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## Nomenclature

		$c_{v,j}^\circ$	Standard state specific heat of species $j$
$\hat{R}$	Universal gas constant $\approx$ 8.314 J/kg-K	$F$	Helmholtz energy
$\lambda$	Lagrange multiplier	$G$	Gibbs free-energy
$\mathcal{L}$	The Lagrangian	$h'$	Sum of contributions from each species towards enthalpy constraint, i.g. $\sum_j^{\text{NS}} \mathcal{N}_j H_j^\circ$
$\mathcal{N}$	Total number of moles in the system	$h'_0$	User-specified enthalpy
$\mathcal{N}_j$	Number of moles of species $j$ in the system	$H_j^\circ$	Standard state enthalpy of species $j$
$\mu_j$	Chemical potential of species $j$	$MW_j$	Molecular weight of species $j$
$\mu_j^\circ$	Standard state chemical potential of species $j$	$p_{\text{ref}}$	Reference temperature used to compute chemical potential
$\rho$	Density ( $kg/m^3$ )	$q_j$	Charge of species $j$ (0 for neutrals, 1 for ions, -1 for electrons)
$a_{ij}$	Stoichiometric coefficients, e.g. number of atoms of element $i$ in species $j$	$T$	Temperature (K)
$b_i$	Sum of contributions from each species towards constraint for element $i$ , i.g. $\sum_{j=1}^{\text{NS}} a_{i,j} \mathcal{N}_j$	$u'$	Sum of contributions from each species towards internal energy constraint, i.g. $\sum_j^{\text{NS}} \mathcal{N}_j U_j^\circ$
$b_i^\circ$	Specified number of moles of element $i$	$u'_0$	User-specified internal energy
$c_{p,j}^\circ$	Standard state specific heat of species $j$	$U_j^\circ$	Standard state internal energy of species $j$
		$V$	Volume ( $m^3$ )

# 1 Minimization Procedures

## 1.1 Constraints for Both Procedures

There are two constraints that are used the most in both energy minimization procedures. The first, equation [1.1], is always used, while the charge constraints in equation [1.2] is only used when ions are present:

$$\sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j - b_i^{\circ} = 0 \quad (1.1)$$

$$\sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j = 0 \quad (1.2)$$

Since these are used in abundance for both procedures, their constraints are placed in the Lagrangian term. Other constraints (such as specified volume, temperature, internal energy, and entropy) are given their own residual equations in the Newton solve without addition into the Lagrangian.

Equation [1.1] says that the number of moles of element  $i$  must remain constant during the minimization process, as atoms can not be created or destroyed without nuclear reactions being involved.  $b_i^{\circ}$  is the number of moles of element  $i$  before minimizing, and  $a_{ij}$  is the stoichiometric coefficient, i.e. how many atoms of element  $i$  are in species  $j$ . In this code, the stoichiometric coefficient is actually multiplied by the element's molecular weight. The current reason is not known, though it needs to be figured out why this method yields correct results.

Equation [1.2] says that the charge of the system must remain neutral, i.e., if cations are formed, then there must be an equal number of free electrons in the gas to balance the charge.

## 1.2 The Lagrangian

The Lagrangian is defined as;

$$\mathcal{L} = f + \sum_j \lambda_j g_j \quad (1.3)$$

where  $f$  is the function we want to minimize,  $\lambda_j$  are Lagrange multipliers, and

$g_j$  are the constraint functions equal to 0. Instead of minimizing just  $f$ , we aim to minimize the Lagrangian  $\mathcal{L}$ .

### 1.3 Newton-Raphson Iterative Method

A Newton-Raphson iterative procedure is used to minimize the energies. Since this is essentially a root finding system of equations, and we are seeking the solution update, the method looks like the following after using a Taylor expansion on the function  $f$ :

$$\sum_{i=1}^N \frac{\partial f}{\partial x_i} \Delta x_i = -f(x) \quad (1.4)$$

Here,  $f(x)$  is the function that is being minimized. In the case of Gibbs and Helmholtz energy minimization,  $f$  takes the form of  $\partial \mathcal{L} / \partial x$ , with  $x$  being non-linear variables used to guide the convergence of the system. The non-linear correction variables are in the form of  $\Delta \ln \mathcal{N}_j$ ,  $\Delta \ln \mathcal{N}$ ,  $\Delta \ln T$ , and  $\pi_{i,q} = \Delta \pi_{i,q}$ . For the last correction variable, it is argued that setting  $\pi$  to 0 at the beginning of each update does not influence the solution for the non-reduced equations, so the  $\Delta$  is dropped for that term. This will influence the form of the update equations, which will be talked about in due time.

### 1.4 Gibbs Minimization

The Gibbs energy is a function of temperature, pressure, and composition of a gas:

$$G = G(T, p, \mathcal{N}_1, \mathcal{N}_2, \dots, \mathcal{N}_{\text{NS}}) = \sum_{j=1}^{\text{NS}} \mathcal{N}_j \mu_j \quad (1.5)$$

Where NS is the number of gas species,  $\mathcal{N}_j$  is the number of kg-moles of species  $j$  per kilogram (i.e., the mole-mass fraction), and  $\mu_j$  is the chemical potential of species  $j$  defined by:

$$\mu_j = \frac{\partial G}{\partial \mathcal{N}_j} = \mu_j^\circ + \hat{R}T \left[ \ln \left( \frac{p}{p_{\text{ref}}} \right) + \ln \left( \frac{\mathcal{N}_j}{\mathcal{N}} \right) \right] \quad (1.6)$$

Here,  $\hat{R}$  is the universal gas constant,  $T$  and  $p$  are the temperature and pressure of the system,  $p_{\text{ref}}$  is the reference pressure (usually takes as 101,325 Pa, or 1 bar depending on the literature), and  $\mathcal{N}$  is the number of kg-moles

per unit mass in the system. In order to find chemical equilibrium, the derivative of  $G$  wrt  $\mathcal{N}_j$  is set to 0 for all species. However, a number of constraints need to be added in.

#### 1.4.1 Constraints

Firstly, the elemental constraint from equation [1.1] is added into the Lagrangian for our Gibbs function. If ions are present, the charge constraint [1.2] is also put in. Therefore, our Lagrangian is:

$$\mathcal{L} = \sum_{j=1}^{\text{NS}} \mu_j \mathcal{N}_j + \sum_{i=1}^{\text{NE}} \lambda_i \left[ \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j - b_i^\circ \right] + \lambda_q \left[ \sum_{j=0}^{\text{NS}} q_j \mathcal{N}_j \right] \quad (1.7)$$

The constraints available for the Gibbs energy are:

- Hold temperature (T) and pressure (P) constant.
- Hold enthalpy (H) and pressure (P) constant.
- Hold entropy (S) and pressure (P) constant.

For all Gibbs minimizations, we need the molar constraint:

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j - \mathcal{N} = 0 \quad (1.8)$$

For (TP) minimization, only the elemental and charge (if present) constraints are necessary. For (HP) minimization, the constraint is defined by:

$$h' - h'_0 = 0 \quad (1.9)$$

Where  $h'_0$  is the specified enthalpy in J/kg, and  $h'$  is solved for during the minimization process as:

$$h' = \sum_{j=1}^{\text{NS}} \mathcal{N}_j H_j^\circ \quad (1.10)$$

For (SP) minimization, the constraint is defined by:

$$s' - s'_0 = 0 \quad (1.11)$$

Where  $s'_0$  is the specified entropy and  $s'$  is solved for in the minimization process as:

$$s' = \sum_{j=1}^{\text{NS}} \mathcal{N}_j S_j \quad (1.12)$$

where:

$$S_j = S_j^\circ - \hat{R} \ln \frac{\mathcal{N}_j}{\mathcal{N}} - \hat{R} \ln p \quad (1.13)$$

#### 1.4.2 Derivatives

We now take the derivatives of  $\mathcal{L}$  wrt  $\mathcal{N}_j$ , and each  $\lambda$  and denote them as  $f$ :

$$f_1 = \frac{\partial \mathcal{L}}{\partial \mathcal{N}_j} = \mu_j + \sum_{i=1}^{\text{NE}} \lambda_i a_{ij} + \lambda_q q_j = 0 \quad (1.14)$$

$$f_2 = \frac{\partial \mathcal{L}}{\partial \lambda_i} = \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j - b_i = 0 \quad (1.15)$$

$$f_3 = \frac{\partial \mathcal{L}}{\partial \lambda_q} = \sum_{j=0}^{\text{NS}} q_j \mathcal{N}_j = 0 \quad (1.16)$$

These three equations are our minimization functions. Through use of the aforementioned Newton-Raphson method, we can solve these equations. Additional residual equations for total moles of the system, enthalpy, and entropy are:

$$f_4 = \sum_{j=1}^{\text{NS}} \mathcal{N}_j - \mathcal{N} = 0 \quad (1.17)$$

$$f_5 = \frac{h' - h'_0}{\hat{R}T} = \frac{\sum_{j=1}^{\text{NS}} \mathcal{N}_j H_j^\circ - h'_0}{\hat{R}T} \quad (1.18)$$

$$f_6 = \frac{s' - s'_0}{\hat{R}} = \frac{\sum_{j=1}^{\text{NS}} \mathcal{N}_j S_j - s'_0}{\hat{R}} \quad (1.19)$$

Special care needs to be taken in the enthalpy constraint to include the enalpies of formation and/or reference enthalpies, if applicable.

### 1.4.3 Derivatives of $f_1$

First, we must do some algebraic manipulation. We start by expanding equation [1.14] with equation [1.6]:

$$\frac{\partial \mathcal{L}}{\partial \mathcal{N}_j} = \mu_j^\circ + \hat{R}T \left[ \ln \left( \frac{p}{p_{\text{ref}}} \right) + \ln \left( \frac{\mathcal{N}_j}{\mathcal{N}} \right) \right] + \sum_{i=1}^{\text{NE}} \lambda_i a_{ij} + \lambda_q q_j = 0 \quad (1.20)$$

Dividing through by  $\hat{R}T$  and setting  $\pi = -\lambda/\hat{R}T$  gives:

$$f_1 = \frac{\mu_j^\circ}{\hat{R}T} + \ln \frac{p}{p_{\text{ref}}} + \ln \mathcal{N}_j - \ln \mathcal{N} - \sum_{i=1}^{\text{NE}} \pi_i a_{i,j} - \pi_q q_j = 0 \quad (1.21)$$

We now need to take the partial derivatives of our functions wrt our non-linear variables as well as each  $\pi$ , and then multiple it by the correction variables.

You can easily take derviatives wrt  $\ln x$  by converting from  $x$  to  $\exp(\ln x)$ .

$$\frac{\partial f_1}{\partial [\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \Delta \ln \mathcal{N}_j \quad (1.22)$$

$$\frac{\partial f_1}{\partial [\ln \mathcal{N}]} \Delta \ln \mathcal{N} = -\Delta \ln \mathcal{N} \quad (1.23)$$

$$\frac{\partial f_1}{\partial [\ln T]} \Delta \ln T = -\frac{H_j^\circ}{\hat{R}T} \Delta \ln T \quad (1.24)$$

$$\frac{\partial f_1}{\partial [\pi_i]} \pi_i = -a_{ij} \pi_i \quad (1.25)$$

$$\frac{\partial f_1}{\partial [\pi_q]} \pi_q = -q_j \pi_q \quad (1.26)$$

Combining these into the form of equation [1.4] gives

$$\Delta \ln \mathcal{N}_j - \Delta \ln \mathcal{N} - \sum_{i=1}^{\text{NE}} a_{ij} \pi_i - q_j \pi_q - \frac{H_j^\circ}{\hat{R}T} \Delta \ln T = \mu_j + \sum_{i=1}^{\text{NE}} \pi_i a_{ij} + \pi_q q_j \quad (1.27)$$

From before, the argument is made that  $\pi_i = 0$  at the start of every iteration, so this equation becomes:

$$\Delta \ln \mathcal{N}_j - \Delta \ln \mathcal{N} - \sum_{i=1}^{\text{NE}} a_{ij} \pi_i - q_j \pi_q - \frac{H_j^\circ}{\hat{R}T} \Delta \ln T = -\frac{\mu_j}{\hat{R}T}$$

There will be one of these equation for each species.

#### 1.4.4 Derivatives of $f_2$

$$\frac{\partial f_2}{\partial[\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = a_{ij} \mathcal{N}_j \Delta \ln \mathcal{N}_j \quad (1.28)$$

$$\frac{\partial f_2}{\partial[\ln \mathcal{N}]} \Delta \ln \mathcal{N} = \frac{\partial f_2}{\partial[\pi_i]} \pi_i = \frac{\partial f_2}{\partial[\ln T]} = \frac{\partial f_2}{\partial[\pi_q]} \pi_q = 0 \quad (1.29)$$

Which gives:

$$\boxed{\sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \Delta \ln \mathcal{N}_j = b_i^\circ - \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j}$$

#### 1.4.5 Derivatives of $f_3$

$$\frac{\partial f_3}{\partial[\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = q_j \mathcal{N}_j \Delta \ln \mathcal{N}_j \quad (1.30)$$

$$\frac{\partial f_3}{\partial[\ln \mathcal{N}]} \Delta \ln \mathcal{N} = \frac{\partial f_3}{\partial[\ln T]} = \frac{\partial f_3}{\partial[\pi_i]} \pi_i = \frac{\partial f_3}{\partial[\pi_q]} \pi_q = 0 \quad (1.31)$$

Giving:

$$\boxed{\sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \Delta \ln \mathcal{N}_j = - \sum_{j=1}^{\text{NS}} q_i \mathcal{N}_j}$$

#### 1.4.6 Derivatives of $f_4$

$$\frac{\partial f_4}{\partial[\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \mathcal{N}_j \Delta \ln \mathcal{N}_j \quad (1.32)$$

$$\frac{\partial f_4}{\partial[\ln \mathcal{N}]} \Delta \ln \mathcal{N} = -\mathcal{N} \Delta \ln \mathcal{N} \quad (1.33)$$

$$\frac{\partial f_4}{\partial[\ln T]} = \frac{\partial f_4}{\partial[\pi_i]} \pi_i = \frac{\partial f_4}{\partial[\pi_q]} \pi_q = 0 \quad (1.34)$$

$$\boxed{\sum_{j=1}^{\text{NS}} \mathcal{N}_j \Delta \ln \mathcal{N}_j - \mathcal{N} \Delta \ln \mathcal{N} = \mathcal{N} - \sum_{j=1}^{\text{N}} \mathcal{N}_j} \quad (1.35)$$



#### 1.4.7 Derivatives of $f_5$

$$\frac{\partial f_5}{\partial[\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \Delta \ln \mathcal{N}_j \quad (1.36)$$

$$\frac{\partial f_5}{\partial[\ln T]} = \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \Delta \ln T \quad (1.37)$$

$$\frac{\partial f_5}{\partial[\ln \mathcal{N}]} \Delta \ln \mathcal{N} = \frac{\partial f_5}{\partial[\pi_i]} \pi_i = \frac{\partial f_5}{\partial[\pi_q]} \pi_q = 0 \quad (1.38)$$

Giving:

$$\boxed{\sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \Delta \ln \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \Delta \ln T = \frac{h' - h'_0}{\hat{R}T}}$$

#### 1.4.8 Derivatives of $f_6$

$$\frac{\partial f_6}{\partial[\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \mathcal{N}_j \frac{S_j}{\hat{R}} \Delta \ln \mathcal{N}_j \quad (1.39)$$

$$\frac{\partial f_6}{\partial[\ln T]} = \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \Delta \ln T \quad (1.40)$$

$$\frac{\partial f_6}{\partial[\ln \mathcal{N}]} \Delta \ln \mathcal{N} = \frac{\partial f_6}{\partial[\pi_i]} \pi_i = \frac{\partial f_6}{\partial[\pi_q]} \pi_q = 0 \quad (1.41)$$

Giving

$$\boxed{\sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{S_j}{\hat{R}} \Delta \ln \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \Delta \ln T = \frac{s'_0 - s'}{\hat{R}} + \mathcal{N} - \sum_{j=1}^{\text{NS}} \mathcal{N}_j}$$

All six of the equations are now listed for convenience:

$$\Delta \ln \mathcal{N}_j - \Delta \ln \mathcal{N} - \sum_{i=1}^{\text{NE}} a_{ij} \pi_i - q_j \pi_q - \frac{H_j^\circ}{\hat{R}T} \Delta \ln T = -\frac{\mu_j}{\hat{R}T} \quad (1.42)$$

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j \Delta \ln \mathcal{N}_j - \mathcal{N} \Delta \ln \mathcal{N} = \mathcal{N} - \sum_{j=1}^{\text{NS}} \mathcal{N}_j \quad (1.43)$$

$$\sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \Delta \ln \mathcal{N}_j = b_i^\circ - \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \quad (1.44)$$

$$\sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \Delta \ln \mathcal{N}_j = - \sum_{j=1}^{\text{NS}} q_i \mathcal{N}_j \quad (1.45)$$

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \Delta \ln \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \Delta \ln T = \frac{h'_0 - h'}{\hat{R}T} \quad (1.46)$$

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{S_j}{\hat{R}} \Delta \ln \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \Delta \ln T = \frac{s'_0 - s'}{\hat{R}} + \mathcal{N} - \sum_{j=1}^{\text{NS}} \mathcal{N}_j \quad (1.47)$$

#### 1.4.9 Reduced Gibbs Equations

A shortcut can be made to make this system of equations smaller. This is achieved by solving equation [1.42] for  $\Delta \ln \mathcal{N}_j$  and plugging it into equations [1.43] - [1.47]

$$\Delta \ln \mathcal{N}_j = \Delta \ln \mathcal{N} + \sum_{i=1}^{\text{NE}} a_{ij} \pi_i - \frac{\mu_j}{\hat{R}T} + q_j \pi_q + \frac{H_j^\circ}{\hat{R}T} \Delta \ln T \quad (1.48)$$

Substitution into equation [1.44] - [1.47] yields:

$$\begin{aligned} \sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{kj} a_{ij} \mathcal{N}_j \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} a_{kj} \mathcal{N}_j \right] \Delta \ln \mathcal{N} + \left[ \sum_{j=1}^{\text{NS}} a_{kj} q_j \mathcal{N}_j \right] \pi_q + \left[ \sum_{j=1}^{\text{NS}} a_{kj} \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \right] \Delta \ln T \\ = b_k^\circ - \sum_{j=1}^{\text{NS}} a_{kj} \mathcal{N}_j + \sum_{j=1}^{\text{NS}} a_{kj} \mathcal{N}_j \frac{\mu_j}{\hat{R}T} \end{aligned} \quad (1.49)$$

$$\begin{aligned}
& \sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j - \mathcal{N} \right] \Delta \ln \mathcal{N} + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \right] \pi_q + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \right] \Delta \ln T \\
& = \mathcal{N} - \sum_{j=1}^{\text{NS}} \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{\mu_j}{\hat{R}T} \quad (1.50)
\end{aligned}$$

$$\begin{aligned}
& \sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{ij} q_j \mathcal{N}_j \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \right] \Delta \ln \mathcal{N} + \left[ \sum_{j=1}^{\text{NS}} q_j^2 \mathcal{N}_j \right] \pi_q + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \right] \Delta \ln T \\
& = \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \frac{\mu_j}{\hat{R}T} - \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \quad (1.51)
\end{aligned}$$

$$\begin{aligned}
& \sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \right] \Delta \ln \mathcal{N} + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \right] \pi_q \\
& + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j \left( \frac{H_j^\circ}{\hat{R}T} \right)^2 + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \right] \Delta \ln T = \frac{h'_0 - h'}{\hat{R}T} + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{H_j^\circ}{\hat{R}T} \frac{\mu_j}{\hat{R}T} \quad (1.52)
\end{aligned}$$

$$\begin{aligned}
& \sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \frac{S_j}{\hat{R}} \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{S_j}{\hat{R}} \right] \Delta \ln \mathcal{N} + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \frac{S_j}{\hat{R}} \right] \pi_q \\
& + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{S_j}{\hat{R}} \frac{H_j^\circ}{\hat{R}T} + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{p,j}^\circ}{\hat{R}} \right] \Delta \ln T = \frac{s'_0 - s'}{\hat{R}} + \mathcal{N} - \sum_{j=1}^{\text{NS}} \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{S_j}{\hat{R}} \frac{\mu_j}{\hat{R}T} \quad (1.53)
\end{aligned}$$

There are NE number of equation [1.50], and only one of all others. Once this system has been solved, you recover  $\mathcal{N}_j$  with equation [1.48].

The equations are colored according to when they are needed. **Red coloring** denotes terms that arise from the elemental constraint condition. These are included no matter what. **Blue** denotes terms that are added when you include the charge constraint. **Violet** terms are added for both HP and SP constraints.

orange and teal are the rows added for enthalpy or entropy constraints, respectively.

## 1.5 Helmholtz Minimization

The Helmholtz energy is defined as:

$$F = G - pV \quad (1.54)$$

Where  $G$  is the Gibbs free energy,  $p$  is the pressure, and  $V$  is the volume. Substitution of  $G$  yields:

$$F = \sum_{j=1}^{\text{NS}} \mu_j \mathcal{N}_j - pV \quad (1.55)$$

Where the chemical potential is redefined as:

$$\mu_j = \mu_j^\circ + \hat{R}T \ln \left( \frac{\mathcal{N}_j R' T}{V} \right) \quad (1.56)$$

and  $R' = \hat{R} \cdot 10^{-5}$  is the same as dividing  $\hat{R}$  by the reference pressure of 1 bar.

### 1.5.1 Constraints

The constraints available for the Helmholtz energy are:

- Hold temperature (T) and volume (V) constant.
- Hold internal energy (U) and volume (V) constant.
- Hold entropy (S) and volume (V) constant.

For (TV) minimization, only the elemental and charge (if present) constraints are necessary. For (UV) minimization, the constraint is defined by:

$$u' - u'_0 = 0 \quad (1.57)$$

Where  $u'_0$  is the specified internal energy, and  $u'$  is solved for during the minimization process as:

$$u' = \sum_{j=1}^{\text{NS}} \mathcal{N}_j U_j^\circ = u'_0 \quad (1.58)$$

As stated before, special care needs to be taken to include the enthalpies of formation and reference enthalpies if applicable. For (SV) minimization, the constraint is defined by:

$$s' - s'_0 = 0 \quad (1.59)$$

Where  $s'_0$  is the specified entropy and  $s'$  is solved for during the minimization process as:

$$s' = \sum_{j=1}^{\text{NS}} \mathcal{N}_j S_j \quad (1.60)$$

where:

$$S_j = S_j^\circ - \hat{R} \ln \mathcal{N}_j - \hat{R} \ln \left( \frac{R'T}{V} \right) \quad (1.61)$$

The Lagrangian for the Helmholtz energy minimization process is then defined as:

$$\mathcal{L} = \sum_{j=1}^{\text{NS}} \mu_j \mathcal{N}_j - pV + \sum_{i=1}^{\text{NE}} \lambda_i \left[ \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j - b_i^\circ \right] + \lambda_q \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \right] \quad (1.62)$$

### 1.5.2 Derivatives

We first find our functions  $f$  that are equal to 0 by taking the derivatives wrt  $\mathcal{N}_j$ ,  $\lambda_i$ , and  $\lambda_q$ :

$$f_1 = \frac{\partial \mathcal{L}}{\partial \mathcal{N}_j} = \mu_j + \sum_{i=1}^{\text{NE}} \lambda_i a_{ij} + \lambda_q q_j = 0 \quad (1.63)$$

$$f_2 = \frac{\partial \mathcal{L}}{\partial \lambda_i} = \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j - b_i^\circ = 0 \quad (1.64)$$

$$f_3 = \frac{\partial \mathcal{L}}{\partial \lambda_q} = \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j - 0 = 0 \quad (1.65)$$

We now form the second derivatives that define our Jacobian in the Newton step. We expand the chemical potential term using equation 1.56 and non-dimensionalize the equation by  $\hat{R}T$ . We also set  $\pi = -\lambda/\hat{R}T$ .

### 1.5.3 Derivatives for $f_1$

The derivatives for  $f_1$  are then:

$$\frac{\partial f_1}{\partial [\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \Delta \ln \mathcal{N}_j \quad (1.66)$$

$$\frac{\partial f_1}{\partial [\ln T]} \Delta \ln T = -\frac{U_j^\circ}{\hat{R}T} \ln T \quad (1.67)$$

$$\frac{\partial f_1}{\partial \pi_i} \pi_i = -a_{ij} \pi_i \quad (1.68)$$

$$\frac{\partial f_1}{\partial \pi_q} \pi_q = -q_j \pi_q \quad (1.69)$$

The derivation for equation [1.67] is carried out in more depth in section [2.2]. Therefore, our final result is:

$$\Delta \ln \mathcal{N}_j - \sum_{i=1}^{\text{NE}} a_{ij} \pi_i - q_j \pi_q - \frac{U_j^\circ}{\hat{R}T} \Delta \ln T = -\frac{\mu_j}{\hat{R}T}$$

There will be NS number of these equations in our system.

### 1.5.4 Derivatives for $f_2$

Next, we take the derivatives of  $f_2$ :

$$\frac{\partial f_2}{\partial [\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \mathcal{N}_j a_{i,j} \Delta \ln \mathcal{N}_j \quad (1.70)$$

$$\frac{\partial f_2}{\partial [\ln T]} \Delta \ln T = \frac{\partial f_2}{\partial \pi_i} \pi_i = \frac{\partial f_2}{\partial \pi_q} \pi_q = 0 \quad (1.71)$$

Which gives:

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j a_{ij} \Delta \ln \mathcal{N}_j = b_i^\circ - \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j$$

There will be NE of these equations.

### 1.5.5 Derivatives for $f_3$

For  $f_3$  we get:

$$\frac{\partial f_3}{\partial[\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \mathcal{N}_j q_j \Delta \ln \mathcal{N}_j \quad (1.72)$$

$$\frac{\partial f_3}{\partial[\ln T]} \Delta \ln T = \frac{\partial f_3}{\partial \pi_i} \pi_i = \frac{\partial f_3}{\partial \pi_q} \pi_q = 0 \quad (1.73)$$

Which gives only one equation:

$$\boxed{\sum_{j=1}^{\text{NS}} \mathcal{N}_j q_j \Delta \ln \mathcal{N}_j = - \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j}$$

### 1.5.6 Derivatives for $f_4$

For internal energy, we have:

$$f_4(\ln \mathcal{N}_j, \ln T) = \sum_{j=1}^{\text{NS}} \mathcal{N}_j U_j^\circ - u'_0 = u' - u'_0 \quad (1.74)$$

Using identity [2.1] helps with the temperature derivative. The derivatives are then:

$$\frac{\partial f_4}{\partial[\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \frac{\mathcal{N}_j U_j^\circ}{\hat{R}T} \Delta \ln \mathcal{N}_j \quad (1.75)$$

$$\frac{\partial f_4}{\partial[\ln T]} \Delta \ln T = \sum_{j=1}^{\text{NS}} [T \mathcal{N}_j c_{v,j}^\circ] \Delta \ln T \quad (1.76)$$

$$\frac{\partial f_4}{\partial \pi_i} \pi_i = \frac{\partial f_4}{\partial \pi_q} \pi_q = 0 \quad (1.77)$$

After non-dimensionalizing, we are left with:

$$\boxed{\sum_{j=1}^{\text{NS}} \frac{\mathcal{N}_j U_j^\circ}{\hat{R}T} \Delta \ln \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \frac{\mathcal{N}_j c_{v,j}^\circ}{R} \Delta \ln T = \frac{u'_0 - u'}{\hat{R}T}}$$

### 1.5.7 Derivatives for $f_5$

For the entropy constraint we have:

$$f_5(\ln \mathcal{N}_j, \ln T) = \sum_{j=1}^{\text{NS}} \mathcal{N}_j S_j - s'_0 = s' - s'_0 \quad (1.78)$$

Again, identity [2.1] assists us. The derivates are:

$$\frac{\partial f_5}{\partial [\ln \mathcal{N}_j]} \Delta \ln \mathcal{N}_j = \mathcal{N}_j [S_j - \hat{R}] \Delta \ln \mathcal{N}_j \quad (1.79)$$

$$\frac{\partial f_5}{\partial [\ln T]} \Delta \ln T = \mathcal{N}_j c_{v,j}^\circ \Delta \ln T \quad (1.80)$$

$$\frac{\partial f_5}{\partial \pi_i} \pi_i = \frac{\partial f_5}{\partial \pi_q} \pi_q = 0 \quad (1.81)$$

Which, after non-dimensionalizing gives the singular equation:

$$\boxed{\sum_{j=1}^{\text{NS}} \mathcal{N}_j \left[ \frac{S_j}{\hat{R}} - 1 \right] \Delta \ln \mathcal{N}_j + \mathcal{N}_j \frac{c_{v,j}^\circ}{\hat{R}} \Delta \ln T = \frac{s'_0 - s'}{\hat{R}}} \quad (1.82)$$

For convenience, they are all listed here together:

$$\Delta \ln \mathcal{N}_j - \sum_{i=1}^{\text{NE}} a_{ij} \pi_i - q_j \pi_q - \frac{U_j^\circ}{\hat{R}T} \Delta \ln T = -\frac{\mu_j}{\hat{R}T} \quad (1.83)$$

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j a_{ij} \Delta \ln \mathcal{N}_j = b_i^\circ - \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \quad (1.84)$$

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j q_j \Delta \ln \mathcal{N}_j = - \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \quad (1.85)$$

$$\sum_{j=1}^{\text{NS}} \frac{\mathcal{N}_j U_j^\circ}{\hat{R}T} \Delta \ln \mathcal{N}_j + \sum_{j=1}^{\text{NS}} \frac{\mathcal{N}_j c_{v,j}^\circ}{R} \Delta \ln T = \frac{u'_0 - u'}{\hat{R}T} \quad (1.86)$$

$$\sum_{j=1}^{\text{NS}} \mathcal{N}_j \left[ \frac{S_j}{\hat{R}} - 1 \right] \Delta \ln \mathcal{N}_j + \mathcal{N}_j \frac{c_{v,j}^\circ}{\hat{R}} \Delta \ln T = \frac{s'_0 - s'}{\hat{R}} \quad (1.87)$$

### 1.5.8 Reduced Helmholtz Equations

A "simplification" can be made to the above system of equations by solving equations [1.83] for  $\Delta \ln \mathcal{N}_j$ :



$$\Delta \ln \mathcal{N}_j = \sum_{i=1}^{\text{NE}} a_{i,j} \pi_i - \frac{\mu_j}{\hat{R}T} + q_j \pi_q + \frac{U_j^\circ}{\hat{R}T} \Delta \ln T \quad (1.88)$$

By substituting this into equations [1.84] - [1.87], we can shrink the system of equations dramatically. The resulting set of equations is:

$$\sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{kj} a_{ij} \mathcal{N}_j \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} a_{kj} q_j \mathcal{N}_j \right] \pi_q + \left[ \sum_{j=1}^{\text{NS}} a_{kj} \mathcal{N}_j \frac{U_j^\circ}{\hat{R}T} \right] \Delta \ln T = b_k^\circ - \sum_{j=1}^{\text{NS}} a_{kj} \mathcal{N}_j + \sum_{j=1}^{\text{NS}} a_{kj} \mathcal{N}_j \frac{\mu_j}{\hat{R}T} \quad (1.89)$$

$$\sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{ij} q_j \mathcal{N}_j \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} q_j^2 \mathcal{N}_j \right] \pi_q + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \frac{U_j^\circ}{\hat{R}T} \right] \Delta \ln T = \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \frac{\mu_j}{\hat{R}T} - \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \quad (1.90)$$

$$\begin{aligned} \sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \frac{U_j^\circ}{\hat{R}T} \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \frac{U_j^\circ}{\hat{R}T} \right] \pi_q + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j \left( \frac{U_j^\circ}{\hat{R}T} \right)^2 + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{v,j}^\circ}{\hat{R}} \right] \Delta \ln T \\ = \frac{u'_0 - u'}{\hat{R}T} + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{U_j^\circ}{\hat{R}T} \frac{\mu_j}{\hat{R}T} \end{aligned} \quad (1.91)$$

$$\begin{aligned} \sum_{i=1}^{\text{NE}} \left[ \sum_{j=1}^{\text{NS}} a_{ij} \mathcal{N}_j \left( \frac{S_j}{\hat{R}} - 1 \right) \right] \pi_i + \left[ \sum_{j=1}^{\text{NS}} q_j \mathcal{N}_j \left( \frac{S_j}{\hat{R}} - 1 \right) \right] \pi_q \\ + \left[ \sum_{j=1}^{\text{NS}} \mathcal{N}_j \left( \frac{S_j}{\hat{R}} - 1 \right) \frac{U_j^\circ}{\hat{R}T} + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{c_{v,j}^\circ}{\hat{R}} \right] \Delta \ln T = \frac{s'_0 - s'}{\hat{R}} + \sum_{j=1}^{\text{NS}} \mathcal{N}_j \frac{\mu_j}{\hat{R}T} \left( \frac{S_j}{\hat{R}} - 1 \right) \end{aligned} \quad (1.92)$$

There will be NE number of equations 1.89, and one of 1.90 if charge is added, and one of 1.91/1.92 depending on which one you made need.

The equations are colored according to when they are needed. **Red coloring** denotes terms that arise from the elemental constraint condition. These are included no matter what. **Blue** denotes terms that are added when you include

the charge constraint. **Violet** terms are added for both UV and SV constraints. **orange** and **teal** are the rows added for either internal energy or entropy constraints, respectively.

## 1.6 Useful Relationships

$$\frac{c_v^\circ}{\hat{R}} = \frac{c_{p,j}^\circ}{\hat{R}} - 1 \quad (1.93)$$

$$\frac{\mu_j^\circ}{\hat{R}T} = \frac{H_j^\circ}{\hat{R}T} - \frac{S_j^\circ}{\hat{R}} \quad (1.94)$$

$$\frac{U_j^\circ}{\hat{R}T} = \frac{H_j^\circ}{\hat{R}T} - 1 \quad (1.95)$$

## 2 Standard State Chemical Potential Derivatives

Some important derivatives are derived here. First, we state a chain rule identity that is very useful:

$$\frac{\partial}{\partial T} = \frac{\partial[\ln(T)]}{\partial T} \frac{\partial}{\partial[\ln(T)]} \rightarrow \frac{\partial}{\partial[\ln(T)]} = T \frac{\partial}{\partial T} \quad (2.1)$$

Then, taking the derivative of  $\mu_j^0$  gives:

$$\frac{\partial}{\partial[\ln(T)]} \left( \frac{\mu_j^0}{RT} \right) = T \frac{\partial}{\partial T} \left( \frac{\mu_j^0}{RT} \right) \quad (2.2)$$

We expand  $\mu_j^0/RT$  as one of the following two equation depending on if we are using Gibbs or Helmholtz minimization:

$$\frac{\mu_j^0}{RT} = \frac{H_j^0}{RT} - \frac{S_j^0}{R} \quad (2.3)$$

$$\frac{\mu_j^0}{RT} = \frac{U_j^0}{RT} - \frac{S_j^0}{R} + 1 \quad (2.4)$$

### 2.1 Gibbs Derivative

First, we take the derivative of [2.3] for Gibbs minimization.

$$T \frac{\partial}{\partial T} \left( \frac{H_j^0}{RT} - \frac{S_j^0}{R} \right) = T \left( \frac{\partial_T(H_j^0) \cdot RT - H_j^0 \cdot R}{(RT)^2} - \frac{\partial_T(S_j^0)}{R} \right) \quad (2.5)$$

Here,  $\partial_T$  denotes  $(\partial/\partial T)$ . If:

$$c_{p,j}^0 = \frac{\partial H_j^0}{\partial T}, \text{ and } \frac{c_{p,j}^0}{T} = \frac{\partial S_j^0}{\partial T} \quad (2.6)$$

This reduces to:

$$T \left[ \frac{c_{p,j}^0}{RT} - \frac{H_j^0}{RT^2} - \frac{c_{p,j}^0}{RT} \right] = -\frac{H_j^0}{RT} \quad (2.7)$$

Therefore:

$$\boxed{\frac{\partial}{\partial [\ln(T)]} \left( \frac{\mu_j^0}{RT} \right) = -\frac{H_j^0}{RT}} \quad (2.8)$$

## 2.2 Helmholtz Derivative

Using equation [2.4] gives us:

$$T \frac{\partial}{\partial T} \left( \frac{U_j^0}{RT} + 1 - \frac{S_j^0}{R} \right) = T \left( \frac{\partial_T(U_j^0) \cdot RT - U_j^0 \cdot R}{(RT)^2} - \frac{\partial_T(S_j^0)}{R} \right) \quad (2.9)$$

Recalling  $\partial_T(S_j^0)$  from equation [2.6] and using:

$$c_{v,j}^0 = \frac{\partial U_j^0}{\partial T} \quad (2.10)$$

Equation [2.9] reduced to:

$$T \left[ \frac{c_{v,j}^0}{RT} - \frac{U_j^0}{RT^2} - \frac{c_{p,j}^0}{RT} \right] \quad (2.11)$$

Since:

$$\frac{c_{v,j}^0}{R} - \frac{c_{p,j}^0}{R} = -1 \quad (2.12)$$

The final derivative is:

$$\boxed{\frac{\partial}{\partial[\ln(T)]} \left( \frac{\mu_j^0}{RT} \right) = -\frac{U_j^0}{RT} - 1} \quad (2.13)$$

### 3 Code description

The University of Minnesota's code for computing chemical equilibrium of a gas mixture uses the well documented method of Gibbs and Helmholtz energy minimization with Lagrange multipliers as well as charge constraints for ionized gas mixtures as well as enthalpy, entropy, and internal energy constraints depending on the minimization method. It computes the composition and thermodynamic state of gas mixtures.