Abstract

We present the results of the first Charged-Particle Transport Coefficient Code Comparison Workshop, which was held in Albuquerque, NM October 4-6, 2016. In this first workshop, scientists from eight institutions and four countries gathered to compare calculations of transport coefficients including thermal and electrical conduction, electron-ion coupling, inter-ion diffusion, ion viscosity, and charged particle stopping powers. Here, we give general background on Coulomb coupling and computational expense, review where some transport coefficients appear in hydrodynamic equations, and present the submitted data. Large variations are found when either the relevant Coulomb coupling parameter is large or computational expense causes difficulties. Understanding the general accuracy and uncertainty associated with such transport coefficients is important for quantifying errors in hydrodynamic simulations of inertial confinement fusion and high-energy density experiments.

Keywords:
charged particle transport, code comparison, conductivity, stopping power, diffusion, viscosity

1. Introduction

Charged-particle transport is a key part of high-energy-density plasma science. Transport coefficients feed into both radiation-hydrodynamic simulations and diagnostic data interpretation, but neither uncertainties in these coefficients nor the features of generally reliable transport models are well established. They are particularly important when inter-particle correlations of the plasma are weak enough that there are important deviations from the ideal fluid (Euler) limit, but strong enough so that the simplest kinetic treatments (e.g. the Vlasov equation) are no longer valid. Reliance on theoretical predictions is driven by the challenges of experimentally isolating various transport processes, together with the paucity of experimental data of any kind at well-characterized extreme conditions. These coefficients have particular impact on the field of inertial confinement fusion, feeding into the development of instabilities and the overall energy balance of burning fusion plasma. Crucial processes include thermal and electrical conduction, electron-ion coupling, inter-ion diffusion, ion viscosity, and charged particle stopping.

The first charged-particle transport coefficient workshop (CPTCW-16) was established to examine theoretical uncertainties in our predictive ability. Workshops of this sort have become a tradition in dense plasma physics. Recently, there has been the 2016 kinetics workshop [1] and 2017 equation-of-state (EOS) workshop [2], which have built on the successes of the long-running non-local thermodynamic equilibrium (non-LTE) opacity code comparison workshops [3, 4, 5, 6, 7, 8, 9, 10, 11] and similar WorkOp LTE opacity workshop [12, 13, 14]. A set of test cases spanning a range of ionization, coupling, and degeneracy regimes was selected with the aim of establishing the present state of agreement among various theoretical approaches. In addition to this goal, the workshop aimed to quantify uncertainties in calculated transport coefficients, address the strengths and limitations of different approaches, provide

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a forum for discussions, and identify research priorities for inertial confinement fusion (ICF) and high energy-density (HED) science.

2. Test Cases

Three plasma compositions were chosen across wide temperature and density variations, including pure hydrogen, pure carbon, and an equimolar carbon-hydrogen mixture. These are summarized in Table 1. Plasmas across these conditions are relevant to fuel and ablator materials important to ICF. In particular, the low-density, high-temperature hydrogen case approaches the conditions of recent Omega experiments measuring stopping powers [15, 16] and the low-density, moderate-temperature carbon case is at conditions relevant to recent Omega experiments on heated beryllium [17, 18], with additional relevance to thermal conductivity experiments in plastic and beryllium [19, 20].

More than thirty researchers attended the workshop, representing eight institutions; participation is summarized in Table 1. Plasmas across these conditions are relevant to fuel and ablator materials important to ICF. In particular, the low-density, high-temperature hydrogen case approaches the conditions of recent Omega experiments measuring stopping powers [15, 16] and the low-density, moderate-temperature carbon case is at conditions relevant to recent Omega experiments on heated beryllium [17, 18], with additional relevance to thermal conductivity experiments in plastic and beryllium [19, 20].

While several approaches presented data for all cases, most contributions only provided transport results (diffusion, viscosity) or electronic transport (thermoelectric conductivities) or stopping powers. The results reported here represent output from the contributed codes at the time of the workshop; any subsequently published updates to those codes are noted in the table of contributors but not represented in the present paper.

3. Dimensionless Parameters and Test Case Coverage in Plasma Parameter Space

HED plasmas span many orders of magnitude in density and temperature, including regimes for which different approximations are valid. In this section we will discuss dimensionless parameters that capture this diversity and show where our test cases fall.

We can characterize the importance of interactions with the Coulomb coupling parameter

\[ \Gamma_{jk} = \frac{q_j q_k}{a_{jk} T_{j,k,\text{eff}}} \]

which gives the relative magnitude of the potential energy of neighboring particles to their kinetic energy. Here, \( j \) and \( k \) are indices for particle types. For ions, \( q_i = Z_i e \), while for electrons, \( q_e = e \), where \( e \) is the magnitude of the electron charge and \( Z_i \) is the mean ionization the ion, which for convenience we set to More’s Thomas-Fermi fit [57] (such a choice is not unique [58]). The typical separation between neighbors is approximated by

\[ a_{jk} = \left[ \frac{6}{4\pi (n_j + n_k)} \right]^{1/3} \]

where for ions, \( n_i = \rho_i/m_i \) and for electrons, \( n_e = \sum_i Z_i \rho_i/m_i \) with the sum over the ions, \( Z_i \) is the bare ion charge, \( \rho_i \) is the mass density of ion \( i \) and \( m_i \) is its mass. A non-unique effective temperature, \( T_{j,k,\text{eff}} \), is a measure of the relative kinetic energy of collisions between particles of types \( j \) and \( k \). We set

\[ T_{j,k,\text{eff}} = \sqrt{T^2 + \frac{2}{25} (T_{j,F}^2 + T_{k,F}^2)} \]

where

\[ k_B T_{j,F} = \frac{\hbar^2}{2m_j (3\pi^2 n_j)^{2/3}} \]

\( k_B \) is Boltzmann’s constant, \( m_j \) is the mass of particles of type \( j \), and \( n_j \) is their number density. This effective temperature is a simple interpolation between the zero and infinite temperature limits.

These coupling parameters fall into three categories: ion-ion, electron-ion, and electron-electron, depending on the particle types, \( j \) and \( k \). Different transport coefficients are more sensitive to some of these Coulomb coupling parameters than others and so become harder to calculate in different regimes. As ion viscosity and ion diffusion are mediated mainly by ion-ion collisions, the ion-ion Coulomb coupling parameter is most important. Of course, electron screening also plays a role. The main hindrance to electrical conductivity is electron-ion scattering, and so the electron-ion Coulomb coupling parameter matters for this property. Stopping power of fast ions is dominated by projectile-electron collisions, which are similar to the target ion-electron collisions except for having a different energy scale: the relative kinetic energy of the ion and the electrons \( K_{rel} = \mu (v_{thic}^2) / 2 \), where \( \mu \) is the reduced mass of the projectile and target particles and \( (v_{thic}) \) is the ensemble mean of the square of their relative velocities), suggesting one replace \( T_{j,k,\text{eff}} \) with \( K_{rel} \) in the coupling parameter expression. So the ion-electron coupling parameter shown in Figs. 1 and 2 should be considered upper bounds for stopping power and mostly relevant to low energy (at and below the Bragg Peak) ions. Thermal conductivity is sensitive to both the electron-electron and electron-ion parameters.

For small \( \Gamma \)’s (\( \ll 1 \)), it is valid to introduce screening and collision physics through cutoffs in collision integrals, which leads to a Coulomb logarithm. As \( \Gamma_{jk} \) approaches unity, such treatments break down and one should use more sophisticated methods, the limits of which are explored in this article. The relevant values of \( \Gamma_{jk} \) for our study are shown in Figs. 1 and 2 for pure hydrogen and carbon plasmas, respectively. We do not show the CH mixture case, but it is qualitatively similar to the other two. We see that all three (ion-ion, ion-electron, and...
Table 2: Summary of contributors and models.

| Contributors          | Institution       | Description                                                                 |
|-----------------------|-------------------|-----------------------------------------------------------------------------|
| Baalrud               | U Iowa            | Effective Potential Theory (EPT) with Average Atom potentials [21, 22]       |
| Baczewski, Jensen,    | SNL               | Ehrenfest-TDDFT (VASP-TDDFT) (stopping powers) [23, 24]                     |
| Shulenburger          |                   |                                                                             |
| Clérouin, Arnault     | CEA               | Global One-Component Plasma (PIJ) [25], orbital-free Thomas Fermi [26, 27] |
| Copeland              | LLNL              |                                                                             |
| Copeland, Stanton,    | LLNL, SJSU        | Effective Yukawa T-Matrix [31]                                              |
| Murillo, Stanek       | MSU               |                                                                             |
| Daligault             | LANL              | classical molecular dynamics (MD) with Average Atom potentials              |
| Desjarlais            | SNL               | SNL-modified quantum MD with Kubo-Greenwood (VASP-SNL) [32]                 |
| Dharma-wardana        | NRC Canada        | Neutral Pseudo-Atom [33, 34, 35]                                            |
| Faussurier, Blancard  | CEA               | Two-component electron-ion Average-Atom (SCAALP) [36, 37]                    |
| Grabowski, Starrett,  | LLNL, LANL        | Pseudo-Atom MD density with strong scattering corrections [17]              |
| Saumon                |                   |                                                                             |
| Hansen                | SNL               | Average Atom and Neutral Pseudo-Atom                                        |
| Hakhimiali, Rudd      | LLNL              | Hybrid Kinetic Molecular Dynamics (KMD) [38]                                |
| Hayes, Singleton,     | LANL              | degenerate Brown-Preston-Singleton (BPS) (Stopping) [39]                    |
| Jungman               |                   |                                                                             |
| Hou                   | NUDT              | average atom hypermetted chain [40]                                         |
| Hu                    | LLE               | Spitzer-Lee-More and quantum MD with Kubo-Greenwood (VASP) [41, 42, 43, 44] |
| Haxhimali, Rudd       | LLNL              | Path Integral Molecular Dynamics (PIMD),                                    |
| Hayes, Singleton,     | LANL              | Quantum MD (Quantum Espresso) [45, 46]                                      |
| Jungman               |                   |                                                                             |
| Meyer, Collins        | LANL              | electron Force Field (eFF) [47]                                             |
| Marciante             | NUDT              | Thomas-Fermi-Yukawa MD                                                      |
| Meyer, Collins        | LANL              | quantum MD with Kubo-Greenwood (VASP) [41, 42, 43, 44]                      |
| Sjostrom              | LANL              | Quantum MD (Quantum Espresso),                                              |
| Sjostrom              |                   | Kohn-Sham MD with nonlocal corrections [48], Thomas-Fermi MD                |
| Starrett, Saumon      | LANL              | Pseudo-Atom MD [49, 50, 51]; updated [52]                                   |
| Ticknor, Čertík, White| LANL              | Orbital-free molecular MD with Thomas-Fermi-Dirac functional [53, 54, 55, 56]|

The maximum impact parameter is given by a representative screening length. Since electrons are usually much faster than the ions, they tend to only be screened by themselves, while ions are screened by both other ions and electrons. This distinction does not apply to static properties involving a long-time average ($\omega = 0$). However, for use in dynamic contexts shorter than ion-motion time scales, we approximate the maximum impact parameter by

$$b_{j,\text{max}} = \left\{ \begin{array}{ll} \frac{b_j^3}{b_j^3} & \text{if } j = \text{electron} \\
\left( \frac{1}{d_{\text{F}}^2} + \frac{1}{D_{\text{H},j}} \right)^{1/2} & \text{if } j = \text{ion} \end{array} \right.$$

The maximum impact parameter is given by a representative screening length. Since electrons are usually much faster than the ions, they tend to only be screened by themselves, while ions are screened by both other ions and electrons. This distinction does not apply to static properties involving a long-time average ($\omega = 0$). However, for use in dynamic contexts shorter than ion-motion time scales, we approximate the maximum impact parameter by

$$C_j = \frac{b_{j,\text{max}}^3}{b_{j,\text{min}}^3}$$

$$b_{j,\text{max}} = \left\{ \begin{array}{ll} \frac{b_j^3}{b_j^3} & \text{if } j = \text{electron} \\
\left( \frac{1}{d_{\text{F}}^2} + \frac{1}{D_{\text{H},j}} \right)^{1/2} & \text{if } j = \text{ion} \end{array} \right.$$
where
\[ \lambda_{T}^{2} = 4 \pi e^{2} \frac{\partial n_{e}}{\partial \mu} \]  
(7)
is the Thomas-Fermi screening length and
\[ \lambda_{DH,j}^{2} = 4 \pi q_{j}^{2} n_{j} \frac{\mu_{j}}{T}. \]  
(8)
is the Debye-Hückel screening length for species \( j \). The minimum impact parameter is given by the maximum of the thermal de Broglie wavelength and the classical distance of closest approach:
\[ b_{j,\text{min}} = \max \left[ \sqrt{\frac{2 \pi \hbar^{2}}{m_{j} T_{\text{eff}}}}, \frac{q_{j}^{2}}{T_{\text{eff}}} \right]. \]  
(9)

These types of length scales are usually the starting point for simple Coulomb logarithms (e.g. Landau-Spitzer [61, 62, 63] or Gericke-Murillo-Schlanges [64]). We plot the numerical complexity, \( C_{j} \), for electrons and ions in pure hydrogen and carbon plasmas in Figs. 3 and 4, respectively. This number gets very large in the high-temperature low-density limit for both electrons and ions. Of course, many things simplify at high temperatures; so simpler models become more valid and many details are washed out. This measure should only apply if one tries to do a brute force calculation, resolving all states and length scales.

Since the \( \Gamma \)'s and \( C \)'s are large in different limits, it is very difficult to have a model which can span the entire range of parameter space and hence, we almost never have a “best” model to compare against for every condition, which would require heroic efforts of theory and computation. Proper interpretation of the results of this code comparison requires keeping these complexity measures in mind.

4. Theoretical Origins of Transport Coefficients

Transport processes in hydrodynamic equations are typically described using linearized flux models, in which the leading order coefficient associated with each process is known as a “transport coefficient”. While the underlying symmetries of a given system will determine the general form of hydrodynamic equations, the actual transport coefficients (along with any equation of state information) must be determined by the micro-physics at the particle scale. For this reason, there are several approaches to calculating transport coefficients, each of which requires connecting micro-physics processes to a particular hydrodynamic model.

We illustrate the most popular strategies of calculating transport coefficients in Figure (5), where we have categorized the methods into two main branches. The first branch, as discussed in Section (4.1), begins with a hydrodynamic model determined by symmetries and conservation laws, and micro-physics calculations are used to determine the transport coefficients. Meanwhile, the second branch, as discussed in Section (4.4), uses a kinetic equation to derive a hydrodynamic model, and connects transport coefficients to micro-physics quantities in the process.

We emphasize that this discussion is not intended to be a comprehensive review. Rather, this article aims to summarize...
the approaches taken by self-selected contributors to the workshop. For the interested reader, we here provide some important general references on the following relevant topics: fluid dynamics [65, 66, 67], kinetic theory [68, 69], dense plasma theory [70, 71, 72], density functional theory [73, 74], quantum Monte Carlo [75], response functions [76], molecular dynamics [77], average atom models [58], atoms in plasma environments [78, 79], wave packet molecular dynamics [80, 81], ion transport [31], diffusion [82, 83, 84, 85], viscosity [86, 87, 88], electrical and thermal conductivity [89, 90, 91, 92, 93, 94], and stopping power [95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105].

4.1. Origin of Transport Coefficients from Conservation Laws

The most fundamental approach to calculating transport coefficients is to compare directly with the equations of hydrodynamics that have been determined by the symmetries and conservation laws of the system of interest. In its most generic form, the conservation of particle number, linear momentum and energy for a continuum field with no external sources can be expressed respectively by the equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (nv) = 0,$$

$$mn \left( \frac{\partial u}{\partial t} + u \cdot \nabla v \right) - \nabla \cdot \sigma = 0,$$

$$n \left( \frac{\partial e}{\partial t} + u \cdot \nabla e \right) - \sigma : (\nabla u) + \nabla \cdot q = 0.$$

Here, $m$ is the particle mass, $n(\mathbf{r}, t)$ is the number density, $\mathbf{u}(\mathbf{r}, t)$ is the velocity field, $e(\mathbf{r}, t)$ is the energy density, $\sigma(\mathbf{r}, t)$ is the Cauchy stress tensor, and $q(\mathbf{r}, t)$ is the heat flux. Furthermore, angular momentum is conserved by enforcing the symmetry $\sigma = \sigma^T$. Relevant approximations and closure relations are required to reduce this system of equations to the more familiar hydrodynamic models (Euler, Navier-Stokes, etc.).

For example, if we consider a binary system, we can introduce the number densities $n_{1,2}(\mathbf{r}, t)$ and velocity fields $\mathbf{u}_{1,2}(\mathbf{r}, t)$
for the individual species, each of which will satisfy a continuity equation associated with conservation of particle number

\[ \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{u}_i) = 0, \quad i = \{1, 2\}. \quad (13) \]

In hydrodynamic models, diffusion is usually measured relative to the bulk motion of the fluid. For a binary fluid we can define the bulk center of mass velocity \( \mathbf{u} = x_1 \mathbf{u}_1 + x_2 \mathbf{u}_2 \), where \( x_i = m_i n_i / \rho \) and \( \rho = (m_1 n_1 + m_2 n_2) \). The continuity equations are transformed into a frame moving at bulk velocity \( \mathbf{u} \) to obtain

\[ \rho \frac{\partial x_i}{\partial t} + \rho \mathbf{u} \cdot \nabla x_i = -\nabla \cdot \mathbf{j}, \quad (14) \]

where \( \mathbf{j} \) is the relative (to \( \mathbf{u} \)) mass flux density of the \( i \)th species. For small gradients in the concentration field, the temperature field \( T(\mathbf{r}, t) \),3 and the total pressure pressure field \( P(\mathbf{r}, t) \), the Taylor expansion of the flux density can be truncated to linear order as

\[ \mathbf{j}_i \approx -\rho D \left( \nabla x_i + \frac{k_T}{T} \nabla T + \frac{k_P}{P} \nabla P \right), \quad (15) \]

where we have defined \( D \) as the diffusion coefficient, \( k_T D \) as the thermal diffusion coefficient, and \( k_P D \) as the barodiffusion coefficient [66]. Of course, gradients in these fields will appear in the remaining hydrodynamic equations as well, in which each term will have its own coefficient that must be calculated from the micro-physics. We have illustrated this approach in the left branch of the diagram in Figure (5).

One such method along this branch is non-equilibrium molecular dynamics (NEMD), where molecular dynamics simulations are used to measure the response of a system to gradients in the appropriate state variables (density, temperature, etc.). This is possible because of the simple linear relationship in (15). NEMD calculations can be particularly challenging due to not only the computational complexity of the simulations, but isolating a gradient in a particular observable without inducing gradients in other quantities is often impossible as well; that is, one wishes to remain deeply in the linear regime to avoid generating the other gradients, and this creates signal-to-noise issues.

4.2. Green-Kubo Relations

For linear transport coefficients one can also employ equilibrium MD. In this approach, one derives transport coefficients from equilibrium time correlation functions to generate the celebrated Green-Kubo (GK) relations for the transport coefficients. In this subsection we will sketch how the GK relationships arise. We illustrate this approach using inter-diffusion again as an example, which is the key process for atomic-scale mixing.

If we assume gradients in the temperature and pressure fields to be negligible, the flux density (15) of the \( i \)th species reduces to the well-known form of Fick’s Law defined in terms of the relative density, \( \mathbf{j}_i = -\rho D \nabla x_i \). Upon linearization, the continuity equation in Equation (14) can thus be written as

\[ \frac{\partial x_i}{\partial t} + \mathbf{u} \cdot \nabla x_i = D \nabla^2 x_i. \quad (16) \]

Note that the Fick’s law for interdiffusion is written in terms of the total fluid mass density \( \rho \) and the fractional density \( x_i \) of species \( i \). The resulting equation is then solved as an initial value problem in Laplace-Fourier space, which allows the equation to be written in terms of a time correlation function. So far, there is no connection to the microscopic dynamics, as all manipulations are consistent with macroscopic/hydrodynamic definitions. Next, the ensemble average of the resulting time-correlation function is written in terms of its macroscopic definition, connecting the transport coefficient \( D \) to the phase-space trajectory of the microscopic many-body system, yielding the GK formula for inter-diffusion [106]

\[ D = \frac{x_1 x_2}{S_{cc}(0)} \int_0^\infty dt V_D(t). \quad (17) \]

Here, the autocorrelation function is defined as

\[ V_D(t) \equiv \frac{1}{3N_x x_2} \langle v_d(t) \cdot v_d(0) \rangle, \quad (18) \]

\[ v_d(t) \equiv \sum_{i=1}^{N_1} \mathbf{v}_i(t) - x_1 \sum_{j=1}^{N_2} \mathbf{v}_j(t), \quad (19) \]

where the first sum is over species 1, the second sum is over species 2, and \( \langle \cdot \rangle \) denotes a dot product between the two vectors. Furthermore, we have introduced the concentration structure factor, which is defined in terms of the partial static structure factors as

\[ S_{cc}(k) = x_1 x_2 \left[ x_2 S_{11}(k) + x_1 S_{22}(k) - 2 \sqrt{x_1 x_2} S_{12}(k) \right]. \quad (20) \]

Importantly, note how the resulting GK relation is intimately connected with specific choices and definitions at the hydrodynamic level. That is, each correlation function corresponds to a specific type of current with a precise definition, which should match what is meant in the hydrodynamic equations. In a similar fashion, one can employ the momentum equation of the Navier-Stokes equation to find a correlation function associated with viscosity that can be connected to microscopic dynamics; this strategy can be used for all of the other coefficients, and is readily adapted to quantum systems [107, 108].

While the GK relations present an elegant connection between transport processes and the underlying statistical mechanics of the system, they still leave the correlation functions themselves to be determined. However, for the past few decades, there are a variety of computational methods, such as equilibrium molecular dynamics simulations, that can inform these correlation functions through detailed calculation of the trajectories.

4.3. Kubo-Greenwood and Ziman approaches

The usual GK formulation can be connected with the Boltzmann equation (under certain assumptions, see Ref. [109])
and this expresses the static conductivity in terms of scattering cross sections and one-body distributions instead of the current-current correlation function. In practice the evaluation of the current-current correlation function can also be simplified by using the Fermi-Golden rule and the assumption of a momentum relaxation time ($\tau$) to calculate a conductivity. The frequency-dependent Kubo-Greenwood approaches uses Kohn-Sham eigenstates as the initial and final states of the scattering process to obtain a dynamic conductivity $\sigma(\omega)$, but the extraction of a static conductivity involves obtaining a $\tau$ by fitting to a Drude model, with the following formula for the static conductivity:

$$\sigma = \frac{ne^2 \tau}{m_e}$$

(21)

in a standard notation. That is, in spite of the complexity of the theories, they all finally depend on the above equation with all its assumptions to extract the static conductivity.

Equation 21 is also used in the Ziman formula. However, the Ziman formula does NOT use the static current-current correlation function, but relies on evaluating the static force-force correlation function. It gives the inverse of the conductivity (i.e., resistivity). In most applications, the result is equivalent to the use of a Fermi golden rule with the initial and final states being plane waves, while the scattering potential is a linearly screened weak pseudopotential. The evaluation of the inverse of the conductivity $R = 1/\sigma$ rather than $\sigma$ is claimed to sum a larger class of scattering graphs, and the Ziman formula had been the preferred method for computations in liquid metals (e.g., see Ref. [110]). In fact Pozzo et al’s computationally very heavy tout de force evaluation of the static conductivity of liquid sodium using the Kubo-Greenwood formula, can be compared with easy calculations from the Ziman formula [111].

The Ziman formula is the favorite route in models based on the neutral-pseudo-atom (NPA) model [112], or various types of average atom (AA) models. The NPA provides a free-electron pile up $\Delta n(r)$ around the nucleus based on a Kohn-Sham calculation, and this is used to construct an electron-ion pseudopotential $U_n$ and an ion-ion pair potential $V_{ii}$. The latter is used in the hypernetted chain equation (with bridge corrections where needed) to generate an ion-ion structure factor $S_{ii}(k)$. The structure factor and the pseudopotential $U_{ii}(k)$ are used in the Ziman formula. This ensures that the Kohn-Sham calculation, the pseudopotential, pair-potential and the structure factor are, in principle, self-consistent with each other.

4.4. Kinetic model based approaches

As an alternative to calculating transport coefficients directly from equilibrium or non-equilibrium many-body simulations, kinetic equations (e.g., Boltzmann, Landau/Fokker-Planck, BGK) can be used to generate a hydrodynamic model through a hierarchy of hydrodynamic moments. The hydrodynamic model will be limited by the often restrictive approximations of the governing kinetic equation, this approach has the advantage of analytic simplicity over the methods listed in Section (4.1), which usually require a numerical many-body calculation. We have illustrated this alternative approach in the right branch of the diagram in Figure (5).

We now demonstrate this approach using a very simple model. Suppose our kinetic equation has the BGK form [68]

$$\frac{\partial f}{\partial t} + \nabla \cdot \mathbf{f} = \frac{f_0 - f}{\tau},$$

where $f = f(r, \mathbf{v}, t)$ is the one-body distribution function, and $f_0 = f_0(n, \mathbf{u}, T)$ is an equilibrium distribution function (e.g., a drifting Maxwellian) in terms of the density, mean velocity and temperature that has the same lowest-order moments as $f(r, \mathbf{v}, t)$, and $\tau$ is a collision time. The lowest-order moment yields the continuity equation for the density $n(r, t)$, whereas the first-order moment yields the momentum equation for the fluid velocity $\mathbf{u}(r, t)$

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{v}) = 0,$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (n \mathbf{u}) + \nabla \cdot \langle \mathbf{cc} \rangle = 0.$$

In the second line the mean velocity has been separated to isolate the central moment in terms of the relative velocity $\mathbf{c} = \mathbf{v} - \mathbf{u}$. This equation is not closed as a result of the term $\langle \mathbf{cc} \rangle = \int d^3 v f \mathbf{c} \mathbf{c}$. If the collision time is very small, which corresponds to a very short mean-free path, the kinetic equation yields the approximate solution $f \approx f_0$; using $f_0$ in $\langle \mathbf{cc} \rangle$ yields the usual pressure term in terms of the temperature, which leads to the Euler form of hydrodynamics. For weaker collisions, an improved solution of the kinetic equation is needed, of which the lowest-order solution is

$$f \approx f_0 - \tau (\mathbf{v} \cdot \nabla f_0).$$

This is a simple form of the Chapman-Enskog (CE) expansion [65].

The second term, when used to evaluate $\langle \mathbf{cc} \rangle$, yields transport terms that are proportional to the collision time $\tau$. Note that the transport terms will contain terms proportional to $\nabla n \cdot \mathbf{u}$ and $\nabla T$ because of the dependencies in $f_0$. Moreover, note that we can identify the various transport processes by inspection and the transport coefficient naturally arises as the coefficient of those terms. In this case, all of the transport coefficients would self-consistently be connected through $\tau$; other kinetic equations, such as Landau/Fokker-Planck or Boltzmann, would have similar properties.

4.5. Open Questions

While the results presented below pertain to the linear transport regime, we wish to mention some extensions worth future study. As we have seen, linearization is used at nearly every step, either in writing the fluxes, or, equivalently, in keeping the lowest order terms in the CE expansion and in obtaining the GK relations. Non-linear contributions yield both higher-order terms in the gradients, but also generate cross terms. The cross terms couple the various transport processes to create new forms of transport; for example, the Biermann battery [113] results from a $\nabla n \times \nabla T$ cross term. Moreover, it is possible in
some cases for the non-linear terms to create a situation where the steady state flux relationships of the form $j \sim -C \nabla U$ no longer hold. In addition, as we will see below, most of the transport coefficients have their largest values, and therefore are more important to the hydrodynamic evolution, at higher temperatures (weaker coupling). At high enough temperature, the mean-free path of the particles will exceed the gradient scale length (e.g., the scale of the density gradient in diffusion); this is the non-local transport regime [114, 115] for which transport coefficients cease to have their usual utility; non-locality in transport is particularly important in thermal conduction [116].

We have also limited ourselves to the canonical ensemble of fixed volume with one temperature for all species. However, the advent of fast lasers and the ability to create two-temperature plasmas that can be probed using femto-second pulses has led to the possibility of studying dynamic conductivities dependent on two temperatures, that is with ion and electron temperatures such that $T_i \neq T_e$. Furthermore, laser techniques allow the study of isochoric conductivities, whereas most techniques used up to the 1980s (e.g., for liquid metals) were for isobaric conductivities. This distinction has not been well understood by the community, and it is not unusual to see papers where isochoric conductivities are compared with isobaric conductivities [117].

5. Models

Many choices go into each model. Their biggest difference is whether the electrons are treated dynamically or statically. A fully dynamic treatment allows an explicit calculation of time-dependent electron-ion and electron-electron correlations, which can be used in GK formulas [118, 119] or the quantity of interest (e.g. the energy of the projectile in stopping power) can be directly tracked. Example time-dependent methods which were contributed to our workshop are Time-Dependent Density Functional Theory (TDDFT) [23, 120] and electron Force Field (eFF) [121, 122]. Alternatively, a great simplification of electronic dynamics can be made by modeling their effect with the Langevin equation [123].

All the other models rely on the Born-Oppenheimer approximation, in which the electrons are assumed to instantaneously screen the much slower ions. The ion motions from molecular dynamics yield the viscosity and diffusion, while electronic dynamics must be inferred through some approximations to the electron-ion and electron-electron collision operators of kinetic theory. Approximations to the electron screening differ most in how they treat ion-ion correlations. For example, the average atom assumes the ion-ion radial distribution function is a step function at the ion-sphere radius. The correlations can later be inferred by mapping the average atom to the one component plasma with an effective ion charge, such as in PIU [25], or altering the ion charge and introducing a screening length as in KMD [38, 31]. Using the quantum hypernetted chain approximation [124, 125, 126] one can obtain spherically symmetric potentials that can exhibit liquid-like behavior as in EPT [21], but angular correlations are neglected unless one does a three-dimensional quantum mechanical density functional theory (DFT) [73] calculation. Such DFT calculations are in several different flavors, all of which are based upon semiclassical approximations about uniform electron density of the electron free energy. In order of increasing expected accuracy and increasing computational cost, these are Thomas-Fermi [127, 128], Sjostrom-Daligault (SDMD) [129], and Kohn-Sham [130]. The derived potentials can be used in two different ways: effective binary interactions can be used within Boltzmann collision operators as in EPT [21] or the binary or many-body interactions can be used in molecular dynamics simulations [50].

Whenever a model includes a sufficient representation of the electrons’ state, quantities dependent on electron-ion or electron-electron collisions (e.g. electrical and thermal conductivities and stopping power) can be calculated. We employed four types of approximations: Ziman-type expressions [131, 132], which are used in various single-center plasma models [133, 134, 135, 136, 137, 138, 139], the Kubo-Greenwood approximation [140], which approximates the electron wave function with the Kohn-Sham wave function and can be employed in either single-center models [141, 142, 143, 144] or three-dimensional multi-atom calculations [145, 146, 147, 148, 149], local density approximations [150, 98], which use homogeneous electron gas formulas as a starting point for the inhomogeneous problem (almost all stopping power models used this approximation when bound electrons are important), and directly simulating dynamics [23, 24, 151].

6. Results

In this section, we present five different quantities (electrical and thermal conductivity, viscosity, diffusion, and stopping power) for three types of materials (hydrogen, carbon, and an equimolar mixture of the two) across twenty different conditions (four different densities, five different temperatures, and in the case of stopping power, seven different energies). There were up to 15 submissions for each of the included 520 cases (we had no submissions for stopping in the CH mixture). Since one of our main goals is to facilitate sensitivity analyses, we focus on mean and spread measures. However, for the researcher interested in making detailed comparisons, we include some discussion below and have included all the submitted data as a supplementary data file, except from those who requested anonymity.

It is useful to give a measure of the spread in the reported values for each quantity. A conservative measure would be the ratio of maximum to minimum values, but this tends to overemphasize outliers. We would also prefer a method that uses information from all of the data rather than the two extrema. A more natural quantity to assess is the standard deviation of the data set for a particular quantity at some condition. However, data which is spread over decades may give a value of $\sigma$ which is very skewed by one data point. Therefore, we define a spread measure

$$\bar{\sigma} = \exp(\sigma(ln d_i)) - 1.$$  \hspace{1cm} (22)
Note, this measure does not depend on the units or scale of the data. Small values of $\bar{\sigma}$ (much less that one) mean that there is little variation while very large values indicate lack of consensus. These values correspond roughly to the fractional variation within the data.

6.1. Electronic Transport

The means and standard deviations of all submissions of electrical and thermal conductivity are plotted in Fig. 6. Individual submissions are listed in the appendix. For all materials, we find fair agreement among the four independent average-atom models for both electrical and thermal conductivities. These models also agree fairly well with the MD models at moderate densities. The outliers tend to be the parameterized analytic models, while values actually used in hydrodynamic simulations tend to fall within the range of more sophisticated models. For carbon, the widely used Lee-More approximation agrees with QMD at 1 g/cc but is a factor of 10 too small at 10 g/cc. Large disagreements at low temperatures and densities are due primarily to differences in calculated ionization, while large disagreements at high densities are attributable to differing treatments of ionic structure and electron degeneracy. For hydrogen in the high-density regime relevant to ICF stagnation, factors of three to ten among models persist even at high temperatures. These spreads can be seen in Figs. 8 to 10.

The Lorentz number is shown in Fig. 7. For both carbon and hydrogen, most codes recover Weideman-Franz scaling [152] at high densities and low temperatures. There is less agreement among calculated thermal to electrical conductivity ratios in the classical limit, where the treatment of electronic collisions in both electrical and thermal conductivities varies among the models.

6.2. Ionic Transport

Ion viscosity and ion diffusion coefficients are presented in the lower two rows of Fig. 6. In the pure element cases, the self-diffusion coefficient is shown, while for the mixture, it is the interdiffusion coefficient. Because ions are much more massive than electrons, they carry most of the momentum in the plasma. Consequently, viscosity is associated with ions. The electric field associated with electrons may influence ion-ion interactions [87], but the electrons themselves do not provide a significant direct contribution.

A striking feature of the shear viscosity coefficient at warm dense matter conditions is that a minimum can be reached as temperature varies. This is associated with the underlying physical mechanisms responsible for viscosity, which are directly illustrated in the Green-Kubo relation [153]. At weak coupling (low density or high temperature), shear viscosity is determined by the kinetic energy of particles. In this regime, traditional Landau-Spitzer [61, 62, 63] theory predicts that the shear viscosity increases with temperature as $\eta \propto T^{5/2}$. Essentially all of the submissions appear to capture this limit. At sufficiently low temperature, the kinetic energy of particles does not contribute significantly, and the shear viscosity is instead determined by the Coulomb potential energy of ions. Much understanding of this transition is based on the one-component plasma model, where it occurs at $\Gamma \approx 17$ [154, 155, 156]. In low temperature dense plasmas, shear viscosity decreases with increasing temperature, as it does in ordinary liquids. This is a challenging regime for theory because the many-body potential energy is difficult to model. It is also a challenging regime for first-principles simulations because ion transport occurs much more slowly than electron transport, which often requires unattainably long simulations to achieve reliable results.

As expected, the spread in data at high density low temperature conditions is especially severe, often spanning several orders of magnitude. At these conditions there is little agreement among any of the submissions, illustrating that this is one of the least understood transport processes considered in this workshop. Ion viscosity in this regime is relevant to modeling the fuel-shell interface in ICF (e.g. Ref. [157]) This highlights one of the most important areas where improved theory and simulations are needed. It may contribute to a high degree of uncertainty for some aspects of hydrodynamic simulations when these conditions are encountered. However, it is important to recall that small values of transport coefficients imply correspondingly small contributions to the hydrodynamic equations: the stronger the collisions, the smaller the transport coefficients, and the smaller the terms in the hydrodynamics model, unless there are extremely large gradients.

The submitted ion diffusion coefficients tend to be in closer agreement than ion viscosity coefficients, but with still substantial disagreement in the strongly coupled regime. Analytic models tend to be outliers. Again, the agreement is best at high temperature and low density conditions (weak coupling), where all submissions appear to asymptote to the $D \propto T^{5/2}$ regime of Landau-Spitzer theory. Similar trends are observed for the self-diffusion processes in the single component systems as for interdiffusion in the CH mixture. With the exception of one analytic model, all submissions predict that $D$ monotonically decreases with decreasing temperature, consistent with expectations from the one-component plasma [158, 159]. The better agreement for diffusion, compared to viscosity, may be that the correlation function for diffusion is entirely determined by the kinetic energy of particles. Thus, there is not a fundamental transition in the physical mechanism responsible for diffusion as there is with viscosity.

Diffusion processes are important in ICF plasmas particularly with regard to deuterium and tritium fuel mixing, or demixing, near a hot spot, but also in the mixing of shell materials near the edge of the fuel. The data suggest that reliable models exist in the weakly coupled plasma regimes, such as may be expected in the former example of fusion fuel mixing in a hot plasma. However, there may be much less reliable models in the latter example concerning mixing of shell materials in the cooler outer regions of the plasma. Continued progress in such simulations will rely on further improvements to the diffusion models particularly in these more dense or cool regions.

6.3. Stopping Power

Accurate values for the stopping powers are needed for ICF target design [160] because alpha particle heating maintains the
Figure 6: Electrical (first row) and thermal (second row) conductivity, ion viscosity (third row), and the diffusion coefficient (fourth row) for pure hydrogen (first column), pure carbon (second column), and an equimolar carbon-hydrogen mixture. For the pure cases the diffusion coefficient is the self diffusion while for the mixture, it is the interdiffusion. Plotted are the mean (position) and standard deviations (error bars) in logarithmic space of all submissions as a function of temperature. The different density cases plotted are \( \rho = 0.1 \text{ g/cm}^3 \) (red, solid), \( \rho = 1 \text{ g/cm}^3 \) (green, dashed), \( \rho = 10 \text{ g/cm}^3 \) (cyan, dotted), and \( \rho = 100 \text{ g/cm}^3 \) (purple, dot-dashed). The spreads tend to be larger at low temperatures or high densities For clarity, the different densities curves are slightly offset from one another in temperature from the actual values of 0.2, 2, 20, 200, and 2000 eV.
Figure 7: Lorenz number \((L = \kappa/(\sigma k_B T))\) divided by the Widermann-Franz limit \((L_{WF} = \pi^2 k_B^2 T/(3e^2))\) of all submitted calculations. The Wiedermann-Franz and Spitzer \((L_S = k_B^2 T/e^2)\) limits are shown by the upper and lower shaded gray regions, respectively. All the data is shown as circles connected by solid red lines except for three dimensional density functional calculations (black x’s), which were the most expensive.
Figure 8: Spread in reported values of transport coefficients for hydrogen. This spread roughly corresponds to the fractional variation in the submitted values. See Eq. 22 for the definition. The large black bold numbers are located at the positions of the workshop cases and their values are the number of submissions at those conditions. Small values (red) indicate agreement among submissions while large values (magenta) indicate disagreement. The larger values correspond to when either the relevant Coulomb coupling parameter or computational expense is large (see Sec. 3).
Figure 9: Same as Fig. 8 but for carbon.
Figure 10: Same as Fig. 8 but for the equimolar carbon-hydrogen mixture. Note, there were not enough electrical conductivity submissions to report a valid spread measure. The reliability of the thermal conductivity spread measure here is also marginal due to having too few submissions.
temperature in the presence of energy loss mechanisms. Warm
dense matter experiments can also rely on charged particle
beams for heating [161, 162, 20] or as a probe [17, 15]. Unlike
the electronic and ionic transport properties, which represent
an integration over a distribution (usually thermal) of charged
particle velocities, stopping powers must be energy-resolved to
track the thermalization of fast fusion products through colli-
sions with the background material. Hence, they more dis-
inctly probe different parts of the underlying collision operator
needed for all transport quantities while also having an extra
dimension of parameter space to explore.

Over the last few decades there have been many different
stopping power experiments in plasmas. These can be divided
into experiments involving high-energy, moderate to heavy
ions in weakly coupled plasmas [163, 164, 165, 166, 167],
matter-energy, fully-ionized, light ions in weakly coupled plasmas [168, 15, 169, 170, 16], high-energy, fully-ionized,
light ions in weakly coupled plasmas [171] moderate-energy, light ions in a moderately coupled plasma [77], and high-
energy, light ions in a moderately coupled plasma [17, 18],
where high (moderate) energy refers to ions with velocities sig-
ificantly greater than (approximately equal to) the thermal ve-
locity of the target electrons. While all of these experiments are
very useful for benchmarking theoretical predictions, it remains
difficult to produce mono-energetic projectiles in a temperature
and density gradient-free dense plasma and precisely measure
energy losses. Such measurements remain sparse in the high-
dimensional space of projectile energy, projectile charge, den-
sity, temperature, and target material. For example, we are not
aware of any such precision measurements of moderate-energy
ions in warm dense matter.

To elucidate the many dependencies in the large parameter
space, we plot several common stopping power models, vary-
ing only one parameter at a time. Note, we have simplified
 matters by doing this exercise for the uniform electron gas (no
sing only one parameter at a time. Note, we have simplified
space, we plot several common stopping power models, vary-
aware of any such precision measurements of moderate-energy
ions in that regime. For this exercise, we focus on alpha
particle stopping in hot dense matter. In particular, the condi-
tions are: the projectile charge, $Z = 2$, electron number density,
$n_e = 10^{25}$ cm$^{-3}$, electron temperature, $T = 1$ keV, and projec-
tile energy, $E_p = 3.5$ MeV. About this common point, one of
these four parameters is varied in Figs. 11-14. We show six
models: that of Li and Petrasso (LP) [172], including the rela-
tively recent erratum [173], that of Brown, Preston, and Sin-
gleton (BPS) [39], that of Maynard and Deutsch (M&D) [174],
Zimmerman’s fit to that model (ZMD) [175], the Zwicknagel
model (Z) [101], and the quantum mechanical version of the
Gould and DeWitt model (qGD) [176]. The LP model is de-

ing length. The M&D model depends on linear response the-
ory (small $Z$) and the random phase approximation (weak cou-
pling), but can handle any degeneracy. The Z model starts with
a $T$-Matrix description, but artificially accounts for dynamic
screening and plasmon excitations by multiplying the screen-
ing length by $\sqrt{1 + v^2/v_{th}^2}$ in the cross section calculation. This
gives the Bohr limit at high energies, but is inaccurate when
quantum diffraction is important (the de Broglie wavelength
is greater that the classical distance of closest approach). The
qGD model adds together the M&D model with a $T$-matrix
(strong scattering) model (the latter is limited to static screen-
ing) and subtracts the statically screened version of M&D so as
to not double count (this model is accurate to at least the same
order as BPS, but is valid for all degeneracies).

In Fig. 11, we show the dependence of stopping power on
energy. At low energies, the plasma exerts a drag force pro-
portional to the velocity. At high energies, the plasma does
not have time to react to the projectile and so the stopping
decreases. The Bragg peak, where the projectile velocity is
roughly the thermal velocity of the target electrons, is when the
stopping is maximized. We see the the LP model stands out by
having a discontinuity near the Bragg peak due to it adding a
step function correction for higher energies). Two models, M&D and qGD are indistinguishable, indicating that
strong scattering effects are negligible at these conditions.
wavelength in this limit. Also, at low temperatures, Zimmerman’s fit can differ from M&D, although not catastrophically so. For example in Fig. 12, the difference is about 18%.

We also plot the dependence of stopping on density in Fig. 13. We see that the stopping per target electron decreases with density since screening becomes stronger. The differences amongst models that include degeneracy and those that do not also becomes apparent (Note, that although the absolute difference is small in the plot, the relative difference is 34% at \( n_e = 10^{27} \text{ cm}^{-3} \).

The last parameter to vary is the charge of the projectile, which is shown in Fig. 14. This distinguishes the linear response models (M&D and ZMD) from those which account for strong scattering. We see that this effect is insignificant for alpha particles or other common fusion products.

All of the above variations are valid for a fully ionized plasma. However, there are often larger uncertainties when there is a partially ionized plasma state. There are two common approaches: mixing a bound electron stopping model (usually fit to cold data [105]) and one of the uniform electron gas models above via a value of the mean ionization, \( Z \), and the local density approximation (LDA). Both of these methods require some knowledge of the electronic state, either in \( Z \) or the electron density. Such quantities are acquired via a self-consistent electronic structure calculation (e.g. density functional theory).

Zimmerman’s model [175] is an example of the first approach; however, it does not give any opinion on what to use for \( \bar{Z} \). One option is to use values from More’s fit to the electron density at the ion-sphere radius of a Thomas-Fermi atom [57] or from a more sophisticated equation-of-state code like Purgatorio [177, 178, 135], which outputs the total number of electrons with positive energy per atom, but the best practice is to use a \( \bar{Z} \) designed for the observable of interest. The one approximation used in warm dense matter for stopping power is the local density approximation (LDA):

\[
\frac{dE}{dx}_{\text{LDA}} [n(r)] = \frac{Z^2 e^2 \omega_p^2}{v^2} L_{\text{LDA}}[n(r)],
\]

\[
L_{\text{LDA}}[n(r)] = \frac{\int dr \, n(r) \omega_{\text{uni}}^2(n(r))}{\int dr \, n(r)},
\]

where the dependencies on energy and temperature are suppressed for clarity, the brackets indicate a functional dependence, the integration is done over a microscopic computational domain (usually either an average atom or a box containing some tens to hundreds of atoms), \( \omega_p^2 = 4\pi\varepsilon_0 n_e/m_e \), \( n_e \) is the volume-averaged electron density, \( (dE/dx)_{\text{uni}} = Z^2 e^2 \omega_p^2 \omega_{\text{uni}}^2(n)/v^2 \) is the the fully ionized uniform electron gas stopping power (approximations to which were shown in the Figs. 11-14), and \( v \) is the projectile velocity. This equation allows us to define a LDA approximation to \( Z \) via

\[
L_{\text{LDA}}[n(r)] = L_{\text{uni}} \left( \frac{Z}{N_i} \sum_i n_i \right),
\]

where the sum is over all \( N_i \) ion species. Here, for computational speed, we use the ZMD model [175] of the free electron.
stopping number for $L_{\text{sum}}$ on both sides of the equation. The three predictions of $Z$ are shown in Fig. 15 for a pure carbon target as a function of temperature for different densities. At low to moderate densities ($\lesssim 10$ g/cc) and low to moderate temperatures ($\lesssim 100$ eV), the differences between models becomes large. Furthermore, the LDA model is dependent on the projectile energy, while the other models are independent. The accuracy of the LDA model over much of this large parameter space is still largely untested and unknown.

Finally, we show the results of the code comparison workshop. We note that we did not study variations in the ion component of stopping nor different models for the charge state of the projectile, both of which can lead to further uncertainties. In order to avoid plotting results that span many orders of magnitude and to emphasize variations amongst the models, we plot the relative differences between the submitted results and the full Zimmerman model [175] (including bound electrons) using More’s fit [57] to $Z$ in Figs. 16 and 17 for hydrogen and carbon, respectively (no results were submitted for the mixed CH case). Almost all submissions were in the average atom category and proceed to make the same local density approximation to account for the inhomogeneous electron density around each ion. So we warn the readers that the variations should be taken as a lower bound for the uncertainty. The greatest variations are seen at low energy and temperature and high densities. Only the BPS submission attempted to model the ion component of the stopping, which is important at the lower energies and high temperatures, so for consistency with the majority that part of the Zimmerman model was removed, even though it is more physical to include it. The outlier at high energies is actually more accurate since there relativistic and Bremsstrahlung effects become more important.

7. Conclusions and Future Workshops

We have reported on the results of an inaugural charge-particle transport workshop, which aimed to assess variations among model predictions for electronic and ionic transport coefficients and velocity-resolved stopping powers. As summarized in Figs. 6-10, 16, and 17, we find significant variation (factors of three or more) for all properties among models that represent the range of available theoretical methods, including the values actually used in the hydrodynamic simulations to design and interpret data from ICF experiments. Agreement among models was generally higher in the classical weakly coupled regime. At low temperatures and densities, uncertainties in the ionization state were the major source of disagreement. For most transport coefficients, typical best-case variations among codes were 20% in the weakly coupled regime, factors of two in warm dense matter, and worsening to factors of ten or more at low temperatures. It is currently not known what the consequences of such uncertainties are, and further integrated modeling of a wide range of experiments is warranted. However, we emphasize that when conduction or diffusion is small, other terms in the hydrodynamic equations will dominate. The result of this workshop may help inform sensitivity studies that would ultimately quantify how important these variations are.

It is important to note that this workshop was not intended to identify the “best” models. Many of the methods have acknowledged deficiencies or become intractable in some regimes. Rather, the workshop aimed to establish a baseline for model comparison, survey the state-of-the art for a range of modeling approaches and plasma regimes, provide initial estimates of plausible variations to inform sensitivity studies, and begin to identify the important physics that must be included in reliable transport calculations. Future workshops would benefit from broader community participation and could examine in more detail the model assumptions, exploring quantities like interionic and electron-ion potentials, structure factors, and collision cross sections for a more limited set of cases and may eventually expand to include non-equilibrium and high-field effects. The results from this and any future workshops will help to assess uncertainties in hydrodynamic modeling and establish a foundation for reliable transport calculations. Ultimately, uncertainties and model variations in transport, equation of state [2], and radiative properties [10] can be rigorously combined to limit as much as possible the potential for inconsistency and offsetting errors.

8. Acknowledgements

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Appendix A. Submitted Data

For completeness, we are including much of the raw data submitted to the workshop in Tab. A.3. Some attendees wished to not make their submissions public, and so those are not included in the table. It is hoped that the data below will help the community further quantify the range of reasonable values of transport coefficients for a variety of conditions. Brief descriptions of and references for the methods can be found in Tab. 2. However, we encourage researchers to directly contact submitters for details of their calculations.
Different $\bar{Z}$ models for a pure carbon target: the stopping power local density approximation (LDA) using Purgatorio’s density and the Zimmerman model for free electrons, Purgatorio, an average atom density functional theory code with $\bar{Z}$ calculated from the positive energy electrons, and More’s fit to an average atom Thomas-Fermi model. The LDA prediction is not only a function of density and temperature but also the projectile energy. The uppermost curve of each family is for an alpha particle with $E = 3.5$ MeV and the bottommost and faintest curve is for $E = 500$ eV. Each line is evenly spaced on a logarithmic scale.
Figure 16: Fractional difference between the electron component of stopping power models and Zimmerman’s bound plus free fits [175]. Curves are TDDFT (black), BPS (magenta), and various average atom (dashed green) and pseudo-neutral atom (solid green) implementations. At low energies and high temperatures, the BPS model includes the ion contribution to the stopping, while the other models do not. Likewise, the outlier at high energies is actually more accurate since there relativistic and Bremsstrahlung effects become more important.
Figure 17: Same as Fig. 16 but for carbon.
Table A.3: Submitted data to the charged particle transport workshop. The columns are the name of the submitter with short descriptor or reference to differentiate multiple submissions from the same person (see Tab. 2 for more information), the case written as H for hydrogen, C for carbon, or CH for the carbon-hydrogen mixture followed by two numbers (the first is an index for the density in the set $\{0.1, 1, 10, 100\}$ g/cm$^3$ and the second is an index for the temperature in the set $\{0.2, 2, 20, 200, 2000\}$ eV - for example, C21 refers to the carbon case at 1 g/cm$^3$ and 0.2 eV), electrical conductivity, thermal conductivity, viscosity, diffusion coefficient (self diffusion for the pure substances and inter-diffusion for the mixture), and stopping power at seven different projectile energies. We note that since the 2016 workshop, the values reported here for Starrett and Saumon have been superseded by the updated model in Ref [52].

| Submitter                | Case | $\sigma$ | $\kappa$ | $\eta$ | $D$ | $dE/dx$ (eV/cm) |
|--------------------------|------|----------|----------|--------|-----|----------------|
|                          |      | (1/\Omega cm) | erg/(s cm K) | g/(s cm) | cm$^2$/s | 1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV | 100 MeV | 1 GeV |
| Clérouin (PIJ)           | H11  | 1.61e3   | 9.13e5   | 4.09e-4 | 0.00511 | 8.37e7 | 4.11e8 | 3.86e8 | 7.33e7 | 1.06e7 | 1.39e6 | 1.72e5 |
| Hansen (Bemuze)          | H11  | 8.37e7   | 4.11e8   | 3.86e8 | 7.33e7 | 1.06e7 | 1.39e6 | 1.72e5 |
| Hansen (Muze-k)          | H11  | 1.41e3   | 7.81e5   | 4.09e-4 | 0.00511 | 8.4e7 | 4.09e8 | 3.85e8 | 7.33e7 | 1.06e7 | 1.39e6 | 1.72e5 |
| Hansen (Muze-s)          | H11  | 2.65e-8  | 1.82e-5  | 7.54e7 | 3.81e8 | 3.37e8 | 6.65e7 | 9.72e6 | 1.28e6 | 1.58e5 |
| Haxhimali, Rudd          | H11  | 6.17e-4  | 0.0234   | 0.14   | 0.00285 | 7.87e7 | 3.45e8 | 8.4e7 | 3.85e8 | 7.33e7 | 1.06e7 | 1.39e6 | 1.72e5 |
| Copeland [28]            | H11  | 0.00428  | 0.00966  | 0.00285 | 0.00966 | 1.39e6 | 1.72e5 |
| Copeland [30]            | H11  | 1.75e-4  | 6.10e-4  | 0.00285 | 0.00966 | 1.39e6 | 1.72e5 |
| Copeland [31]            | H11  | 6.10e-4  | 0.00285  | 0.00966 | 0.00285 | 1.39e6 | 1.72e5 |
| Kang, Dai (QE)           | H11  | 0.0957   | 0.00613  | 0.0701  | 0.00613 | 0.00613 | 0.0701 |
| Copeland [29]            | H11  | 0.00613  | 0.0701   | 0.00613 | 0.0701  | 0.00613 | 0.0701 |
| Clérouin (PIJ)           | H12  | 854.     | 4.66e6   | 0.00383 | 0.0701  | 7.87e7 | 2.92e8 | 3.69e8 | 7.23e7 | 1.05e7 | 1.38e6 | 1.71e5 |
| Hansen (Bemuze)          | H12  | 58.      | 3.45e5   | 0.00383 | 0.0701  | 7.87e7 | 2.92e8 | 3.69e8 | 7.23e7 | 1.05e7 | 1.38e6 | 1.71e5 |
| Hansen (Muze-k)          | H12  | 260.     | 1.31e6   | 0.00383 | 0.0701  | 7.87e7 | 2.92e8 | 3.69e8 | 7.23e7 | 1.05e7 | 1.38e6 | 1.71e5 |
| Hansen (Muze-s)          | H12  | 331.     | 1.61e6   | 0.00383 | 0.0701  | 7.87e7 | 2.92e8 | 3.69e8 | 7.23e7 | 1.05e7 | 1.38e6 | 1.71e5 |
| Haxhimali, Rudd          | H12  | 0.00425  | 0.0686   | 0.0127  | 0.076   | 8.07e-6 | 0.148 |
| Copeland [28]            | H12  | 0.0686   | 0.0127   | 0.076   | 0.0127  | 8.07e-6 | 0.148 |
| Copeland [30]            | H12  | 0.00425  | 0.0686   | 0.0127  | 0.076   | 8.07e-6 | 0.148 |
| Copeland [31]            | H12  | 0.00957  | 0.0127   | 0.076   | 0.0127  | 8.07e-6 | 0.148 |
| Hou (AAHNC)              | H12  | 0.0026   | 0.049    | 0.00613 | 0.0701  | 8.07e-6 | 0.148 |
| Kang, Dai (QE)           | H12  | 552.     | 8.07e-6  | 0.148   | 0.00613 | 0.0701  | 8.07e-6 | 0.148 |
| Copeland [29]            | H12  | 1.32e3   | 4.69e6   | 0.148   | 0.00613 | 0.0701  | 8.07e-6 | 0.148 |
| Clérouin (PIJ)           | H13  | 8.57e3   | 2.31e8   | 0.055   | 0.893   | 4.47e7 | 1.35e8 | 3.02e8 | 7.43e7 | 1.08e7 | 1.41e6 | 1.74e5 |
| Hansen (Bemuze)          | H13  | 7.85e3   | 2.58e8   | 0.055   | 0.893   | 4.47e7 | 1.35e8 | 3.02e8 | 7.43e7 | 1.08e7 | 1.41e6 | 1.74e5 |
| Hansen (Muze-k)          | H13  | 9.25e3   | 2.81e8   | 0.055   | 0.893   | 4.47e7 | 1.35e8 | 3.02e8 | 7.43e7 | 1.08e7 | 1.41e6 | 1.74e5 |
| Hansen (Muze-s)          | H13  | 8.63e3   | 2.72e8   | 0.055   | 0.893   | 4.47e7 | 1.35e8 | 3.02e8 | 7.43e7 | 1.08e7 | 1.41e6 | 1.74e5 |
| Haxhimali, Rudd          | H13  | 0.0683   | 0.893    | 0.055   | 0.893   | 4.47e7 | 1.35e8 | 3.02e8 | 7.43e7 | 1.08e7 | 1.41e6 | 1.74e5 |
Table A.3 – continued from previous page

| Submitter           | Case | $\sigma$ (l/(Ω cm)) | $\kappa$ (erg/(s cm K)) | $\eta$ (g/(s cm)) | $D$ (cm$^2$/s) | $dE/dx$ (eV/cm) |
|---------------------|------|---------------------|--------------------------|-------------------|----------------|-----------------|
| Copeland [28]       | H13  | 0.0957              |                          |                   | 0.574          |                 |
| Copeland [30]       | H13  | 0.0723              |                          |                   | 1.11           |                 |
| Copeland [31]       | H13  | 0.0827              |                          |                   | 1.29           |                 |
| Hou (AAHNC)         | H13  | 0.026               |                          |                   | 0.507          |                 |
| Copeland [29]       | H13  | 1.75e4              | 1.68e8                   | 1.82e7            | 4.36e7         | 5.87e7          | 1.04e7          |
| Hayes               | H14  | 3.62e10             | 4.04                     | 1.82e7            | 4.36e7         | 5.87e7          | 1.04e7          |
| Clérouin (PIJ)     | H14  | 1.32e5              | 3.91e10                  | 4.96e6            | 1.55e7         | 4.43e7          | 6.55e7          | 1.09e7          | 1.42e6          | 1.75e5          |
| Hansen (Bemuze)    | H14  | 1.52e5              | 4.08e10                  | 5.05e6            | 1.58e7         | 4.57e6          | 6.62e7          | 1.09e7          | 1.43e6          | 1.75e5          |
| Hansen (Muze-k)    | H14  | 1.49e5              | 4.05e10                  | 5.05e6            | 1.58e7         | 4.57e6          | 6.62e7          | 1.09e7          | 1.43e6          | 1.75e5          |
| Hansen (Muze-s)    | H14  | 1.32e5              | 3.91e10                  | 4.96e6            | 1.55e7         | 4.43e7          | 6.55e7          | 1.09e7          | 1.42e6          | 1.75e5          |
| Haxhimali, Rudd    | H14  | 4.11                |                          |                   |                |                 |                 |
| Copeland [28]       | H14  | 6.51                |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [30]       | H14  | 4.24                |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [31]       | H14  | 4.23                |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hou (AAHNC)        | H14  | 0.106               |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [29]       | H14  | 2.37e5              | 2.12e10                  | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hayes               | H15  | 7.26e12             | 70.4                     | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Clérouin (PIJ)     | H15  | 7.26e12             | 70.4                     | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hansen (Bemuze)    | H15  | 7.88e12             | 70.4                     | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hansen (Muze-k)    | H15  | 8.12                | 70.4                     | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hansen (Muze-s)    | H15  | 7.97e12             | 70.4                     | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Haxhimali, Rudd    | H15  | 67.3                |                          |                   |                |                 |                 |
| Copeland [28]       | H15  | 1.17e3              |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [30]       | H15  | 67.7                |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [31]       | H15  | 68.1                |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [29]       | H15  | 4.69e6              | 4.2e12                   | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Clérouin (PIJ)     | H21  | 2.62e4              | 1.49e7                   | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Baczewski           | H21  |                    |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hansen (Bemuze)    | H21  | 2.58e4              | 1.37e7                   | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hansen (Muze-k)    | H21  | 2.84e4              | 1.5e7                    | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Hansen (Muze-s)    | H21  | 1.9e4               | 1.01e7                   | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Clérouin (OFMD)    | H21  | 2.38e4              | 1.35e7                   | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Haxhimali, Rudd    | H21  |                    |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Sjostrom (KSMD)    | H21  |                    |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Sjostrom (SDMD)    | H21  | 1.61e4              | 2.5e7                    | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Sjostrom (TFMD)    | H21  |                    |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [28]       | H21  | 0.406               |                          | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [30]       | H21  | 2.97e-4             | 4.71e-4                  | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |
| Copeland [31]       | H21  | 8.34e-4             | 0.00129                  | 6.16e6            | 3.03e6         | 7.6e6           | 8.8e6           |

Continued on next page
| Submitter          | Case | $\sigma$ (l/(Ω cm)) | $\kappa$ (erg/(s cm K)) | $\eta$ (g/(s cm)) | $D$ (cm$^2$/s) | $dE/dx$ (eV/cm) |
|--------------------|------|---------------------|-------------------------|-------------------|----------------|-----------------|
| Kang, Dai (QE)    | H21  | 1.63e4              | 0.00635                 | 0.00161           | 1 keV         | 10 keV          |
| Copeland [29]     | H21  | 4.8e3               | 2.72e6                  |                   | 100 keV       | 1 MeV           |
| Clérouin (PIJ)    | H22  | 1.31e4              | 7.41e7                  | 0.00737           | 10 MeV        | 100 MeV         |
| Baczewski          | H22  | 9.05e3              | 4.8e7                   |                   | 1 GeV         |                 |
| Hansen (Bemuze)   | H22  | 1.07e4              | 5.63e7                  |                   | 10 keV        | 20 keV          |
| Hansen (Muze-k)   | H22  | 7.41e3              | 3.96e7                  |                   | 200 keV       | 5 MeV           |
| Hansen (Muze-s)   | H22  | 1.36e4              | 8.15e7                  |                   | 200 MeV       | 50 MeV          |
| Ma (eFF)           | H22  | 2.49e3              | 5.57e-4                 | 0.017             |                |                 |
| Kang, Dai (QE)    | H22  | 1.33e4              | 5.57e-4                 |                   | 1 keV         | 10 keV          |
| Copeland [29]     | H22  | 5.15e3              | 2.89e7                  |                   | 100 keV       | 1 MeV           |
| Clérouin (PIJ)    | H23  | 1.17e4              | 5.05e8                  | 0.103             | 10 MeV        | 100 MeV         |
| Hansen (Bemuze)   | H23  | 2.12e4              | 6.85e8                  | 1.44e8            | 1.44e8        | 1.44e8          |
| Hansen (Muze-k)   | H23  | 2.23e4              | 7.02e8                  | 1.52e8            | 4.53e8        | 4.53e8          |
| Hansen (Muze-s)   | H23  | 1.96e4              | 6.55e8                  | 1.52e8            | 6.01e8        | 6.01e8          |
| Baarud             | H23  | 0.11                | 0.168                   | 1.44e8            | 1.44e8        | 1.44e8          |
| Daligault          | H23  | 0.104               | 0.18                    | 4.53e8            | 4.53e8        | 4.53e8          |
| Haxhimali, Rudd    | H23  | 0.151               | 0.18                    | 1.52e8            | 1.52e8        | 1.52e8          |
| Sjostrom (SDMD)   | H23  | 2.2e4               | 1.34e9                  | 1.52e8            | 6.01e8        | 6.01e8          |
| Sjostrom (TFMD)   | H23  | 2.4e4               | 6.87e8                  | 1.52e8            | 9.37e7        | 9.37e7          |
| Starrett, Saumon  | H23  | 2.4e4               | 6.87e8                  | 1.52e8            | 9.37e7        | 9.37e7          |
| Copeland [28]     | H23  | 0.22                | 0.132                   | 1.52e8            | 9.37e7        | 9.37e7          |
| Copeland [30]     | H23  | 0.141               | 0.224                   | 1.52e8            | 9.37e7        | 9.37e7          |
| Copeland [31]     | H23  | 0.201               | 0.32                    | 1.52e8            | 9.37e7        | 9.37e7          |
| Hou (AAHNC)       | H23  | 0.077               | 0.145                   | 1.52e8            | 9.37e7        | 9.37e7          |
| Ma (eFF)           | H23  | 1.66e4              | 1.86e8                  | 1.52e8            | 9.37e7        | 9.37e7          |
| Copeland [29]     | H23  | 2.29e4              | 4.62e8                  | 1.52e8            | 9.37e7        | 9.37e7          |
| Hayes             | H24  | 1.83e5              | 5.06e10                 | 1.52e8            | 9.37e7        | 9.37e7          |

Continued on next page
| Submitter                  | Case | $\sigma$ (l/Ω cm) | $\kappa$ (erg/(s cm K)) | $\eta$ (g/(s cm)) | $D$ (cm²/s) | $dE/dx$ (eV/cm) |
|---------------------------|------|-------------------|-------------------------|-------------------|-------------|-----------------|
|                           |      |                   |                         |                   | 1 keV       | 10 keV         | 100 keV        | 1 MeV          | 10 MeV        | 100 MeV        | 1 GeV          |
| Hansen (Bemuze)           | H24  | 1.94e5            | 5.58e10                 |                   |             | 3.16e7         | 9.9e7          | 2.89e7         | 4.89e8         | 9.24e7         | 1.26e7         | 1.59e6         |
| Hansen (Muze-k)           | H24  | 2.29e5            | 5.96e10                 |                   |             | 3.26e7         | 1.02e8         | 2.98e8         | 4.98e8         | 9.31e7         | 1.26e7         | 1.59e6         |
| Hansen (Muze-s)           | H24  | 2.25e5            | 5.92e10                 |                   |             | 3.26e7         | 1.02e8         | 2.98e8         | 4.98e8         | 9.31e7         | 1.26e7         | 1.59e6         |
| Baalrud                   | H24  | 6.3               |                         | 8.49              |             | 6.1e7          | 3.5e7          | 2.45e7         | 6.1e7          | 7.38e7         |                 |                |
| Daligault                 | H24  |                   |                         | 8.25              |             |                 |                |                 |                 |                |                 |                |
| Haxhimali, Rudd           | H24  |                   |                         | 5.89              |             |                 |                |                 |                 |                |                |                |
| Sjostrom (SDMD)           | H24  |                   |                         |                   |             | 8.55           |                 |                 |                 |                |                |                |
| Sjostrom (TFMD)           | H24  |                   |                         | 8.7               |             |                 |                |                 |                |                |                |                |
| Starrett, Saumon          | H24  | 1.32e5            | 2.68e10                 |                   |             |                 |                |                 |                 |                |                |                |
| Copeland [28]             | H24  | 8.89              |                         | 5.33              |             |                 |                |                 |                 |                |                |                |
| Copeland [30]             | H24  | 6.33              |                         | 8.98              |             |                 |                |                 |                 |                |                |                |
| Copeland [31]             | H24  | 6.19              |                         | 8.91              |             |                 |                |                 |                 |                |                |                |
| Copeland [29]             | H24  | 3.4e5             | 3.28e10                 |                   |             |                 |                |                 |                 |                |                |                |
| Hayes                     | H25  |                   |                         | 6.1e7             | 3.5e7       | 2.45e7         | 6.1e7          | 7.38e7         |                 |                |                |                |
| Clérouin (PIJ)            | H25  | 3.27e6            | 8.89e12                 | 824.              | 1.02e3      |                 |                |                 |                 |                |                |                |
| Hansen (Bemuze)           | H25  | 2.74e6            | 8.71e12                 |                   |             | 2.13e6         | 6.73e6         | 2.17e6         | 5.94e7         | 8.21e7         | 1.25e7         | 1.59e6         |
| Hansen (Muze-k)           | H25  | 4.03e6            | 1.02e13                 |                   |             | 2.15e6         | 6.79e6         | 2.12e7         | 5.99e7         | 8.25e7         | 1.26e7         | 1.59e6         |
| Hansen (Muze-s)           | H25  | 4.01e6            | 1.02e13                 |                   |             | 2.15e6         | 6.79e6         | 2.12e7         | 5.99e7         | 8.25e7         | 1.26e7         | 1.59e6         |
| Baalrud                   | H25  |                   |                         | 1.31e3            | 1.63e3      |                 |                |                 |                |                |                |                |
| Haxhimali, Rudd           | H25  |                   |                         | 799.              |             |                 |                |                 |                 |                |                |                |
| Copeland [28]             | H25  | 1.36e3            |                         | 814.              |             |                 |                |                 |                 |                |                |                |
| Copeland [30]             | H25  | 806.              |                         | 1.03e3            |             |                 |                |                 |                 |                |                |                |
| Copeland [31]             | H25  | 811.              |                         | 1.07e3            |             |                 |                |                 |                 |                |                |                |
| Copeland [29]             | H25  | 5.74e6            | 5.15e12                 |                   |             |                 |                |                 |                 |                |                |                |
| Clérouin (PIJ)            | H31  | 3.2e5             | 1.81e8                  | 0.0906            | 9.48e-5     |                 |                |                 |                 |                |                |                |
| Baczewski                  | H31  |                   |                         | 2.32e8            | 1.42e9      | 2.76e9         | 3.75e9         | 2.83e8         | 9.74e7         |                 |                |
| Hansen (Bemuze)           | H31  | 3.73e5            | 1.87e8                  |                   |             | 3.06e8         | 9.73e8         | 3.26e9         | 4.21e9         | 7.7e8          | 1.1e8          | 1.43e7         |
| Hansen (Muze-k)           | H31  | 1.73e6            | 7.38e8                  |                   |             | 3.09e8         | 9.83e8         | 3.27e9         | 4.29e9         | 7.74e8         | 1.1e8          | 1.43e7         |
| Hansen (Muze-s)           | H31  | 1.57e6            | 6.78e                   |                   |             | 3.09e8         | 9.83e8         | 3.27e9         | 4.29e9         | 7.74e8         | 1.1e8          | 1.43e7         |
| Clérouin (OFMD)           | H31  | 2.88e5            | 1.63e8                  | 0.098             | 1.06e-4     |                 |                |                 |                |                |                |                |
| Haxhimali, Rudd           | H31  |                   |                         | 138.              |             |                 |                |                 |                |                |                |                |
| Sjostrom (KSMD)           | H31  |                   |                         | 1.70e-4           |             |                 |                |                 |                |                |                |                |
| Sjostrom (SDMD)           | H31  | 5.8e5             | 5.7e8                   |                   |             | 1.00e-4         |                |                 |                |                |                |                |
| Sjostrom (TFMD)           | H31  |                   |                         | 1.20e-4           |             |                 |                |                 |                |                |                |                |
| Copeland [28]             | H31  | 5.39              |                         | 0.324             |             |                 |                |                 |                |                |                |                |
| Copeland [30]             | H31  | 6.59e-4           | 1.02e-4                 |                   |             |                 |                |                 |                |                |                |                |
| Copeland [31]             | H31  | 0.00162           | 2.47e-4                 |                   |             |                 |                |                 |                |                |                |                |
| Kang (PIMD)               | H31  |                   |                         | 3.07e-4           |             |                 |                |                 |                |                |                |                |
| Kang, Dai (QE)            | H31  | 3.81e5            |                         | 2.15              | 2.23e-4     |                 |                |                 |                |                |                |                |

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Table A.3 – continued from previous page

| Submitter       | Case | $\sigma$  | $\kappa$  | $\eta$  | $D$  | $dE/dx$ (eV/cm) |
|-----------------|------|-----------|------------|---------|------|-----------------|
|                 |      | (l/\Omega \text{ cm}) | (erg/(s cm K)) | (g/(s cm)) | (cm$^2$/s) | 1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV | 100 MeV | 1 GeV |
| Copeland [29]   | H31  | 4.8e4     | 2.72e7    | 0.0281  | 0.00279 | 1.91e8 | 1.37e9 | 2.92e9 | 3.49e9 | 2.12e8 | 2.51e7 |
| Clérouin (PIJ)  | H32  | 2.18e5    | 1.24e9    |         |        |       |       |       |       |       |       |
| Baczewski       | H32  | 2.46e5    | 1.37e9    |         |        |       |       |       |       |       |       |
| Desjarlais      | H32  | 1.62e5    | 8.98e8    |         |        |       |       |       |       |       |       |
| Hansen (Bemuze) | H32  | 3.74e5    | 2.04e9    |         |        |       |       |       |       |       |       |
| Hansen (Muze-k) | H32  | 3.43e5    | 1.87e9    |         |        |       |       |       |       |       |       |
| Hansen (Muze-s) | H32  | 2.36e5    | 1.34e9    | 0.0188  | 0.0026 |       |       |       |       |       |       |
| Clérouin (OFMD)| H32  | 2.18e5    | 1.24e9    | 0.0284  | 0.00276|       |       |       |       |       |       |
| Daligault       | H32  | 2.46e5    | 1.37e9    | 0.0289  | 0.00295|       |       |       |       |       |       |
| Haxhimali, Rudd | H32  | 1.62e5    | 8.98e8    | 0.0331  |        |       |       |       |       |       |       |
| Sjostrom (KSMD) | H32  | 3.74e5    | 2.04e9    | 0.016   | 0.00254|       |       |       |       |       |       |
| Sjostrom (SDMD) | H32  | 3.43e5    | 1.87e9    | 0.0191  | 0.0025 |       |       |       |       |       |       |
| Starrett, Saumon| H32  | 2.5e5     | 1.41e9    |         |        |       |       |       |       |       |       |
| Copeland [28]   | H32  | 1.71      | 1.02      | 0.00322 |        |       |       |       |       |       |       |
| Copeland [30]   | H32  | 0.00868   | 0.00141   |         |        |       |       |       |       |       |       |
| Copeland [31]   | H32  | 0.016     | 0.00254   |         |        |       |       |       |       |       |       |
| Hou (AAHNC)     | H32  | 1.94e4    | 0.00322   | 0.03322 |        |       |       |       |       |       |       |
| Ma (eFF)        | H32  | 1.4e5     | 8.19e9    | 0.0348  |        |       |       |       |       |       |       |
| Kang (PIMD)     | H32  | 1.71      | 1.02      | 0.00322 |        |       |       |       |       |       |       |
| Kang, Dai (QE)  | H32  | 2.29e5    | 0.023     | 0.00319 |        |       |       |       |       |       |       |
| Sjostrom (TFMD) | H32  | 3.09e8    | 9.79e8    | 3.17e9  | 4.19e9 | 7.7e8 | 1.1e8 | 1.43e7 |       |       |       |
| Sjostrom (SDMD) | H32  | 3.13e8    | 9.91e8    | 3.22e9  | 4.27e9 | 7.74e8 | 1.1e8 | 1.43e7 |       |       |       |
| Sjostrom (TFMD) | H32  | 3.13e8    | 9.91e8    | 3.22e9  | 4.27e9 | 7.74e8 | 1.1e8 | 1.43e7 |       |       |       |
| Starrett, Saumon| H33  | 1.87e5    | 6.36e9    | 3.09e8  | 9.79e8 | 3.17e9 | 4.19e9 | 7.7e8 | 1.1e8 | 1.43e7 |       |
| Hansen (Bemuze)| H33  | 2.47e5    | 7.41e9    | 3.13e8  | 9.91e8 | 3.22e9 | 4.27e9 | 7.74e8 | 1.1e8 | 1.43e7 |       |
| Hansen (Muze-k)| H33  | 2.28e5    | 7.07e9    | 3.13e8  | 9.91e8 | 3.22e9 | 4.27e9 | 7.74e8 | 1.1e8 | 1.43e7 |       |
| Hansen (Muze-s)| H33  | 1.16e5    | 6.55e9    | 0.222   | 0.034  |       |       |       |       |       |       |
| Clérouin (OFMD)| H33  | 2.225     | 0.0394    | 0.225   | 0.0394 |       |       |       |       |       |       |
| Daligault       | H33  | 0.23      | 0.0362    |         |        |       |       |       |       |       |       |
| Haxhimali, Rudd | H33  | 0.293     |          |         |        |       |       |       |       |       |       |
| Sjostrom (SDMD)| H33  | 0.145     | 0.0395    | 0.293   | 0.0395 |       |       |       |       |       |       |
| Sjostrom (TFMD)| H33  | 0.04      |          |         |        |       |       |       |       |       |       |
| Starrett, Saumon| H33  | 0.722     | 0.0433    | 0.722   | 0.0433 |       |       |       |       |       |       |
| Sjostrom (SDMD)| H33  | 0.208     | 0.0338    | 0.208   | 0.0338 |       |       |       |       |       |       |
| Sjostrom (TFMD)| H33  | 0.322     | 0.0529    | 0.322   | 0.0529 |       |       |       |       |       |       |
| Hou (AAHNC)     | H33  | 0.172     | 0.0326    | 0.172   | 0.0326 |       |       |       |       |       |       |

Continued on next page
| Submitter               | Case | $\sigma$ | $\kappa$ | $\eta$ | $D$ | $dE/dx$ (eV/cm) |
|------------------------|------|----------|----------|--------|-----|----------------|
| Ma (eFF)               | H33  | 7.2e4    |          |        |     |                |
| Copeland [29]          | H33  | 5.99e4   | 2.81e9   |        |     |                |
| Hayes                  | H34  |          |          |        |     |                |
| Clérouin (PIJ)         | H34  | 2.71e5   | 7.89e10  | 8.58   | 1.16|                |
| Hansen (Bemuze)        | H34  | 5.17e5   | 1.14e11  |        |     |                |
| Hansen (Muze-k)        | H34  | 5.47e5   | 1.16e11  |        |     |                |
| Hansen (Muze-s)        | H34  | 5.32e5   | 1.15e11  |        |     |                |
| Baalrud                | H34  |          |          | 9.26   | 1.31|                |
| Clérouin (OFMD)        | H34  | 2.7e5    | 7.84e10  | 11.5   | 1.5 |                |
| Daligault              | H34  |          |          | 8.66   | 1.34|                |
| Haxhimali, Rudd        | H34  |          |          | 9.48   |     |                |
| Sjostrom (SDMD)        | H34  | 3.2e5    | 1.8e11   |        |     |                |
| Sjostrom (TFMD)        | H34  |          |          |        |     |                |
| Starrett, Saumon       | H34  | 2.57e5   | 6.11e10  |        |     |                |
| Copeland [28]          | H34  |          |          | 13.6   | 0.819|                |
| Copeland [30]          | H34  |          |          | 10.8   | 1.62 |                |
| Copeland [31]          | H34  |          |          | 10.5   | 1.58 |                |
| Copeland [29]          | H34  | 5.39e5   | 6.26e10  |        |     |                |
| Hayes                  | H35  |          |          |        |     | 3.61e8         |
| Clérouin (PIJ)         | H35  | 4.19e6   | 1.14e13  | 996.   | 123.|                |
| Hansen (Bemuze)        | H35  | 5.26e6   | 1.33e13  |        |     |                |
| Hansen (Muze-k)        | H35  | 5.5e6    | 1.35e13  |        |     |                |
| Hansen (Muze-s)        | H35  | 5.48e6   | 1.35e13  |        |     |                |
| Baalrud                | H35  |          |          | 1.33e3 | 167.|                |
| Clérouin (OFMD)        | H35  | 4.14e6   | 1.13e13  |        | 825.| 218.           |
| Haxhimali, Rudd        | H35  |          |          | 987.   |     |                |
| Copeland [28]          | H35  |          |          | 1.63e3 | 97.6|                |
| Copeland [30]          | H35  |          |          | 1.01e3 | 135.|                |
| Copeland [31]          | H35  |          |          |        |     |                |
| Copeland [29]          | H35  | 7.45e6   | 7.18e12  |        |     |                |
| Clérouin (PIJ)         | H41  | 3.51e6   | 1.99e9   |        |     |                |
| Hansen (Bemuze)        | H41  | 8.6e6    | 4.5e9    |        |     |                |
| Hansen (Muze-k)        | H41  | 1.42e8   | 4.75e10  |        |     |                |
| Hansen (Muze-s)        | H41  | 1.37e8   | 4.58e10  |        |     |                |
| Clérouin (OFMD)        | H41  | 1.96e6   | 1.08e9   |        |     |                |
| Haxhimali, Rudd        | H41  | 7.34e5   |          |        |     |                |
| Copeland [28]          | H41  |          |          | 61.8   | 0.371|                |
| Copeland [30]          | H41  | 4.54e-4  | 7.03e-6  |        |     |                |
| Copeland [31]          | H41  | 0.00391  | 5.88e-5  |        |     |                |

Continued on next page
| Submitter                  | Case | $\sigma$ $(1/(\Omega \text{ cm})$ | $\kappa$ g/(s cm K) | $\eta$ g/(s cm) | $D$ cm$^2$/s | $dE/dx$ (eV/cm) |
|---------------------------|------|----------------------------------|---------------------|----------------|-------------|----------------|
| Kang, Dai (QE)            | H41  | 3.94e6                           | 2.72e8              | 0.232          | 6.97e-4     |                |
| Copeland [29]             | H41  | 4.8e5                            | 1.99e10             | 4.51e8         | 1.43e9      | 4.55e9         |
| Clérouin (PIJ)            | H42  | 3.51e6                           | 7.46e6              | 3.82e10        | 4.54e8      | 1.44e9         |
| Hansen (Bemuze)           | H42  | 5.62e6                           | 2.94e10             | 3.69e10        | 4.54e8      | 1.44e9         |
| Hansen (Muze-k)           | H42  | 7.46e6                           | 3.82e10             | 3.69e10        | 4.54e8      | 1.44e9         |
| Hansen (Muze-s)           | H42  | 7.22e6                           | 3.69e10             | 3.69e10        | 4.54e8      | 1.44e9         |
| Clérouin (OFMD)           | H42  | 2.11e6                           | 1.2e10              | 6.80e-4        |             |                |
| Haxhimali, Rudd           | H42  | 19.5                             | 0.117               | 2.72e8         | 1.43e9      | 4.55e9         |
| Copeland [28]             | H42  | 0.8224                           | 3.56e-4             | 4.54e8         | 1.44e9      | 4.57e9         |
| Copeland [30]             | H42  | 0.8224                           | 3.56e-4             | 4.54e8         | 1.44e9      | 4.57e9         |
| Copeland [31]             | H42  | 0.8224                           | 3.56e-4             | 4.54e8         | 1.44e9      | 4.57e9         |
| Hou (AAHNC)               | H42  | 0.103                            | 7.00e-4             | 4.54e8         | 1.44e9      | 4.57e9         |
| Kang (PIMD)               | H42  |                                  |                     | 8.13e-4        |             |                |
| Kang, Dai (QE)            | H42  | 2.1e6                            | 8.06e-4             | 4.54e8         | 1.44e9      | 4.57e9         |
| Copeland [29]             | H42  | 4.8e5                            | 2.72e9              | 3.69e10        | 4.54e8      | 1.44e9         |
| Clérouin (PIJ)            | H43  | 1.51e6                           | 8.58e10             | 0.548          | 4.52e8      | 1.43e9         |
| Hansen (Bemuze)           | H43  | 3.76                             | 1.78e11             | 1.78e11        | 4.52e8      | 1.43e9         |
| Hansen (Muze-k)           | H43  | 3.83e6                           | 1.84e11             | 1.84e11        | 4.54e8      | 1.44e9         |
| Hansen (Muze-s)           | H43  | 3.76                             | 1.78e11             | 1.78e11        | 4.54e8      | 1.44e9         |
| Baalrud                   | H43  | 0.528                            | 0.00795             | 0.528          | 4.52e8      | 1.43e9         |
| Clérouin (OFMD)           | H43  | 1.54e6                           | 8.74e10             | 0.468          | 4.52e8      | 1.43e9         |
| Daligault                 | H43  | 0.547                            | 0.00843             | 0.547          | 4.52e8      | 1.43e9         |
| Haxhimali, Rudd           | H43  | 0.735                            | 0.00843             | 0.735          | 4.52e8      | 1.43e9         |
| Starrett, Saumon          | H43  | 1.43e6                           | 8.02e10             | 1.43e6         | 4.52e8      | 1.43e9         |
| Copeland [28]             | H43  | 6.32                             | 0.00379             | 6.32           | 4.54e8      | 1.44e9         |
| Copeland [30]             | H43  | 0.371                            | 0.00608             | 0.371          | 4.54e8      | 1.44e9         |
| Copeland [31]             | H43  | 0.513                            | 0.00825             | 0.513          | 4.54e8      | 1.44e9         |
| Hou (AAHNC)               | H43  | 0.403                            | 0.0073              | 0.403          | 4.54e8      | 1.44e9         |
| Copeland [29]             | H43  | 4.85e5                           | 2.7e10              | 2.7e10         | 4.52e8      | 1.44e9         |
| Hayes                     | H44  |                                  |                     | 7.13e9         | 2.54e9      | 3.02e9         |
| Clérouin (PIJ)            | H44  | 7.66e5                           | 4.13e11             | 4.13e11        | 3.02e9      | 1.02e10        |
| Hansen (Bemuze)           | H44  | 3.363                            | 4.93e11             | 4.93e11        | 3.02e9      | 1.02e10        |
| Hansen (Muze-k)           | H44  | 3.563                            | 4.56e11             | 4.56e11        | 3.02e9      | 1.02e10        |
| Hansen (Muze-s)           | H44  | 3.463                            | 4.53e11             | 4.53e11        | 3.02e9      | 1.02e10        |
| Baalrud                   | H44  | 14.3                             | 0.212               | 14.3           | 4.53e11     | 1.38e9         |
| Clérouin (OFMD)           | H44  | 7.725                            | 4.17e11             | 4.17e11        | 1.38e9      | 1.38e9         |
| Daligault                 | H44  | 14.5                             | 0.222               | 14.5           | 4.35e11     | 1.38e9         |
| Haxhimali, Rudd           | H44  | 15.6                             | 0.222               | 15.6           | 4.35e11     | 1.38e9         |
| Starrett, Saumon          | H44  | 1.11e6                           | 4.27e11             | 4.27e11        | 1.38e9      | 1.38e9         |
| Submitter       | Case | $\sigma$ (l/(Ω cm)) | $\kappa$ (erg/(s cm K)) | $\eta$ (g/(s cm)) | $D$ (cm/s) | $dE/dx$ (eV/cm) |
|-----------------|------|---------------------|-------------------------|-----------------|-----------|-----------------|
|                 |      |                     |                         |                 |           | 1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV | 100 MeV | 1 GeV |
| Copeland [28]   | H44  | 22.2                | 0.133                   |                 |           |       |       |        |       |        |         |       |
| Copeland [30]   | H44  | 16.5                | 0.257                   |                 |           |       |       |        |       |        |         |       |
| Copeland [31]   | H44  | 17.2                | 0.269                   |                 |           |       |       |        |       |        |         |       |
| Copeland [29]   | H44  | 8.8e5               | 2.31e11                 |                 |           |       |       |        |       |        |         |       |
| Hayes           | H45  |                     |                         |                 |           | 2.11e9 | 1.26e9 | 3.03e9 | 4.46e9 |         |         |       |
| Clérouin (PIJ)  | H45  | 5.82e6              | 1.62e13                 | 1.27e3          | 15.6      |       |       |        |       |        |         |       |
| Hansen (Bemuze) | H45  | 1.15e7              | 2.19e13                 |                 |           | 9.79e7 | 3.09e8 | 9.7e8  | 2.84e8 | 4.91e8  | 9.27e8  | 1.26e8 |
| Hansen (Muze-k) | H45  | 1.16e7              | 2.2e13                  | 1.6e8           |           | 9.91e8 | 2.9e9  | 4.97e9 | 9.31e8 | 1.26e8  |         |       |
| Hansen (Muze-s) | H45  | 1.16e7              | 2.2e13                  | 1.6e8           |           | 9.91e8 | 2.9e9  | 4.97e9 | 9.31e8 | 1.26e8  |         |       |
| Baalrud         | H45  |                     |                         |                 |           | 1.49e3 | 19.3   |        |        |         |         |       |
| Clérouin (OFMD)| H45  | 5.8e6               | 1.6e13                  | 4.3              | 24.9      |       |       |        |       |        |         |       |
| Hansen (Muze-k) | H45  |                     |                         |                 |           | 1.29e3 |         |        |       |         |         |       |
| Hansen (Muze-s) | H45  |                     |                         |                 |           | 1.33e3 | 18.2   |        |       |         |         |       |
| Hansen (Bemuze) | C11  | 7.95                | 2.75e3                  |                 |           | 3.23e7 | 1.05e8 | 9.69e7 | 2.56e7 | 4.37e6  | 6.05e5  | 7.71e4 |
| Hansen (Muze-s) | C11  | 3.8e-7              | 2.62e-4                 |                 |           | 2.72e7 | 8.5e7  | 9.7e7  | 2.49e7 | 4.31e6  | 5.99e5  | 7.65e4 |
| Hansen (Bemuze) | C11  |                     |                         |                 |           | 8.42e-4|         |        |       |         |         |       |
| Hansen (Muze-k) | C11  |                     |                         |                 |           | 0.00783| 0.047  |        |       |         |         |       |
| Hansen (Muze-s) | C11  |                     |                         |                 |           | 1.89e-4| 0.0031 |        |       |         |         |       |
| Hansen (Bemuze) | C11  |                     |                         |                 |           | 9.6e-4 | 0.0152 |        |       |         |         |       |
| Hansen (Muze-k) | C11  |                     |                         |                 |           | 61.2   | 3.56e4 |        |       |         |         |       |
| Hansen (Muze-s) | C11  |                     |                         |                 |           | 284.   | 8.77e5 | 0.00211| 0.036  |         |         |       |
| Hansen (Bemuze) | C12  | 432.                | 1.14e6                  |                 |           | 2.67e7 | 8.19e7 | 9.48e7 | 2.53e7 | 4.35e6  | 6.03e5  | 7.69e4 |
| Hansen (Muze-k) | C12  | 451.                | 1.17e6                  |                 |           | 3.34e7 | 1.03e8 | 1.8e7  | 2.59e7 | 4.41e6  | 6.08e5  | 7.74e4 |
| Hansen (Muze-s) | C12  | 89.8                | 4.12e5                  |                 |           | 2.4e7  | 7.22e7 | 8.82e7 | 2.49e7 | 4.31e6  | 5.98e5  | 7.64e4 |
| Hansen (Bemuze) | C12  |                     |                         |                 |           | 0.00349|         |        |       |         |         |       |
| Hansen (Muze-k) | C12  |                     |                         |                 |           | 0.0069 | 0.0414 |        |       |         |         |       |
| Hansen (Muze-s) | C12  |                     |                         |                 |           | 0.00215| 0.0349 |        |       |         |         |       |
| Hansen (Muze-k) | C12  |                     |                         |                 |           | 0.00525| 0.0855 |        |       |         |         |       |
| Hansen (Muze-s) | C12  |                     |                         |                 |           | 0.0026 | 0.046  |        |       |         |         |       |
| Hansen (Bemuze) | C13  | 586.                | 1.16e6                  |                 |           | 1.5e7  | 4.44e7 | 8.59e7 | 2.37e7 | 4.27e6  | 5.96e5  | 7.61e4 |
| Hansen (Muze-k) | C13  | 2.55e3              | 1.18e8                  |                 |           | 2.25e7 | 6.66e7 | 1.27e8 | 3.05e7 | 4.85e6  | 6.5e5   | 8.14e4 |
| Hansen (Muze-s) | C13  | 2.64e3              | 1.21e8                  |                 |           | 2.21e7 | 6.56e7 | 1.25e8 | 3.02e7 | 4.83e6  | 6.48e5  | 8.11e4 |
| Hansen (Muze-k) | C13  | 2.49e3              | 1.16e8                  |                 |           | 2.21e7 | 6.56e7 | 1.25e8 | 3.02e7 | 4.83e6  | 6.48e5  | 8.11e4 |
| Submitter                  | Case | $\sigma$ | $\kappa$ | $\eta$ | $D$ | $dE/dx$ (eV/cm) |
|---------------------------|------|----------|----------|--------|-----|-----------------|
| Copeland [28]             | C13  | 1/($\Omega$ cm) | 0.0158 | 0.0948 |     |                 |
| Copeland [30]             | C13  | 1/($\Omega$ cm) | 0.00569 | 0.0927 |     |                 |
| Copeland [31]             | C13  | 1/($\Omega$ cm) | 0.00951 | 0.156  |     |                 |
| Hou (AAHNC)               | C13  | 1/($\Omega$ cm) | 0.0073  | 0.141  |     |                 |
| Copeland [29]             | C13  | 1/($\Omega$ cm) | 5.12e3  | 9.88e7 |     |                 |
| Clérouin (PIJ)            | C14  | 1.34e10  | 2.05e10  | 0.0433 | 0.835 |                 |
| Hansen (Bemuze)           | C14  | 2.48e4   | 1.34e10  | 2.59e6 | 8.1e6 | 2.31e7          |
| Hansen (Muze-k)           | C14  | 2.61e4   | 1.39e10  | 2.73e6 | 8.52e6 | 2.42e7          |
| Hansen (Muze-s)           | C14  | 2.59e4   | 1.38e10  | 2.73e6 | 8.52e6 | 2.42e7          |
| Haxhimali, Rudd           | C14  | 1.39e10  | 5.03e4   | 1.41e5 | 4.44e5 | 1.39e6          |
| Copeland [28]             | C14  | 1.39e10  | 6.7e5    | 3.42e12 | 3.8 | 47. |
| Hansen (Bemuze)           | C15  | 4.32e5   | 2.4e12   | 1.43e5 | 4.1e5  | 1.41e6          |
| Hansen (Muze-k)           | C15  | 4.39e5   | 2.43e12  | 1.43e5 | 4.51e5 | 1.41e6          |
| Hansen (Muze-s)           | C15  | 4.38e5   | 2.43e12  | 1.43e5 | 4.51e5 | 1.41e6          |
| Haxhimali, Rudd           | C15  | 3.73     | 3.76     | 52.8   | 52.6  |                 |
| Copeland [28]             | C15  | 5.72     | 3.84     | 34.3   | 52.8  |                 |
| Copeland [30]             | C15  | 3.76     | 3.76     | 52.6   | 52.6  |                 |
| Copeland [31]             | C15  | 8.2e5    | 2.54e12  | 0.00645 | 2.73e-4 |                 |
| Clérouin (PIJ)            | C21  | 1.14e6   | 2.01e3   | 1.2e8  | 4.47e8 | 9.06e8          |
| Hansen (Muze-k)           | C21  | 4.01e3   | 6.45     | 1.14e8 | 4.43e8 | 8.34e8          |
| Hansen (Muze-s)           | C21  | 3.54e6   | 6.6e3    | 1.14e8 | 4.43e8 | 8.34e8          |
| Clérouin (OFMD)           | C21  | 1.54e6   | 2.71e3   | 0.0017 | 8.00e-4 |                 |
| Haxhimali, Rudd           | C21  | 0.00128  | 0.00128  | 0.00128 | 0.00128 |                 |
| Copeland [28]             | C21  | 0.362    | 0.362    | 0.217  | 0.217 |                 |
| Copeland [30]             | C21  | 1.40e-4  | 1.40e-4  | 2.19e-4 | 2.19e-4 |                 |
| Copeland [31]             | C21  | 8.44e-4  | 8.44e-4  | 0.00128 | 0.00128 |                 |
| Copeland [29]             | C21  | 406.     | 406.     | 2.3e5  | 2.3e5  |                 |
| Clérouin (PIJ)            | C22  | 7.09e6   | 1.26e3   | 0.00395 | 0.00484 |                 |
| Desjarlais                | C22  | 850.     | 850.     | 3.7e6  | 3.7e6  |                 |
| Hansen (Bemuze)           | C22  | 4.41e5   | 78.9     | 1.15e8 | 4.04e8 | 8.42e8          |
| Hansen (Muze-k)           | C22  | 1.26e6   | 253.     | 1.21e8 | 4.23e8 | 8.99e8          |
| Hansen (Muze-s)           | C22  | 1.79e6   | 394.     | 1.05e8 | 3.72e8 | 7.69e8          |

Continued on next page
| Submitter                  | Case | $\sigma$ (l/(Ω cm)) | $\kappa$ (erg/(s cm K)) | $\eta$ (g/(s cm)) | $D$ (cm^2/s) | $dE/dx$ (eV/cm) |
|---------------------------|------|---------------------|------------------------|-------------------|-------------|----------------|
| Clérouin (OFMD)           | C22  | 1.3e3               | 7.25e6                 | 0.0087            | 0.0067      |                |
| Haxhimali, Rudd           | C22  | 7.25e6              | 0.124                  | 0.0063            |             |                |
| Sjostrom (TFMD)           | C22  | 0.0063              | 0.0066                 |                   |             |                |
| Copeland [28]             | C22  | 0.124               | 0.0066                 |                   |             |                |
| Copeland [30]             | C22  | 0.00163             | 0.00266                |                   |             |                |
| Copeland [31]             | C22  | 0.00719             | 0.0114                 |                   |             |                |
| Copeland [29]             | C22  | 626.                | 3.58e6                 |                   |             |                |
| Grabowski                 | C23  | 1.3e3               | 7.25e6                 | 0.0087            | 0.0067      |                |
| Clérouin (PIJ)            | C23  | 4.3e3               | 1.71e8                 | 0.0204            | 0.0321      | 3.75e8 7.86e8 2.51e8 4.19e7 |
| Dharmawardana             | C23  | 1.9e3               |                        |                   |             |                |
| Hansen (Bemuze)           | C23  | 4.55e3              | 2.12e8                 | 7.12e7 2.19e8 5.67e8 2.18e8 4.07e7 5.76e6 7.41e5 |
| Hansen (Muze-k)           | C23  | 4.91e3              | 2.24e8                 | 8.88e7 2.76e8 7.46e8 2.57e8 4.4e7 6.07e6 7.72e5 |
| Hansen (Muze-s)           | C23  | 4.54e3              | 2.12e8                 | 8.77e7 2.72e8 7.33e8 2.55e8 4.38e7 6.05e6 7.7e5 |
| Baalrud                   | C23  | 1.9e3               | 9.23e7                 | 0.022 0.0362      |             |                |
| Daligault                 | C23  | 0.0971              | 0.0583                 |                   |             |                |
| Haxhimali, Rudd           | C23  | 0.0161              | 0.0264                 |                   |             |                |
| Sjostrom (TFMD)           | C23  | 0.0356              | 0.0572                 |                   |             |                |
| Starrett, Saumon          | C23  | 0.0203              | 0.0372                 |                   |             |                |
| Copeland [28]             | C23  | 3.19e3              | 9.23e7                 | 0.022 0.0362      |             |                |
| Copeland [30]             | C23  | 0.0971              | 0.0583                 |                   |             |                |
| Copeland [31]             | C23  | 0.0161              | 0.0264                 |                   |             |                |
| Hou (AAHNC)               | C23  | 0.0356              | 0.0572                 |                   |             |                |
| Copeland [29]             | C23  | 6.25e3              | 1.75e8                 | 0.022 0.0362      |             |                |
| Clérouin (PIJ)            | C24  | 5.02e4              | 2.7e10                 | 0.111 0.201       |             |                |
| Dharmawardana             | C24  | 5.85e4              |                        | 0.022 0.0362      |             |                |
| Hansen (Bemuze)           | C24  | 3.59e4              | 1.91e10                | 1.66e7 5.19e7 1.5e8 2.46e8 4.67e7 6.36e6 8.02e5 |
| Hansen (Muze-k)           | C24  | 3.62e4              | 1.92e10                | 1.88e7 5.88e7 1.7e8 2.72e8 4.9e7 6.58e6 8.23e5 |
| Hansen (Muze-s)           | C24  | 3.56e4              | 1.9e10                 | 1.87e7 5.87e7 1.7e8 2.71e8 4.9e7 6.58e6 8.22e5 |
| Haxhimali, Rudd           | C24  | 0.152               |                        |                   |             |                |
| Sjostrom (SDMD)           | C24  | 0.22                |                        |                   |             |                |
| Sjostrom (TFMD)           | C24  | 0.22                |                        |                   |             |                |
| Copeland [28]             | C24  | 0.216               | 0.129                  |                   |             |                |
| Copeland [30]             | C24  | 0.12                | 0.195                  |                   |             |                |
| Copeland [31]             | C24  | 0.149               | 0.241                  |                   |             |                |
| Hou (AAHNC)               | C24  | 0.097               | 0.184                  |                   |             |                |
| Copeland [29]             | C24  | 6.83e4              | 1.88e10                | 1.15e6 3.64e6 1.14e7 3.21e7 4.37e7 6.55e6 8.24e5 |
| Clérouin (PIJ)            | C25  | 8.28e5              | 4.24e12                | 5.33 6.6        |             |                |
| Hansen (Bemuze)           | C25  | 5.5e5               | 3.03e12                | 1.17e6 3.68e6 1.15e7 3.24e7 4.4e7 6.57e6 8.25e5 |
| Hansen (Muze-k)           | C25  | 5.46e5              | 3.01e12                | 1.17e6 3.68e6 1.15e7 3.24e7 4.4e7 6.57e6 8.25e5 |

Continued on next page
| Submitter                  | Case | $\sigma$ (l/Ω cm) | $\kappa$ (erg/s cm K) | $\eta$ (g/s cm) | $D$ (cm²/s) | $dE/dx$ (eV/cm) |
|---------------------------|------|------------------|-----------------------|-----------------|-------------|-----------------|
| Hansen (Muze-s)           | C25  | 5.45e5           | 3.01e12               |                 | 1.17e6      |                 |
| Haxhimali, Rudd           | C25  | 5.38             | 6.18                 |                 | 3.68e6      |                 |
| Copeland [28]             | C25  | 5.78             | 8.41                 |                 | 1.15e7      |                 |
| Copeland [30]             | C25  | 5.78             | 8.41                 |                 | 3.24e7      |                 |
| Copeland [31]             | C25  | 5.41             | 7.91                 |                 | 4.4e7       |                 |
| Copeland [29]             | C25  | 1.02e6           | 3.16e12              |                 | 6.57e6      |                 |
| Clérouin (PIJ)            | C25  | 1.124            | 6.36e6               |                 | 8.25e5      |                 |
| Hansen (Bemuze)           | C25  | 1.03e4           | 5.83e6               |                 | 3.75e8      |                 |
| Hansen (Muze-k)           | C25  | 6.54e4           | 3.65e7               |                 | 5.43e7      |                 |
| Hansen (Muze-s)           | C25  | 5.29e4           | 2.96e7               |                 | 7.26e6      |                 |
| Clérouin (OFMD)           | C31  | 2.4e4            | 1.36e7               |                 | 7.93e6      |                 |
| Haxhimali, Rudd           | C31  | 1.19e5           |                      |                 | 8.25e5      |                 |
| Sjostrom (TFMD)           | C31  | 11.9             | 0.714                |                 | 5.43e7      |                 |
| Copeland [28]             | C31  | 1.46e-5          | 2.26e6               |                 | 7.26e6      |                 |
| Copeland [30]             | C31  | 0.00131          | 1.94e-4              |                 | 7.26e6      |                 |
| Copeland [29]             | C31  | 4.03e3           | 2.28e6               |                 | 7.26e6      |                 |
| Clérouin (PIJ)            | C31  | 1.124            | 6.35e7               |                 | 7.26e6      |                 |
| Hansen (Bemuze)           | C31  | 8.22e3           | 4.65e7               |                 | 7.26e6      |                 |
| Hansen (Muze-k)           | C31  | 1.34e4           | 7.55e7               |                 | 7.26e6      |                 |
| Hansen (Muze-s)           | C31  | 1.15e4           | 6.49e7               |                 | 7.26e6      |                 |
| Bhalla                    | C31  | 1.61e4           | 9.01e7               |                 | 7.26e6      |                 |
| Hansen (Bemuze)           | C32  | 8.22e3           | 4.65e7               |                 | 7.26e6      |                 |
| Hansen (Muze-k)           | C32  | 1.34e4           | 7.55e7               |                 | 7.26e6      |                 |
| Hansen (Muze-s)           | C32  | 1.15e4           | 6.49e7               |                 | 7.26e6      |                 |
| Clérouin (OFMD)           | C32  | 1.24e4           | 7.05e7               |                 | 7.26e6      |                 |
| Daligault                 | C32  | 0.0422           | 8.53e-4              |                 | 7.26e6      |                 |
| Haxhimali, Rudd           | C32  | 0.0256           |                      |                 | 7.26e6      |                 |
| Sjostrom (KSMD)           | C32  | 0.00101          |                      |                 | 7.26e6      |                 |
| Sjostrom (TFMD)           | C32  | 6.90e-4          |                      |                 | 7.26e6      |                 |
| Starrett, Saumon          | C32  | 1.17e4           | 6.34e7               |                 | 7.26e6      |                 |
| Copeland [28]             | C32  | 3.78             | 0.227                |                 | 7.26e6      |                 |
| Copeland [30]             | C32  | 0.00217          | 3.39e-4              |                 | 7.26e6      |                 |
| Copeland [31]             | C32  | 0.00892          | 0.00136              |                 | 7.26e6      |                 |
| Hou (AAHNC)               | C32  | 0.019            | 6.00e-4              |                 | 7.26e6      |                 |
| Copeland [29]             | C32  | 4.08e3           | 2.32e7               |                 | 7.26e6      |                 |
| Grabowski                 | C33  | 0.0587           | 0.0075               |                 | 7.26e6      |                 |
| Clérouin (PIJ)            | C33  | 9.28e3           | 5.09e8               |                 | 7.26e6      |                 |
| Dharma-wardana            | C33  | 7.44e3           |                      |                 | 7.26e6      |                 |
| Hansen (Bemuze)           | C33  | 1.31e4           | 6.68e8               |                 | 7.26e6      |                 |

Continued on next page
| Submitter                     | Case | $\sigma$ l/(Ω cm) | $\kappa$ erg/(s cm K) | $\eta$ g/(s cm) | $D$ cm$^2$/s | $dE/dx$ (eV/cm) | 1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV | 100 MeV | 1 GeV |
|-------------------------------|------|-------------------|-----------------------|-----------------|-------------|----------------|-------|-------|--------|-------|-------|--------|-------|
| Hansen (Muze-k)               | C33  | 1.35e4            | 6.85e8                |                 |             |                |       |       |        |       |       |        |       |
| Hansen (Muze-s)               | C33  | 1.23e4            | 6.32e8                |                 |             |                |       |       |        |       |       |        |       |
| Baalrud                       | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Clérouin (OFMD)               | C33  | 9.43e3            | 5.15e8                |                 |             |                |       |       |        |       |       |        |       |
| Daligault                     | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Haxhimali, Rudd               | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Sjostrom (TFMD)               | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Starrett, Saumon              | C33  | 1.33e4            | 4.9e8                 |                 |             |                |       |       |        |       |       |        |       |
| Copeland [28]                 | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Copeland [30]                 | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Copeland [31]                 | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Hou (AAHNC)                   | C33  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Copeland [29]                 | C33  | 7.91e3            | 4.17e8                |                 |             |                |       |       |        |       |       |        |       |
| Grabowski                     | C34  |                   |                       |                 |             |                |       |       |        |       |       |        |       |
| Clérouin (PIJ)                | C34  | 7.54e4            | 3.72e10               | 0.342           | 0.0557      |                |       |       |        |       |       |        |       |
| Dharma-wardana                | C34  | 1.66e4            |                       |                 |             |                |       |       |        |       |       |        |       |
| Hansen (Bemuze)               | C34  | 5.48e4            | 2.92e10               | 8.67          | 5.67e8      |                |       |       |        |       |       |        |       |
| Hansen (Muze-k)               | C34  | 5.53e4            | 2.94e10               | 9.67e7        | 9.04e8      |                |       |       |        |       |       |        |       |
| Hansen (Muze-s)               | C34  | 5.37e4            | 2.87e10               | 9.67e7        | 9.02e8      |                |       |       |        |       |       |        |       |
| Baalrud                       | C34  |                   |                       | 0.342         | 0.0562      |                |       |       |        |       |       |        |       |
| Clérouin (OFMD)               | C34  | 7.74e4            | 3.79e10               | 0.38           | 0.064       |                |       |       |        |       |       |        |       |
| Daligault                     | C34  | 3.43             | 0.0589                |               |             |                |       |       |        |       |       |        |       |
| Haxhimali, Rudd               | C34  | 4.78             |                       |               |             |                |       |       |        |       |       |        |       |
| Sjostrom (TFMD)               | C34  |                   |                       |               |             |                |       |       |        |       |       |        |       |
| Starrett, Saumon              | C34  | 4.6e4             | 1.1e10                |               |             |                |       |       |        |       |       |        |       |
| Copeland [28]                 | C34  | 1.09             | 0.0652                |               |             |                |       |       |        |       |       |        |       |
| Copeland [30]                 | C34  | 0.297            | 0.0485                |               |             |                |       |       |        |       |       |        |       |
| Copeland [31]                 | C34  | 0.466            | 0.076                 |               |             |                |       |       |        |       |       |        |       |
| Hou (AAHNC)                   | C34  | 0.329            | 0.0408                |               |             |                |       |       |        |       |       |        |       |
| Copeland [29]                 | C34  | 1.e5             | 3.03e10               |               |             |                |       |       |        |       |       |        |       |
| Clérouin (PIJ)                | C35  | 1.07e6           | 5.49e12               | 7.61          | 1.24        |                |       |       |        |       |       |        |       |
| Dharma-wardana                | C35  | 10.5             |                       |               |             |                |       |       |        |       |       |        |       |
| Hansen (Bemuze)               | C35  | 7.13e5           | 3.92e12               | 8.76e6        | 2.75e7      |                |       |       |        |       |       |        |       |
| Hansen (Muze-k)               | C35  | 7.31e5           | 3.99e12               | 8.86e6        | 2.8e7       |                |       |       |        |       |       |        |       |
| Hansen (Muze-s)               | C35  | 7.29e5           | 3.99e12               | 8.86e6        | 2.8e7       |                |       |       |        |       |       |        |       |
| Baalrud                       | C35  | 1.e5             | 3.03e10               |               |             |                |       |       |        |       |       |        |       |
| Clérouin (OFMD)               | C35  | 1.09e6           | 5.59e12               | 9.7           | 1.41        |                |       |       |        |       |       |        |       |
| Haxhimali, Rudd               | C35  | 8.89             |                       |               |             |                |       |       |        |       |       |        |       |
| Copeland [28]                 | C35  | 11.6             | 0.697                 |               |             |                |       |       |        |       |       |        |       |

Continued on next page
| Submitter                  | Case | \( \sigma \) \( \text{I/(\Omega \text{ cm})} \) | \( \kappa \) \( \text{erg/(s cm K)} \) | \( \eta \) \( \text{g/(s cm)} \) | \( D \) \( \text{cm}^2/\text{s} \) | \( \text{dE/dx} \) (\( \text{eV/cm} \)) |
|---------------------------|------|---------------------------------|---------------------------------|---------------------------------|-----------------|---------------------------------|
| Copeland [30]             | C35  | 10.                             | 1.55                            |                                |                 |                                 |
| Copeland [31]             | C35  | 8.87                            | 1.36                            |                                |                 |                                 |
| Hou (AAHNC)               | C35  | 2.66                            | 0.531                           |                                |                 |                                 |
| Copeland [29]             | C35  | 1.33e6                          | 4.03e12                         |                                |                 |                                 |
| Crérouin (PIJ)            | C41  | 8.91e4                          | 5.06e7                          |                                |                 |                                 |
| Hansen (Bemuze)           | C41  | 5.81e4                          | 3.28e7                          | 3.85e8                          | 1.22e9          | 3.93e9                          | 1.10e10           | 3.04e9                         | 4.76e8             | 6.41e7 |
| Hansen (Muze-k)           | C41  | 3.38e6                          | 1.48e9                          | 4.01e8                          | 1.27e9          | 4.07e9                          | 1.21e10           | 3.22e9                         | 4.9e8              | 6.55e7 |
| Hansen (Muze-s)           | C41  | 3.2e6                           | 1.41e9                          | 4.01e8                          | 1.27e9          | 4.07e9                          | 1.21e10           | 3.22e9                         | 4.9e8              | 6.55e7 |
| Crérouin (OFMD)           | C41  | 3.03e5                          | 1.72e8                          |                                |                 |                                 |
| Copeland [28]             | C41  | 230.                            | 1.38                            |                                |                 |                                 |
| Copeland [30]             | C41  | 3.32e-6                         | 5.14e-8                         |                                |                 |                                 |
| Copeland [31]             | C41  | 0.00263                         | 3.87e-5                         |                                |                 |                                 |
| Copeland [29]             | C41  | 4.03e4                          | 2.28e7                          |                                |                 |                                 |
| Crérouin (PIJ)            | C42  | 8.91e4                          | 5.06e8                          |                                |                 |                                 |
| Hansen (Bemuze)           | C42  | 3.49e4                          | 1.98e8                          | 3.84e8                          | 1.22e9          | 3.93e9                          | 1.10e10           | 3.03e9                         | 4.75e8             | 6.41e7 |
| Hansen (Muze-k)           | C42  | 2.51e5                          | 1.41e9                          | 4.01e8                          | 1.27e9          | 4.07e9                          | 1.21e10           | 3.22e9                         | 4.9e8              | 6.55e7 |
| Hansen (Muze-s)           | C42  | 2.39e5                          | 1.35e9                          | 4.01e8                          | 1.27e9          | 4.07e9                          | 1.21e10           | 3.22e9                         | 4.9e8              | 6.55e7 |
| Crérouin (OFMD)           | C42  | 1.28e5                          | 7.26e8                          |                                |                 |                                 |
| Haxhimali, Rudd           | C42  | 2.12e4                          |                                 |                                |                 |                                 |
| Copeland [28]             | C42  | 72.8                            | 0.437                           |                                |                 |                                 |
| Copeland [30]             | C42  | 0.00105                         | 1.62e-5                         |                                |                 |                                 |
| Copeland [31]             | C42  | 0.0159                          | 2.38e-4                         |                                |                 |                                 |
| Copeland [29]             | C42  | 4.03e4                          | 2.28e8                          |                                |                 |                                 |
| Crérouin (PIJ)            | C43  | 8.9e4                           | 5.05e9                          | 0.464                           | 0.00151         |                                 |
| Hansen (Bemuze)           | C43  | 6.24e4                          | 3.51e9                          | 3.85e8                          | 1.22e9          | 3.92e9                          | 9.91e9            | 3.03e9                         | 4.75e8             | 6.41e7 |
| Hansen (Muze-k)           | C43  | 7.68e4                          | 4.3e9                           | 4.02e8                          | 1.27e9          | 4.07e9                          | 1.21e10           | 3.22e9                         | 4.9e8              | 6.55e7 |
| Hansen (Muze-s)           | C43  | 7.43e4                          | 4.16e9                          | 4.01e8                          | 1.27e9          | 4.07e9                          | 1.21e10           | 3.22e9                         | 4.9e8              | 6.55e7 |
| Baalrud                   | C44  | 0.11                            | 0.00162                         |                                |                 |                                 |
| Crérouin (OFMD)           | C44  | 9.72e4                          | 5.52e9                          | 0.43                            | 0.0017          |                                 |
| Daligault                 | C44  | 0.414                           | 0.00175                         |                                |                 |                                 |
| Haxhimali, Rudd           | C44  | 0.342                           |                                 |                                |                 |                                 |
| Starrett, Saumon          | C44  | 6.43e4                          | 3.49e9                          |                                |                 |                                 |
| Copeland [28]             | C44  | 23.1                            | 0.139                           |                                |                 |                                 |
| Copeland [30]             | C44  | 0.0481                          | 7.65e-4                         |                                |                 |                                 |
| Copeland [31]             | C44  | 0.125                           | 0.00195                         |                                |                 |                                 |
| Hou (AAHNC)               | C44  | 0.192                           | 0.0017                          |                                |                 |                                 |
| Copeland [29]             | C44  | 4.18e4                          | 2.37e9                          |                                |                 |                                 |
| Grabowski                 | C44  | 1.08e5                          | 5.57e10                         | 1.1                             | 0.0163          |                                 |

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Table A.3 – continued from previous page

| Submitter                  | Case | $\sigma$ | $\kappa$ | $\eta$ | $D$ | $dE/dx$ (eV/cm) |
|----------------------------|------|---------|---------|-------|-----|-----------------|
| Hansen (Bemuze)            | C44  | 1.05e5  | 5.68e10 |       |     | 2.89e8          |
| Hansen (Muze-k)            | C44  | 1.16e5  | 6.14e10 |       |     | 3.33e8          |
| Hansen (Muze-s)            | C44  | 1.12e5  | 5.99e10 |       |     | 3.22e9          |
| Baalrud                    | C44  | 1.       | 1.1     |       |     | 0.0179          |
| Clérouin (OFMD)            | C44  | 1.03e5  | 5.37e10 | 1.3   | 0.0171|                |
| Daligault                  | C44  | 1.17    |         | 0.0186|     |                 |
| Haxhimali, Rudd            | C44  | 1.55    |         |       |     |                 |
| Starrett, Saumon           | C44  | 1.02e5  | 3.08e10 |       |     |                 |
| Copeland [28]              | C44  | 8.54    |         | 0.0512|     |                 |
| Copeland [30]              | C44  | 0.712   |         | 0.0117|     |                 |
| Copeland [31]              | C44  | 1.36    |         | 0.0218|     |                 |
| Hou (AAHNC)                | C44  | 0.776   |         | 0.0157|     |                 |
| Copeland [29]              | C44  | 1.34e5  | 5.86e10 |       |     |                 |
| Clérouin (PIJ)             | C45  | 1.38e6  | 6.97e12 | 13.1  | 0.252|                |
| Hansen (Bemuze)            | C45  | 1.01e6  | 5.49e12 |       |     | 5.71e7          |
| Hansen (Muze-k)            | C45  | 1.05e6  | 5.71e12 |       |     | 5.94e7          |
| Hansen (Muze-s)            | C45  | 1.05e6  | 5.68e12 |       |     | 5.94e7          |
| Baalrud                    | C45  | 1.       | 15.     | 0.242 |     |                 |
| Clérouin (OFMD)            | C45  | 1.34e6  | 6.84e12 | 17.8  | 0.253|                |
| Haxhimali, Rudd            | C45  | 1.       | 17.9    |       |     |                 |
| Copeland [28]              | C45  | 22.2    |         | 0.133 |     |                 |
| Copeland [30]              | C45  | 17.3    |         | 0.275 |     |                 |
| Copeland [31]              | C45  | 17.4    |         | 0.274 |     |                 |
| Hou (AAHNC)                | C45  | 8.69    |         | 0.171 |     |                 |
| Copeland [29]              | C45  | 1.72e6  | 5.59e12 |       |     |                 |
| Clérouin (PIJ)             | CH11 | 211.    | 1.2e5   | 3.51e-4 | 0.0105|                |
| Haxhimali, Rudd            | CH11 | 9.50e-4|         |       |     |                 |
| Marciante                  | CH11 | 0.        | 0.0255 |     |     |                 |
| Copeland [28]              | CH11 | 0.00842 |         | 0.104 |     |                 |
| Copeland [30]              | CH11 | 2.01e-4 |         | 0.00742|     |                 |
| Copeland [31]              | CH11 | 9.24e-4 |         | 0.0312|     |                 |
| Clérouin (PIJ)             | CH12 | 312.    | 1.15e6  | 0.00268 | 0.13|                |
| Haxhimali, Rudd            | CH12 | 0.00456 |         |       |     |                 |
| Marciante                  | CH12 | 0.        | 0.24 |     |     |                 |
| Copeland [28]              | CH12 | 0.00777 |         | 0.105 |     |                 |
| Copeland [30]              | CH12 | 0.00286 |         | 0.117 |     |                 |
| Copeland [31]              | CH12 | 0.0066  |         | 0.26  |     |                 |
| Clérouin (PIJ)             | CH13 | 4.66e3  | 1.76e8  | 0.01  | 0.63 |                |
| Haxhimali, Rudd            | CH13 | 0.0136  |         |       |     |                 |

Continued on next page
| Submitter        | Case      | σ (1/Ω cm) | κ (erg/(s cm K)) | η (g/(s cm)) | D (cm^2/s) | dE/dx (eV/cm) | 1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV | 100 MeV | 1 GeV |
|------------------|-----------|------------|------------------|--------------|------------|--------------|-------|--------|---------|-------|--------|---------|-------|
| Marciante        | CH13      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [28]    | CH13      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [30]    | CH14      | 0.203      |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [31]    | CH14      | 0.207      |                  |              |            |              |       |        |         |       |        |         |       |
| Clérouin (PIJ)   | CH14      | 0.201      | 2.5e10           |              |            |              |       |        |         |       |        |         |       |
| Haxhimali, Rudd  | CH14      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [28]    | CH14      | 0.284      |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [30]    | CH14      | 0.23       |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [31]    | CH14      | 0.207      |                  |              |            |              |       |        |         |       |        |         |       |
| Clérouin (PIJ)   | CH15      | 1.02e6     | 4.51e12          |              |            |              |       |        |         |       |        |         |       |
| Haxhimali, Rudd  | CH15      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [28]    | CH15      | 33.4       |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [30]    | CH15      | 22.        |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [31]    | CH15      | 21.9       |                  |              |            |              |       |        |         |       |        |         |       |
| Clérouin (PIJ)   | CH21      | 4.11e3     | 2.33e6           |              |            |              |       |        |         |       |        |         |       |
| Desjarlais       | CH21      |            | 130.             |              | 7.2e4      |              |       |        |         |       |        |         |       |
| Clérouin (OFMD)  | CH21      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Haxhimali, Rudd  | CH21      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Marcianto        | CH21      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [28]    | CH22      | 0.312      |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [30]    | CH22      | 1.83e-4    |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [31]    | CH22      | 8.76e-4    |                  |              |            |              |       |        |         |       |        |         |       |
| Clérouin (PIJ)   | CH22      | 2.44e3     | 1.39e7           |              |            |              |       |        |         |       |        |         |       |
| Desjarlais       | CH22      | 1.61e3     | 6.58e6           |              |            |              |       |        |         |       |        |         |       |
| Clérouin (OFMD)  | CH22      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Haxhimali, Rudd  | CH22      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Marcianto        | CH22      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Sjostrom (TFMD)  | CH22      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [28]    | CH22      | 0.105      |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [30]    | CH22      | 0.00231    |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [31]    | CH22      | 0.00833    |                  |              |            |              |       |        |         |       |        |         |       |
| Clérouin (PIJ)   | CH23      | 5.53e3     | 2.04e8           |              |            |              |       |        |         |       |        |         |       |
| Desjarlais       | CH23      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Haxhimali, Rudd  | CH23      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Marcianto        | CH23      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Sjostrom (TFMD)  | CH23      |            |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [28]    | CH23      | 0.104      |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [30]    | CH23      | 0.0303     |                  |              |            |              |       |        |         |       |        |         |       |
| Copeland [31]    | CH23      | 0.0562     |                  |              |            |              |       |        |         |       |        |         |       |

Continued on next page
| Submitter               | Case | $\sigma$ | $\kappa$ | $\eta$ | $D$ | $dE/dx$ (eV/cm) |
|------------------------|------|----------|----------|--------|-----|-----------------|
| Clérouin (PIJ)         | CH24 | 7.24e4   | 5.2e10   | 0.312  | 2.34 |                 |
| Haxhimali, Rudd        | CH24 | 0.387    |          |        |     |                 |
| Copeland [28]          | CH24 | 0.576    |          |        | 1.55 |                 |
| Copeland [30]          | CH24 | 0.402    |          |        | 2.75 |                 |
| Copeland [31]          | CH24 | 0.411    |          |        | 2.77 |                 |
| Clérouin (PIJ)         | CH25 | 1.26e6   | 5.55e12  | 31.4   | 344. |                 |
| Haxhimali, Rudd        | CH25 | 28.      |          |        |     |                 |
| Copeland [28]          | CH25 | 41.7     |          |        | 150. |                 |
| Copeland [30]          | CH25 | 29.3     |          |        | 215. |                 |
| Copeland [31]          | CH25 | 28.3     |          |        | 213. |                 |
| Clérouin (PIJ)         | CH31 | 2.47e4   | 1.4e7    | 0.17   | 2.10e-5 |                 |
| Clérouin (OFMD)        | CH31 | 0.0982   |          |        |       |                 |
| Haxhimali, Rudd        | CH31 | 0.0982   |          |        | 1.15e-4 |                 |
| Marcianete             | CH31 |          |          |        | 1.25e-6 |                 |
| Sjostrom (TFMD)        | CH31 |          |          |        | 2.50e-4 |                 |
| Copeland [28]          | CH31 | 8.6      |          | 1.07   |       |                 |
| Copeland [30]          | CH31 | 4.90e-5  |          | 4.15e-5 |       |                 |
| Copeland [31]          | CH31 | 0.00141  |          | 4.44e-4 |       |                 |
| Clérouin (PIJ)         | CH32 | 2.47e4   | 1.4e8    | 0.049  | 0.00259 |                 |
| Meyer, Collins         | CH32 | 1.83e4   | 1.04e8   | 0.0266 | 1.90e-4 |                 |
| Hu (QMD)               | CH32 | 2.25e4   | 1.26e8   | 0.0266 | 1.90e-4 |                 |
| Baalrud                | CH32 |          |          |        |       |                 |
| Clérouin (OFMD)        | CH32 | 0.00702  |          | 0.0026 |       |                 |
| Daligault              | CH32 | 0.041    |          | 0.00201 |       |                 |
| Haxhimali, Rudd        | CH32 | 0.0309   |          | 0.00261 |       |                 |
| Marcianete             | CH32 | 0.00254  |          |        | 0.00342 |                 |
| Marcianete             | CH42 |          |          |        | 3.66e-4 |                 |
| Sjostrom (TFMD)        | CH32 |          |          |        | 0.0035  |                 |
| Hu (Spitzer-Lee-More)  | CH32 | 1.54e6   |          | 0.339  |       |                 |
| Copeland [28]          | CH32 | 2.73     |          | 0.339  |       |                 |
| Copeland [30]          | CH32 | 0.00335  |          | 0.00129 |       |                 |
| Copeland [31]          | CH32 | 0.0105   |          | 0.00378 |       |                 |
| Clérouin (PIJ)         | CH33 | 1.79e4   | 9.96e8   | 0.0753 | 0.0362 |                 |
| Hu (QMD)               | CH33 | 1.76e4   | 1.08e9   | 0.0753 | 0.0362 |                 |
| Baalrud                | CH33 | 0.0596   |          | 0.0276 |       |                 |
| Clérouin (OFMD)        | CH33 | 0.0831   |          | 0.0364 |       |                 |
| Daligault              | CH33 | 0.0796   |          | 0.0302 |       |                 |
| Haxhimali, Rudd        | CH33 | 0.0116   |          |        |       |                 |
Table A.3 – continued from previous page

| Submitter                  | Case | $\sigma$ (1/(Ω cm)) | $\kappa$ (erg/(s cm K)) | $\eta$ (g/(s cm)) | $D$ (cm^2/s) | $dE/dx$ (eV/cm) |
|----------------------------|------|---------------------|--------------------------|-------------------|--------------|-----------------|
|                            |      |                     |                          |                   | 1 keV        | 10 keV          | 100 keV         | 1 MeV           | 10 MeV         | 100 MeV        | 1 GeV          |
| Marciante                  | CH33 |                     |                          |                   | 0.0505       |                |                 | 0.00752         |                |                |                |
| Marciante                  | CH43 |                     |                          |                   | 0.055        |                |                 |                  |                |                |
| Sjostrom (TFMD)            | CH33 |                     |                          |                   | 0.055        |                |                 |                  |                |                |
| Hu (Spitzer-Lee-More)      | CH33 |                     |                          |                   | 0.0505       |                |                 | 0.00752         |                |                |
| Copeland [28]              | CH33 |                     |                          |                   | 0.115        |                |                 | 0.0519          |                |                |
| Copeland [30]              | CH33 |                     |                          |                   | 0.048        |                |                 | 0.0234          |                |                |
| Copeland [31]              | CH33 |                     |                          |                   | 0.115        |                |                 | 0.0519          |                |                |
| Clérouin (PIJ)             | CH34 |                     |                          |                   | 1.02e5       | 4.35e10         | 0.7            | 0.315           |                |                |
| Baalrud                    | CH34 |                     |                          |                   | 0.674        |                |                 | 0.531           |                |                |
| Clérouin (OFMD)            | CH34 |                     |                          |                   | 1.02e5       | 4.35e10         | 0.7            | 0.315           |                |                |
| Haxhimali, Rudd            | CH34 |                     |                          |                   | 0.674        |                |                 | 0.531           |                |                |
| Sjostrom (TFMD)            | CH34 |                     |                          |                   | 0.0932       |                |                 |                  |                |                |
| Ticknor                    | CH34 |                     |                          |                   | 0.9          |                |                 | 0.57            |                |                |
| Hu (Spitzer-Lee-More)      | CH34 |                     |                          |                   | 4.04e10      |                |                 |                  |                |                |
| Copeland [28]              | CH34 |                     |                          |                   | 1.79         |                |                 | 0.339           |                |                |
| Copeland [30]              | CH34 |                     |                          |                   | 0.836        |                |                 | 0.533           |                |                |
| Copeland [31]              | CH34 |                     |                          |                   | 1.03         |                |                 | 0.623           |                |                |
| Clérouin (PIJ)             | CH35 |                     |                          |                   | 1.61e6       | 7.21e12         | 41.7           | 46.8            |                |                |
| Baalrud                    | CH35 |                     |                          |                   | 32.8         |                |                 | 43.6            |                |                |
| Clérouin (OFMD)            | CH35 |                     |                          |                   | 39.9         |                |                 | 21.3            |                |                |
| Haxhimali, Rudd            | CH35 |                     |                          |                   | 3.93         |                |                 |                  |                |                |
| Hu (Spitzer-Lee-More)      | CH35 |                     |                          |                   | 6.42e12      |                |                 |                  |                |                |
| Copeland [28]              | CH35 |                     |                          |                   | 56.1         |                |                 | 19.5            |                |                |
| Copeland [30]              | CH35 |                     |                          |                   | 43.6         |                |                 | 31.9            |                |                |
| Copeland [31]              | CH35 |                     |                          |                   | 39.6         |                |                 | 29.6            |                |                |
| Clérouin (PIJ)             | CH41 |                     |                          |                   | 2.14e5       | 1.21e8         | 0.339          | 0.00699         |                |                |
| Haxhimali, Rudd            | CH41 |                     |                          |                   | 2.53e4       |                |                 |                  |                |                |
| Copeland [28]              | CH41 |                     |                          |                   | 155          |                |                 | 1.92            |                |                |
| Copeland [30]              | CH41 |                     |                          |                   | 1.82e-5      |                |                 | 1.58e-6         |                |                |
| Copeland [31]              | CH41 |                     |                          |                   | 0.00292      |                |                 | 9.11e-5         |                |                |
| Clérouin (PIJ)             | CH42 |                     |                          |                   | 2.14e5       | 1.21e9         | 0.339          | 0.00699         |                |                |
| Haxhimali, Rudd            | CH42 |                     |                          |                   | 0.815        |                |                 |                  |                |                |
| Ticknor                    | CH15 |                     |                          |                   | 2.39e-4      |                |                 |                  |                |                |
| Copeland [28]              | CH42 |                     |                          |                   | 4.9          |                |                 | 0.608           |                |                |
| Copeland [30]              | CH42 |                     |                          |                   | 0.00325      |                |                 | 3.02e-4         |                |                |
| Copeland [31]              | CH42 |                     |                          |                   | 0.0191       |                |                 | 6.62e-4         |                |                |
| Clérouin (PIJ)             | CH43 |                     |                          |                   | 1.94e5       | 1.1e10         | 0.339          | 0.00699         |                |                |
| Baalrud                    | CH43 |                     |                          |                   | 0.146        |                |                 | 0.00614         |                |                |
| Clérouin (OFMD)            | CH43 |                     |                          |                   | 0.35         |                |                 | 0.0055          |                |                |

Continued on next page
| Submitter            | Case  | $\sigma$ (1/($\Omega$ cm)) | $\kappa$ (erg/(s cm K)) | $\eta$ (g/(s cm)) | $D$ (cm$^2$/s) | $dE/dx$ (eV/cm) |
|----------------------|-------|-----------------------------|--------------------------|-------------------|-----------------|-----------------|
| Daligault            | CH43  | 0.393                       |                          | 0.00587           |                 |                 |
| Haxhimali, Rudd      | CH43  | 0.355                       |                          |                   |                 |                 |
| Ticknor              | CH25  | 0.006                       |                          |                   |                 |                 |
| Copeland [28]        | CH43  | 15.6                        | 0.193                    |                   |                 |                 |
| Copeland [30]        | CH43  | 0.0869                      | 0.0039                   |                   |                 |                 |
| Copeland [31]        | CH43  | 0.177                       | 0.00745                  |                   |                 |                 |
| Clérouin (PIJ)       | CH44  | 1.8e5 1.09e10               | 1.78                     | 0.123             |                 |                 |
| Baalrud              | CH44  | 1.78                         | 0.117                    |                   |                 |                 |
| Clérouin (OFMD)      | CH44  | 19.5                         | 0.107                    |                   |                 |                 |
| Haxhimali, Rudd      | CH44  | 2.53                         |                          |                   |                 |                 |
| Ticknor              | CH35  |                             |                          |                   |                 | 0.129           |
| Copeland [28]        | CH44  | 8.57                         | 0.11                     |                   |                 |                 |
| Copeland [30]        | CH44  | 1.74                         | 0.103                    |                   |                 |                 |
| Copeland [31]        | CH44  | 2.62                         | 0.149                    |                   |                 |                 |
| Clérouin (PIJ)       | CH45  | 2.24e6 1.01e13              | 60.4                     | 5.96              |                 |                 |
| Baalrud              | CH45  | 47.1                         | 5.49                     |                   |                 |                 |
| Clérouin (OFMD)      | CH45  | 71.1                         | 6.9                      |                   |                 |                 |
| Haxhimali, Rudd      | CH45  | 61.9                         |                          |                   |                 |                 |
| Ticknor              | CH45  | 70.                           | 6.7                      |                   |                 |                 |
| Copeland [28]        | CH45  | 86.2                         | 2.78                     |                   |                 |                 |
| Copeland [30]        | CH45  | 69.4                         | 4.99                     |                   |                 |                 |
| Copeland [31]        | CH45  | 62.8                         | 4.57                     |                   |                 |                 |
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