pellets, after this cycle to 1300C in UHP argon (obtained by rotating the final bonded pellet stack )



# Appendix E. MPN Reports

Test = 2023092501

MPN023109.mcd

AnDat = 20230926

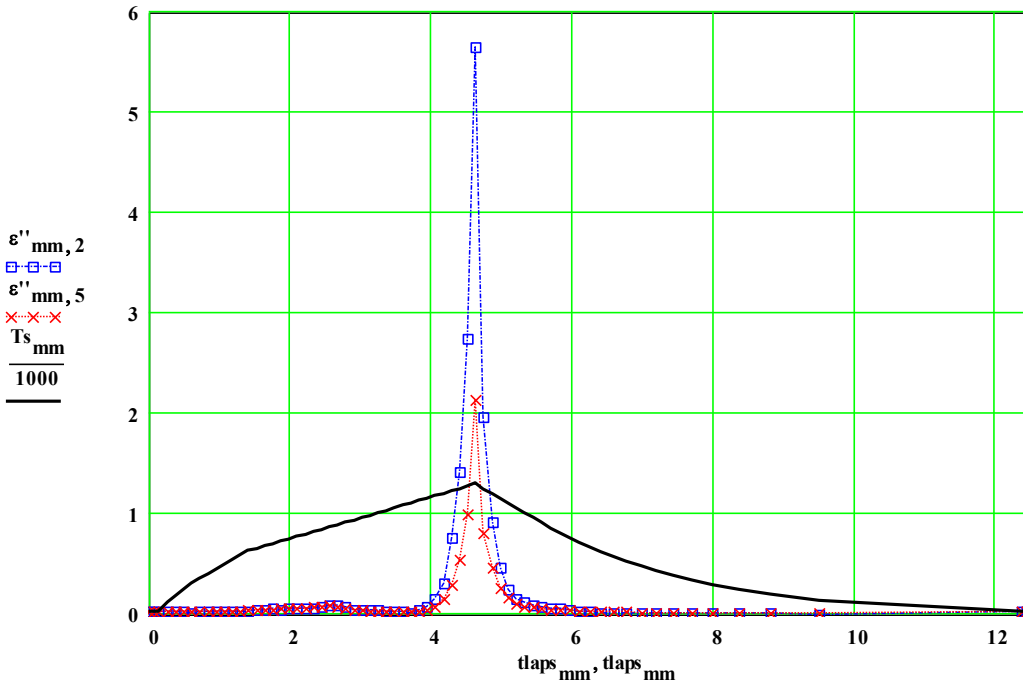
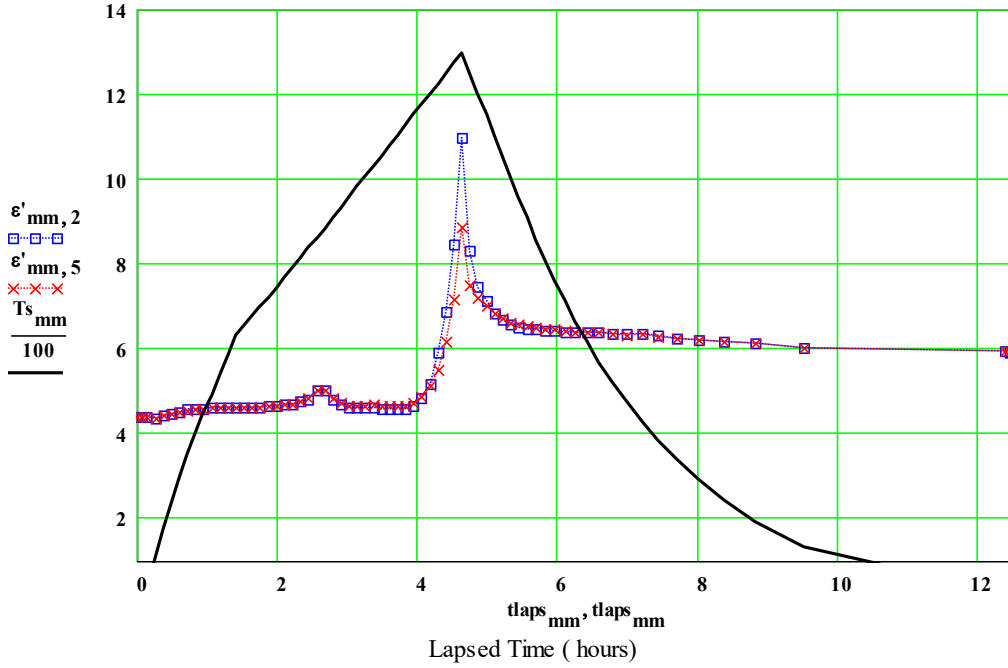
5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon,

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ ,

Thermal exp. coeff.

Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$        $\text{FracMassChange} = 1$

$\alpha_1 = 3 \cdot 10^{-6}$



# Appendix E. MPN Reports

Test = 2023092501

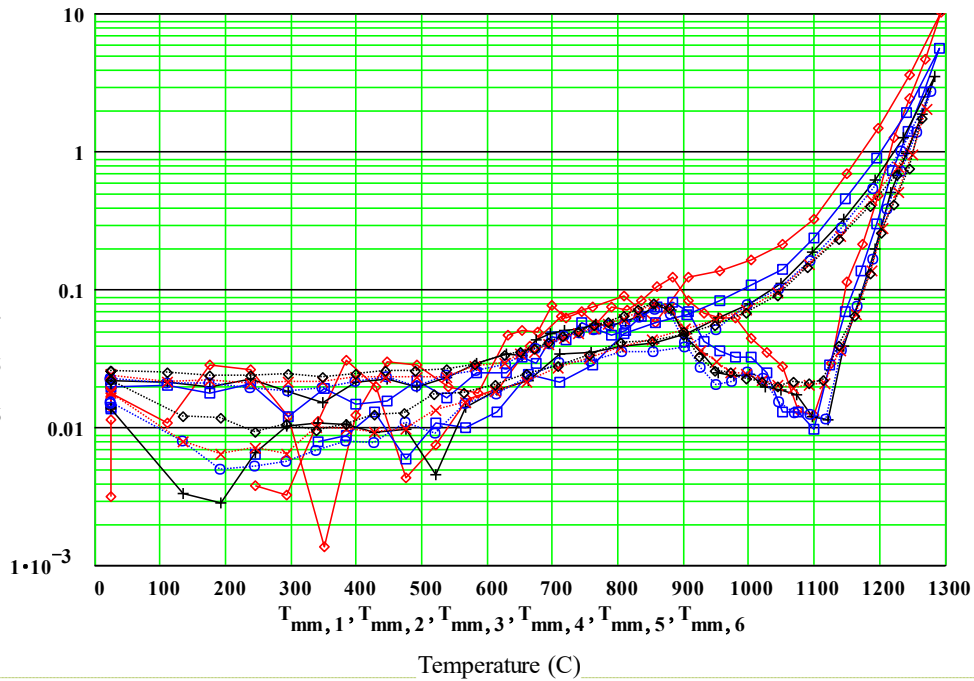
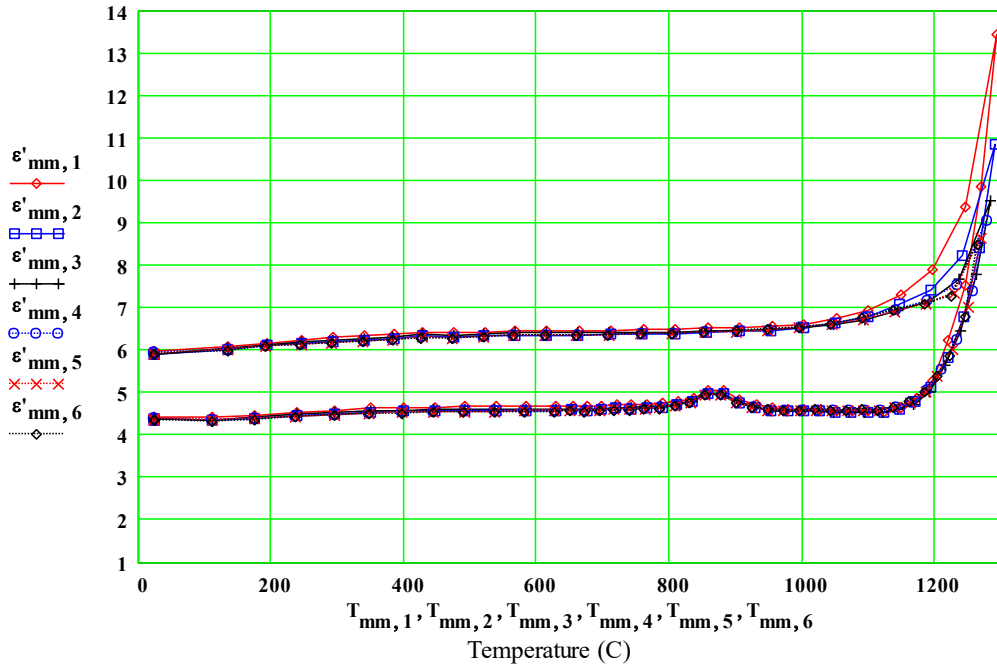
MPN023109.mcd

AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon,

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$   $\alpha_1 = 3 \cdot 10^{-6} \text{ /C}$

$\alpha_2 = 1 \cdot 10^{-5} \text{ /C}$



The lower  $\epsilon'$  trace is the data for the ramp up (ramp rate  $\sim 3.6 \text{ }^\circ\text{C/min}$  between 600C and 1300C).

The upper  $\epsilon'$  trace is the data for the ramp down ( rate  $\sim 7.2$  °C/min ) and suggests the simple quenching of a glass.

Test = 2023092501

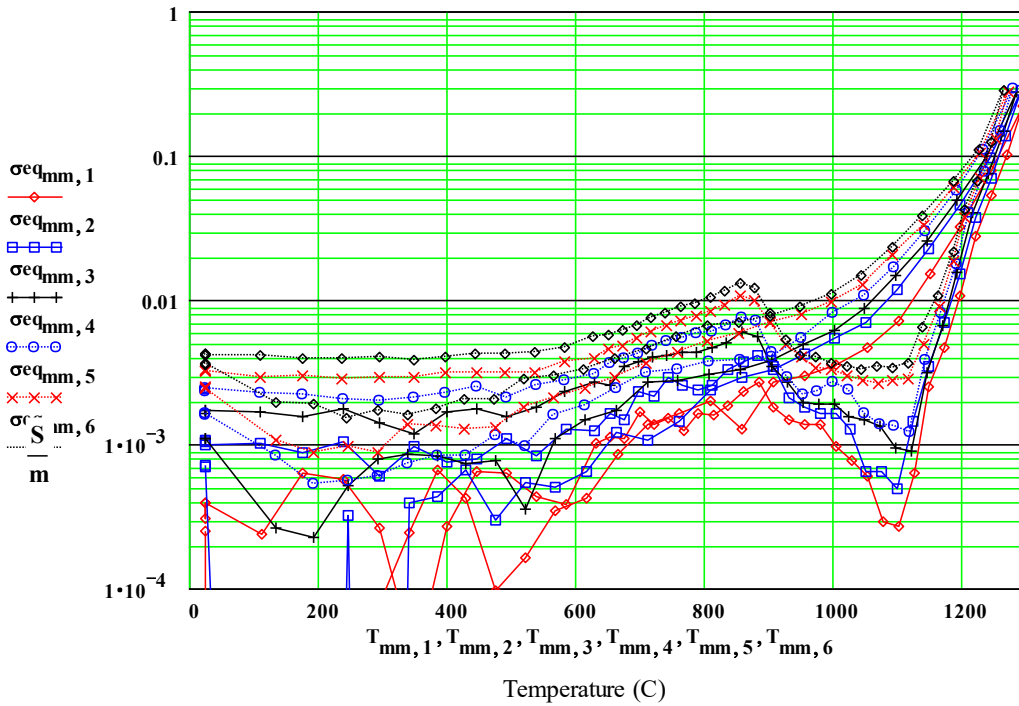
MPN023109.mcd

AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon,

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04$  gm/cc, Final density(25C) =  $\text{dnsfinal} = 2.34$  gm/cc

Equivalent Free Electron Conductivity ( Siemens/metre)



The overlap of the ramp up and ramp down values makes viewing and understanding of the data difficult.

The following data presentation will be divided into ramp up and ramp down sections .

**Data for ramp up from room temperature to 1300 °C**

# Appendix E. MPN Reports

Test = 2023092501

MPN023109.mcd

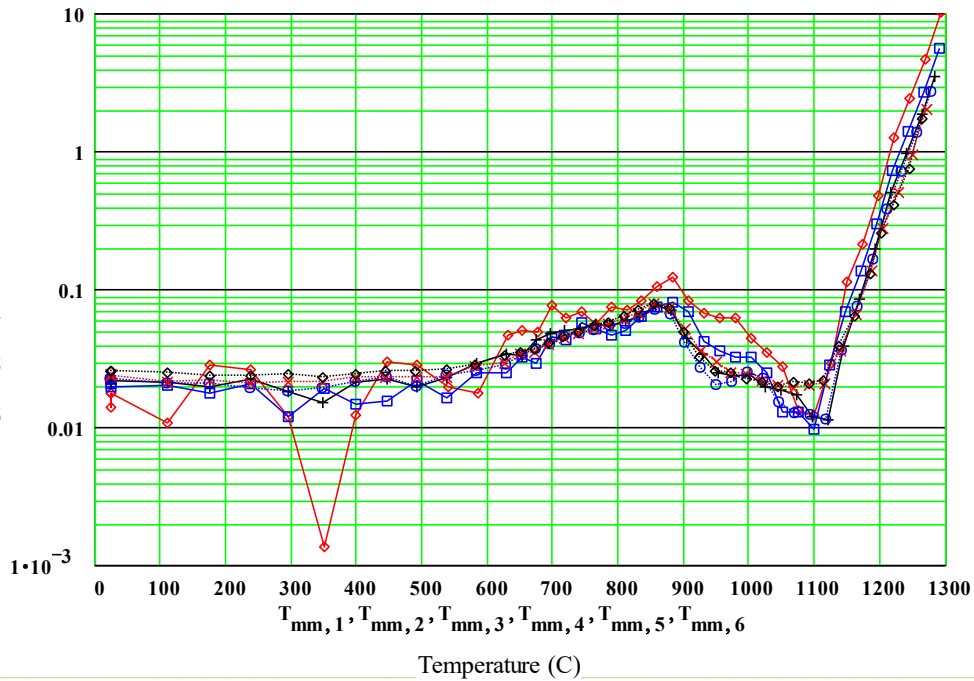
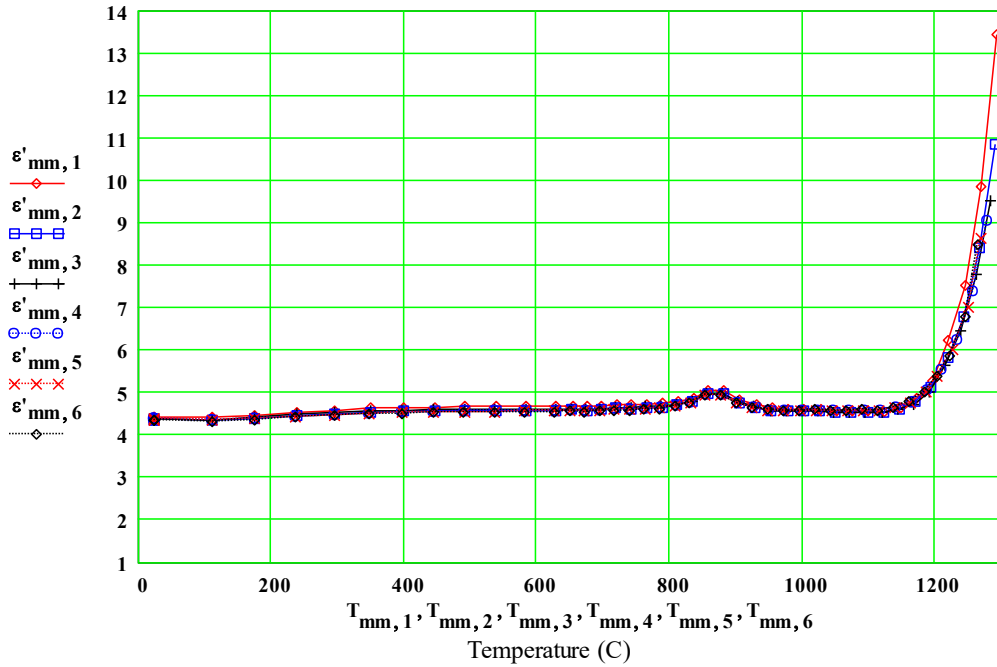
AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon,

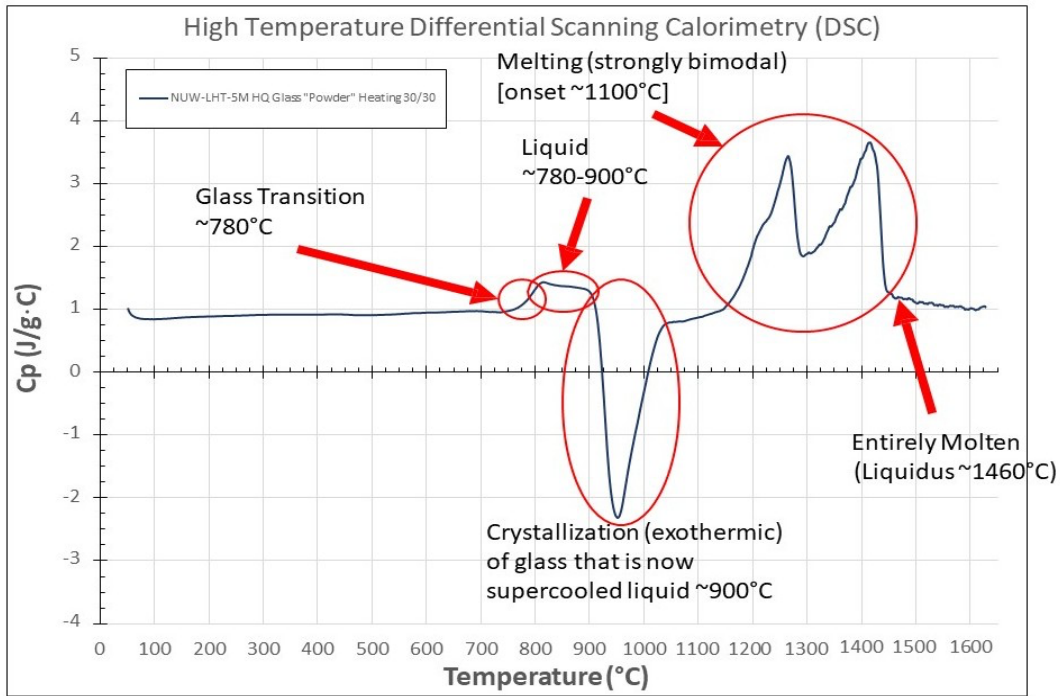
Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$   $\alpha_1 = 3 \cdot 10^{-6} \text{ /C}$

**Temperature Ramp Up to 1300 C**

$\alpha_2 = 1 \cdot 10^{-5} \text{ /C}$



Appendix E. MPN Reports



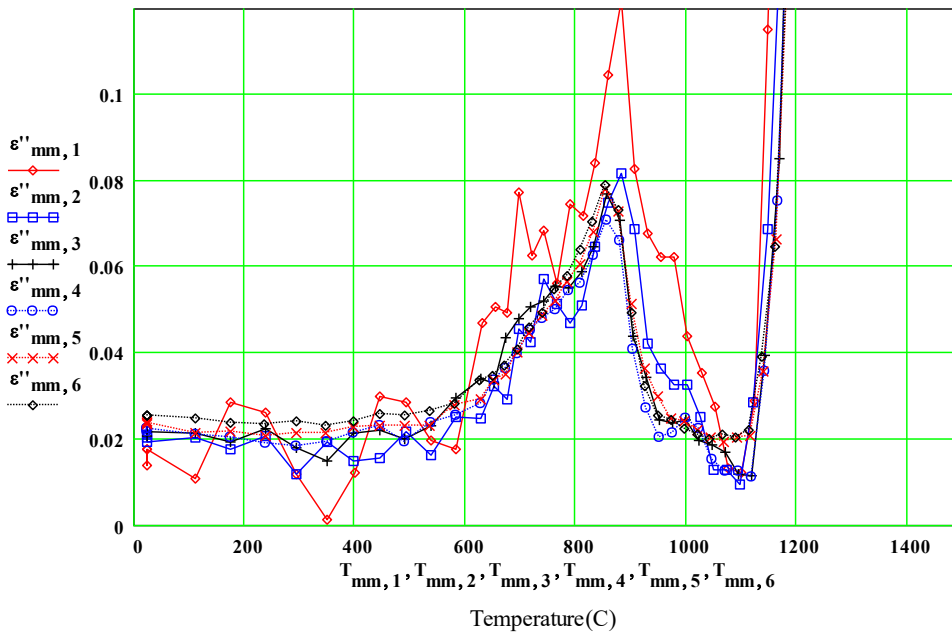
Test = 2023092501

MPN023109.mcd

AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon,

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$



A comparison of the Patridge DSC data for the ramp-up of a powder sample of 5M glass with the MPN values of the loss factor,  $\epsilon''$ . The glass transition at ~780C is evident in both. The completion of the re-crystallization at 1050C is also obvious in both. The maximum in the number of "mobile" ions at 880 C is seen in the loss factor.

# Appendix E. MPN Reports

Test = 2023092501

MPN023109.mcd

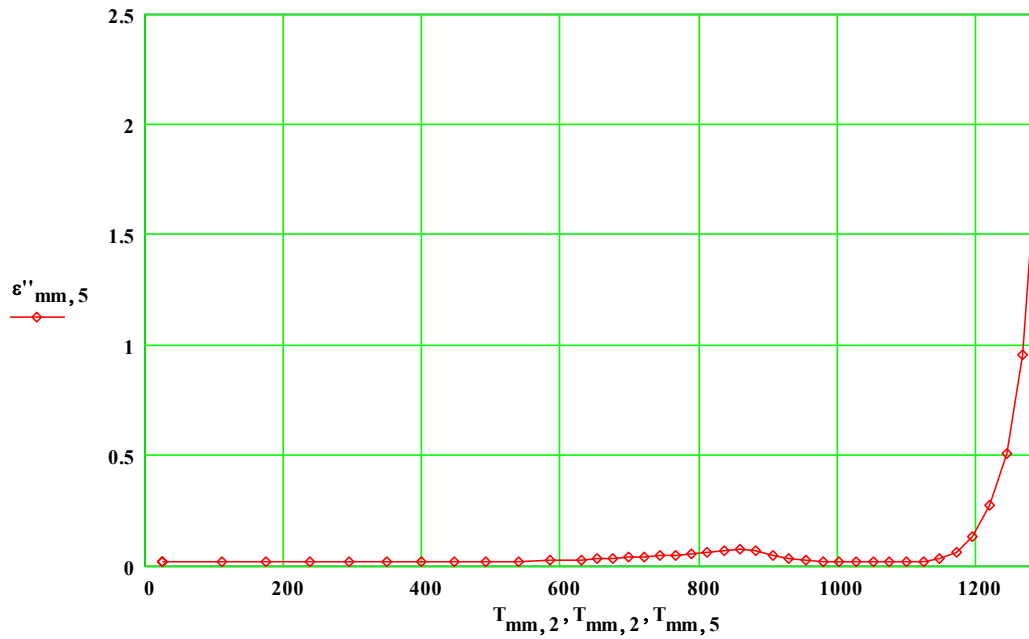
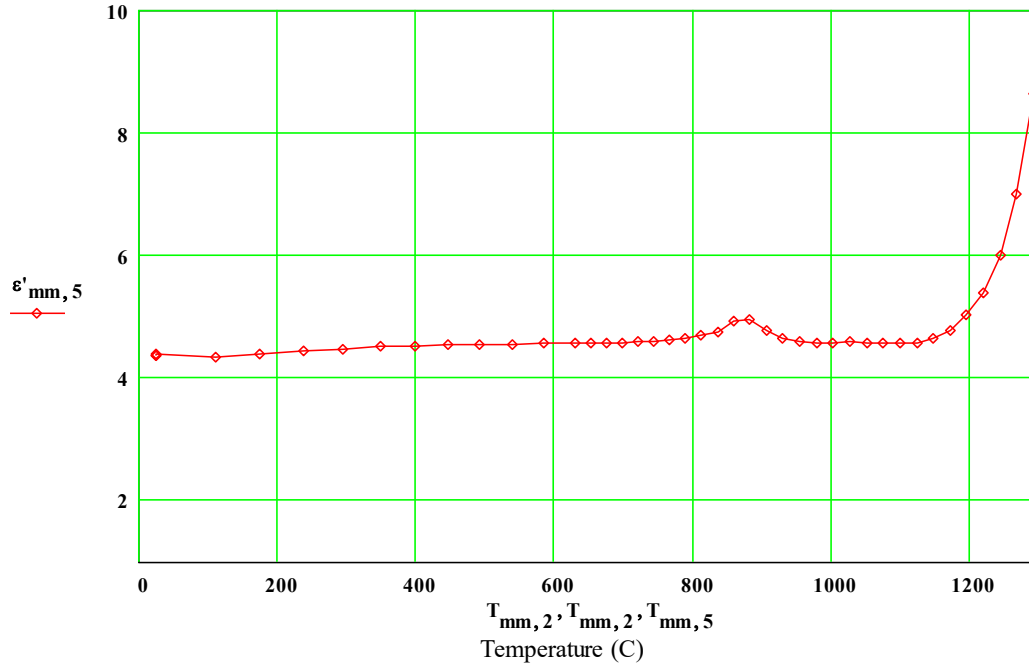
AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon.

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Thermal exp. coeff.  $\alpha_1 = 3 \cdot 10^{-6}$   $\alpha_2 = 10 \cdot 10^{-6}$

## Temperature Ramp Up to 1300 C

### Values for 2450 MHz



# Appendix E. MPN Reports

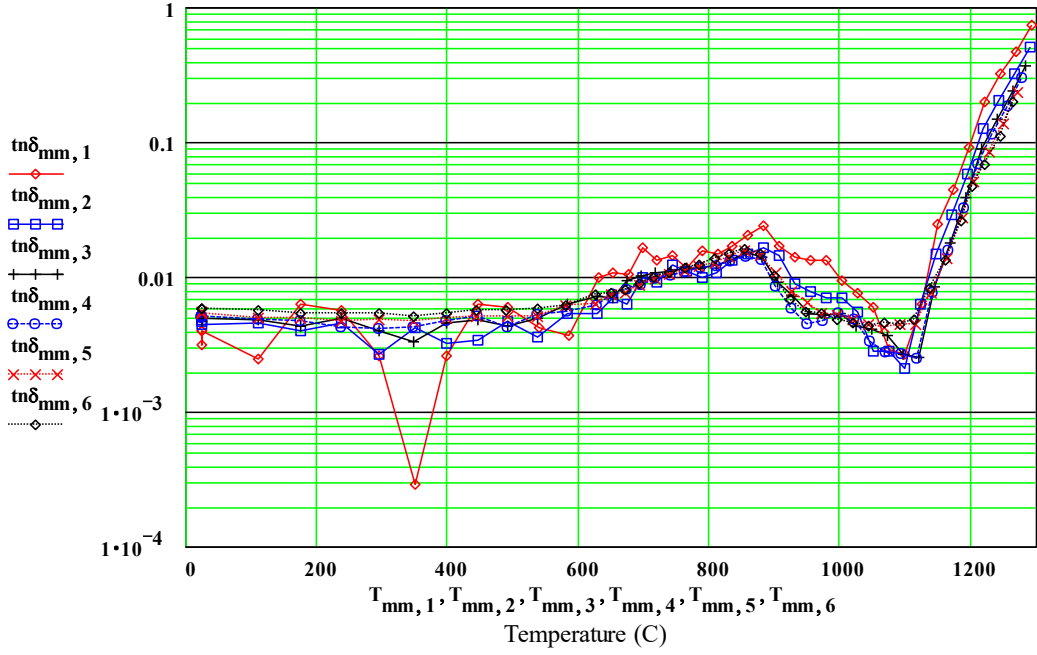
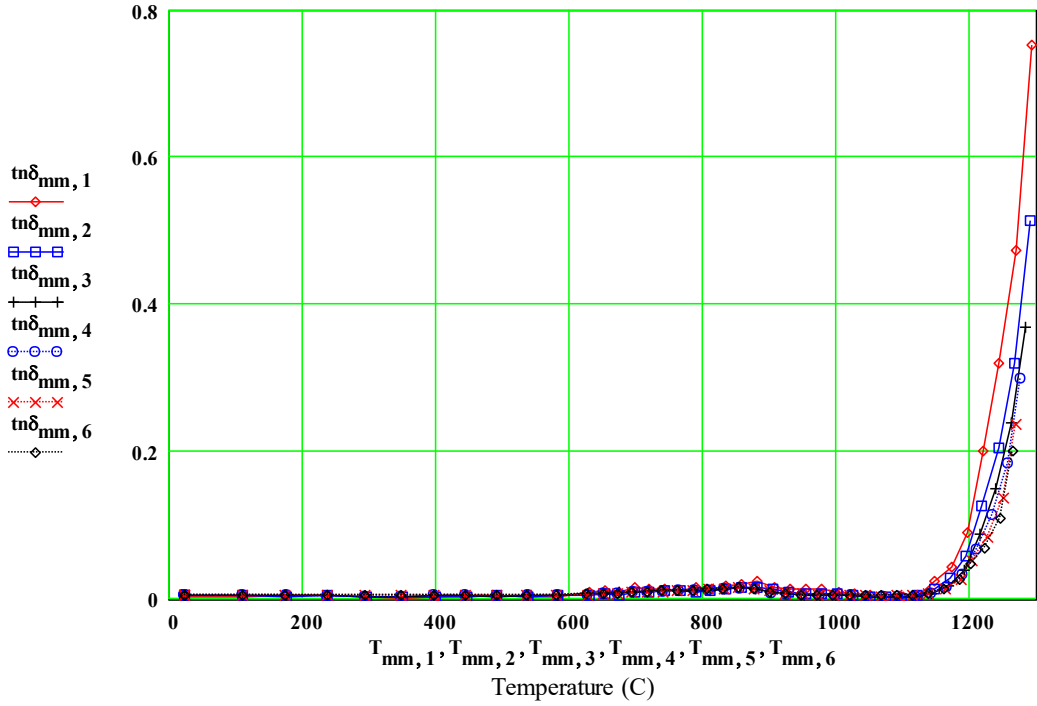
Test = 2023092501

MPN023109.mcd

AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$





### Data for ramp down from 1300 °C to room temperature

Test = 2023092501

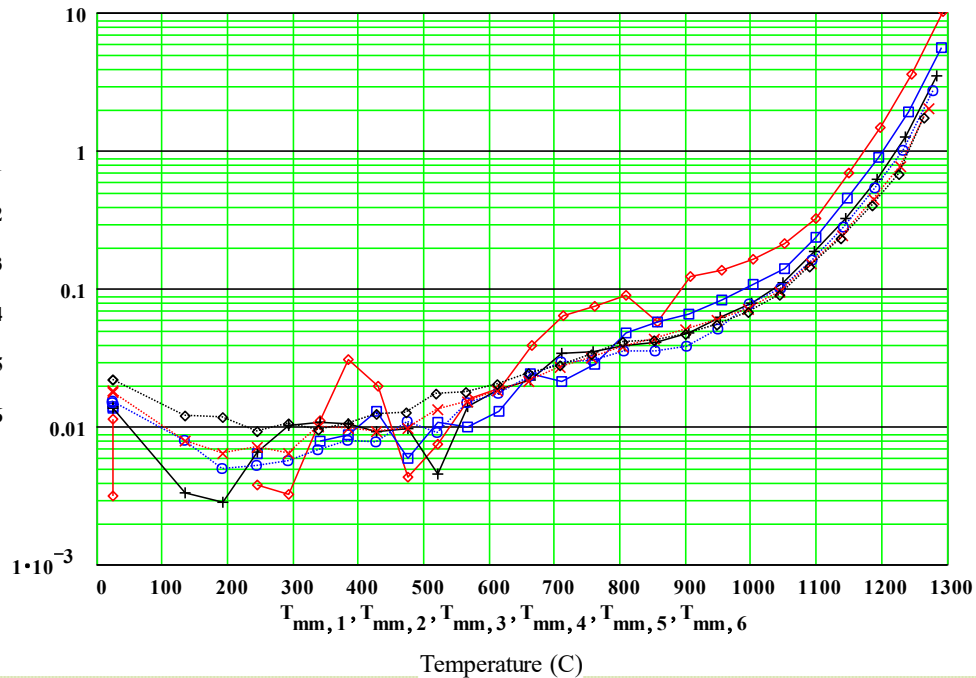
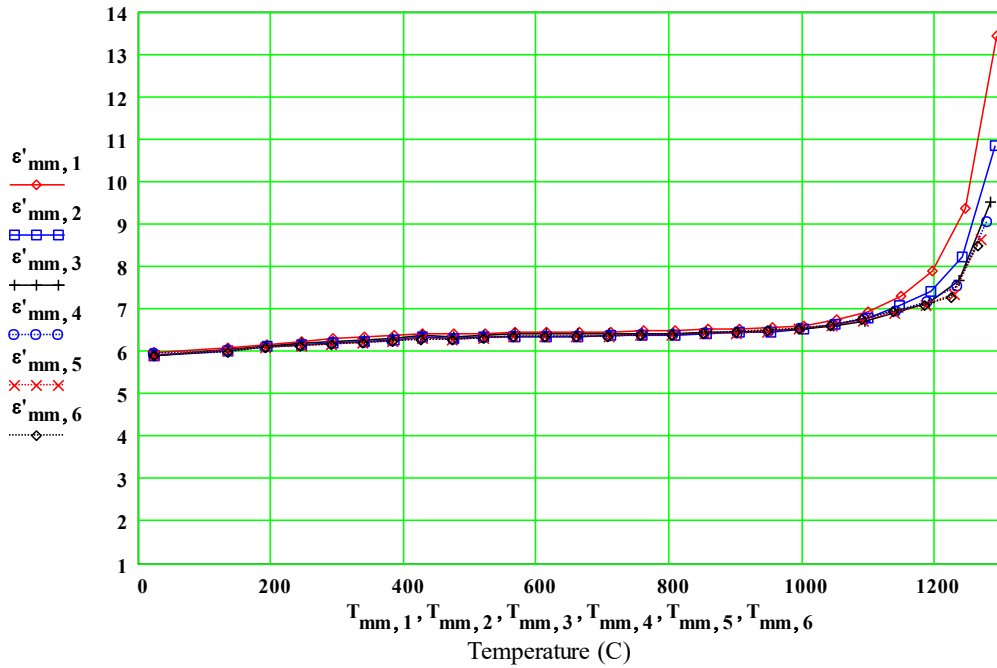
MPN023109.mcd

AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon,

Initial density =  $\text{samdns}_{\text{NCaI} + 1} = 2.04 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$   $\alpha_1 = 3 \cdot 10^{-6} \text{ /C}$

Temperature Return Down from 1300 C  $\alpha_2 = 1 \cdot 10^{-5} \text{ /C}$



# Appendix E. MPN Reports

Test = 2023092501

MPN023109.mcd

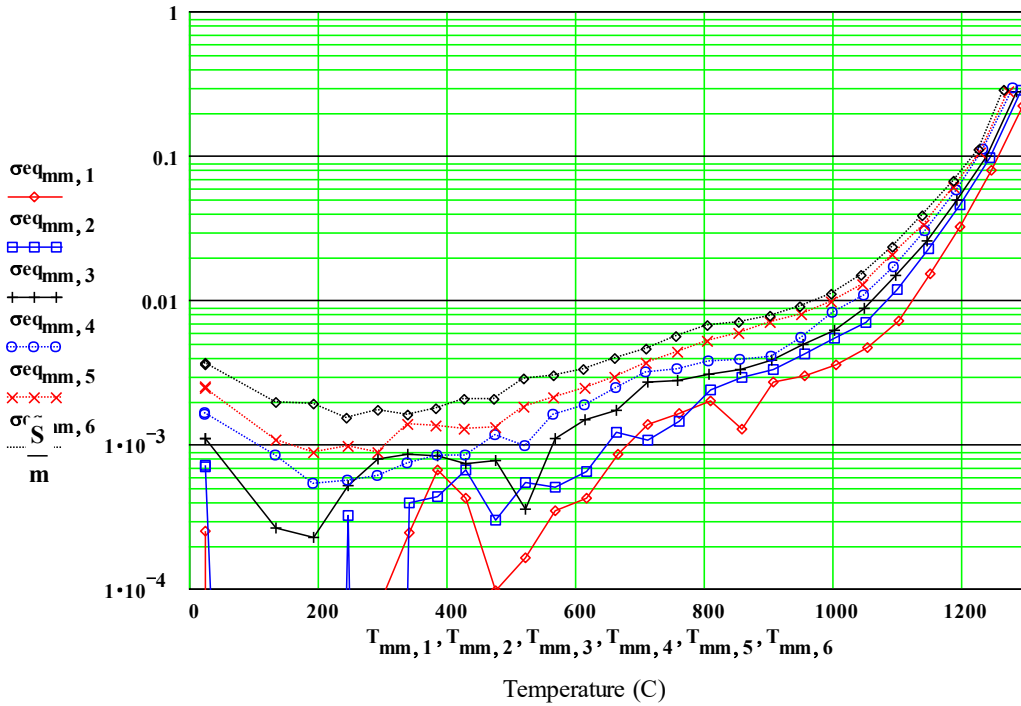
AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon,

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$

## Temperature Return Down from 1300 C to RT

Equivalent Free Electron Conductivity ( Siemens/metre)



# Appendix E. MPN Reports

Test = 2023092501

MPN023109.mcd

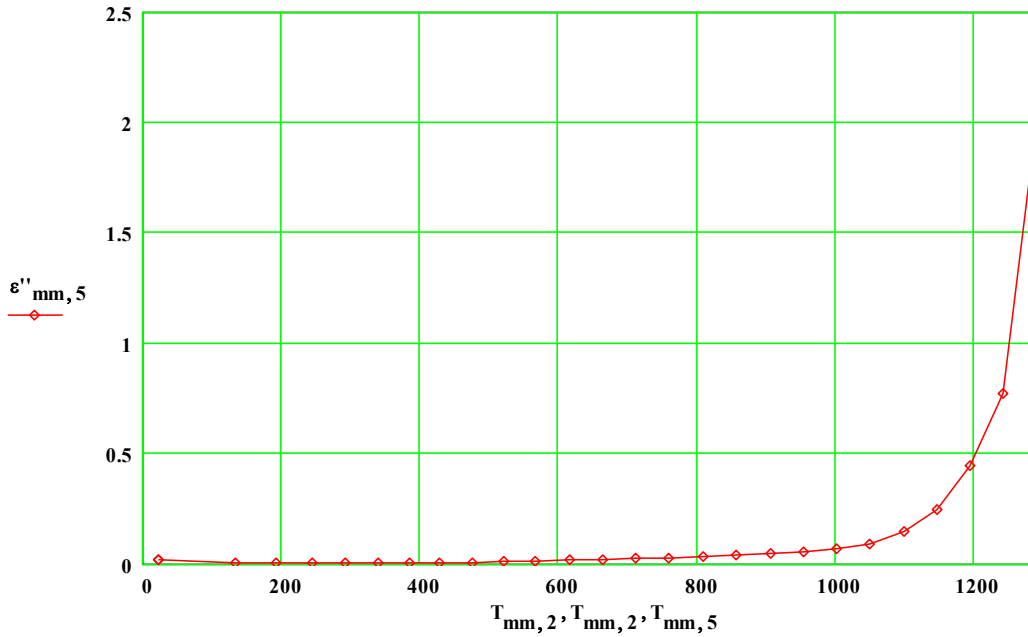
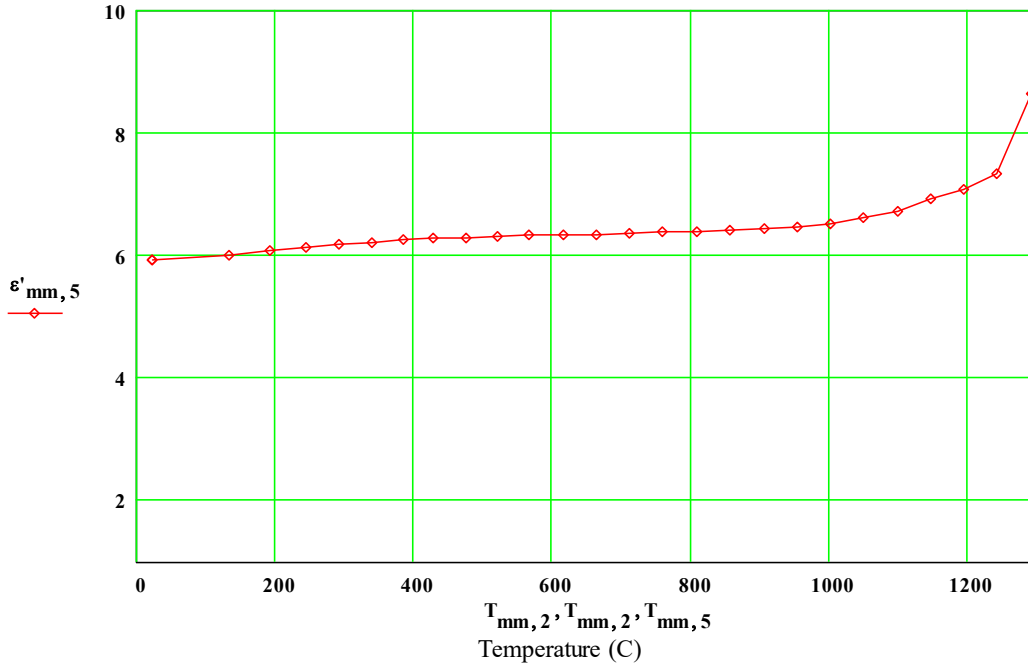
AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon.

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Thermal exp. coeff.  $\alpha_1 = 3 \cdot 10^{-6}$   $\alpha_2 = 10 \cdot 10^{-6}$

## Temperature Return Down from 1300 C to RT

### Values for 2450 MHz



# Appendix E. MPN Reports

Test = 2023092501

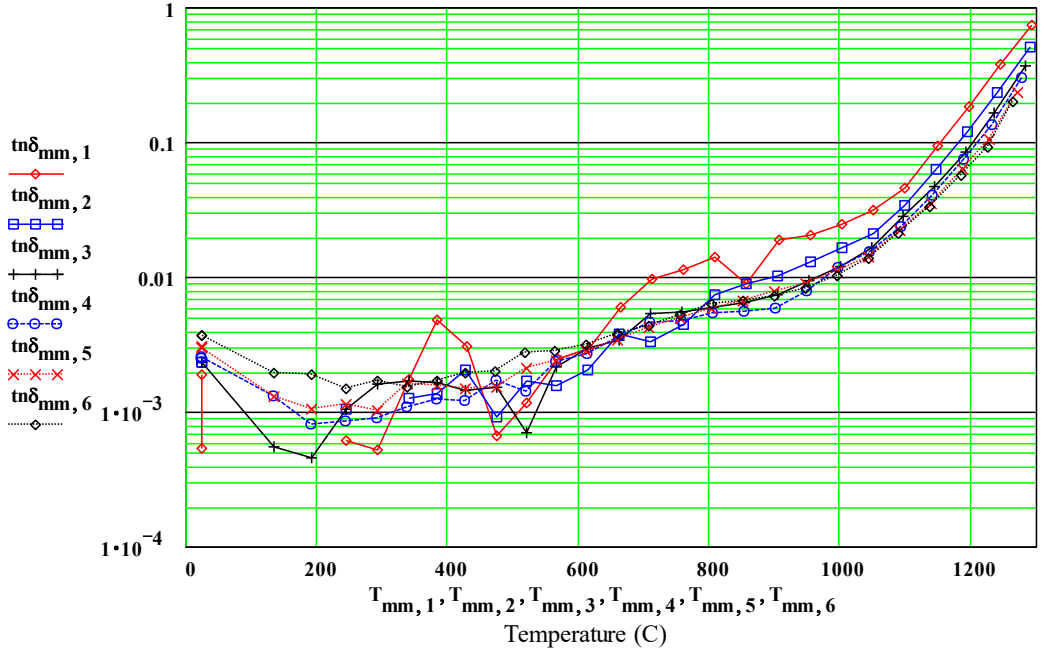
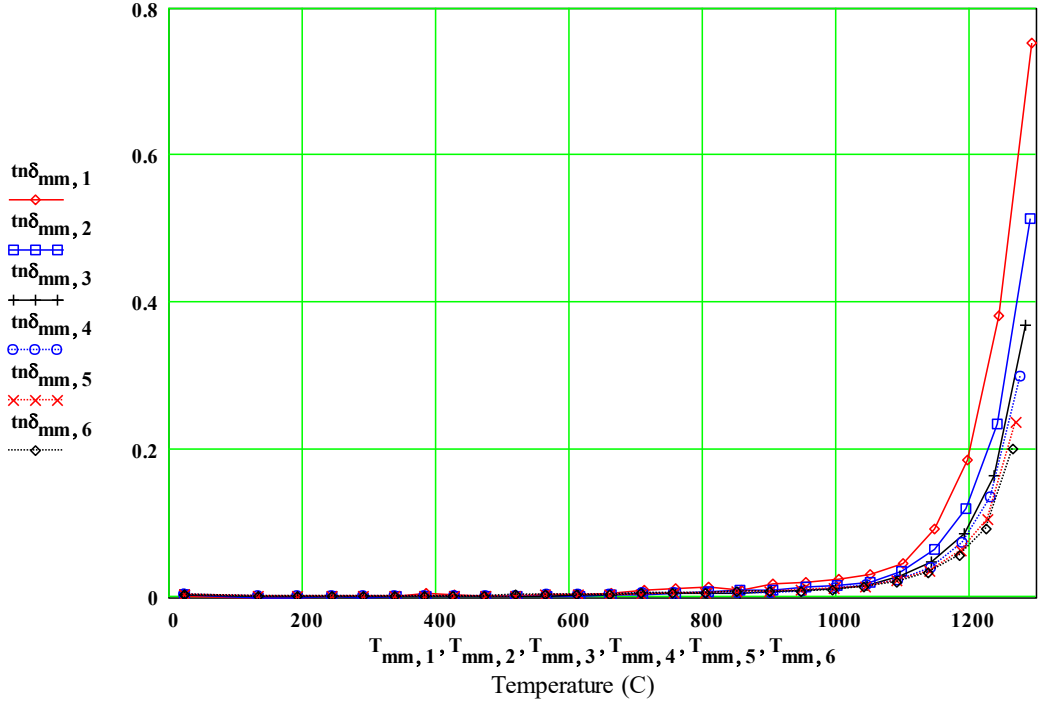
MPN023109.mcd

AnDat = 20230928

5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2.04 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 2.34 \text{ gm/cc}$

## Temperature Return Down from 1300 C to RT





**APPENDIX 1 : Second Run to 1000 °C on 5M Simulant Glass**  
Glass Used in NUW-LHT-5M Lunar Simulant , from Washington Mills,  
Measurements of Complex Dielectric Constant of Pressed Pellets  
RT to 1000°C to RT, in downward- flowing (30 sccm) UHP Argon

For this 5M glass measurement, MPN again pressed pellets of the powder material in a uniaxial press at ~ 33,000 psi. The pellets were not initially baked by MPN to ensure dryness. This run was a simple cycle to 1000C and back to room temperature. A steel tube was inserted into the top of the holder and its bottom end positioned 5 cm above the top of the pellet stack, bathing the pellets in UHP argon.

The initial sample parameters were:

- a) effective diameter 3.65 +- 0.02 mm
- b) length of 3 pellet stack: 14.89 +- 0.05 mm
- c) mass 0.295 +- 0.002 gm
- iii) room temperature density  $1.90 \pm 0.05$  gm/cc.
- jjj) appearance - three light grey pellets
- kkk) magnetic response - The pellets had a very weak attraction to a strong magnet.

The dielectric properties measurements were performed three times at RT, and then the temperature was ramped up to 500C in 50C steps, then to 1000C in 25 C steps. After this, the temperature was brought back down to 100C in -50C steps, then RT.

The holder was removed from the apparatus and it and the final sample were weighed together. The pellets were easily removed, and their combined mass determined. Then the empty holder was run up to 1000C to measure backgrounds and check for contamination. There was no significant contamination.

The final sample properties, at room temperature were :

- a) effective diameter  $3.74 \pm 0.03$  mm
- b) pellet stack length  $14.89 \pm 0.05$  mm
- c) mass  $0.296 \pm 0.002$  gm
- hhh) room temperature density  $1.81 \pm 0.05$  gm/cc.
- iii) appearance - three light grey pellets
- jjj) magnetic response - The pellets had a very weak attraction to a strong magnet.

Note: The percent mass loss was zero within our errors .

# Appendix E. MPN Reports

Test = 2023090801

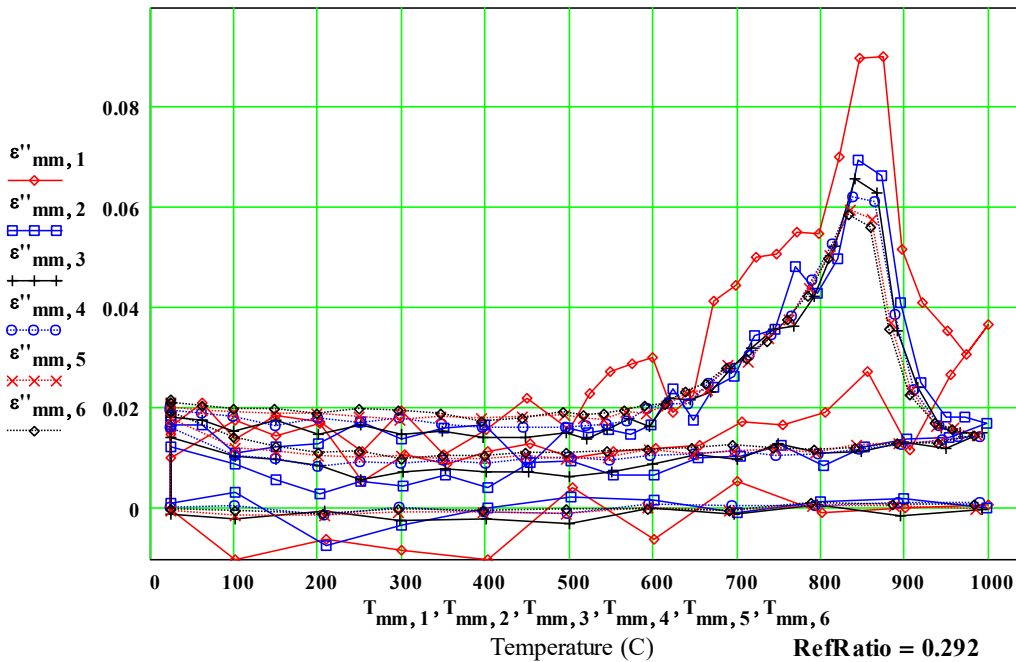
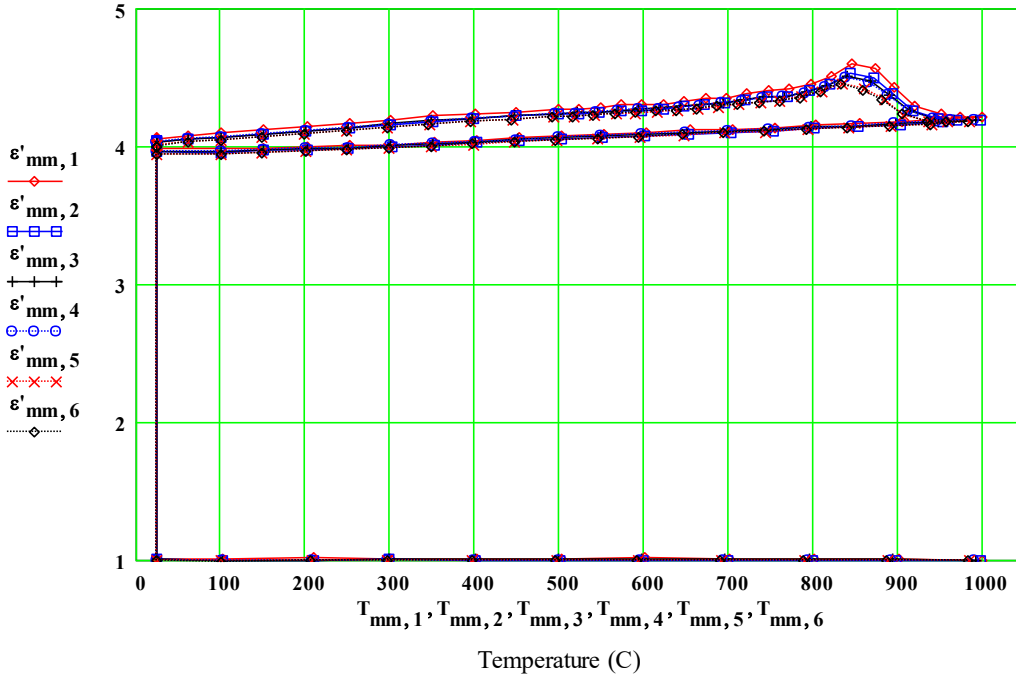
MPN023101.mcd

AnDat = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$

**Final\_over\_Initial\_mass = 1.003**



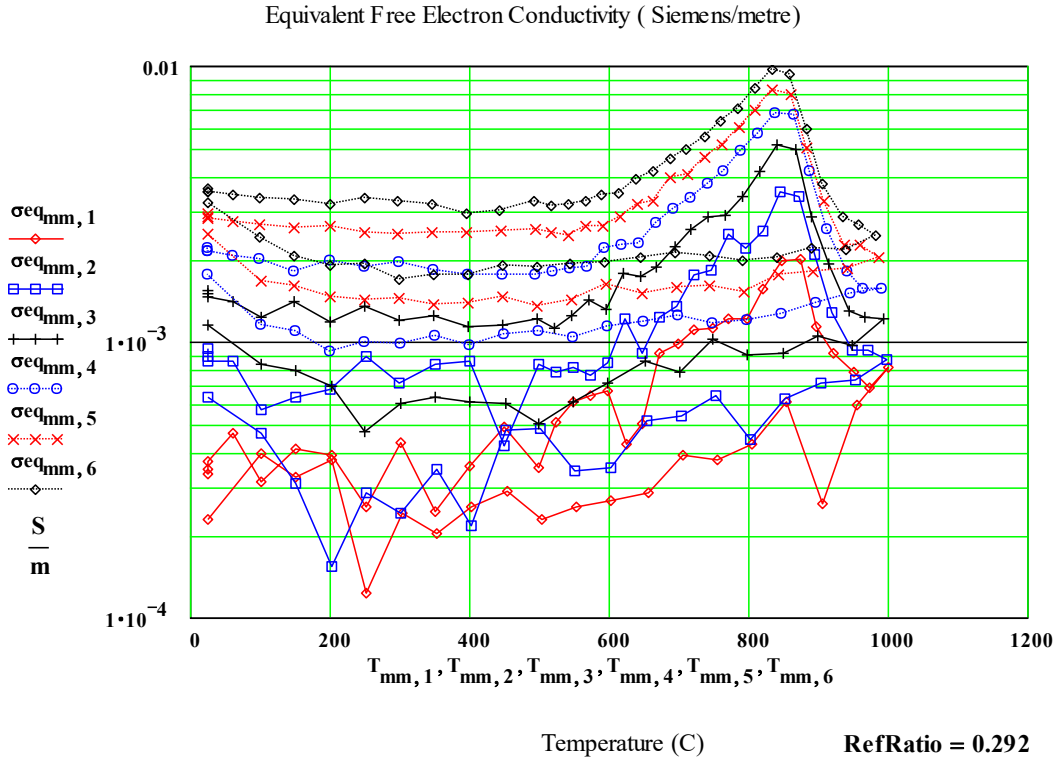
# Appendix E. MPN Reports

Test = 2023090801

MPN023101.mcd

AnDat = 20230910

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon



Final pellets after 2<sup>nd</sup> run to 1000C in UHP argon on 5M Glass pellets from Matt Creedon

# Appendix E. MPN Reports

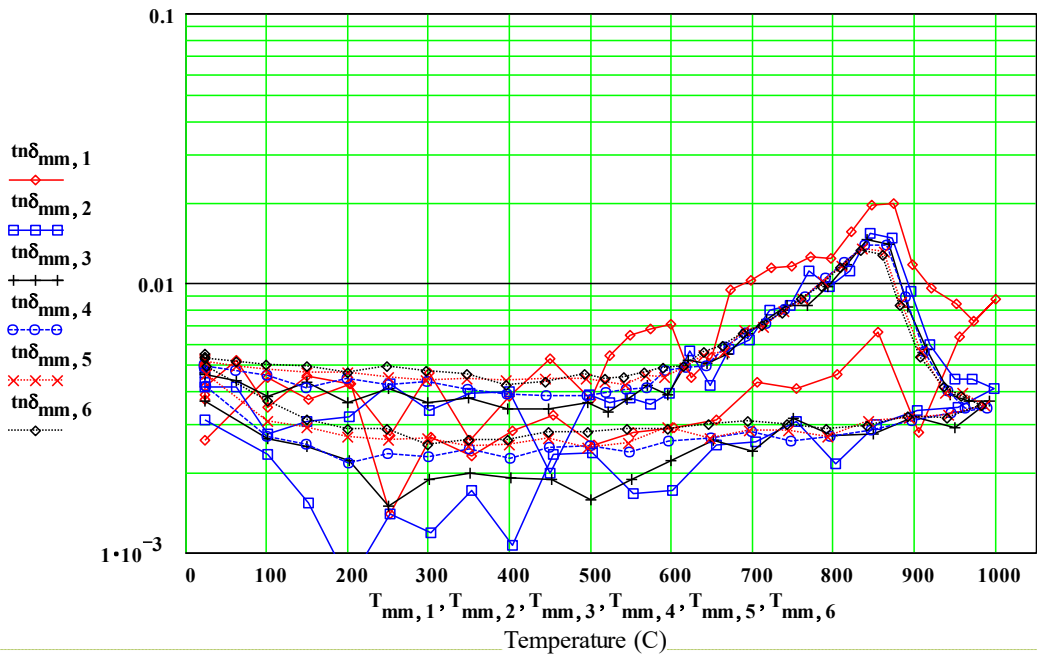
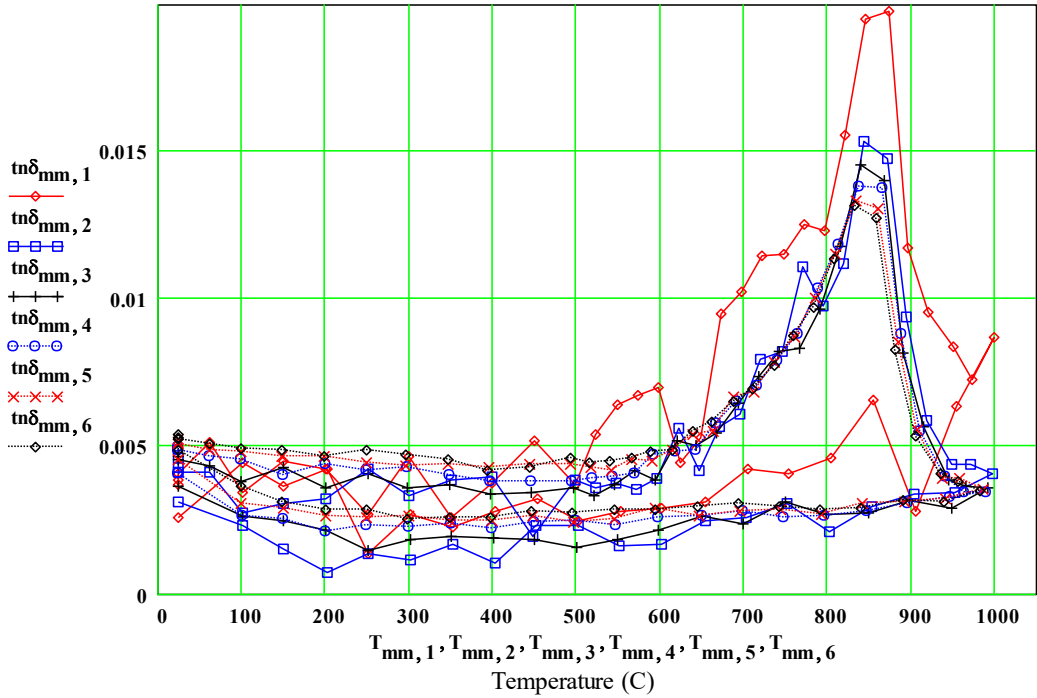
Test = 2023090801

MPN023101.med

AnDat = 20230910

5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ , Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$



# Appendix E. MPN Reports

Half-power Depth (millimeters)

$$D_{\text{halfP}}(\text{mm}, n) := \left( \frac{\ln(2)}{2} \right) \cdot (\text{inverse}\alpha_{\text{mm}, n} \cdot 1)$$

Test = 2023090801

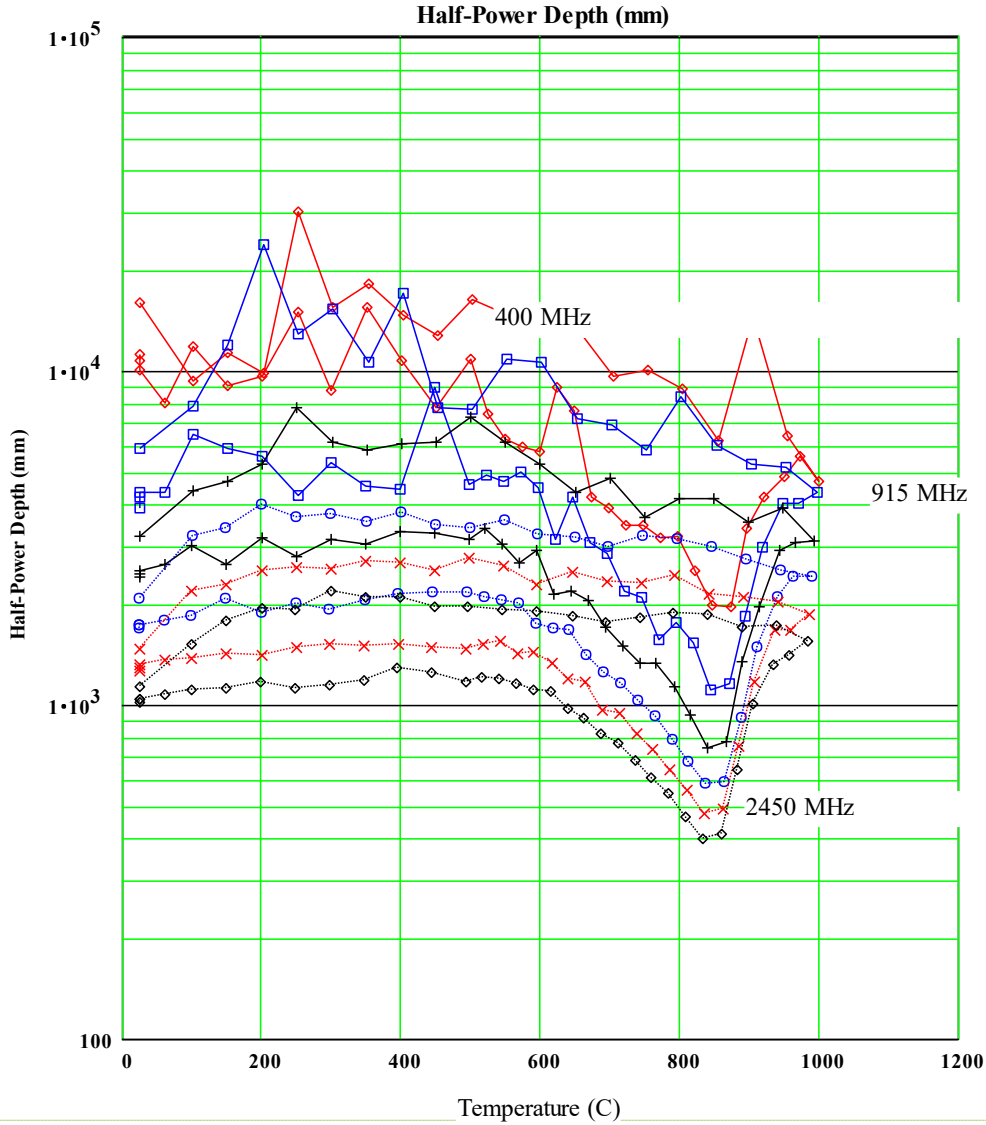
MPN023101.mcd

AnD at = 20230910

Repeat: 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1000C to RT, in flowing UHP argon

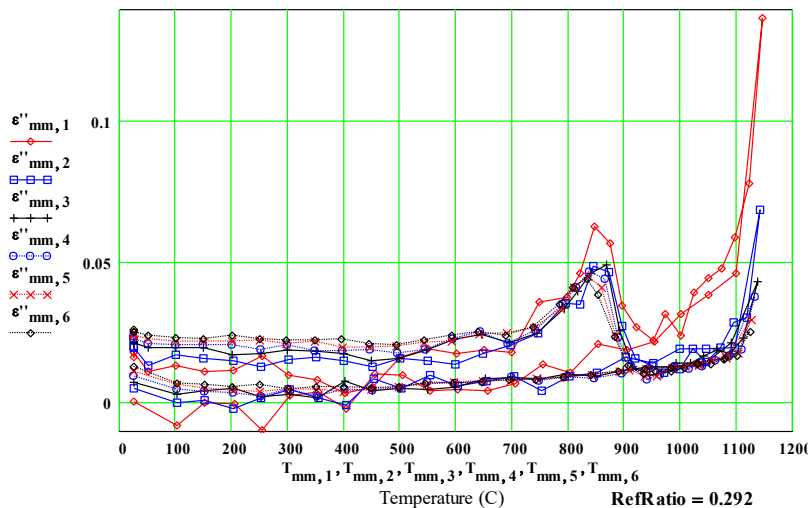
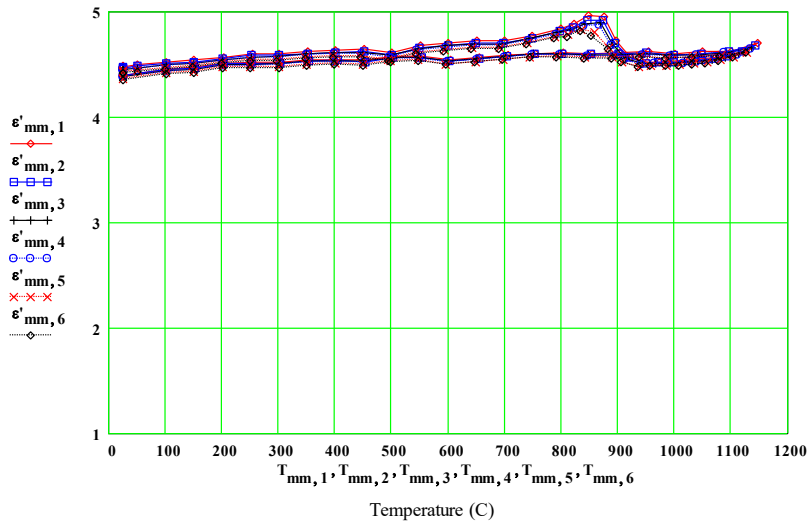
Initial density =  $\text{samdns}_{\text{NCal} + 1} = 1.9 \text{ gm/cc}$ ,

Final density(25C) =  $\text{dnsfinal} = 1.81 \text{ gm/cc}$



**APPENDIX 2 : First Run - to 1150 °C on 5M Simulant Glass**  
Glass Used in NUW-LHT-5M Lunar Simulant , from Washington Mills,  
Measurements of Complex Dielectric Constant of Pressed Pellets  
RT to 1150°C to RT, in upward - flowing (10 sccm) UHP Argon

Test = 2023090501                      MPN023100.mcd                      AnDat = 20230907  
 5M Glass for Simulant, from Matt Creedon, Washington Mills, RT to 1150C to RT, in flowing UHP argon  
 Initial density =  $\text{samdns}_{\text{NCal} + 1} = 2$  gm/cc,                      Final density(25C) =  $\text{dnsfinal} = 1.98$  gm/cc  
 Final\_over\_Initial\_mass = 1



Note the very rapid increase in  $\epsilon''$  values above 1100 °C. This is indicative of approaching the melting fluid conditions above  $T_g$ . The thermal activation energy is large – very approximately 400 Kjoule/mole ( $\sim 4.2$  eV) by fitting the points between 1100C and 1150 C. The feature at 850 C seen in the simulant runs is evident in this glass 5M run. It likely represents the re-crystallization of the glass ( crystalline material generally has lower microwave absorption than the glass of the same composition at a specific temperature), as suggested by the drop in  $\epsilon''$

values between 700C and 950C, and the fact that the final sample was slightly larger than the initial sample, although the same mass! The peak at 860C represents the maximum in the density of mobile/diffusing ions during the re-crystallization. The beginning of the increase of the number of mobile ions is at ~ 700C.

**Data for the complete run to 1300C and back to room temperature :**



# Appendix E. MPN Reports

Test = 2023092501                      MPN023109.mcd                      AnDat = 20230928  
 5M Glass from Matt Creedon, Washington Mills, 8 mm with well-modified Crucible RT - 1300C, in flowing argon  
 List of Measured Values of  $\epsilon'$  and  $\epsilon''$  and  $\tan\delta$  :

Initial density =  $\text{samdns}_{\text{Cal} + 1} = 2.036$  gm/cc                      Final density(25C) =  $\text{dnsfinal} = 2.338$  gm/cc  
 Lapsed  
 density index T(C) 397MHz 912MHz 1429MHz 1948MHz 2466MHz 2986MHz  
 Time  
 (hours)

| samdns | mm | T    | $\epsilon''_{\text{mm},1}$ | $\epsilon''_{\text{mm},2}$ | $\epsilon''_{\text{mm},3}$ | $\epsilon''_{\text{mm},4}$ | $\epsilon''_{\text{mm},5}$ | $\epsilon''_{\text{mm},6}$ | tlaps | sammas |
|--------|----|------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|-------|--------|
| 2.036  | 11 | 24   | 0.018                      | 0.021                      | 0.021                      | 0.022                      | 0.024                      | 0.026                      | 0     | 0.28   |
| 2.036  | 12 | 24   | 0.014                      | 0.021                      | 0.022                      | 0.022                      | 0.024                      | 0.026                      | 0.07  | 0.28   |
| 2.036  | 13 | 24   | 0.018                      | 0.02                       | 0.022                      | 0.023                      | 0.024                      | 0.025                      | 0.13  | 0.28   |
| 2.034  | 14 | 111  | 0.011                      | 0.02                       | 0.021                      | 0.021                      | 0.021                      | 0.025                      | 0.26  | 0.28   |
| 2.033  | 15 | 176  | 0.029                      | 0.018                      | 0.02                       | 0.021                      | 0.022                      | 0.024                      | 0.38  | 0.28   |
| 2.032  | 16 | 238  | 0.026                      | 0.021                      | 0.022                      | 0.019                      | 0.021                      | 0.024                      | 0.49  | 0.28   |
| 2.031  | 17 | 295  | 0.012                      | 0.012                      | 0.018                      | 0.018                      | 0.021                      | 0.024                      | 0.61  | 0.28   |
| 2.03   | 18 | 349  | 0.001                      | 0.019                      | 0.015                      | 0.019                      | 0.022                      | 0.023                      | 0.72  | 0.28   |
| 2.029  | 19 | 399  | 0.012                      | 0.015                      | 0.021                      | 0.021                      | 0.023                      | 0.024                      | 0.84  | 0.28   |
| 2.028  | 20 | 446  | 0.03                       | 0.016                      | 0.022                      | 0.023                      | 0.023                      | 0.026                      | 0.95  | 0.28   |
| 2.027  | 21 | 492  | 0.029                      | 0.022                      | 0.02                       | 0.02                       | 0.023                      | 0.026                      | 1.07  | 0.28   |
| 2.026  | 22 | 539  | 0.02                       | 0.016                      | 0.023                      | 0.024                      | 0.023                      | 0.027                      | 1.18  | 0.28   |
| 2.026  | 23 | 584  | 0.018                      | 0.025                      | 0.03                       | 0.026                      | 0.028                      | 0.028                      | 1.3   | 0.28   |
| 2.025  | 24 | 630  | 0.047                      | 0.025                      | 0.034                      | 0.028                      | 0.029                      | 0.034                      | 1.41  | 0.28   |
| 2.024  | 25 | 654  | 0.051                      | 0.033                      | 0.033                      | 0.034                      | 0.034                      | 0.035                      | 1.53  | 0.28   |
| 2.024  | 26 | 675  | 0.05                       | 0.029                      | 0.044                      | 0.037                      | 0.035                      | 0.037                      | 1.64  | 0.28   |
| 2.023  | 27 | 698  | 0.077                      | 0.046                      | 0.048                      | 0.04                       | 0.04                       | 0.041                      | 1.76  | 0.28   |
| 2.023  | 28 | 720  | 0.063                      | 0.043                      | 0.051                      | 0.045                      | 0.045                      | 0.046                      | 1.87  | 0.28   |
| 2.023  | 29 | 743  | 0.069                      | 0.057                      | 0.052                      | 0.048                      | 0.049                      | 0.049                      | 1.99  | 0.28   |
| 2.022  | 30 | 766  | 0.056                      | 0.052                      | 0.056                      | 0.05                       | 0.052                      | 0.055                      | 2.1   | 0.28   |
| 2.022  | 31 | 789  | 0.075                      | 0.047                      | 0.055                      | 0.054                      | 0.057                      | 0.058                      | 2.22  | 0.28   |
| 2.021  | 32 | 812  | 0.072                      | 0.051                      | 0.059                      | 0.056                      | 0.061                      | 0.064                      | 2.33  | 0.28   |
| 2.021  | 33 | 836  | 0.084                      | 0.065                      | 0.065                      | 0.063                      | 0.068                      | 0.07                       | 2.45  | 0.28   |
| 2.02   | 34 | 859  | 0.105                      | 0.075                      | 0.077                      | 0.071                      | 0.078                      | 0.079                      | 2.56  | 0.28   |
| 2.02   | 35 | 883  | 0.122                      | 0.082                      | 0.071                      | 0.066                      | 0.073                      | 0.073                      | 2.68  | 0.28   |
| 2.02   | 36 | 906  | 0.083                      | 0.069                      | 0.044                      | 0.041                      | 0.051                      | 0.049                      | 2.79  | 0.28   |
| 2.019  | 37 | 930  | 0.068                      | 0.042                      | 0.034                      | 0.027                      | 0.037                      | 0.032                      | 2.91  | 0.28   |
| 2.019  | 38 | 955  | 0.062                      | 0.036                      | 0.025                      | 0.02                       | 0.03                       | 0.025                      | 3.02  | 0.28   |
| 2.018  | 39 | 979  | 0.062                      | 0.033                      | 0.024                      | 0.021                      | 0.025                      | 0.025                      | 3.14  | 0.28   |
| 2.018  | 40 | 1003 | 0.044                      | 0.033                      | 0.024                      | 0.025                      | 0.024                      | 0.022                      | 3.25  | 0.28   |
| 2.017  | 41 | 1027 | 0.036                      | 0.025                      | 0.02                       | 0.022                      | 0.022                      | 0.021                      | 3.37  | 0.28   |
| 2.017  | 42 | 1051 | 0.028                      | 0.013                      | 0.019                      | 0.015                      | 0.02                       | 0.02                       | 3.49  | 0.28   |
| 2.017  | 43 | 1075 | 0.013                      | 0.013                      | 0.017                      | 0.013                      | 0.019                      | 0.021                      | 3.6   | 0.28   |
| 2.016  | 44 | 1100 | 0.012                      | 0.01                       | 0.012                      | 0.012                      | 0.02                       | 0.021                      | 3.72  | 0.28   |
| 2.015  | 45 | 1124 | 0.029                      | 0.029                      | 0.011                      | 0.011                      | 0.021                      | 0.022                      | 3.83  | 0.28   |
| 2.023  | 46 | 1148 | 0.115                      | 0.069                      | 0.039                      | 0.036                      | 0.036                      | 0.039                      | 3.95  | 0.28   |
| 2.039  | 47 | 1172 | 0.216                      | 0.138                      | 0.085                      | 0.075                      | 0.066                      | 0.065                      | 4.06  | 0.28   |
| 2.061  | 48 | 1196 | 0.483                      | 0.302                      | 0.197                      | 0.166                      | 0.138                      | 0.131                      | 4.18  | 0.28   |
| 2.088  | 49 | 1220 | 1.254                      | 0.738                      | 0.506                      | 0.376                      | 0.278                      | 0.258                      | 4.29  | 0.28   |
| 2.119  | 50 | 1245 | 2.422                      | 1.397                      | 0.965                      | 0.714                      | 0.508                      | 0.407                      | 4.41  | 0.28   |
| 2.154  | 51 | 1269 | 4.681                      | 2.706                      | 1.864                      | 1.364                      | 0.956                      | 0.749                      | 4.52  | 0.28   |
| 2.193  | 52 | 1293 | 10.134                     | 5.586                      | 3.535                      | 2.709                      | 2.046                      | 1.719                      | 4.64  | 0.28   |
| 2.232  | 53 | 1245 | 3.581                      | 1.941                      | 1.269                      | 1.011                      | 0.777                      | 0.671                      | 4.75  | 0.28   |
| 2.272  | 54 | 1196 | 1.469                      | 0.9                        | 0.617                      | 0.528                      | 0.445                      | 0.404                      | 4.87  | 0.28   |
| 2.312  | 55 | 1148 | 0.686                      | 0.454                      | 0.328                      | 0.281                      | 0.245                      | 0.233                      | 4.99  | 0.28   |
| 2.315  | 56 | 1099 | 0.323                      | 0.235                      | 0.19                       | 0.158                      | 0.152                      | 0.143                      | 5.1   | 0.28   |
| 2.316  | 57 | 1051 | 0.214                      | 0.14                       | 0.111                      | 0.101                      | 0.094                      | 0.091                      | 5.22  | 0.28   |
| 2.317  | 58 | 1003 | 0.163                      | 0.108                      | 0.078                      | 0.076                      | 0.072                      | 0.067                      | 5.33  | 0.28   |
| 2.318  | 59 | 954  | 0.137                      | 0.084                      | 0.062                      | 0.051                      | 0.059                      | 0.054                      | 5.45  | 0.28   |
| 2.319  | 60 | 906  | 0.124                      | 0.066                      | 0.048                      | 0.038                      | 0.051                      | 0.047                      | 5.57  | 0.28   |

m<sub>q</sub> = 61, 62...nd - Nempties

| samdns | mm <sub>q</sub> | T   | $\epsilon''_{\text{mq},1}$ | $\epsilon''_{\text{mq},2}$ | $\epsilon''_{\text{mq},3}$ | $\epsilon''_{\text{mq},4}$ | $\epsilon''_{\text{mq},5}$ | $\epsilon''_{\text{mq},6}$ | tlaps <sub>mq</sub> | sammas <sub>mq</sub> |
|--------|-----------------|-----|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------|----------------------|
| 2.32   | 61              | 857 | 0.058                      | 0.057                      | 0.042                      | 0.035                      | 0.043                      | 0.043                      | 5.7                 | 0.28                 |
| 2.321  | 62              | 809 | 0.091                      | 0.048                      | 0.039                      | 0.035                      | 0.038                      | 0.041                      | 5.83                | 0.28                 |
| 2.322  | 63              | 760 | 0.074                      | 0.029                      | 0.036                      | 0.03                       | 0.032                      | 0.034                      | 5.96                | 0.28                 |
| 2.323  | 64              | 712 | 0.063                      | 0.021                      | 0.035                      | 0.029                      | 0.027                      | 0.028                      | 6.11                | 0.28                 |
| 2.324  | 65              | 663 | 0.039                      | 0.024                      | 0.022                      | 0.023                      | 0.022                      | 0.024                      | 6.26                | 0.28                 |
| 2.325  | 66              | 615 | 0.019                      | 0.013                      | 0.019                      | 0.017                      | 0.018                      | 0.02                       | 6.42                | 0.28                 |
| 2.326  | 67              | 568 | 0.016                      | 0.01                       | 0.014                      | 0.015                      | 0.015                      | 0.018                      | 6.59                | 0.28                 |
| 2.327  | 68              | 521 | 0.007                      | 0.011                      | 0.005                      | 0.009                      | 0.013                      | 0.017                      | 6.78                | 0.28                 |
| 2.328  | 69              | 476 | 0.004                      | 0.006                      | 0.01                       | 0.011                      | 0.01                       | 0.013                      | 6.98                | 0.28                 |
| 2.329  | 70              | 428 | 0.02                       | 0.013                      | 0.009                      | 0.008                      | 0.009                      | 0.012                      | 7.2                 | 0.28                 |
| 2.33   | 71              | 385 | 0.031                      | 0.009                      | 0.011                      | 0.008                      | 0.01                       | 0.011                      | 7.44                | 0.28                 |
| 2.331  | 72              | 340 | 0.011                      | 0.008                      | 0.011                      | 0.007                      | 0.01                       | 0.01                       | 7.71                | 0.28                 |
| 2.332  | 73              | 293 | 0.003                      | -0.001                     | 0.01                       | 0.006                      | 0.006                      | 0.01                       | 8.01                | 0.28                 |
| 2.333  | 74              | 245 | 0.004                      | 0.006                      | 0.007                      | 0.005                      | 0.007                      | 0.009                      | 8.37                | 0.28                 |
| 2.334  | 75              | 193 | -0.006                     | -0.003                     | 0.003                      | 0.005                      | 0.006                      | 0.012                      | 8.82                | 0.28                 |
| 2.335  | 76              | 135 | -0.008                     | -0.006                     | 0.003                      | 0.008                      | 0.008                      | 0.012                      | 9.51                | 0.28                 |
| 2.338  | 77              | 24  | 0.003                      | 0.014                      | 0.014                      | 0.015                      | 0.018                      | 0.022                      | 12.38               | 0.28                 |
| 2.338  | 78              | 24  | 0.011                      | 0.014                      | 0.014                      | 0.015                      | 0.018                      | 0.022                      | 12.45               | 0.28                 |