

# Lawrence Berkeley National Laboratory

## LBL Publications

### Title

TOUGHREACT V4.12-OMP and TReactMech V1.0 Geochemical and Reactive-Transport User Guide

### Permalink

<https://escholarship.org/uc/item/8945d2c1>

### Authors

Sonnenthal, Eric  
Spycher, Nicolas  
Xu, Tianfu  
[et al.](#)

### Publication Date

2021-06-25

Peer reviewed

---

**TOUGHREACT V4.12-OMP  
and TReactMech V1.0**

**Geochemical and Reactive-Transport User Guide**

---

*Eric Sonnenthal, Nicolas Spycher, Tianfu Xu, and Liange Zheng*

Energy Geosciences Division  
Lawrence Berkeley National Laboratory  
University of California, Berkeley, CA 94720

June 25, 2021

**Acknowledgements.** Documentation of TOUGHREACT was supported by the TOUGH2 Royalty Fund, an LBNL Innovation Grant, and by the Geothermal Program (EERE) within the U.S. Department of Energy. Documentation of TOUGHREACT V2 was supported by the Zero Emission Research and Technology Project (ZERT) of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231. The development of TOUGHREACT was initiated with funding from the Laboratory Directed Research and Development Program of the Ernest Orlando Lawrence Berkeley National Laboratory. Subsequent development was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Geothermal Technologies; by the Director, Office of Science, Office of Basic Energy Sciences; by the Director, Office of Civilian Radioactive Waste Management; and by the Zero Emission Research and Technology project (ZERT), of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

# TABLE OF CONTENTS

1	INTRODUCTION .....	1
1.1	Development History .....	1
1.2	Capabilities .....	3
2	COMPUTATIONAL REQUIREMENTS .....	6
2.1	Computer Requirements, Code Installation, and Execution .....	6
2.2	OpenMP Usage and Performance .....	8
2.3	Memory Requirements .....	12
2.4	User Knowledge Requirements .....	13
3	MODEL DESCRIPTION .....	13
3.1	Model Scope and Limits .....	13
3.2	Major Processes .....	14
3.3	Governing Equations .....	15
3.4	Simplifying Approximations .....	16
3.5	Solution Method .....	17
4	GENERAL DESCRIPTION OF INPUT AND OUTPUT FILES .....	21
4.1	Input Files .....	21
4.2	Output Files .....	22
4.2.1	Fixed name output files .....	23
4.2.2	User-specified output files .....	24
5	INPUT FILE FORMATS AND CONTENTS .....	25
5.1	Flow Input ( <i>flow.inp</i> ) .....	25
5.2	Transport and Convergence Inputs and Chemical Zone Assignments ( <i>solute.inp</i> ) .....	35
5.3	Geochemical Input ( <i>chemical.inp</i> ) .....	49
5.3.1	Definition of the Geochemical System .....	50
5.3.2	Composition of initial and injection (boundary) waters ( <i>Water</i> ) .....	64
5.3.3	Initial mineral zones ( <i>Imin</i> ) .....	68
5.3.4	Initial and injection gas zones ( <i>Igas</i> ) .....	72
5.3.5	Permeability-porosity law zones ( <i>Zppr</i> ) .....	74
5.3.6	Surface adsorption zones ( <i>Zads</i> ) .....	76
5.3.7	Linear <i>Kd</i> zones ( <i>Zlkd</i> ) .....	78
5.3.8	Cation exchange zones ( <i>Zexc</i> ) .....	79
5.4	Thermodynamic Database .....	81
6	BUILT-IN ERROR MESSAGES .....	92
6.1	From Routine: INIT (reads the CHEMICAL.INP file) .....	93
6.2	From Routine: NRINIT (initial Newton-Raphson iterations) .....	93
6.3	From Routine: READTHERM (reads thermodynamic database file) .....	94
6.4	From Routine: CR_CP (kinetic data calculations) .....	94
7	CONCLUDING REMARKS .....	95
8	REFERENCES .....	97
	APPENDIX A MATHEMATICAL EQUATIONS FOR FLOW AND TRANSPORT .....	109

APPENDIX B	MATHEMATICAL FORMULATION OF CHEMICAL REACTIONS .....	110
B.1	Kinetic reactions among primary species .....	111
B.2	Aqueous complexation.....	111
B.3	Equilibrium mineral dissolution/precipitation .....	112
B.4	Kinetic mineral dissolution/precipitation.....	112
B.5	Gas dissolution/exsolution .....	116
B.6	Cation exchange.....	117
B.7	Surface Complexation.....	120
APPENDIX C	SOLUTION METHOD FOR SOLUTE TRANSPORT EQUATIONS.....	124
C.1	Transport in the Aqueous Phase .....	124
C.2	Transport in the Gas Phase .....	128
APPENDIX D	SOLUTION METHOD FOR MIXED EQUILIBRIUM-KINETICS CHEMICAL SYSTEM .....	130
APPENDIX E	EVALUATION OF THE JACOBIAN MATRIX FOR THE CHEMICAL EQUATIONS.....	133
APPENDIX F	EFFECTS OF MINERAL PRECIPITATION/DISSOLUTION ON HYDROLOGIC PROPERTIES	134
F.1	Porosity Changes .....	134
F.2	Fracture Permeability Changes .....	135
F.3	Matrix Permeability Changes .....	137
F.4	Effects of Permeability and Porosity Changes on Capillary Pressures.....	138
APPENDIX G	MINERAL REACTIVE SURFACE AREAS .....	138
G.1	General Methodology .....	139
G.2	Estimation of Surface Areas for Fractures.....	142
G.3	Estimation of Surface Areas in the Rock Matrix (Porous Medium).....	143
APPENDIX H	CALCULATION OF ACTIVITY AND FUGACITY COEFFICIENTS .....	145
H.1	Extended Debye-Hückel Model for Ionic Species and Water .....	145
H.1.1	Activity Coefficients of Charged Aqueous Species .....	145
H.1.2	Activity of Water .....	147
H.1.3	Applicability of the HKF Extended Debye-Hückel Model.....	147
H.1.4	Fugacity Coefficients of Gases .....	154
APPENDIX I	TREATMENT FOR MINERAL SOLID SOLUTIONS .....	155
APPENDIX J	IMPLEMENTATION OF THE HELLMANN AND TISSERAND (2006) RATE LAW FOR MINERAL DISSOLUTION AND PRECIPITATION .....	157
J.1	Rate Expression .....	157
J.2	Implementation .....	158
APPENDIX K	TREATMENT OF CATION EXCHANGE UNDER WATER UNSATURATED CONDITIONS ...	159
APPENDIX L	HEAT CAPACITIES AND THERMAL CONDUCTIVITIES OF ROCKS AND MINERALS .....	160
L.1	Rock Grain Heat Capacities.....	160
L.2	Mineral Heat Capacities.....	161
L.3	Rock Grain Heat Capacities Derived from Mineral Heat Capacities .....	161
L.4	Bulk Rock Thermal Conductivities .....	162
L.5	Mineral Thermal Conductivities .....	163
L.6	Bulk Rock Thermal Conductivities Calculated from Mineral Values.....	163
L.7	Effect of Porosity Changes on Bulk Rock Thermal Conductivities .....	163

APPENDIX M	HEATS OF REACTION.....	164
APPENDIX N	SINGLE-PHASE WELLBORE FLOW MODEL .....	164
APPENDIX O	AQUEOUS SPECIES DIFFUSION .....	167
APPENDIX P	UTILITY PROGRAMS FOR THE THERMODYNAMIC DATABASE.....	167
P.1	Converting from other databases .....	167
P.2	Switching Basis (Primary) Species.....	169
P.3	Regression of log(K) Data .....	170
P.4	Checking Mass and Charge Balances .....	171

## LIST OF FIGURES

Figure 2-1	Increase in speed for sample problems as a function of the number of threads (ratio of cpu time for 1 thread to cpu time for multiple threads). .....	10
Figure 2-2	Calculation times (seconds) for a 3-D 84,000 grid block biogeochemical reactive transport problem on Linux Xeon and Mac Pro workstations using TOUGHREACT V3.32-OMP.....	11
Figure 3-1	Flow chart of the TOUGHREACT program.....	18
Figure 3-2	Space discretization and geometric data for the integral finite difference method (Pruess et al., 1999).....	19
Figure 5-1	Example of a TOUGHREACT V3-OMP thermodynamic database file. Note addition of thermal parameters (heat capacity, thermal expansion, and thermal conductivity coefficients) for “albit-hi”.....	91
Figure B-1	Variation of reaction rate with pH. Slopes shown are for the dissolution of silicate and aluminosilicate minerals (After Drever, 1997). .....	114
Figure B-2	Supersaturation window dependence on temperature. ....	115
Figure H-1	Mean-ion activity coefficients of NaCl and CaCl <sub>2</sub> at 25°C derived from individual activity coefficients calculated with Equation (H.1).....	150
Figure H-2	Activities of MgSO <sub>4</sub> and Na <sub>2</sub> SO <sub>4</sub> at 25°C derived from individual activity coefficients calculated with Equation (H.1).....	150
Figure H-3	Activities of water in NaCl and CaCl <sub>2</sub> solutions at 25°C calculated with Equations (H.6) and (H.7). ....	151
Figure H-4	Comparison of measured (Colin et al. 1985) and computed activities for NaCl solutions. ....	151
Figure H-5	Comparison of measured (Ananthaswamy and Atkinson, 1985) and computed activities for CaCl <sub>2</sub> solutions. ....	152

## LIST OF TABLES

Table 2-1 CPU times (seconds) as a function of threads for TOUGHREACT V3.32-OMP Sample Problems as shown in Figure 2-1.....	10
Table A-1 Governing equations for fluid and heat flow, and chemical transport, using EOS3 and EOS4 equation-of-state modules for example. ....	109
Table A-2 Symbols used in Table A-1. ....	110
Table H-1 Estimated values of effective ionic radii ( $r_{e,j}$ ) currently in the TOUGHREACT thermodynamic database for species that are not reported in HKF Table 3.....	146
Table H-2 Comparison of measured and computed activity data for NaCl and CaCl <sub>2</sub> solutions.....	153

## 1 Introduction

---

TOUGHREACT V4.0-OMP is a parallel simulator for 3-D nonisothermal multiphase reactive transport in porous and fractured rock. TOUGHREACT has been used to simulate many geological, environmental, and subsurface engineering problems, including diagenetic-weathering processes, geological carbon sequestration, subsurface nuclear waste emplacement, geothermal reservoir management, hydrothermal system exploration, hydrocarbon reservoir engineering and exploration, acid mine drainage, contaminant transport, and groundwater quality.

TOUGHREACT makes use of “self-documenting” features. It is distributed with a number of input data files for sample problems. Besides providing benchmarks for proper code installation, these can serve as a self-teaching tutorial in the use of TOUGHREACT, and they provide templates to help jump-start new applications. The fluid and heat flow calculations and inputs in TOUGHREACT are derived from TOUGH2 V2, so in addition to the current manual, users will need the TOUGH2 V2 manual (Pruess et al., 1999).

### 1.1 Development History

---

To investigate these and other problems, TOUGHREACT was developed by introducing reactive transport into the existing framework of the non-isothermal multi-component fluid and heat flow simulator TOUGH2 (Pruess et al., 1999). TOUGHREACT was developed initially by Xu and Pruess (1998, 2001), with several later major revisions (Xu et al., 2006, 2011; Sonnenthal et al., 2014, 2017). Many of the unique capabilities for simulating reactive transport in nonisothermal multiphase systems in fractured rock by multiple continuum methods were developed through projects funded by the Department of Energy for the investigation of a potential nuclear waste isolation site at Yucca Mountain, Nevada. As part of the work leading up to the Yucca Mountain License Application, significant effort was spent on Quality Assurance testing and validation of TOUGHREACT, along with evaluation of a wealth of coupled problems at a wide range of spatio-temporal scales, from simulating Underground Heater Tests, evaluating infiltration rates, predicting potential seepage chemistry under potential climate change scenarios, migration of volcanic gases associated with intrusive activity, and high-temperature flow-through reactor experiments.



A renewed emphasis on evaluating Enhanced Geothermal Systems and hydrothermal exploration led to the development of TOUGHREACT V3.0-OMP, which was released in 2014. V3.0-OMP added shared memory parallelization of the reactive chemistry using OpenMP as well as many new features. In addition to parallelization, and several new capabilities, many of the reactive transport routines have been significantly revised and improved since V2 with improved algorithms, additional options, higher accuracy, and better mass balance between flow, transport, reaction, and physical property (e.g., porosity) changes. V3.32-OMP, released in 2017, adds several new features, input/output options, and many improvements.

This reference manual describes code options and governing equations for reactive transport, as well as revisions to the core TOUGH2 heat and fluid flow parameters and capabilities. In addition to this manual, the TOUGH2 V2 manual is required. Because there are many options which are used frequently, a concise description of the main input flags is provided in “TOUGHREACT\_V410omp\_QuickRef.pdf”. In TOUGHREACT V2 and earlier, the User’s Guide included a set of Sample Problems with relevant inputs, outputs and conceptual model descriptions. For ease of use and documentation, in V3.0-OMP the User’s Guide was split into a Reference Manual and a separate sample problem description “TOUGHREACT\_V3-OMP\_SampleProblems.pdf”. It should be noted that the problems have been updated for use with the current TOUGHREACT version, which has many improvements in options, speed, and accuracy since the initial publication of the sample problems, some nearly 20 years ago. Therefore, the sample problems are meant as examples of the code usage, not as state-of-the-art reactive-transport problems. Some of the results are also different from the original published results, because the problems have been revised for finer time-stepping, better initial conditions, etc.

The first public release of TOUGHREACT was through the US Department of Energy’s Energy Science and Technology Software Center (ESTSC) in August 2004. For some years, it was one the most frequently requested of ESTSC’s codes. The code has been widely used for studies in CO<sub>2</sub> geological sequestration, geothermal energy development, watershed reactive transport, nuclear waste isolation, environmental remediation, sedimentary basin diagenesis, and petroleum exploration applications. Over the last several years, many new capabilities have been developed within different research projects at Lawrence Berkeley National Laboratory. To effectively serve our in-house projects and to share with the user community, many new capabilities were added,

with new versions distributed through LBNL Tech Transfer (V3.32-OMP in 2017; V3.0-OMP in 2014, and V2 in 2012). This document describes the features of TOUGHREACT V4.10-OMP.

## 1.2 Capabilities

---

Version 4.10-OMP added the following capabilities and improvements to V3.32-OMP:

- Upgrade of ECO2N V1 to ECO2N V2 covering a temperature range up to 300°C
- Addition of updated EOS8 module (dead oil-water-air)
- Addition of EOS5 and EOS7c modules
- Addition of the Pitzer ion activity model to model brines (see supplemental TOUGHREACT-Brine user's manual)
- Capability to recirculate the composition of waters in certain gridblocks (e.g., production wells) into injection/boundary zones (e.g., injection wells)
- Decay and sorption of gas species
- Equation reordering option for iterative flow solvers
- Option for fixed enthalpy time-dependent mass injection in GENER
- Calculation of electrical conductivities from aqueous species concentrations
- New file and options for aqueous species diffusion coefficients
- New options for chemical and mass balance convergence, and timestepping
- Improvements in OpenMP parallelization
- Improved output files for plotting with VisIt, ParaView, and TecPlot
- Improved version control
- Many bug fixes and improvements throughout

Version 3.32-OMP added the following capabilities and improvements to V3.0-OMP:

- Temperature and species-dependent aqueous diffusion coefficients calculated using Arrhenius parameters given in thermodynamic data file (accurate for uncharged species, isotopes, tracers)
- New time-dependent pressure-temperature boundary using input file "FIXPT" with same format as "GENER"
- Simulation of heat conduction at temperatures exceeding supercritical (e.g. to simulate magmatic intrusion thermal effects)
- Improved mass balance and coupling for water and CO<sub>2</sub> between flow, transport, and reaction with new option for coupling solely with mineral-water reactions
- Option to calculate flux and velocity vector magnitudes and 3-D spatial components (eg., for water, brine, CO<sub>2</sub>, air, heat, etc.) and output to Visit-compatible tecplot files
- Option to write flow outputs to Visit-compatible tecplot file
- Addition of TOUGH2 EOS module "EWASG"
- New options for assigning mineral zones and water chemistry based on material types in "ROCKS" block
- New options to read water chemistry in mg/L and pH, and write output to ppm

- Additional OpenMP parallelization of routines outside main chemical iteration loop
- Modifications for improved consistency with TOUGH2 V2.1
- Many bug fixes, improvements in chemical convergence, and improved output file readability

Version 3.0-OMP added the following major capabilities and improvements to V2:

- OpenMP parallelization of chemical and coupling routines for much faster performance on multi-core shared memory computers.
- Composition and temperature-dependent mineral heat capacities dynamically updated
- Composition and temperature-dependent mineral thermal conductivities dynamically updated
- Temperature-dependent bulk-rock heat capacities
- Temperature-dependent bulk-rock thermal conductivities
- Heats of reaction calculated from thermodynamic data coupled to energy conservation (heat transport) equation
- Option to fix specified gas species fugacities
- Transport of trace gas species in CO<sub>2</sub>-H<sub>2</sub>O carrier gas (EOS2 & ECO2n)
- Option to inject trace gas species and assign gas injection zones
- Consistent use of gas properties using calculated densities rather than ideal gas law
- Option to recalculate reactive surface areas within chemical iterations
- Improved flow and reaction coupling for ECO2n and EOS2 (water and CO<sub>2</sub> from reactions)
- New single (aqueous) phase nonisothermal wellbore flow model with wellbore output file
- Options for Leverett-scaling of capillary pressures in fractured and multiple-continua media
- Read and write meshes up to 999,999 grid blocks instead of <100,000
- Improvements in permeability-porosity coupling and tracking through restarts
- Improvements and bug fixes for chemical convergence, efficiency, and accuracy
- Improvements and new options for inputs and outputs

Major additions and improvements in Version 2 included:

- Intra-aqueous reaction kinetics and biodegradation
- Surface complexation models
- Multi-site exchange
- Improvements on the reactive surface area algorithm for mineral-water reactions, and fugacity coefficient corrections for gas-water reactions
- Improvements on coupling between chemistry and physics (such as with porosity and permeability changes)
- Improvement on the ideal mineral solid-solution model

- Improvement on functionalities such as printout of mineral reaction rates, and output of aqueous and surface complexes concentrations with time
- More flexible input formats for chemical parameters
- Significant increase in computational efficiency

TOUGHREACT has been applied to a wide variety of problems, some of which are included as examples in this manual, such as:

- Supergene copper enrichment (Xu et al., 2001)
- Coupled thermal, hydrological, and chemical processes for nuclear waste disposal (Xu et al., 2001; Sonnenthal et al., 2003, 2005; Spycher et al., 2003a, b; Dobson et al., 2003; Mukhopadhyay et al., 2009)
- Mineral alteration in hydrothermal and geothermal systems (Xu and Pruess, 2001a; Xu et al., 2004a and 2006; Dobson et al., 2004; Todaka et al., 2004; Xu et al., 2009a, Wanner et al., 2014)
- Mineral trapping for CO<sub>2</sub> disposal in deep saline aquifers and basaltic rocks (Audigane et al., 2007; Gherardi et al., 2007; Xu et al., 2004b, 2006, 2007; Zhang et al., 2009, Aradottir et al., 2012, 2013)
- Reactive transport and biogeochemical nitrogen cycling in vadose zone systems (Singleton et al., 2004; Xu, 2008; Gu et al., 2008, Maggi et al., 2008)

This version of TOUGHREACT provides the following TOUGH2 fluid property or “EOS” (equation-of-state) modules:

- EOS1 for water, or two waters with typical applications to hydrothermal problems
- EOS2 for multiphase mixtures of water and CO<sub>2</sub> also with typical applications to hydrothermal problems
- EOS3 for multiphase mixtures of water and air with typical applications to vadose zone and nuclear waste disposal problems
- EOS4 that has the same capabilities as EOS3 but with vapor pressure lowering effects due to capillary pressure
- EOS7 for multiphase mixtures of water, brine, and air with density and viscosity effects of salinity as an extension of EOS3
- EOS7c for multiphase mixtures of water, brine, methane, and noncondensable gas with density and viscosity effects of salinity as an extension of EOS7 (in V4.10-OMP and above)
- EOS8 for multiphase mixtures of "dead" oil, water, and air (in V4.10-OMP and above)
- EOS9 for single phase water (Richards' equation) with typical applications to ambient temperature and pressure reactive geochemical transport problems

- ECO2N V2.0 for multiphase mixtures of water, supercritical CO<sub>2</sub> and NaCl with typical applications to CO<sub>2</sub> geological storage (sequestration) in deep saline aquifers
- EWASG for multiphase mixtures of water, noncondensable gases (i.e., H<sub>2</sub>, CH<sub>4</sub>, CO<sub>2</sub>), and NaCl with typical applications to geothermal reservoirs and sedimentary basins.

## 2 Computational Requirements

---

### 2.1 Computer Requirements, Code Installation, and Execution

---

TOUGHREACT is written in FORTRAN 77 with FORTRAN-90 extensions. It has been tested on various computer platforms, including Apple Macintosh, Microsoft Windows-based PCs, and multiprocessor multi-core Linux clusters. On most machines the code should compile using recent (2013+) Fortran 95 or Fortran 90 compilers. This version of TOUGHREACT has been tested using Intel Fortran V17 to V20 on MacOS X, Linux, and Windows. It compiles using recent versions of gfortran (6.3.0+), however significantly slower code is generated (~30%), and therefore it is highly recommended to use Intel Fortran. Executables were compiled using Intel Fortran V18.0 on Linux, and V19 on Mac and Windows. This version of TOUGHREACT (like TOUGH2 V2.0) requires 64-bit arithmetic (8 byte word length for floating point numbers) for successful execution.

The TOUGHREACT source program contains IMPLICIT DOUBLE PRECISION (A-H, O-Z) and IMPLICIT INTEGER\*8 (I-N) statements that will automatically generate 64-bit arithmetic on 32 bit processors, however it is still advisable to utilize flags in the makefiles (provided) to force 64-bit arithmetic. The distribution file folders include documentation (this manual), test problems, executable files and/or source files (depending on the license) generated with compilers described in accompanying README files. Compilation scripts and makefiles for Intel Fortran on Linux cluster (Intel CPU), MacOS, and Windows (nmakefile) are included.

Unlike TOUGH2, TOUGH3, and ITOUGH2, TOUGHREACT requires no input or output file arguments. A command line window must first be opened and the directory changed to the folder containing the input files). On Mac, the *Terminal* application can be used to open a bash shell. On Linux, a bash shell can also be opened using X11 or by remote login (e.g., using ssh). TOUGHREACT is run solely by typing the path to the executable file within the folder containing

the input files. For example if TOUGHREACT has been copied to the simulation folder containing the input files, the following commands are used:

**On Mac:** *./treactv...omp\_eos1\_macos*

**On Linux:** *./treactv...omp\_eos1\_linux*

**On Windows:** *Treactv...omp\_eos1\_pc.exe*

For background execution on Linux, Mac, or Cygwin, add an &, as follows:

*./treactv...omp\_eos1\_linux &*

If TOUGHREACT is installed in another folder, the full path is given, for example:

**On Mac:**

*/Users/MyHome/toughreact\_v...\_exe/linux/treactv...omp\_eco2n\_macos*

**On Linux:**

*/Users/MyHome/toughreact\_v...\_exe/linux/treactv...omp\_eco2n\_linux*

**On Windows:**

*|Users|MyHome|toughreact\_V...\_exe|windows|treactv...omp\_eco2n\_pc.exe*

Upon execution, a completed simulation will show the following information on the screen (some variations possible depending on the options chosen):

----- TOUGHREACT Version 4.10-OMP -----

Lawrence Berkeley National Laboratory

February 8, 2017

\*\*\*\* OpenMP Parallel Code Settings \*\*\*\*

\*\*\* maximum number of threads allotted = 6

\*\*\* maximum number of threads available = 12

--> reading multiphase flow input data

--> reading solute transport input data

--> reading chemical input data

--> read input data complete

--> performing simulation

END OF TOUGHREACT V4.10-OMP SIMULATION --- ELAPSED TIME = 0.273 SEC-- CALCULATION TIME  
= 0.262 SEC-- DATA INPUT TIME = 0.011 SEC

Another example is shown below:

----- TOUGHREACT Version 4.10-OMP -----  
Lawrence Berkeley National Laboratory  
February 8, 2017

\*\*\*\*\* OpenMP Parallel Code Settings \*\*\*\*\*

\*\*\* maximum number of threads allotted = 12

\*\*\* maximum number of threads available = 12

--> reading multiphase flow input data

--> reading solute transport input data

--> reading chemical input data

--> read input data complete

...start initial surface complexation calcs

...done initial surface complexation calcs

!! Run Transport & Chemistry: Skip flow, MOPR(1) = 4

--> performing simulation

END OF TOUGHREACT V4.10-OMP SIMULATION --- ELAPSED TIME = 16.108 SEC-- CALCULATION TIME  
= 16.104 SEC-- DATA INPUT TIME = 0.004 SEC

## 2.2 OpenMP Usage and Performance

---

This version of TOUGHREACT employs the most recent OpenMP framework (v4.5) (<http://www.openmp.org/>) for parallelization of chemical reactions and various other cpu-intensive routines. OpenMP is based on the shared memory parallel model. Therefore, all CPUs or cores sharing memory (as on multicore Macs, PCs, and many Linux workstations) are available for the simulation. Basic requirements and usage of OpenMP for this version of TOUGHREACT are described in this manual. For more detailed information see the OpenMP website. OpenMP is built into Fortran compilers such as Intel Fortran and gfortran, and therefore a separate installation is not required. However, on Windows PCs, OpenMP cannot be statically linked with Intel Fortran, and therefore one must install the redistributable runtime library "libiomp5md.dll" in a location where TOUGHREACT can access the location (path). The location can be either in a folder accessible to all users (e.g., /opt/intel/redist\_lib) or with the folder containing the TOUGHREACT executables. Redistributable libraries are included with the package, however newer versions may be downloaded from Intel directly at the following site:

*<https://software.intel.com/content/www/us/en/develop/articles/intel-compilers-redistributable-libraries-by-version.html>*

The calculation time (cpu time) for problems using this version of TOUGHREACT on multiple cores is a function primarily of the geochemical problem size, the number of grid blocks, and the proportion of time spent solving the multiphase flow computations which are run primarily in serial. With larger numbers of cores (or threads) computation times typically decline to a minimum, and then increase for larger numbers of cores/threads. This is expected for all parallel codes, since at some point each core is fast enough to solve more calculations than it takes to spread them out over many cores, including the extra OpenMP overhead, and other serial parts of the code become a limiting factor. The relation between cpu time and threads employed depends on several factors, in particular the floating-point performance, the memory available, the problem size, the workload distribution, the time spent for multiphase flow, the time spent for the transport calculations, and the time spent in writing to output files.

Ratios of cpu time for a single thread to that for multiple threads (Speed-up) are shown in Figure 2-1 for the example problems using V3.32-OMP. Results for the current version are roughly similar. These tests were performed on a Mac Pro workstation with an Intel Xeon 6-core (12-thread) 3.5 GHz E5 processor using MacOS 10.12.5 (Sierra). The theoretical linear increase with the number of cores is shown as the dashed line. The cpu times for these problems are given in Table 2-1. Note that many of these problems are quite small and only benefit from using 4 to 6 threads. Also, the best performance is usually gained from the 6 physical cores on this computer, and less benefit from the multithreading. Even though it is a very small problem (46 grid blocks), the speed continues to improve up to the full 12 threads available for Problem 10 (P10-EOS1). The reason for the increased parallel performance in Problem 10 is because the flow equations are only solved once, and then reactive transport is performed using a steady-state flow field. Hence, most of the calculations are in the parallelized chemical reaction routines.



Figure 2-1 Increase in speed for sample problems as a function of the number of threads (ratio of cpu time for 1 thread to cpu time for multiple threads). Tests were performed on a Mac Pro workstation (late 2013 model) with an Intel Xeon 6-core (12-thread) 3.5 GHz E5 processor using MacOS 10.12.5 (Sierra). Both platforms show about the same performance until the number of threads exceeds the physical cores on the Mac Pro (6), at which point the Linux cluster with more physical cores and threads shows better parallel performance.

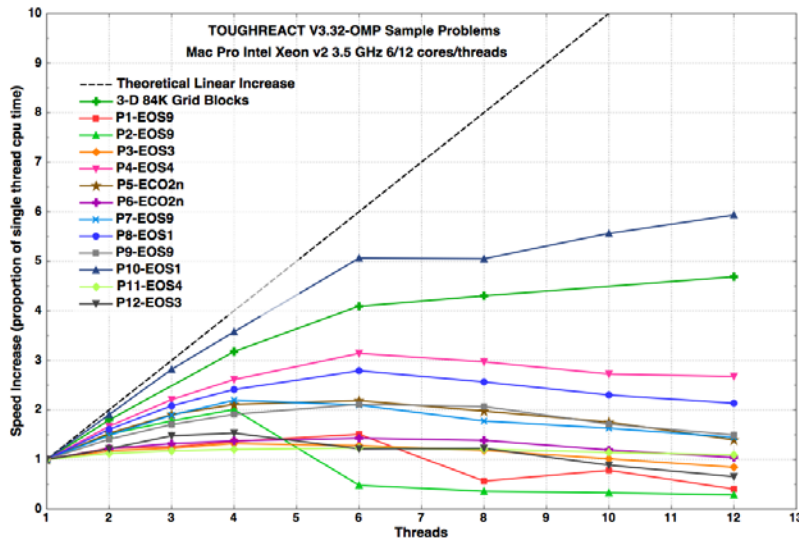
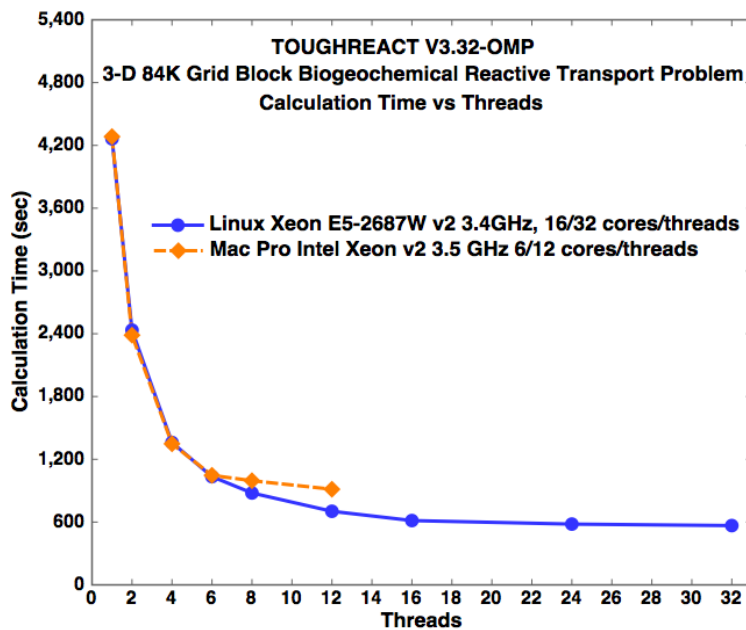


Table 2-1 CPU times (seconds) as a function of threads for TOUGHREACT V3.32-OMP Sample Problems as shown in Figure 2-1. Results for the current version are roughly equivalent.

Threads	P1-EOS9	P2-EOS9	P3-EOS3	P4-EOS4	P5-ECO2n	P6-ECO2n	P7-EOS9	P8-EOS1	P9-EOS9	P10-EOS1	P11-EOS4	P12-EOS3
1	0.338	0.702	1.857	99.102	11.467	159.631	17.640	69.829	87.922	95.587	328.754	1.511
2	0.275	0.465	1.580	59.369	7.507	130.835	11.864	43.466	62.406	50.229	292.441	1.242
3	0.269	0.395	1.513	44.950	6.021	120.845	9.317	33.556	51.570	33.900	279.743	1.022
4	0.248	0.350	1.404	37.912	5.435	116.097	8.041	28.971	46.056	26.738	273.156	0.986
6	0.224	1.469	1.452	31.562	5.249	111.595	8.412	25.011	41.652	18.883	266.293	1.243
8	0.299	1.491	1.567	33.355	5.804	115.206	9.937	27.223	42.532	18.936	272.190	1.231
10	0.434	2.148	1.829	36.371	6.540	133.792	10.821	30.386	51.299	17.185	287.128	1.711
12	0.841	2.468	2.206	37.029	8.208	153.537	12.194	32.739	58.829	16.104	300.852	2.324

Results for a 3-D 84,000 grid block biogeochemical reactive transport test problem (with injection and monitoring wells) are also shown in Figure 2-1. It continues to increase in performance at higher numbers of threads. This same problem was run on a Linux (Ubuntu) workstation with dual 8-core (16 cores and 32 threads total) Intel Xeon 3.4 GHz processors (Figure 2-2). The computation time continues to decrease till the full 32 threads is reached, with an increase in speed by a factor of 7.52. Note, however, that most of the speed increase is attained with 16 threads (6.94x).

**Figure 2-2 Calculation times (seconds) for a 3-D 84,000 grid block biogeochemical reactive transport problem on Linux Xeon and Mac Pro workstations using TOUGHREACT V3.32-OMP. Results for the current version are roughly equivalent.**



Based on these observations, it is advisable to determine how fast the problem runs using the full number of threads and with the number of physical cores. For problems running only flow (no reactive transport), the number of threads should be set to one, because the most computationally intensive flow routines are not parallelized, and increasing the number of threads will just increase the computational overhead, and increase the cpu time. Setting the number of threads is also useful for running multiple simulations so that they do not compete for computational resources. Limiting the amount and frequency of output can also lead to better computational performance for some problems.

### Setting the number of cores/threads:

If the number of cores/threads are the computer are unknown, and are not set, the maximum will be used and displayed on the screen. The number of threads can be set on the command line, external to the code inputs, and applies only to the shell where it is invoked. For example, two terminal shells can be opened, one using 2 threads and another using 6 threads, if there are 8 or more threads available. The command to set the number of threads uses the same command to set other environmental variables, as follows:

For example, using a Windows-based PC with the command line to set the number of threads to 12:

```
set OMP_NUM_THREADS=12
```

For Linux or Mac OS X using the default bash shell:

```
export OMP_NUM_THREADS=12
```

Under Linux or Mac OS X using tcsh:

```
setenv OMP_NUM_THREADS 12
```

## 2.3 Memory Requirements

---

The computer memory required by this version of TOUGHREACT depends on the problem size. PARAMETER statements are used in two INCLUDE files: flowpar\_v4.inc (for fluid and heat flow dimensions) and chempar\_v4.inc (for reactive chemistry dimension parameters). All major arrays in the problem are automatically adjusted according to these dimension parameters. Different size problems can be modeled by changing the dimensions in the parameter statements, compiling all source files, and linking them to create an executable file. At the beginning of a simulation, the program automatically checks the array dimensions related to reactive geochemistry. If the dimensions are insufficient for the specific problem, it typically provides the user with an error message. The memory requirement for these dimensions is typically from 1-2 Gbytes, and for parallel computing, computers should have at least 1 Gbyte per core (thread) available. Executables are distributed that should be able to simulate most reactive

transport problems up to 1 million grid blocks on MacOS and Linux, and about 64,000 grid blocks on Windows. Most 64 bit computer platforms from laptops to large computing clusters should be able to run this version of TOUGHREACT.

## **2.4 User Knowledge Requirements**

---

The correct implementation, setup, problem formulation, and interpretation of the results of TOUGHREACT requires knowledge of the basic equations of multiphase non-isothermal fluid flow and transport in geologic media and a basic understanding of the numerical solution of the equations that are used to describe these processes. In addition, the formulation of the geochemical problem requires familiarity with geochemical modeling and an in-depth understanding of the system that is being modeled and of the data used for input to the model. The model boundary conditions, time step length, convergence criteria, and grid properties are crucial elements for a realistic and accurate solution to a problem. The input files for flow parameters are based on TOUGH2 V2.1, with some extensions. However, for backward compatibility, TOUGH2 V2.1 input files can generally be used with little or no modification. A comprehensive reference for TOUGH2 input formats along with illustrative sample problems are provided in the TOUGH2 user's guide, Version 2.0 (Pruess et al., 1999). This information is essential for successful application of TOUGHREACT; it is not duplicated in the TOUGHREACT manual. The file "TOUGHREACT\_V...\_QuickRef.pdf" conveniently lists all MOP parameters and their use in this version of TOUGHREACT.

## **3 Model Description**

---

### **3.1 Model Scope and Limits**

---

This version of TOUGHREACT is applicable to one-, two-, or three-dimensional geologic domains with physical and chemical heterogeneity and can be applied to a wide range of subsurface conditions. The temperature (T) and pressure (P) limits are controlled by the applicable range of the chemical thermodynamic database, and the limits of the EOS module employed. Thermodynamic databases from external sources, with some additions by the authors, are included with the distribution files. Typically, these thermodynamic databases are available for temperatures between 0 and 300°C, at 1 bar below 100°C, and water saturation pressure above

100°C. The temperature and pressure range of thermodynamic data can be extended by changing the thermodynamic database without code modifications. It is the user's responsibility to ensure that the thermodynamic data used with this software is appropriate for the temperature and pressure range of the simulated systems. Water saturation can vary from completely dry to fully water-saturated. The model can be used for waters with ionic strengths from dilute to moderately saline water (up to ionic strengths in the 2–4 molal range, for an NaCl-dominant solution, depending on the system being modeled; see Appendix H for details). The code may run with waters having higher ionic strengths, however, the results may not be qualitatively or quantitatively correct.

Sample problems described in the TOUGHREACT V3.0-OMP Sample Problem Guide describe (a) contaminant transport with linear  $K_d$  adsorption and radioactive decay (Sample problem 1), (b) natural groundwater chemistry evolution under ambient conditions (Sample 2), (c) assessment of potential nuclear waste geological isolation sites (Samples 3, 4, and 11), (d) CO<sub>2</sub> geological storage in deep formations (Samples 5 and 6), (e) mineral deposition such as supergene copper enrichment (Sample 7), and (f) mineral alteration and silica scaling in hydrothermal systems under natural and production conditions (Sample 8), biogeochemical transport and environmental remediation (Samples 9 and 10), and multiple tracer gas species transport (Problem 12).

### 3.2 Major Processes

---

The major processes for fluid and heat flow are: (1) fluid flow in both liquid and gas phases occurs under pressure, viscous, and gravity forces; (2) interactions between flowing phases are represented by characteristic curves (relative permeability and capillary pressure); (3) heat flow by conduction and advection with effects of boiling/evaporation, and (4) diffusion of water vapor, air, or other gas components (e.g. CO<sub>2</sub>). Thermophysical and geochemical properties are calculated as a function of temperature, such as fluid (gas and liquid) density and viscosity, and thermodynamic and kinetic data for mineral-water-gas reactions. Transport of aqueous and gaseous species by advection and molecular diffusion are considered in both liquid and gas phases. Depending on the available computer memory, any number of chemical species in the liquid, gas and solid phases can be accommodated. Aqueous and surface complexation, acid-base, redox, gas dissolution/exsolution, and multi-site cation exchange are considered under the local equilibrium assumption. Mineral dissolution and precipitation proceed under either equilibrium or kinetic

constraints (Xu et al., 1999b), with modifications for boiling systems (Sonnenthal et al., 2005). Intra-aqueous kinetics and biodegradation (Xu, 2008; Xu et al., 2009b; Spycher et al., 2009) and surface complexation using non-electrostatic, constant capacity and double layer electrostatic models (Zheng et al., 2009), were incorporated into TOUGHREACT V2. Linear adsorption and simple decay can be also included.

### 3.3 Governing Equations

---

The primary governing equations for multiphase fluid and heat flow, and chemical transport have the same structure, derived from the principle of mass (or energy) conservation. These equations are presented in Appendix A. Expressions for non-isothermal multiphase flow are given in Pruess (1987) and Pruess et al. (1999). The transport equations are written in terms of total dissolved concentrations of chemical components, which are concentrations of the basis species plus their associated aqueous secondary species (Yeh and Tripathi, 1991; Steefel and Lasaga, 1994; Walter et al., 1994; Lichtner, 1996; and Xu and Pruess, 2001b). If kinetically-controlled reactions occur between aqueous species, then additional ordinary differential equations need to be solved to link the total concentrations of the primary species with the evolving concentrations of the secondary species (Steefel and MacQuarrie, 1996). Kinetically-controlled reactions between aqueous species are considered in the present version. Slow aqueous phase reactions are common in the case of redox reactions. Advection and diffusion processes are considered for both the aqueous and gaseous species. Aqueous species diffusion coefficients can be calculated as a function of temperature from parameters given in the thermodynamic database. While the full charge balance formulation has not been implemented yet, the option allows for simulation of tracer diffusion, particularly for simulating mass-dependent diffusive isotopic fractionation. Gaseous species, having a neutral valence, can also have differing diffusion coefficients calculated as a function of T, P, molecular weight, and molecular diameter. The local chemical interactions in the transport equations are represented by reaction source/sink terms.

The primary governing equations must be complemented with constitutive local relationships that express all parameters as functions of fundamental thermophysical and chemical variables. The equations for chemical reactions are presented in Appendix B. Mass conservation in the closed chemical system is written in terms of basis (component) species. The species

distribution must be governed by the total concentrations of the components. The oxygen is used for formulating redox reactions by attributing the oxidizing potential to the dissolved oxygen (Nordstrom and Muñoz, 1986; Wolery, 1992). In contrast to the free electron in the hypothetical electron approach (Yeh and Tripathi, 1991), oxygen can be present and can be transported in natural subsurface flow systems. The formulation for cation exchange is similar to that of Appelo and Postma (1993). For intra-aqueous kinetic reactions, sorption kinetic reactions, and biodegradation, a general-rate law that can deal with multiple mechanisms and multiple products, Monod, and inhibition terms (Xu et al., 2008), is used (Appendix B). For kinetically-controlled mineral dissolution and precipitation, a general form of the rate law (Lasaga, 1984; Steefel and Lasaga, 1994; Palandri and Kharaka, 2004) is used (Appendix B). Thermodynamic and kinetic data are functions of temperature.

Temporal changes in porosity, permeability, and unsaturated hydrologic properties owing to mineral dissolution and precipitation can modify fluid flow. This feedback between transport and chemistry can be important (e.g., Steefel and Lasaga, 1994; Sonnenthal and Ortoleva, 1994; Raffensperger, 1996), and can be treated by TOUGHREACT. Changes in porosity during the simulation are calculated from changes in mineral volume fractions and/or molar volumes (e.g. clay swelling). The porosity-permeability correlation in geologic media can be complex, depending on several factors, such as pore size distribution, pore shapes, connectivity (Verma and Pruess, 1988), and crystal morphology. Several porosity-permeability and fracture aperture-permeability relationships are included and can be assigned to different geologic units or individual grid blocks (Appendix F). TOUGHREACT also has an option to monitor changes in porosity and permeability during the simulation without feedback to fluid flow. In unsaturated systems, capillary pressures in porous and fractured media can be modified via permeability and porosity changes using Leverett scaling (based on Slider, 1976).

### **3.4 Simplifying Approximations**

---

Hydrodynamic dispersion can be an important solute transport phenomenon that arises from subgrid-scale differences in flow velocity in different pathways (e.g., pores, capillaries, or fractures). This process is not explicitly implemented in TOUGHREACT for various reasons, one of which being that typical representations of this process (such as Fickian dispersion models) have fundamental flaws and limitations, as demonstrated in numerous studies in the hydrogeology

literature over the last twenty years. The numerical approximations (i.e., upstream weighting for transport) used in TOUGHREACT can introduce some spatial and temporal numerical dispersion, and thus adding hydrodynamic dispersion may result in excessive dispersion. In addition, molecular diffusion can be modeled explicitly in TOUGHREACT, which often is lumped into a single "hydrodynamic dispersion parameter" as determined from field transport studies. As necessary, hydrodynamic dispersion can be modeled through appropriate spatial resolution on multiple scales, using multiple continua (or multi-region) models (Pruess and Narasimhan, 1985; Gwo et al., 1996; Sonnenthal et al., 2005) or explicit incorporation of fine-scale porosity and permeability heterogeneity (e.g., Mukhopadhyay et al., 2009) to describe interactions between fluid regions with different velocities.

Changes in thermophysical properties of fluid phases (such as viscosity, surface tension, and density) as a function of the fluid chemical composition are not considered in this version of TOUGHREACT. Pressure effects on chemical equilibrium constants are typically neglected; however, molar volume data for specific reactions can be introduced in the thermodynamic database for pressure corrections to be included (Section 6.4)

### 3.5 Solution Method

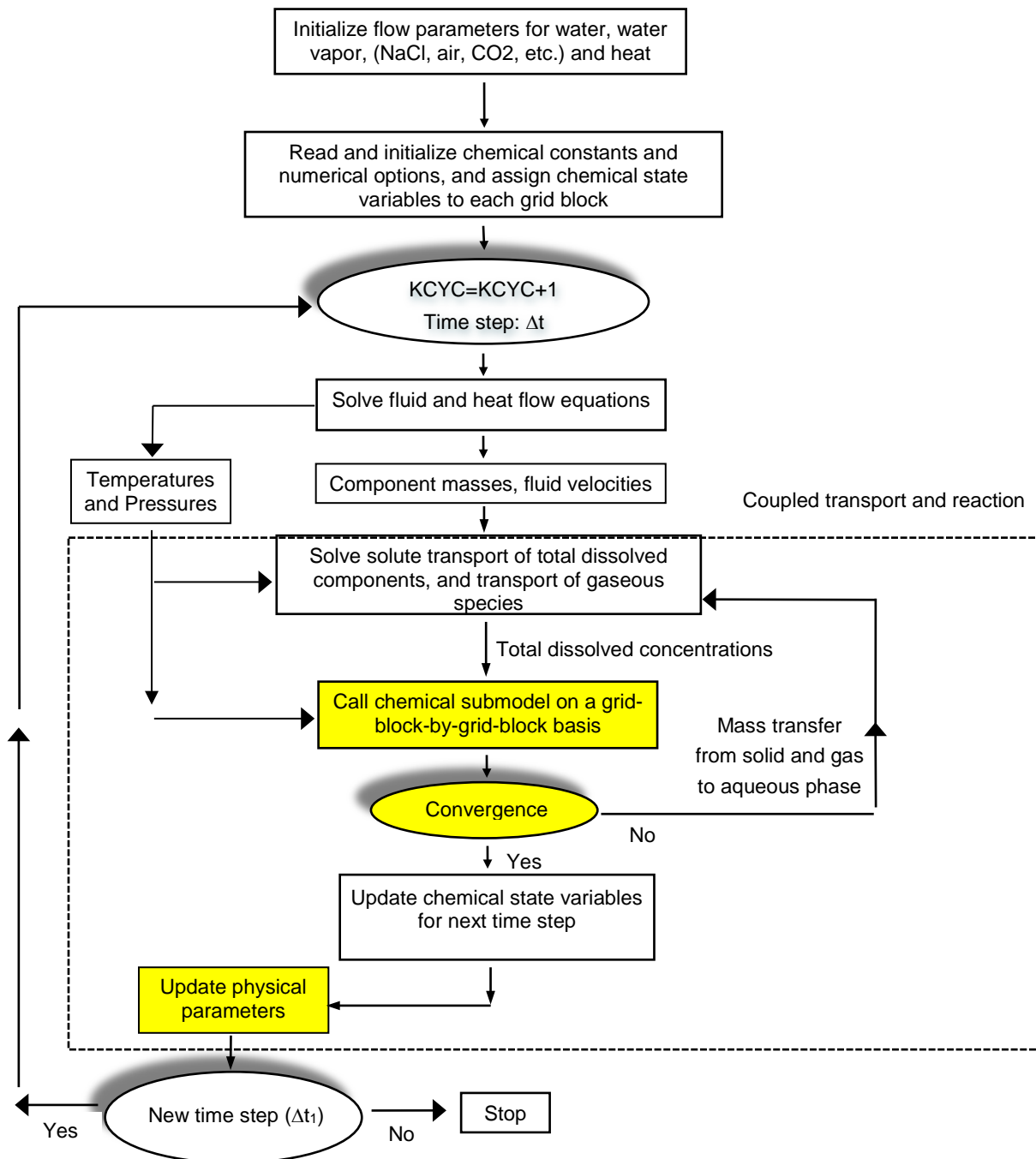
---

Figure 3-1 shows the flow chart for solving coupled non-isothermal multiphase fluid flow, solute transport, and reactive geochemistry in TOUGHREACT. Boxes shaded in yellow are the primary parts of the code that run in parallel using OpenMP. Some other calculations are also parallelized. With minor modifications, the numerical solution of multi-phase fluid and heat flow is equivalent to TOUGH2 V2. Space discretization is employed by means of integral finite differences (IFD; Narasimhan and Witherspoon, 1976). Because the chemical transport equations (derived from mass conservation) have the same structure as the fluid and heat flow equations, the transport equations can be solved by the same numerical method. The discretization approach used in the IFD method and the definition of the geometric parameters are illustrated in Figure 3-2. The basic mass- (for water, air, and chemical components) and energy- (for heat) balance equations are written in integral form for an arbitrary domain  $V_n$

$$V_n \frac{\Delta M_n}{\Delta t} = \sum_m A_{nm} F_{nm} + V_n q_n \quad (4.1)$$

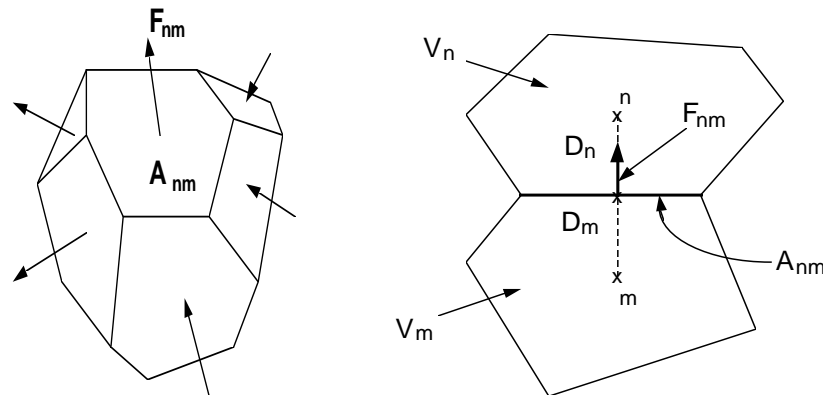


Figure 3-1 Flow chart of the TOUGHREACT program



where subscript  $n$  labels a grid block, subscript  $m$  labels grid blocks connected to grid block  $n$ ,  $\Delta t$  is time step size, and  $M_n$  is the average mass or energy density in grid block  $n$ . Surface integrals are approximated as a discrete sum of averages over surface segments  $A_{nm}$ ,  $F_{nm}$  is the average flux (of mass or energy) over the surface segment  $A_{nm}$  between volume elements  $n$  and  $m$ , and  $q_n$  is the average source/sink rate in grid block  $n$  per unit volume. Time is discretized fully implicitly as a first-order finite difference to achieve unconditional stability. More detail on the numerical discretization is given in Pruess et al. (1999). The IFD method gives a flexible discretization for geologic media that allows the use of irregular unstructured grids, which is well suited for simulation of flow, transport, and fluid-rock interaction in multi-region heterogeneous and fractured rock systems. For systems with regular grids, IFD is equivalent to conventional finite differences.

**Figure 3-2 Space discretization and geometric data for the integral finite difference method (Pruess et al., 1999)**



The time discretization of fluid and heat flow equations results in a set of coupled non-linear algebraic equations for the unknown thermodynamic state variables in all grid blocks. These equations are solved by Newton-Raphson iteration as implemented in the original TOUGH2 simulator (Pruess, 1991). The set of coupled linear equations arising at each iteration step is solved iteratively by means of preconditioned conjugate gradient methods (Moridis and Pruess, 1998).

TOUGHREACT uses a sequential iteration approach (SIA) similar to Yeh and Tripathi (1991), Engesgaard and Kipp (1992), Simunek and Soares (1994), Sonnenthal and Ortoleva (1994), and Walter et al. (1994). Coupling permeability to porosity changes is similar to that used

in Steefel and Lasaga (1994), Sonnenthal and Ortoleva (1994), and Sonnenthal and McBirney (1998). After solution of the flow equations, the fluid velocities and phase saturations are used for transport of total concentrations of aqueous species and trace gases. Advective and diffusive chemical transport are solved on a component-by-component basis (details on the solution method are given in Appendix C). The resulting concentrations obtained from solving the transport equations are substituted into the chemical reaction model. The system of mixed equilibrium-kinetic chemical reaction equations is solved on a grid block by grid block basis by Newton-Raphson iteration (details are given in Appendix D). Optionally, the reactive surface areas, chemical transport and reactions are solved iteratively until convergence.

After chemical convergence, the porosity, permeability, and the capillary pressure (for multiphase systems), can be updated owing to mineral dissolution/precipitation and molar volume changes. Additions to V3.0-OMP allow for updating grain and rock heat capacities and thermal conductivities as a function of changing mineral abundances and temperature. Moles of water and/or CO<sub>2</sub> consumed or liberated by chemical reactions are also stored for possible effects on source terms for multiphase fluid flow in the following time step. Heats of reaction source terms can be calculated for explicit incorporation into the energy conservation equations at following time step.

As an alternative to the sequential iterative approach, a sequential non-iterative approach (SNIA) may be used, in which the sequence of transport and reaction equations is solved only once (Walter et al., 1994; Steefel and MacQuarrie, 1996; and Xu et al., 1999a). Xu et al. (1999a) analyzed the accuracy of SIA and SNIA using several test cases. They concluded that the accuracy of SNIA depends mainly on the Courant number, which is defined as  $C = v\Delta t/\Delta x$ , where  $v$  is fluid velocity and  $\Delta x$  is grid spacing. For small Courant numbers, satisfying the stability condition  $C \leq 1$ , the differences between SNIA and SIA are generally small. The accuracy of SNIA also depends on the type of chemical process. Therefore, the applicability of the decoupling of chemical reactions from transport will depend on time and space discretization parameters, the nature of the chemical reactions and the desired accuracy. When SNIA is used, the Courant number condition  $C \leq 1$  can be automatically enforced during the simulation. SNIA should be used for most problems, because the SIA more oftentimes encounters convergence difficulties, and generally does not allow for a significantly larger time step.

An automatic time stepping scheme is implemented in TOUGHREACT, which includes an option to recognize "quasi-stationary states" (QSS; Lichtner, 1988) and perform a "large" time step towards the end of a QSS.

For analyzing water flow through partially saturated porous media, the gas phase may often be considered a passive bystander and not be represented explicitly (Richards, 1931). This means that for the purpose of solving for water flow, the entire gas phase is at the same pressure (usually the atmospheric pressure). TOUGHREACT allows a choice of considering saturated-unsaturated liquid phase flow in which case only molecular diffusion is considered for gaseous species transport. Alternatively, the full non-isothermal multiphase flow equations (liquid, gas, and heat) may be solved. To test the passive gas phase approach under ambient conditions, Xu et al. (2000) performed numerical simulation experiments on pyrite oxidation in a variably saturated porous medium. They found that under ambient conditions the effects of partial pressure reduction due to oxygen consumption on the fluid flow is not significant, and oxygen diffusion is the dominant gas phase transport process. However, when fluid flow and chemical reactions are strongly coupled, as e.g. in boiling hydrothermal reservoirs, gas phase advection could be essential (White, 1995; Sonnenthal et al., 2005).

## 4 General Description of Input and Output Files

---

### 4.1 Input Files

---

At least three fixed-name input files are required (i.e., names cannot be specified by the user). General descriptions of these input files are given below. Details on input formats and contents are given in Section 6. ECO2n requires the additional input file "CO2TAB" that should not be modified.

*flow.inp* – Flow input. The arbitrary input file name for TOUGH2 was changed to the fixed filename *flow.inp* to simplify execution. This file mainly includes rock properties, time-stepping information, geometric grid information, initial and boundary conditions, and data related to a multiphase fluid and heat flow simulation. The flow input is in most cases compatible with the original TOUGH2 V2 (see the manual; Pruess et al., 1999), with the additional data blocks REACT (see Section 6.1) and OUTPT, and a several other extensions. This is a "fixed" format file.

*solute.inp* – Transport, zone assignment, output, convergence, and other run parameters. This is a “free” format file. This file contains various flags and input parameters for calculations of reactive transport, such as diffusion coefficients, tolerance limits for convergence of transport and chemical iterations, flags for printout of minerals and aqueous species, and the assignment of model zones with different chemical properties (the properties of each zone, however, are given in file *chemical.inp* described below). Some minor changes were made since versions prior to TOUGHREACT V3.32-OMP, and therefore *solute.inp* files used for pre V3.32 code versions must be updated. No changes are required for the current version since V3.32.

*chemical.inp* – Chemical parameters and properties. This is “free” format file. This file is used to define the chemical system (i.e. the type and number of aqueous component species, minerals, gases, and sorbed species considered in the simulation). It also includes the initial compositions of water, minerals, and gases in zones that are assigned to grid blocks in file *solute.inp*, and kinetic data for intra-aqueous reactions and minerals (rate constants, surface areas, etc.). The current version of TOUGHREACT is mostly compatible with formats required for V3.32 and above. Pre V3.32 *chemical.inp* files must be updated.

In addition to the above-mentioned three input files, the program requires a thermodynamic database file with a file name specified in the *solute.inp* file. This file contains reaction stoichiometries, dissociation constants ( $\log(K)$ ), and regression coefficients of  $\log(K)$  as a function of temperature and pressure (see Section 6.4 for details). The current version optionally includes Arrhenius constants for temperature-dependent aqueous diffusion coefficients (primary species), mineral heat capacity coefficients, mineral thermal conductivity coefficients, and mineral thermal expansion parameters. The thermodynamic database is a “free” format file.

## 4.2 Output Files

---

Two types of output files are generated from this version of TOUGHREACT: (1) fixed file names, and (2) user-specified file names.

### 4.2.1 Fixed name output files

---

*flow.out* – Flow output. This file is very close to the TOUGH2 V2 output file, including data on temperature, pressure, liquid saturation, mass flux, and phase velocities for all grid blocks of the model.

*solute.out* – Echo of input file *solute.inp*. This file lists data that was read from input file *solute.inp*, including all transport parameters, chemical zone configuration, and other run-specific parameters.

*chemical.out* – Echo of input file *chemical.inp*. This file lists data that was read from input files *chemical.inp* and the thermodynamic database, including initial water, rock, and gas compositions, equilibrium constants and stoichiometries of chemical reactions, kinetic data, and linear adsorption Kd values and decay constants for certain species.

*runlog.out* – Log of the simulation progress. This file is updated throughout the simulation. It lists some run input parameters and all run-related messages, including error messages (Chapter 7).

*chdump.out* – chemical speciation data. This file contains results of geochemical speciation calculations for each initial water composition input into the model, including a printout of chemical mass balances (total mass balance and aqueous species mass balance). It also lists these data for grid blocks where chemical convergence fails (not reaching the specified convergence criteria). For debugging purposes, or for a small number of grid blocks, the flag ICHDUMP in file *solute.inp* allows geochemical speciation results to be output in the *chdump.out* file for every grid block, or certain specific grid blocks, at time step intervals. As a precaution to avoid filling up disk space, results of speciation calculations are output only for the first thousand grid blocks and/or time steps, after which output in this file is suspended.

*savechem* – save of geochemical data for restart. This file can be used to restart a TOUGHREACT run from the end of a previous run. Geochemical conditions obtained in one run are written to disk file *savechem*, and can be used as initial conditions in a subsequent run. The restart run for reactive geochemical transport simulation must be used together with a restart of the flow simulation (see p. 61 of the TOUGH2 V2 manual; Pruess et al., 1999). For a restart run,

the name of file *savechem* must be changed to *inchem*, and the name of file *SAVE* to *INCON* (same as in TOUGH2). Starting with V3.0-OMP, the initial permeabilities and porosities from the first simulation in the run sequence are saved so that permeability changes after multiple restarts are correctly calculated. Therefore, *savechem* files created with TOUGHREACT V2 and earlier cannot be used to restart a TOUGHREACT V3.0-OMP (or later) simulation.

In addition, this version of TOUGHREACT creates several optional fixed-name output files.

Fluid and heat flow outputs (controlled by *kdata* in PARAM.1):

*flowdata.tec* – Visit-compatible TECPLOT format file of data written to *flow.out*

*flowvector.tec* - Visit-compatible TECPLOT format file for flux/velocity vector components and magnitudes

Gas phase outputs at specified grid blocks (controlled by adding "wdata" in PARAM.1):

*GASOBS.DAT* - Gas phase saturations, relative humidity, pressure, temperature at each time step

Single-phase wellbore flow model outputs (controlled by MOP(17)):

*wellbore.out* – Reynolds number, friction, permeabilities at wellbore elements/connections

Reactive chemistry outputs (controlled by MOPR(8) in the *flow.inp* file) :

*min\_SI.tec* – mineral saturation indices

*rct\_sfarea.tec* – mineral reactive surface areas

*rctn\_rate.tec* – mineral reaction rates

*thermalparam.tec* - mineral and rock thermal conductivities, diffusivities, and heat capacities

*heatreaction.tec* - mineral and bulk system heats of reaction

*mbalance.out* – chemical mass balance information

## 4.2.2 User-specified output files

---

The names of these files must be specified in the input file *solute.inp*, and cannot be left blank. The output files are described below:

Iteration data (e.g., *iter.out*): Number of flow, transport, and chemical iterations used to reach convergence at specified time step intervals.

Aqueous species data (e.g., *aqconc.tec*): This file contains times, grid block coordinates (m), gas and liquid saturations, pressure, temperature (°C), pH, and aqueous species concentrations at all grid blocks for times specified in the *flow.inp* file. The number and types of species output are specified by flags in the input file *solute.inp*. This file has a Visit-compatible TECPLOT format.

Solid phase data (e.g., *minerals.tec*): This file contains time, grid point coordinates (m), temperature (°C), mineral abundances (or abundance changes), and exchanged species concentrations at all grid blocks for time printout intervals specified in the *flow.inp* file. This file has a Visit-compatible TECPLOT format.

Gas phase data (e.g., *gases.tec*): Time, grid point coordinates (m), temperature (°C), and gas partial pressures (or volume fractions) for all grid blocks at times specified in the *flow.inp* file. This file has a Visit-compatible TECPLOT format.

Chemical data (aqueous species, minerals, gases) at specified grid blocks at specified time step intervals (e.g., *time.out*): This file contains the element name, time, gas and liquid saturations, pressure, temperature, pH, aqueous species concentrations, mineral abundances, gas pressures, exchanged species concentrations, and aqueous charge balance for specific grid blocks and time intervals, as specified in the input file *solute.inp*.

## 5 Input File Formats and Contents

---

### 5.1 Flow Input (*flow.inp*)

---

Input formats for multiphase flow are similar to TOUGH2 Version 2.0 (Pruess et al. 1999), with several new features and the addition of keyword blocks 'REACT', 'OUTPT', and 'FIXPT'. In contrast to TOUGH2 V2, the flow input file must be named *flow.inp*. The REACT block is used for invoking a reactive transport simulation and setting numerous flags for reactive transport options. The REACT block has one record that specifies option parameters related to reactive transport. Without this data block, the program runs a multiphase flow simulation only. The keyword block OUTPT was added to V3.32-OMP to write out the correct number of grid blocks in the X, Y, Z dimensions (for a structured grid) to use in Visit-compatible TECPLOT format output files. Starting with TOUGHREACT V3.85-OMP, additional options not in TOUGH2 V2



are present in keyword blocks 'ROCKS', 'PARAM', 'INCON', 'CONNE', and 'GENER'. Inputs for these options are discussed below. Also note that the TOUGH2 capability of defining an “inactive” grid block with a zero or negative volume in the input block 'ELEM' (used for a constant boundary condition), is not operational in TOUGHREACT. Instead, constant chemical boundary conditions are set in TOUGHREACT by input of a very large volume ( $\geq 10^{20}$  m<sup>3</sup>) for boundary grid blocks, and for volumes  $\geq 10^{50}$  m<sup>3</sup> pressure and temperature will also remain constant. Chemical concentrations in these grid blocks will not undergo speciation or mineral-gas-water-reactions. In TOUGH2 V2.0, setting the volume to greater than  $10^{50}$  will also remove the boundary grid blocks from mass balance calculations. FIXPT is a new block (file) that allows for assigning time-varying pressures and temperatures in specific grid blocks.

This version of TOUGHREACT also incorporates some options of other TOUGH2 versions that were developed specifically for unsaturated flow and boiling in fractured rock. The additions to the flow input file are given below. An example precedes each option.

```

REACT-789012345678-2----*----3----*----4----*----5----*----6----*----7----*----8
00021106000200000000

```

**REACT**                      Parameter choices for reactive transport simulation

Variable: MOPR(20)

Format:    20I1

MOPR(1)        = 0 perform reactive transport

                  = 1 no reactive transport, but input files with chemical data are read

                  = 2 no reactive transport, no chemical data files are read

                  = 3 solves flow and transport without chemical reaction

                  = 4 solves transport and chemical reactions using constant velocity field (flow calculated at first time step only)

                  = 5 solves transport (no chemical reactions) using constant velocity field (flow calculated at first time step only)

MOPR(2) > 0 writes the transport coefficient matrix, Darcy velocities, porosities, and other transport data in the *runlog.out* file during calculations of aqueous species and gas transport. Primarily used for debugging (very large output!).

MOPR(3) > 0 writes source terms, old and new aqueous concentrations, and various other parameters in the *runlog.out* file during transport calculations. Also outputs the permeability, porosity, and capillary pressure correction factor at each grid block in the *runlog.out* file. Primarily used for debugging (very large output!).

MOPR(4) ≠ 1 Force at least one fluid flow step to be calculated (MOPR(4)=2 is normally suggested).

= 1 does not force at least one fluid flow step to be calculated. This option can be useful to compute chemical reactions in single-grid block problems. For the chemical quasi-stationary states (QSS) option, MOPR(4) must be set equal to 1.

MOPR(5) = 0 Results in printout of time step iteration information in *flow.out*, as in TOUGH2 V2. MOPR(5) = 0 is recommended unless file *flow.out* becomes too large.

= 1 Disables printout at every time step in *flow.out*.

= 2 In addition to MOPR(5)=1, does not write porosities and permeabilities to *SAVE* file.

MOPR(6) = 0 No Leverett scaling of capillary pressure

= 1 Leverett scaling of capillary pressure assuming capillary flow (Eq. F.9a in Appendix F) for heterogeneous porosity and permeability fields and/or from porosity-permeability changes owing to mineral dissolution and precipitation.

= 2 Leverett scaling of capillary pressure assuming channel (e.g., fracture) flow (Eq. F.9b in Appendix F).

= 3 Leverett scaling of capillary pressure assuming mixed capillary and channel (e.g., fracture) flow with the function linearly weighted by the porosity (porosity of 1.0 yields pure channel flow scaling, tending to pure capillary flow scaling as the limit of zero porosity is approached; see Appendix F).

MOPR(7) ≥ 0 Allow the specification of the number of digits past the decimal in tecplot-format output files (up to 8 digits). For accurate ratios of components or calculation of isotopic ratios it is usually necessary to write out at least 6 digits. Zero or blank gives the default of 4 digits.

MOPR(8) = 0 No printout of extra output files.

≥ 1 Outputs mineral saturation indices, for each grid block, in file *min\_SI.tec*. This information is output at the same intervals as specified in *flow.inp* for the flow (and chemistry) information.

≥ 2 Creates an additional output file (at same time intervals as above) with mineral reaction rates (mol/kg H<sub>2</sub>O/s) at all grid blocks. The file name is fixed as *rctn\_rate.tec*.

≥ 3 Creates an additional output file (at same time intervals as above) with mineral reactive surface areas (m<sup>2</sup>/kg H<sub>2</sub>O) and other parameters (e.g., active fracture parameter) for liquid saturation-dependence that are used in the rate equation after all conversions. The file name is fixed as *rct\_sfarea.tec*.

≥ 4 Outputs mass balance information in file *mbalance.out*.

≥ 5 Outputs thermal conductivities and heat capacities (C<sub>p</sub>) of minerals, and calculated rock C<sub>p</sub> coefficients from mineral values in file *thermalparam.tec*.

≥ 6 Outputs system and mineral heats of reaction in file *heatreaction tec*.

MOPR(9) = 1 Use heat capacities of minerals based on data in thermodynamic database to calculate rock heat capacity. See Appendix L for details.

= 2 Use thermal conductivities of minerals based on data in thermodynamic database to calculate rock value. See Appendix L for details.

= 3 Both temperature-dependent mineral heat capacities and thermal conductivities used to calculate rock values

MOPR(10) = 1 The time step length is NOT reduced based on chemical convergence

= 2 Chemical convergence bounds for timestepping read in block CONVP in *solute.inp*

MOPR(11) = 1 Enables approximating sedimentation/compaction processes by forward explicit advection of solids and aqueous species. If enabled, a sedimentation velocity (constant in time but optionally variable with depth) must be entered in record 11 and 12 of file *solute.inp* (Section 6.2). This option works only for a vertical 1D column with grid blocks and connections ordered sequentially from top to bottom.

MOPR(12) = 1 Heat of reaction source terms are calculated from *log(K)* values in thermodynamic database and are added as source/sink terms in heat flow calculations (using sequential noniterative approach). See Appendix M for details.

MOPR(13) = 1 Temperature-dependent mineral and rock densities are calculated based on thermal expansion coefficients read in from thermodynamic database (placeholder- not fully implemented yet).

MOPR(14) ≥ 1 Exponent to apply to writing out SAVE and savechem files. NTSAVE (dimensioned in *flowpar\_v3.inc*) is modified according to NTSAVE\*(10\*\*MOPR(14)), such that the default of MOPR(14)=0, gives the

increment of printout as every NTSAVE time steps (NTSAVE is dimensioned to 100 in released executable files).

MOPR(15) = 1 Permeability will be modified according to the domain "SEED" specified in file *flow.inp* (see the TOUGH2 V2 manual).

MOPR(16) = 1 Enables reading a heterogeneous field of mineral volume fractions. An ascii input file with name *min\_volf.inp* must be provided in addition to the other input files. This file must contain a header in record 1, immediately followed (starting in record 2) with one record per mesh gridblock (for all gridblocks in the mesh) in the same gridblock order as specified in file *flow.inp* (or *MESH*). Each of these records must include, separated by blanks: grid block ID (format A5); initial volume fraction of each mineral in the solid phase (free format), in the same mineral order as specified in the input file *chemical.inp*. Only works in conjunction with the properties of the first rock zone in *chemical.inp*.

MOPR(17) = 1 Reads high P-T thermodynamic database in soltherm.xpt format

MOPR(18) = 1 Reads Arrhenius parameters from thermodynamic database for species- and temperature-dependent aqueous diffusion coefficients (total transported concentrations)

= 2 Reads Arrhenius parameters from file "aqdiffusion.dat"

MOPR(19) = 1 Reads file "electric\_cond.dat" and calculates fluid and rock electrical conductivities

MOPR(20) Not used

MOPR(21)-MOPR(24) enable modeling of concentrated solutions using the Pitzer ion activity model, as described in the TOUGHREACT-Brine manual that supplements this user's guide.

MOPR(25) Allows modeling water diffusion according to its chemical potential, as described in the TOUGHREACT-Brine manual that supplements this user's guide.

## PARAM

```
PARAM      123456789012345678901234
  49999  9999000000000120000401005000  2.14e-5  2.334      ! PARAM.1
0.00000 0.157785e8  1.e+006.0480e+05wdata 0.01 -9.806650    ! PARAM.2
wp001
dr357
d2357
  1.0000e-4                                           ! PARAM.3
0.00000000000000D+00 0.00000000000000D+00 0.00000000000000D+00    ! PARAM.4
```

## PARAM.1

**KDATA = 4** Writes flow output to VisIT-compatible Tecplot-format file *flowdata.tec* instead of *flow.out*. Mass and heat fluxes, velocities, and their vector components recalculated at grid block centers are written to file *flowvector.tec* (also VisIT-compatible Tecplot-format).

**MCYC = 9999** The maximum number of time steps in Record was extended slightly from the original TOUGH2. In TOUGHREACT, if **MCYC = 9999**, the number of time steps is not controlled by **MCYC**, and therefore the maximum simulation time is only controlled by **TIMAX** in Record **PARAM.2**. IF **MCYC**  $\leq$  9998, it is the same as in TOUGH2 V2.

## MOP Value Changes

**MOP(14)** = 0 Fixed rock thermal conductivities and grain heat capacities (as in TOUGH2)

= 1 Temperature-dependent rock grain heat capacities used (calculated from coefficients read in **ROCKS.4**)

= 2 Temperature-dependent bulk rock thermal conductivities used (calculated from coefficients read in **ROCKS.3**)

= 3 Both temperature-dependent bulk rock thermal conductivity and grain heat capacity used

**MOP(17)**  $\geq$  1 Invoke single-phase wellbore simulator for turbulence and momentum effects on pressure through revised permeability scheme based in part on Battistelli et al. (2011). When invoked, the initial wellbore permeability is assumed to be in permeability direction '3'. This wellbore permeability is used to calculate the wellbore diameter assuming Poiseuille flow. Only grid block connections designated as 'ISOT=5' in **CONNE** will be subject to wellbore flow calculations. Details are given in Appendix XX. Two options for numerical convergence are available as follows:

= 1 Wellbore permeability at current iteration is calculated from the average of the current turbulence/friction calculation and the value from previous iteration (most stable).

= 2 Wellbore permeability at current iteration is calculated from geometric mean of the value calculated from the current turbulence/friction calculation and the value from previous iteration.

## PARAM.2

Variable **ELST** in record was modified so that if the keyword "wdata" is used, the program will look for a line after **PARAM.2** giving the number of grid blocks to write out specific flow data. Following the integer variable, the 5 character identifiers for the grid blocks must be listed sequentially in column format. The name of the output file is fixed as

GASOBS.DAT. The records PARAM.3 and PARAM.4 should follow immediately after the last grid block name. An example is shown above.

Variable "dtmin" is read in directly after "wdata" to set the minimum time step that is allowed during time step reduction. Example above shows 0.01 seconds. Format is E5.

## PARAM.4

The format of default initial condition for the primary variables was changed from E20.14 to E20.13, as shown on last line in the example above.

## ROCKS

The following options were added to those in TOUGH2 V2 (Pruess et al., 1999) within the ROCKS input records.

### ROCKS 1.1

Format (9E10.4) (TORTX was modified and PTORT and PHICRIT were added)

COM, EXPAN, CDRY, **TORTX**, GK, XKD3, XKD4, **PTORT**, **PHICRIT**

TORTX < 0 Generalized power law (Burnol and Claret, 2012; Lagneau, 2002) with saturation-dependence added:

$$\tau = \left( \frac{\theta - \theta_{crit}}{\theta_0 - \theta_{crit}} \right)^p \tau_0$$

where  $\tau$  is tortuosity,  $\theta$  is porosity,  $\theta_{crit}$  (PHICRIT) is the critical porosity under which diffusion is supposed to stop (percolation threshold),  $p$  (PTORT) is a power coefficient (e.g., 0.3 for a nonconsolidated sand, 1.2 for a limestone, and 2 for a cement paste),  $\theta_0$  is initial porosity, and  $\tau_0$  (-TORTX) is initial tortuosity. For direct porosity or saturation-porosity dependence, set TORTX = -1.0. If TORTX < 0, then PTORT and PHICRIT must be set. For TORTX = 0.0, the option reverts to the Millington-Quirk formulation as in TOUGH2 V2 (Millington and Quirk, 1961):

$$\tau = \theta^{1/3} S^{10/3}$$

where  $S$  is phase saturation. If TORTX > 0.0 then tortuosity is a fixed value, as in TOUGH2 V2.

PTORT Exponent for generalized power law. Required for TORTX < 0, and is an added parameter in the ROCKS 1.1 line (entries 71-80).

PHICRIT Critical porosity for generalized power law. Required for TORTX < 0, and is an added parameter in the ROCKS 1.1 line (entries 81-90).

### ROCKS 1.2 (If "NAD" $\geq$ 4)

Format (I5,5X,3E10.4)

ITP, TCONDPAR(1), TCONDPAR(2), TCONDPAR(3)

### ROCKS 1.3 (If "NAD" $\geq$ 5)

Format (I5,5X,4E14.6)

IHCPLAW, CPRKCF(1), CPRKCF(2), CPRKCF(3), CPRKCF(4)

### ROCKS 1.2 or ROCKS 1.4

RP(5) > 0.0 This option, with IRP = 7 and RP(4) = 0.0, enables the modified Brooks-Corey for gas relative permeability, as implemented by Wu et al. (1999). Note that RP(4) must be smaller than or equal to zero if this option (RP(5) > 0.0) is used.

### ROCKS 1.3 or ROCKS 1.5

ICP = 10 Capillary pressure linearization at small liquid saturations, as implemented in Wu and Mishra (1998). With this option, the input parameters CP(I) are the same as for the Van Genuchten function option (ICP = 7), except that CP(4) is set to parameter *epsilon* instead of  $P_{max}$ . In this case, the capillary pressure is linearly extrapolated from  $S_l = S_r + \epsilon$  (with  $S_l$  and  $S_r$  being the current and residual liquid saturations, respectively) down towards  $S_l = 0$ . The slope of the linear extrapolation corresponds to the slope of the capillary-pressure/liquid-saturation function at  $S_l = S_r + \epsilon$ .

CP(6) > 0.0 This option, with either ICP = 7 or ICP = 10, and together with flag ISOT = -10 in the CONNE first input record, enables the active fracture model (Liu et al., 1998) as implemented by Wu et al. (1999). In this option, CP(6) is used to input the active fracture parameter  $\gamma$ .

**INCON** Three variables for three components of permeability were added to Record INCON.1 after porosity PORX (... , PORX, PER1, PER2, PER3 with format ... , E15.9, 3E15.9). Porosities and permeabilities at every grid block are stored (instead of only for a material type as in TOUGH2), for the current time, previous time, time zero, and at the beginning of the simulation. If zero or blank, and option START is used, the porosity and three permeability values will be taken from block 'ROCKS'. If the values of porosity and/or permeability are different in INCON and ROCKS, then the ratios will be used for calculation of modified capillary pressures if the Leverett scaling option is selected (MOPR(6)  $\geq$  1). The SAVE file also includes the updated porosity and permeability values resulting from mineral precipitation, dissolution, or changes owing to pore compressibility and thermal expansion (unless MOPR(5) = 2). If zero or blank, temperature will be taken as default value specified in block PARAM'.

A minor format difference is present in Record INCON.2 (changed from E20.14 to E20.13):

Format (4E20.13)

X1, X2, X3, X4

For use of the EOS9 flow module, in Record INCON.2 the second primary variable X2 is used for specifying grid block dependent temperature (in °C). EOS9 in TOUGH2 V2 only allows a fixed 25°C temperature. This addition allows for temperature-dependent gas species diffusion coefficients and chemical speciation/reactions to be performed assuming a fixed yet spatially-varying temperature field.

As explained in the TOUGH2 manual for restarts (Pruess et al., 1999, p. 61–62, 169), when record INCON.3 starts with the string ‘+++’, the code will look for time stepping information in one additional record. This record is generated by the code and is output in file SAVE. This additional record has been modified slightly to the following format:

Format (2I6, I3, 2E15.8)

KCYCX, INTERCX, NMX, TSTX, TIMINX

where KCYCX is the total (cumulative) number of time steps at the current time, INTERCX is the total (cumulative) number of iterations at the current time, NMX is the total number of rock types in the present simulation, TSTX is the prior starting simulated time, and TIMINX is the current simulated time (i.e. when the SAVE file was generated).

**MESH** Reading and writing the indexing for MESH files for 100,000 to 999,999 grid blocks extends the functionality of TOUGHREACT to problem sizes larger than 99,999 grid blocks. No flag is required, and TOUGHREACT will read MESH files created from TOUGH2 V2.0 and prior TOUGHREACT versions. The revised indexing (I6 instead of I5) is written on output for grids with 100,000 to 999,999 grid blocks.

**CONNE** Additional options for the parameter ISO:

ISO ≤ -7 and ISO ≥ -9

ISO ≤ -10 and ISO ≥ -12

ISO ≤ -13 and ISO ≥ -15

ISO = 5 Connections for single-phase wellbore flow calculations (enabled if MOP(17) ≥ 1).

**GENER** An option was added for time-dependent thermal conductivity. For this option, one more parameter, KTAB, was added at the end of record GENER.1:



Format (2A5, 4I5, 5X, A4, A1, 3E10.4, I2)

ELEG, SOURCE, NSEQ, NADD, NADS, LTABG, TYPE, ITAB, GX, EX, HX, KTAB

KTAB is the number of points (number of time values and same number of factors) to read in following records for time-dependent thermal conductivities (variables before KTAB are unchanged from Pruess et al., 1999, p. 174).

If  $KTAB > 0$ , the following sets of time values and factors are read:

Record GENER.1.4 (format unchanged from GENER.1.1):

Format (4E14.7)

TIMKTH (1:KTAB)

TIMEKTH (1:KTAB) are the time values (“generation times”) at which thermal conductivity values change

Record GENER.1.5:

Format (4E14.7)

FACKTH (1:KTAB)

FACKTH (1:KTAB) are the values of the time-dependent factors corresponding to the list of time values given in GENER.1.4. At each time values specified in record GENER.1.4, the thermal conductivity (determined from wet and dry conductivity values input in records ROCKS.1 and ROCKS.2) is multiplied by these factors.

Reading and writing the indexing for GENER files for 100,000 to 999,999 grid blocks was added for consistency with the MESH file. No flag is required, and TOUGHREACT will read GENER files created from TOUGH2 V2 and prior TOUGHREACT versions.

**FIXPT** The FIXPT file was added in V3.3-OMP to allow for time-dependent multiphase pressure and temperature boundary conditions (liquid, gas, or multiphase). It was implemented by temporarily increasing the grid block volume to a value greater than  $10^{50}$  during the time step when the pressure and temperature are being fixed.

Consistent with the usage of the GENER file, an empty FIXPT file is created if no file is present, or no FIXPT block is present in *flow.inp*. The format of FIXPT is similar to the time-dependent GENER block input format. Currently, only stepwise changes in pressure and temperature have been implemented.

Format(A5)

DENT

Format (A5, 20X, I5,1X,E10.4)

ELEF, LTABF, TEMPBND

FORMAT(4E14.7)

Example lines extracted from FIXPT file containing 1102 time entries ("stage2" is just a comment):

```
FIXPT          stage2
n6473          1102
4.2522000E+06 4.2528000E+06 4.2534000E+06 4.2540000E+06      ! Times
4.2546000E+06 4.2552000E+06 4.2558000E+06 4.2564000E+06
4.2570000E+06 4.2576000E+06 4.2582000E+06 4.2588000E+06
.
.
.
3.3481126E+06 3.6530033E+06 3.7252231E+06 3.7336207E+06      ! Pressures
4.0090637E+06 4.3066764E+06 4.3449697E+06 4.2351284E+06
3.8572341E+06 4.0473569E+06 5.4181894E+06 6.8763573E+06
.
.
.
1.0000000E+01 1.0000000E+01 1.0000000E+01 1.0000000E+01      ! Temperatures
1.0000000E+01 1.0000000E+01 1.0000000E+01 1.0000000E+01
1.0000000E+01 1.0000000E+01 1.0000000E+01 1.0000000E+01
.
.
.
+++
6473
```

## 5.2 Transport and Convergence Inputs and Chemical Zone Assignments (*solute.inp*)

---

The input file *solute.inp* is used to provide the thermodynamic data input file name, several reactive transport output file names, input and output parameters, convergence options, and assignments of chemical zones to grid blocks. Parameters to be specified include aqueous and gaseous diffusion coefficients, tolerance limits for convergence of transport and chemical iterations, and flags specifying the units in output files of mineral abundances, aqueous and gaseous species concentrations. Except for non-numeric variables (title, grid block names, and names of species and minerals), data from this file are read in free format.

The first input record to be read in this file is the title. It is followed by 14 main data records. “Skip” records (see below) can be included anywhere in the file, as long as not within a sequence of array inputs of the same variable (e.g., list of species, or list of grid blocks). Some records and some variables in data records are not required under certain conditions. In such cases, one should input them as zero values or omit them (see examples). Each record is described below, including the description of each input variable and its corresponding FORTRAN format for appropriate reading. Note that the meaning and options associated with several of the flags and variables in *solute.inp* have changed significantly since V3.85-OMP, compared to TOUGHREACT V1.2 and V2, and in some cases also V3.0-OMP. Again note, although the file format has not changed dramatically, some of the flags/parameters are not interpreted in the same manner. Therefore, when using input files developed for earlier code versions, one should carefully inspect all of the inputs, review their usage in this Reference Manual, the Quick Reference Guide, and/or the Sample Problems, and revise them appropriately.

### “Skip” records:

One or more heading (comment) line can precede each record described below (see inputs of the sample problems). The comment line is indicated by beginning with # followed by one blank, or any blank record. These records will be skipped on input, and can be inserted anywhere in the file. These “skip” records can be also used for data source references, or other purpose.

### Record\_1. Title

Variable: TITLE

Format: A82

TITLE: title and comments.

### Record\_2. Options for reactive geochemical transport (1)

Variable: ISPIA ITERSFA ISOLVC NGAMM NGAS1 ICHDUMP KCPL ICO2H2O  
iTDS\_REACT

Format: 9I (integer free format)

ISPIA : flag for iteration scheme between transport and reaction. ISPIA = 2 is much faster and more commonly used. For some simpler problems, ISPIA = 0 gives a more accurate result, however for more complex problems, convergence is often much more difficult.

- = 0 Sequential iteration between transport and chemistry
- = 2 No sequential iteration (fully explicit reaction source terms)

ITERSFA : Reactive surface areas are calculated either outside or inside the chemical reaction Newton-Raphson iterations.

- = 0 Reactive surface areas calculated outside Newton-Raphson iterations.
- = 1 Reactive surface areas calculated inside Newton-Raphson iterations.

ISOLVC : flag for the linear equation solver for transport. The solvers are the same as in TOUGH2 V2 (see p. 73 of the manual, Pruess et al., 1999), except for the removal of MA28. ISOLVC = 5 is generally the most stable and fastest solver, followed by DSLUCS (ISOLVC = 3). In many cases DLUSTB (ISOLVC = 5) converges when other solvers fail.

- = 2 DSLUBC, a bi-conjugate gradient solver
- = 3 DSLUCS, a Lanczos-type bi-conjugate gradient solver
- = 4 DSLUGM, a general minimum residual solver
- = 5 DLUSTB, a stabilized bi-conjugate gradient solver (preferred)

NGAMM : flag for sub-iteration between calculation of activity coefficients and secondary species concentrations at the beginning of each chemical Newton-Raphson iteration. NGAMM is the number of subiterations. For most problems NGAMM can be set to 0 (which internally implements a default value of 2). If convergence of the Newton-Raphson iterations for the chemical system fails, NGAMM can be increased up to a maximum of about 10. Note that increasing the value of NGAMM can significantly increase computation time.

NGAS1 : Flag for gaseous species to be included in transport calculations (excluding gases considered in the EOS modules such as H<sub>2</sub>O, CO<sub>2</sub> and H<sub>2</sub>O in ECO2n, etc.). Note that the meaning of NGAS1 was changed in V3.0-OMP to only control gas species transport.

- = 0 Gas species are not transported (other than gases transported in flow, such as H<sub>2</sub>O and CO<sub>2</sub> in EOS2 or ECO2n).
- ≥ 1 Gas species are transported (besides H<sub>2</sub>O and CO<sub>2</sub> in EOS2 or ECO2n), unless fixed individually using the IGASFIX flag in chemical.inp.

ICHDUMP : flag to enable detailed printout of chemical speciation results (typically enabled only for debugging chemical convergence problems).

- = 0 Disabled
- = 1 Printout of chemical speciation at each grid block and each time step

- = 2 Printout of chemical speciation at time intervals specified by NWTI in Record\_7 and the grid blocks specified in Record\_8. If this option is enabled, TOUGHREACT will abort after the output of speciation results for the first 1000 grid blocks and/or time steps, to avoid accidentally filling up disk space.

KCPL : flag to consider feedback effects of changes of porosity, permeability, and capillary pressure due to mineral dissolution and precipitation on flow.

- = 0 Disabled
- = 1 Enabled
- = 2 Only monitor changes in output files, without feedback on flow. (To consider porosity changes from sedimentation, with option MOPR(11)=1, KCPL must be  $\geq 1$ )

ICO2H2O : flag to consider effects of CO<sub>2</sub> and/or H<sub>2</sub>O reaction source/sink terms on fluid flow calculations. ICO2H2O can be used for H<sub>2</sub>O reaction source/sink terms in all EOS modules, however, CO<sub>2</sub> and H<sub>2</sub>O are only possible using the EOS2 and ECO2N EOS modules. Note that the algorithm for calculating source/sink terms was revised significantly in V3.0-OMP and again in V3.3-OMP.

- = 0 Coupling ignored
- = 1 Coupling of CO<sub>2</sub> reaction source/sink terms for all reactions
- = 2 Coupling of CO<sub>2</sub> and H<sub>2</sub>O reaction source/sink terms for all reactions
- = 3 Coupling of CO<sub>2</sub> and H<sub>2</sub>O source/sink terms solely from mineral-water reactions

iTDS\_REACT : Must be set to zero in this version (not used)

### Record\_3. Options for reactive geochemical transport (2)

Variable: SL1MIN, RCOUR, STIMAX, CNFACT

Format: Real (free format)

SL1MIN: Geochemical calculations are skipped at grid blocks where the liquid saturation is less than SL1MIN. For typical boiling simulations, use SL1MIN less than or equal to  $10^{-3}$ .

RCOUR : both a variable and a flag to limit the time step size.  $RCOUR \neq 0.0$  limits the maximum time step size to  $|RCOUR| \times \text{Courant Number}$ . Positive RCOUR values limit the time step by either the gas or liquid phase velocity, whichever is highest. Negative RCOUR values limit the time step by the velocity of the liquid phase only. This option is disabled if  $RCOUR = 0.0$ .

STIMAX : Maximum ionic strength for geochemical calculations. If the stoichiometric ionic strength exceeds STIMAX in the input composition, or during the Newton-Raphson iterations, then STIMAX is used for calculation of

HKF activity coefficients. Note that TOUGHREACT versions prior to V3.32-OMP used STIMAX as a cutoff to skip chemical computations, but in some cases allowed internal ionic strengths to greatly exceed STIMAX. STIMAX may be valid up to 6 mol/kg H<sub>2</sub>O for NaCl-dominant solutions. For other solutions, STIMAX may only be valid in the range of 2.0 and 4.0. However, in some cases, a higher ionic strength may be needed to allow convergence, even if the final converged solution ionic strength is well below STIMAX. See Appendix H regarding the calculation of activity coefficients at elevated ionic strengths.

CNFACT : Weighting factor for mineral and gas reaction source terms in the transport equations (1.0 = fully implicit source terms, 0.0 = fully explicit source terms). This parameter has an effect only if sequential iterations are enabled (ISPIA = 0). In this program version, CNFACT always defaults to 1.0 if a non-zero value is input (implicit only). Simulations with CNFACT = 0.0 using sequential iterations will produce the same results as simulations without sequential iterations (explicit source terms) but requires increased computing time and therefore should be avoided.

#### **Record\_4.1 through 4.6. Names of input thermodynamic database and output files regarding chemical data and numerical iterations**

Variable: THERMO\_in , OUTiter, OUTplot, OUTsolid, OUTgas, OUTtime

Format: A20, each file name occupies one line.

THERMO\_in : name of thermodynamic data input file.

OUTiter : name of file (e.g., *iter.out*) to output iteration information.

OUTplot : name of file (e.g., *aqconc.tec*) to output aqueous concentrations in VisIT-compatible Tecplot-format for all grid blocks at specified printout times defined in flow.inp.

OUTsolid : name of file (e.g., *minerals.tec*) to output mineral abundances and exchanged species concentrations in VisIT-compatible Tecplot-format for all grid blocks at specified printout times defined in flow.inp.

OUTgas : name of file (e.g., *gases.tec*) to output gas pressures in VisIT-compatible Tecplot-format for all grid blocks at specified times defined in flow.inp.

OUTtime : name of file (e.g., *time.out*) to output aqueous concentrations, mineral/gas abundances, and adsorbed/exchanged species concentrations versus time, in tecplot format, for specific grid blocks input in Record\_8, at time step intervals (NWTI) input in Record\_7.

#### **Record\_5. Weighting parameters and diffusion coefficients**

Variable: WTIME, WUPC, DIFUN, DIFUNG

Format: 4F (real free format)

WTIME : time weighting factor, ranging from 0.0 to 1.0. WTIME = 1.0 (implicit) is recommended.

WUPC : upstream weighting factor, ranging from 0.0 to 1.0. WUPC = 1.0 (fully upstream) is recommended.

DIFUN : aqueous species diffusion coefficient for total concentrations (m<sup>2</sup>/s).

DIFUN is multiplied by the tortuosity ( $\tau$ ) (defined in the ROCKS block in *flow.inp*), porosity, and liquid saturation. Notice that if  $\tau$  is 0.0, TOUGHREACT (consistent with TOUGH2) computes  $\tau$  from  $\tau_{\beta} = \phi^{1/3} S_{\beta}^{7/3}$  (Millington and Quirk, 1961), where  $\phi$  is porosity,  $S_{\beta}$  is phase saturation, and  $\beta$  is the fluid phase index. If  $\tau$  is < 0.0, TOUGHREACT computes  $\tau$  from a generalized power law (Burnol and Claret, 2012; Lagneau, 2002; see the ROCKS 1.1 input record of the *flow.inp* file described earlier in this document). Note that in this code version if the variable NOTRANS = -1 in *chemical.inp*, diffusion coefficients for individual primary species (total concentrations) are computed as a function of temperature using the Arrhenius equation with coefficients given in the thermodynamic database (see Appendix ).

DIFUN = 0.0: Aqueous species diffusion turned off (in reactive transport only) for all species, except for primary species having NOTRANS = -1.

DIFUN < 0.0: Aqueous species diffusion coefficients (total concentrations) calculated as a function of temperature using DIFUN as the pre-exponential factor (A), and the activation energy set to 10<sup>-4</sup> (typical value from Oelkers and Helgeson, 1988), except for primary species having NOTRANS = -1.

DIFUN > 0.0: Aqueous species diffusion coefficients fixed to DIFUN (in m<sup>2</sup>/s), except for primary species having NOTRANS = -1.

DIFUNG : molecular diffusion coefficient (m<sup>2</sup>/s) of gas species other than H<sub>2</sub>O. The gas species diffusivity is calculated in TOUGHREACT by multiplication of DIFUNG by the tortuosity ( $\tau$ ), defined in the ROCKS block of the flow input (*flow.inp*), the porosity, and gas saturation.

DIFUNG = 0.0: Gas species diffusion (trace gases in reactive transport only) turned off.

DIFUNG < 0.0 (any negative value): Gas species diffusion coefficients calculated as a function of molecular weight and diameter, temperature, and pressure according to Eq. A.1 (Appendix A). Data for gas species must be provided in the thermodynamic database.

DIFUNG > 0.0: All gas species diffusion coefficients fixed to DIFUNG (in m<sup>2</sup>/s)

## Record\_6. Data related to convergence criteria

Variable: MAXITPTR, TOLTR, MAXITPCH, TOLCH, TOLMB, TOLDC, TOLDR

Format: I, E, I, E, I, E, E (all free format)

MAXITPTR: maximum number of sequential iterations between transport and chemistry. If MAXITPTR=1, a sequential non-iterative approach is used where transport and chemistry are sequentially solved without iteration. Note that the value of MAXITPTR has no effect if ISPIA in Record\_2 is set to 2 (non-iterative approach). Computing performance will significantly decrease as MAXITPTR increases.

TOLTR: convergence criterion (as relative change of aqueous concentrations) for the sequential iterative (transport/chemistry) scheme; a value between 1.0E-03 to 1.0E-06 is suggested. This convergence criterion is used only when MAXITPTR > 1 and ISPIA=0.

MAXITPCH: maximum number of iterations allowed for solving chemical speciation. In most cases, a value of 300 is appropriate.

TOLCH: convergence criterion (as relative change of aqueous concentrations) for chemical speciation computations; a typical value is 1.0E-06, with a range of 1.0E-05 to 1.0E-12. For simulations with a large number of time steps (> 10,000), values larger than 1.0E-6 should be avoided to minimize the potential for cumulative mass balance errors.

TOLMB: mass balance convergence criterion - typically set as 1.e-2 x TOLCH

TOLDC: relative concentration change (between two consecutive time steps) tolerance for quasi-stationary state (QSS); a value between 1.0E-03 to 1.0E-06 is suggested; if not using the QSS option, set equal to zero. MOPR(4) (in *flow.inp*) must be set to 1 to enable this option. When KCPL>0 or ICO2H2O>0 or iTDS\_REACT in Record\_2, no QSS can be attained and this option is not available, set equal to zero.

TOLDR: relative dissolution and/or precipitation rate change tolerance for the quasi-stationary state option (QSS) (i.e., if TOLDC ≠ 0); a value between 1.0E-03 to 1.0E-06 is suggested; if not using QSS approximation set equal to zero. When KCPL>0 or ICO2H2O>0 or iTDS\_REACT in Record\_2, set equal to zero.

## Record\_7. Output control variables

Variable: NWTI, NWNOD, NWCOM, NWMIN, NWAQ, NWADS, NWEXC, ICONFLAG, MINFLAG, IGASFLAG

Format: 10I (integer free format)



NWTI : printout frequency (i.e., every NWTI time steps) of model output for selected grid blocks (NWNOD≠0). These data will be output in the file specified on Record\_4.6. NWTI also controls the printout frequency in the iteration file (Record 4.2), after the first 20 time steps are written. If NWTI is negative, then all time steps are written in the iteration file but data at every |NWTI| time steps are written for the selected grid blocks in the time evolution file.

NWNOD : number of grid blocks for time evolution printout. NWNOD grid blocks (with names EL) will be read below on Record\_8. NWNOD can be set to a negative value as a flag for line-by-line input starting on Record\_8.

NWCOM : number of chemical components (species) for which to output total concentrations in files specified on Record\_4.3 and Record\_4.6. NWCOM primary species (with indices IWCOM) will be read below on Record\_9. If NWCOM is set to 0, then all chemical components will be written out (IWCOM(1) must then be a blank line). NWCOM can also be set to a negative value, in which case species names (instead of indices) will be read line-by-line starting on Record\_9.

NWMIN : number of minerals for which to output abundances in files specified on Record\_4.4 and Record\_4.6. NWMIN minerals (with indices IWMIN) will be read below in Record\_10. If NWMIN is set to 0, then all minerals will be written out (IWMIN(1) must then be a blank line). NWMIN can also be set to a negative value, in which case mineral names (instead of indices) will be read line-by-line starting on Record\_10.

NWAQ : number of individual aqueous species for which to output concentrations in files specified on Record\_4.3 and Record\_4.6. NWAQ species (with indices IWAQ) will be read below in Record\_11. NWAQ can be set to a negative value, in which case species names (instead of indices) will be read line-by-line starting on Record\_11.

NWADS : number of surface complexes for which to output concentrations in files specified on Record\_4.3 and Record\_4.6. NWADS surface complexes (with indices IWADS) will be read below in Record\_12. NWADS can be set to a negative value, in which case names of surface complexes (instead of indices) will be read line-by-line starting on Record\_12.

NWEXC : number of exchange species for which to output concentrations in files specified on Record\_4.3 and Record\_4.6. NWEXC exchange species (with indices IWEXC) will be read below in Record\_13. NWEXC can be set to a negative value, in which case names of exchange species (instead of indices) will be read line-by-line starting on Record\_13.

ICONFLAG: flag to specify the aqueous concentration units in output files specified on Record\_4.3 and Record\_4.6 (note that these output units for ICONFLAG have

not changed since version V3.32-OMP, but have changed since pre-V3.32-OMP versions).

- = 0 mol/kg H<sub>2</sub>O (molal)
- = 1 mol/L liquid (molar - Note: concentrations will vary as water density changes owing to temperature, pressure, etc.)
- = 2 mg/L liquid (Note: concentrations will vary as water density changes with temperature, pressure, etc.)
- = 3 ppm (by mass)

MINFLAG: flag for units of mineral abundances output in files specified on Record\_4.4 and Record\_4.6.

- = 0 Change (relative to  $t = 0$ ) in mineral abundance (mol/m<sup>3</sup> medium)
- = 1 Change (relative to  $t = 0$ ) in mineral volume fraction (m<sup>3</sup> min/ m<sup>3</sup> solid)
- = 2 Current total mineral volume fraction (m<sup>3</sup> min/ m<sup>3</sup> solid)
- = 3 Change (relative to  $t = 0$ ) of mineral abundance in volume %
- = 4 Change (relative to  $t = t - dt$ ) in mineral abundance (mol/m<sup>3</sup> medium)
- = 5 Current total mineral abundance (mol/m<sup>3</sup> medium)

IGASFLAG: flag for units of gas concentration output in files specified on Record\_4.5 and Record\_4.6.

- = 0 Partial pressure (bars)
- = 1 Mole fraction (equivalent to volume fraction for ideal gas)

### **Record\_8. List of grid blocks for printout of time evolution results**

If NWNOD (on Record\_7) > 0:

Variable: EL(I), I=1,NWNOD

Format: 15A5

Description: five-character code name of a grid block (up to 200 names, 15 per record). NWNOD names will be read. Each name must match one of those specified in the flow.inp input file or MESH file. No blank line follows the list!

If NWNOD (on Record\_7) < 0:

Variable: EL(I), I=1,N

Format: A5

Description: Five-character code name of a grid block (up to 200, one name per record). The list of names must end with a blank record. Each name must match one of those specified in the flow.inp input file or MESH file.

If NWNOD (on Record\_7) =0: leave a blank record.

### **Record\_9. Indices or names of component species for which to output total concentrations**

If NWCOM (on Record\_7) >= 0:

Variable: IWC<sub>COM</sub>(I), I=1,NWCOM

Format: Integer (free format). One record up to 200 characters long.  
NWCOM indices will be read, up to total number of primary species. If NWCOM = 0 and IWC<sub>COM</sub>(1) = 0, then all species will be written out. No blank line follows this record!

Description: indices of component species.

If NWCOM (on Record\_7) <0:

Variable: PRT\_<sub>COM</sub>(I), I=1,N

Format: A20 (one name per record, without quotes, up to total number of primary species). The list of names must end with a blank record. Each name must match one of those specified in the thermodynamic database and included in the simulation (e.g. in file chemical.inp).

Description: names of component species

If NWCOM (on Record\_7) =0: leave a blank record.

### **Record\_10. Indices or names of minerals to output amounts**

If NWMIN (on Record\_7) >= 0:

Variable: (IWMIN(I), I=1, NWMIN)

Format: Integer (free format). One record up to 200 characters long.  
NWMIN indices will be read, up to total number of minerals. If NWMIN = 0 and IWMIN(1) = 0, then all minerals will be written out. No blank line follows this record!

Description: indices of minerals (which correspond to order entered in chemical.inp)

If NWMIN (on Record\_7) <0:

Variable: PRT\_<sub>MIN</sub>(I), I=1,N

Format: A20 (one name per record, without quotes, up to total number of minerals). The list of names must end with a blank record. Each name must match one of those specified in the thermodynamic database and included in the simulation (e.g. in file chemical.inp).

Description: names of minerals

If NWMIN=0 (on Record\_7): leave a blank record.

**Record\_11. Indices or names of individual aqueous species for which to output concentrations**

If NWAQ (on Record\_7) > 0:

Variable: (IWAQ(I), I=1, NWAQ)

Format: Integer (free format). One record, up to 200 characters long. NWAQ indices will be read, up to total number of individual species. No blank line follows this record!

Description: indices of aqueous species (e.g., as shown in chemical.inp)

If NWAQ (on Record\_7) <0:

Variable: PRT\_AQ(I), I=1,N

Format: A20 (one name per record, without quotes, up to total number of individual species). The list of names must end with a blank record. Each name must match one of those specified in the thermodynamic database and included in the simulation (e.g. in file chemical.inp).

Description: names of aqueous species

If NWAQ=0 (on Record\_7): leave a blank record.

**Record\_12. Indices or names of surface complexes for which to output concentrations**

If NWADS (on Record\_7) > 0:

Variable: (IWADS(I), I=1, NWADS)

Format: Integer (free format). One record up to 200 characters long. NWADS indices will be read, up to total number of surface complexes. No blank line follows this record!

Description: indices of surface complexes (e.g., as shown in chemical.inp)

If NWADS (on Record\_7) <0:

Variable: PRT\_ADS(I), I=1,N

Format: A20 (one name per record, without quotes, up to total number of surface complexes). The list of names must end with a blank record. Each

name must match one of those specified in the thermodynamic database and included in the simulation (e.g. in file chemical.inp).

Description: names of surface complexes

If NWADS=0 (on Record\_7): leave a blank record.

### **Record\_13. Indices or names of exchange species for which to output concentrations**

If NWEXC (on Record\_7) > 0:

Variable: (IWEXC(I), I=1, NWEXC)

Format: Integer (free format). One record up to 200 characters long. NWEXC indices will be read, up to total number of exchange species. No blank line follows this record!

Description: indices of exchange species (e.g., as shown in chemical.inp)

If NWEXC (on Record\_7) < 0:

Variable: PRT\_EXC(I), I=1,N

Format: A20 (one name per record, without quotes, up to total number of exchange species). The list of names must end with a blank record. Each name must match one of those specified in the simulation (e.g. in file chemical.inp).

Description: names of exchange species

If NWEXC=0 (on Record\_7): leave a blank record.

### **Record\_14. Default indices for all chemical property zones**

If MOPR(11) ≠ 1 (in flow.inp)

Variable: IZIWDF, IZBWDF, IZMIDF, IZGSDF, IZADDF, IZEXDF, IZPPDF, IZKDDF, IZBGDF, (IZBOUT)

Format: 9I, (I) (integer free format)

Description: IZIWDF, IZBWDF, IZMIDF, IZGSDF, IZADDF, IZEXDF, IZPPDF, IZKDDF, and IZBGDF are default values of IZIW, IZBW, IZMI, IZGS, IZAD, IZEX, IZPP, IZKD, IZBG, and IZBOUT, respectively, as described for Record\_15. The last parameter (IZBOUT) is optional; if this parameter is omitted, do not insert comments at the end of this record or this will result in an input error.

If MOPR(11) = 1 (in *flow.inp*)

Variable: IZIWDF, IZBWDF, IZMIDF, IZGSDF, IZADDF, IZEXDF, IZPPDF, IZKDDF, IZBGDF, VSED

Format: 9I, F (free format)

Description: Same as above, except for the last variable, VSED, which is the sedimentation velocity (m/s). This option will only work for a vertical 1D column with grid blocks and connections sequentially ordered from top to bottom.

### **Record\_15. Chemical property zone indices for specific grid blocks**

If MOPR(11)  $\neq$  1 (in *flow.inp*):

Variable: EL, NSEQ, NADD, IZIW, IZBW, IZMI, IZGS, IZAD, IZEX, IZPP, IZKD, IZBG, (IZBOUT)

Format: A5,11I, (I) (free format), one record per grid block, up to the total number of grid blocks. The list of records must end with a blank record. The last parameter (IZBOUT) is optional; if this parameter is omitted, do not insert comments at the end of this record or this will result in an input error.

EL: grid block name

NSEQ: number of additional grid blocks having the same chemical properties

NADD: increment between the code numbers of two successive grid blocks

Indices of the various zones (for different waters, mineralogies, gas compositions, sorption characteristics, etc.) defined in file *chemical.inp* (Note: In this version, if the rock name is used to assign the water chemistry or mineral zones to grid blocks, the zone numbers below are overwritten):

IZIW: initial water zone number

IZBW: injection (boundary) water zone number

IZMI: mineral zone number

IZGS: gas zone number

IZAD: adsorption zone number

IZEX: ion exchange zone number

IZPP: porosity-permeability relation zone number

IZKD: linear adsorption Kd zone number

IZBG: injection (boundary) gas zone number

IZBOUT (optional): set to one of the IZBW values; if non-blank or non-zero, the water composition of this gridblock will be recirculated as an injection water into grid blocks specified with IZBW=IZBOUT.

If MOPR(11) = 1 (in flow.inp)

Variable: EL, NSEQ, NADD, IZIW, IZBW, IZMI, IZGS, IZAD, IZEX, IZPP, IZKD, IZBG, VSED

Format: A5, 11I, F (free integer and real format) one record per grid block, up to the total number of grid blocks. The list of records must end with a blank record.

Description: Same as above, except for the last variable, VSED, which is the sedimentation velocity (m/s). This option will only work for a vertical 1D column with grid blocks and connections sequentially ordered from top to bottom. By specifying decreasing velocities with depth, the effect of compaction can be approximated (set KCPL > 0 in Record\_2 to capture resulting porosity changes).

## **Record\_16. Optional input of chemical convergence bounds for timesteppng**

**CONV:** Block read if MOPR(10)=2.

Limits for maximum number of chemical iterations for increasing/decreasing time steps, and the factor (dtincr1 to dtincr3, and dtdecr1 to dtdecr3) applied to the timestep for each maximum chemical iteration value (maxchem1 to maxchem4). Example given below.

CONVP

# Read in chemical convergence limits if mopr(10)=2

# maxchem1,maxchem2,maxchem3,maxchem4

50 75 100 150

# dtincr1,dtincr2,dtincr3,dtdecr1,dtdecr2,dtdecr3

2.d0 1.5d0 1.25d0 0.75d0 0.5d0 0.25d0

Default values (hardwired in TOUGHREACT v4.10-OMP) if CONVP is not read:

# maxchem1,maxchem2,maxchem3,maxchem4

30 50 75 100

# dtincr1,dtincr2,dtincr3,dtdecr1,dtdecr2,dtdecr3

2.d0 1.5d0 1.0d0 0.8d0 0.6d0 0.5d0

### 5.3 Geochemical Input (*chemical.inp*)

---

The input file *chemical.inp* is used to define the chemical system (i.e. the aqueous component species, minerals, gases, and sorbed species). It also includes the initial compositions of water, minerals, and gases, injected water and gas compositions, kinetic data for intra-aqueous reactions and minerals (rate constants, surface areas, etc.), and permeability-porosity laws and parameters. The chemical zones are later assigned to grid blocks, either as a function of the rock name or by designation in file *solute.inp*, as described above. Several additions were made for TOUGHREACT V3.85-OMP and above, and therefore *chemical.inp* files used for earlier code versions must be updated. All variables in *chemical.inp* are input in free format. Variables that are not used must be entered as zero values and cannot be left blank, unless specifically indicated otherwise.

Inputs are organized in groups (e.g., records Akin for aqueous kinetics, Aque for aqueous species, Mine for minerals, etc.). These groups are always preceded by a header record, and always end with a trailing record starting with \* (or a blank record). Entries for any group can be skipped altogether (e.g., if no minerals are present), however one or more “skip” records followed by a trailing \* record must always be entered in the file for all groups. The order in which input groups are entered cannot be changed from that shown below.

Names of all aqueous species, gases, and minerals input in this file are internally converted to lower case characters. The electronic charge in the names of cations and anions are also internally converted to display the charge sign followed by the number of charges (for example, CO<sub>3</sub><sup>--</sup> is converted to co3-2 and Al<sup>+++</sup> is converted to al+3. This allows for input flexibility and maintains internal consistency. Examples of *chemical.inp* are given in the TOUGHREACT Sample Problems Guide.

#### “Skip” records:

One or more heading (comment) line can precede each record described below (see inputs of the sample problems). The comment line is indicated by beginning with “#” followed by one blank (without quotes), or any blank record, and will be skipped on input. These “skip” records can be inserted anywhere in the file, except within input blocks that end with \*. These “skip” records can be also used for data source references, or other purpose.



### **Record-1. Title**

Variable: TITLE

Format: A (free format)

TITLE: title and comments in one line.

### **Record-2. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments to appear in the output file.

## **5.3.1 Definition of the Geochemical System**

---

These records contain the information on aqueous species, minerals, gases, surface complexes, species with linear adsorption  $K_d$  and radioactive decay, and exchangeable cations. Their names must match exactly those in the thermodynamic database file (it's not case sensitive).

### **Record-3. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments to appear in the output file.

### **Primary species (Prim)**

#### **Prim-1. Header for Prim records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Prim records.

#### **Prim-2. Primary aqueous species**

Variable: NAPRI, NOTRANS, NAADS\_MIN, SDENS, IMOD, CAPAC

Format: A, I, A, F, I, F (free format, one record per primary species)

NAPRI: name of the primary species, enclosed in quotes (truncated after 20 characters). It must match exactly that in the thermodynamic database file. A

record starting with \* is needed to indicate the end of the list of the primary species.

NOTRANS: flag for transport and surface complexation options. Note: All species specified with NOTRANS  $\geq 2$  must be listed at the end of the list of species.

- = -1 species (component) will be transported with a temperature-dependent diffusion coefficient calculated from parameters given in thermodynamic database
- = 0 species (component) will be transported (diffusion coefficient given by variable DIFUN in solute.inp)
- = 1 species (component) is immobile (no diffusive or advective transport)
- = 2 flag to indicate this is a surface (primary) species, with molality-based surface complexation constants in the thermodynamic database. All species specified with NOTRANS  $\geq 2$  must be listed at the end of the list of species.
- = 3 flag to indicate this is a surface (primary) species, with mole-fraction based surface complexation constants in the thermodynamic database.
- = 4 flag to indicate this is a surface (primary) species, with equivalent-fraction based surface complexation constants in the thermodynamic database (e.g., as with Phreeqc v2).

The remaining variables on record Prim-2 are required only if NOTRANS=2:

NAADS\_MIN: name of mineral associated with this surface species (in quotes, up to 20 characters). More than one surface species (NAPRI) can be associated with the same mineral. NAADS\_MIN can be either:

A name (in quotes) matching the name of one of the minerals included in the simulation (on record Mine-1), or

'no\_mineral' (including quotes), in this case sorption is not tied to a specific mineral, and a constant sorption surface area is entered in  $\text{cm}^2/\text{g}_{\text{mineral}}$  on record Zads-6, or

'surface.....' (including quotes; the first 7 characters after the initial quote must spell *surface*): in this case adsorption is tied to a generic surface with a constant sorption surface area input in  $\text{m}^2/\text{kg}_{\text{H}_2\text{O}}$  on record Zads-6.

SDENS: sorption site density in  $\text{mol}_{\text{sites}}/\text{m}^2_{\text{mineral}}$  for this surface species

IMOD: adsorption model type.

- = 0 surface complexation without electrostatic terms
- = 1 constant capacitance model
- = 2 double diffuse layer model, linear
- = 3 double diffuse layer model, Gouy-Chapman (most common)

CAPAC: this variable must be entered only if IMOD=1. Capacitance in  $F\ m^{-2}$  (these units are identical to  $C\ V^{-1}\ m^{-2}$ )

### **Prim-3. Trailer for Prim records**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

### **Aqueous Kinetics (Akin)**

#### **Akin-1: Header for Akin records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL : character string starting with AQUEOUS KINETICS (upper or lower case).

#### **Akin-2:**

Variable: NTRX

Format: I (free format)

NTRX : Total number of kinetic reactions among aqueous species

**The following records, from Akin-3 through Akin-9, are repeated NTRX times. The format of this input block is given below.**

#### **Akin-3:**

Variable: IRX

Format: I (free format)

IRX : Index of kinetic reaction, from 1 to NTRX.

#### **Akin-4:**

Variable: NCP, (S(i), NAM(i), I = 1, NCP), irkaq\_typ, rkaq\_logK, rkaq\_cf

Format: I, NCP(F, A), I, 2F (free format)

NCP : number of aqueous species involved in each reaction

S : stoichiometric coefficients of primary species NAM included in the reaction. Negative values are for reactants, positive values for products. The stoichiometric coefficients must be in terms of moles for the species involving in other reactions such as aqueous complexation, cation exchange and mineral dissolution and precipitation (undergoing mass-action calculations). Otherwise, they can be input in any units such as mg and g. Details are illustrated in the related sample problems (in Sections 8.9 and 8.10).

The last three entries below are optional and are used to define a reaction affinity term to limit, stop, and potentially reverse the rate of the reaction as it reaches and potentially crosses the equilibrium point. The affinity term is based on the reaction ion activity product  $Q$  and the reaction equilibrium constant  $K$ . Note that  $Q/K$  is always positive and equals 1 at equilibrium. When  $Q/K$  is  $< 1$  and the specified reaction rate (RKAQ) is positive, the reaction proceeds from left to right (the “normal” case). If  $Q/K > 1$  (with a positive RKAQ), the reaction can reverse and proceeds from right to left.

irkaq\_typ: if not zero nor blank, this flag enables limiting the reaction rate by an affinity term ( $f_G$ ) factor that tends to zero at equilibrium. The form of the affinity term depends on the value of irkaq\_typ, as shown below.

= 0  $f_G = 1$  (no limit – beware, the equilibrium point may be overshoot!)

= 1 Function based on transition state theory (TST):

$f_G = (1 - Q/K)^{rkaq\_cf}$  ( $f_G$  varies from +1 to 0 when reaction is from left to right)

( $f_G$  varies from 0 to large numbers when reaction is from right to left)

Note that primary species defined with NOTRANS=1 in record Prim-2 (see Section 6.3.1) are not included in the calculation of  $Q$ . When  $Q/K \leq 1$ , the reaction proceeds from left to right, and  $f_G$  varies from 1 away from equilibrium to 0 at equilibrium (positive rate). When  $Q/K > 1$ , the reaction reverses (proceeds from right to left, i.e., negative rate) and  $f_G$  can become very large. Note that setting the coefficient  $rkaq\_cf$  to a small value limits the upper value of  $f_G$  and can help convergence.

= 2 Symmetric TST form with  $f_G$  varying between +1 and -1:

$f_G = (1 - Q/K)^{rkaq\_cf}$  when  $Q/K \leq 1$  ( $f_G$  varies from +1 to 0; reaction from left to right)

$f_G = -(1 - K/Q)^{rkaq\_cf}$  when  $Q/K \geq 1$  ( $f_G$  varies from 0 to -1; reaction from right to left)

This option is useful in limiting the rate by the same amount on each side of the equilibrium point. It has no real theoretical basis.

= 3 Similar effect as with irkaq\_typ=2, with  $f_G$  varying between +1 and -1, but using a different function shape:

$$f_G = \frac{\log\left(\frac{Q}{K}\right)}{|\log\left(\frac{Q}{K}\right)| + rkaq\_cf}$$

Here the value of  $rkaq\_cf$  is the value of  $\log(Q/K)$  at which the rate is cut in half (i.e., at which  $f_G = \pm 0.5$ ). This function has no real theoretical basis.

- = 4 Same effect as  $irkaq=1$  in the forward direction (TST affinity term when reaction operates from left to right), but reversal of the reaction is not allowed (i.e.,  $f_G = 0$  in the reverse direction).

$rkaq\_cf$ : value of coefficient  $c$  in the affinity functions described above.

$rkaq\_logK$ : log of the equilibrium constant  $K$  of the reaction.

### Akin-5:

Variable: I\_MOD, N\_MECH

Format: 2I (free format)

I\_MOD : Type-index of kinetic rate model.

- = 1 Main model currently implemented (Eq. B.2 in Appendix B)
- = 2 Not used (do not use as it may create an input error)
- = 3 Special case: Monod and inhibition limiters in Eq. B.2 are suppressed when the reaction operates in a reverse direction (i.e., when  $f_G$  becomes negative, the rate is not multiplied by Monod and inhibition terms).

N\_MECH : Number of mechanisms (pathways) to include in the rate expression.

### Akin-6:

Variable: RKAQ

Format: F (free format)

RKAQ : forward rate constant or maximum specific growth rate (mass/L/s). If RKAQ = -1.0, the rate constant will be temperature-dependent, and dynamically calculated according to the following equation:

$$k = k_{25} \exp \left[ \frac{-E_a}{R} \left( \frac{1}{T} - \frac{1}{298.15} \right) \right]$$

Where  $k_{25}$  is a rate constant (1/s) at 25°C, and  $E_a$  is activation energy (kJ/mol), and  $T$  is the absolute temperature.  $k_{25}$  and  $E_a$  need to read from additional record AKIN-6-1

**Akin-6-1:**

Variable: RK\_a, RK\_b

Format: F, F (free format)

RK\_a :  $k_{25}$  of the above equation (1/s).

RK\_b :  $E_a$  of the above equation (kJ/mol).

**Akin-7:**

Variable: NCP\_rx1, (NAM\_rx1(i), ia1(i), S\_rx1(i), i=1,NCP\_rx1)

Format: F, NCP\_rx1(A, I, F) (free format)

NCP\_rx1 : Number of species (primary or secondary) involved in product terms, see Eq. B.2 in Appendix B

NAM\_rx1 : chemical formula of the species.

ia1: flag for using activity (ia1 = 1) or concentration (ia1 = 2) of the species for calculations of the product term

S\_rx1 : value of power term applied to activity or concentration of the species

**Akin-8:**

Variable: NCP\_rx2, (NAM\_rx2(i), ia2(i), S\_rx2(i), i=1,NCP\_rx2)

Format: F, NCP\_rx2(A, I, F) (free format)

NCP\_rx2 : Number of species (primary or secondary) involved in Monod terms, see Eq. B.2 in Appendix B

NAM\_rx2 : chemical formula of the species.

Ia2: flag for using activity (ia1 = 1) or concentration (ia1 = 2) or total concentration (ia1 = 3, only for primary species) of the species for calculations of the Monod term

S\_rx2 : value of half-saturation constant for the species

**Akin-9:**

Variable: NCP\_rx3, (NAM\_rx3(i), ia3(i), S\_rx3(i), i=1,NCP\_rx3)

Format: F, NCP\_rx3(A, I, F) (free format)

NCP\_rx3 : Number of species (primary or secondary) involved in Inhibition terms, see Eq. B.2 in Appendix B

NAM\_rx3 : chemical formula of the species.

Ia3: flag for using activity (ia1 = 1) or concentration (ia1 = 2) or total concentration (ia1 = 3, only for primary species) of the species for calculations of the inhibition term

S\_rx3 : value of inhibition constant for the species

#### **Akin-10: Trailer for Akin records**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

#### **Secondary aqueous species (Aque)**

##### **Aque-1. Header for Aque records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Aque records.

##### **Aque-2. Secondary aqueous species**

This input block can be omitted. In this case, all possible secondary aqueous species found in the input thermodynamic database will be automatically selected.

Variable: NAAQX

Format: A (free format, one record per secondary species)

NAAQX: name of secondary aqueous species, in quotes (truncated after 20 characters). The name must match exactly that in the thermodynamic database file.

##### **Aque-3. Trailer for Aque records**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

## **Minerals (Miner)**

### **Miner-1. Header for Miner records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Miner records.

The following two main records (Miner-2 and Miner-3) are repeated as many times as the number of minerals. Minerals can be entered in any order as long as the minerals at equilibrium precede those under kinetic constraints. The specified minerals consist of reactants and any possible products. Their names must match exactly the names of minerals in the database. Minerals with identical stoichiometries (e.g., quartz and cristobalite) cannot both be specified at equilibrium, but can be specified to react under kinetic constraints. Minerals under kinetic constraints require more records (per mineral) than minerals under equilibrium constraints.

### **Miner-2.**

Variable: NAMIN, IKIN, IDISPRE, ISS, M1

Format: A, 4I (free format)

NAMIN: name of the mineral phase (truncated after 20 characters). It must be consistent with the name in the thermodynamic database. Omit NAMIN if no minerals are required. However, the trailer record starting with \* (or blank) is always needed to indicate the end of the list.

IKIN: flag for the type of mineral: 0 for minerals at equilibrium, and 1 for those under kinetic constraints.

IDISPRE: flag for the type of kinetic constraint: 1 for dissolution only, 2 for precipitation only, and 3 for both (mineral can either precipitate or dissolve). Always set IDISPRE = 0 if IKIN = 0; and IDISPRE > 0 if IKIN = 1.

ISS: index for a solid solution mineral endmember. All endmembers for a specified phase are given the same ISS value: ISS = 1 for each endmember of the first solid solution, ISS = 2 for each endmember of the second solid solution, and so on (numbers cannot be skipped). Records for each member can appear in any order in the mineral records.

M1: flag to indicate that the mineral may precipitate in a dry grid block as a result of complete evaporation (when liquid saturation < sl1min specified in the solute.inp file), or if there is water flux into the grid block that dries out during the flow step (and therefore liquid saturation is zero). The mineral with M1 = 1 precipitates first, with M1 = 2 second, and so on. If this flag is set to zero, then the mineral will not be formed in the dry grid block.



If IKIN = 1 and IDSPRE = 1 or 3, one or more additional records (Miner-2.1) are required to define dissolution rate law parameters.

If IKIN = 1 and IDSPRE = 2 or 3, one or more additional records (Miner-2.2) are required to define precipitation rate law parameters.

### **Miner-2.1.**

Variable: RKF, IDEP, CK1, CK2, EA, ACFDISS, BCFDISS, CCFDISS

Format: F, I, 6F (free format)

RKF: coefficient  $k_{25}$  in the expression (B.7) given in Appendix B, where  $k_{25}$  is the rate constant (in mol/m<sup>2</sup>/sec) at 25°C, EA is the activation energy in kJ/mol. The form of the rate law is given in Eq. B.6.

IDEP: flag for rate constant dependence on pH (see Figure B-1) or multiple mechanisms (see Eq. B.13 in Appendix B). If IDEP = 0, pH (species) dependent rate constants and multiple mechanisms are not considered. If IDEP = 1, an additional record (Miner-2.1.1) must be entered to include information on the rate dependence on pH. If IDEP = 2, additional records Miner-2.1.2 and Miner-2.1.2.1 must be entered to include information on the rate constants contributed from additional mechanisms.

CK1 and CK2: the exponents  $\eta$  and  $\theta$ , respectively in Eq. B.6.

EA: the activation energy (kJ/mol).

ACFDISS, BCFDISS, and CCFDISS: should be set to zero, unless a different form of rate constant dependence with temperature is desired. This alternate form is:  $\log_{10}(k) = a + b \cdot T + c/T$ , where T is absolute temperature in K. To enable this option, RKF must be set to 1.0, EA must be set to 0.0, CK1 and CK2 can be set to any value, and ACFDISS, BCFDISS, and CCFDISS must be specified as the coefficients  $a$ ,  $b$ , and  $c$ , respectively, in the above expression.

#### **Miner-2.1.1 (only if IDEP = 1)**

Variable: PH1, SLOPE1, PH2, SLOPE2

Format: 4F (free format)

See Figure B-1 (in Appendix B) for the meaning of these parameters.

#### **Miner-2.1.2 (only if IDEP = 2)**

Variable: NDIS

Format: I (free format)

NDIS is the number of additional mechanisms contributed to the rate constant (see Eq. B. 13 in Appendix B) (maximum allowed is 5). An example of the multiple mechanisms can be found in the CO<sub>2</sub> disposal sample problem (Section 8.5).

**Miner-2.1.2.1 (repeat NDIS times after Miner-2.1.2, only if IDEP=2)**

Variable: RKDS, EADS, NSPDS, NADIS, EXPDSP

Format: 2F, I, A, F (free format)

RKDS is  $k_i$  in Eq. (B. 13) where  $i$  is the additional mechanism index.

EADS: is the activation energy (kJ/mol) for each additional mechanism.

NSPDS: is the number of species involved in each mechanism (a maximum of five species can be considered).

NADIS is the name of species involved in the mechanism that must be in the list of primary or secondary species. NADIS and the following variable EXPDSP must be repeated as many as NSPDS times.

EXPDSP is the power term  $n_j$  in Eq. (B. 13).

**Miner-2.2.**

Variable: RKPREC, IDEPREC, CK1PREC, CK2PREC, EAPREC, ACFPREC, BCFPREC, CCFPREC, RNUCL, NPLAW

Format: F, I, 7F, I (free formats)

The first 8 input parameters are listed in the same order and have the same functions as those described above for mineral dissolution, except that the parameters apply to mineral precipitation instead of dissolution. Therefore if IDEPREC = 1, an additional record identical to Miner-2.1.1 needs to include information on the rate dependence on pH; if IDEPREC = 2, additional records identical to Miner-2.1.2 and Miner-2.1.2.1 need to be inserted with information on the rate constants contributed from additional mechanisms.

RNUCL: the initial volume fraction ( $V_{\text{mineral}}/V_{\text{solid}}$ ) to be assumed for calculating initial effective surface area if the mineral is not present at the start of a simulation but precipitates as a new reaction product. If zero, RNUCL is assumed to be  $10^{-15}$ .

NPLAW: precipitation law index. NPLAW = 0 for Eq. (B.6 and B.13) in Appendix B; NPLAW = 1 for Eq. (B.9).

### **Miner-3.**

This record is required for all minerals reacting at equilibrium, but only for those minerals reacting under kinetic constraints that are allowed to precipitate (IDSPRE = 2 or 3).

Variable: SSQK0, SSTK1, SSTK2

Format: 3F (free format)

SSQK0: log (Q/K) gap (supersaturation window, see Eq. B.14 in Appendix B). A zero value represents no gap.

SSTK1: temperature (in °C) at which to begin reducing gap.

SSTK2: temperature (in °C) endpoint at which the gap has diminished to nearly zero (1% of original value). The gap decreases exponentially from the first (SSTK1) to the second (SSTK2) temperature, and SSTK2 must always be greater than SSTK1.

### **Miner-4. Trailer for Mine records**

Variable: LABEL

Format: A (free format)

### **Gaseous species (Gas)**

Note that H<sub>2</sub>O gas should not be entered in the list of gases here, because H<sub>2</sub>O transport and thermodynamics are always treated by the TOUGH2 EOS modules. TOUGHREACT V3.0-OMP added two new capabilities/options: (1) Trace gas species transport in multiphase EOS modules having other "carrier" gases such as CO<sub>2</sub>, and (2) Option to fix individual gas species fugacities (IGASFIX).

#### **Gas-1. Header for Gas records (a "Skip" record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Gas records.

#### **Gas-2. Gases**

Variable: NAGAS, IGASFIX

Format: A, I (free format, one record per gas)

NAGAS: name of a gaseous species, in quotes (truncated after 20 characters). It must match exactly that in the thermodynamic database file. Omit NAGAS if no

gaseous species are required. However, the trailer record starting with \* (or blank) is always needed to indicate the end of the list.

IGASFIX: flag to fix individual gas species fugacities

= 0 Gas species fugacity allowed to change according to reactive-transport calculations

= 1 Fixed gas species fugacity based on value assigned in gas zone or calculated from initial water composition

### **Gas-3. Trailer for Gas records**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

### **Surface complexes (Surx)**

#### **Surx-1. Header for Surx records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Surx records.

#### **Surx-2. Surface complexes**

This input block can be omitted. In this case, all possible surface complexes found in the input thermodynamic database will be automatically selected.

Variable: NAADS

Format: A (free format, one record per surface complex)

NAADS: name of surface complex (truncated after 20 characters). Omit NAADS if no surface complexes are required. However, the trailing record starting with \* (or blank) is always needed to indicate the end of the list.

#### **Surx-3. Trailer for Surx records**

Variable: LABEL

Format: A (free format)

LABEL: header describing Kdde records.

## Aqueous (primary) and gas species with Kd and decay (Kdde)

### **Kdde-1. Header for Kdde records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Kdde records.

### **Kdde-2. Species with Kd and decay (Aqueous species must precede gas species)**

Variable: NAKDD, DECAVC, a\_TDecay, b\_TDecay

Format: A, F, F, F (free format, one species per record)

NAKDD: name of the aqueous primary species and/or gas species with Kd and/or decay, in quotes (truncated after 20 characters). These names must appear in the above mentioned primary species records (Prim records). Omit these records if no primary species with Kd and/or decay are required. However, the trailing record starting with \* (or blank) is always needed to indicate the end of the list. Aqueous species must precede gas species.

DECAVC: a positive value is radioactive decay constant (in 1/s). For species with only Kd adsorption and without decay, set DECAVC equal to 0.0. For DECAVC greater than or equals to zero (0.0), set the following two parameters (a\_TDecay and b\_TDecay) to zero. If DECAVC=-1.0, the decay constant is temperature-dependent according to  $\ln(k) = a - b/T$  ( $\ln$  stands for natural logarithm), where k is the decay constant (in **1/day**), a and b are two parameters that will read from the following two variables, and T is absolute temperature in K.

a\_TDecay: parameter a in the above equation.

b\_TDecay: parameter b in the above equation.

### **Kdde-3. Trailer for Kdde records**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

## Exchanged species (Exch)

### **Exch-1. Header for Exch records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Exch records.

### **Exch-2. Number of exchange sites**

Variable: NXsites, Mod\_Xsl

Format: 2I (free format)

NXsites: number of exchange sites

Mod\_Xsl: Models for dependence of exchange sites on water saturation. Mod\_Xsl = 1 for ideal-wetting condition; Mod\_Xsl = 2 for considers multiplying a (correction) factor  $f$  that depends on liquid saturation,  $f(S_l)$ . Details can be found in Appendix K.

### **Exch-3. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: sub-header describing the data that follows.

### **Exch-4. Exchanged species**

Variable: NAEXC IMS IEX (EKX(i),  $i=1, NXsites$ )

Format: A, 2I, NXsites(F) (free format, one record per exchanged species)

NAEXC: name of exchangeable species (truncated after 20 characters). Omit NAEXC if no exchangeable cations are required. However, a record starting with \* is always needed to indicate the end of the list.

IMS: If IMS = 1, the cation is used as reference for the exchange reactions (normally  $Na^+$ ). For the remaining cations, IMS must be 0.

IEX: exchange convention type used in the calculations: 1= Gaines-Thomas; 2= Vanselow; 3= Gapon (see Section B.6 of Appendix B for definition)). The value of IEX must be the same for all the exchanged cations.

EKX: exchange coefficient of the cation with respect to the reference cation. If IMS = 1, then EKX = 1.0. Note, for example, if  $Na^+$  is selected as the reference cation, using Gaines-Thomas convention (commonly used), for Na-Ca exchange  $Ca^{2+}$  selectivity must be specified according to the following reaction,  $Na^+ + 0.5Ca-X_2 = 0.5Ca^{2+} + Na-X$  where X represents cation exchange site (see Section B.6 of Appendix B for details). Note also that there are NXsites values, one for each exchange site).

## Exch-5. Trailer for Exch records

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

## 5.3.2 Composition of initial and injection (boundary) waters (Water)

This section describes the different water zones initially assigned to various parts of the modeled system. These zones are mapped to the numerical grid through variables defined on Record\_14 and Record\_15, respectively, in file *solute.inp*. A few examples of an input initial waters are shown first.

```
#INITIAL AND INJECTION WATER TYPES
5 3 !niwtype, nbwtype = number of initial and boundary waters
1 10.5 1.2 !iwtype initial, temp (C), pressure (bars)
# Equilibrate with atmospheric CO2 and quartz
# icon guess ctot constraint log Q/K
H2O 1 1. 1. * 0.
H+ 3 5.00e-07 5.01187e-7 * 0.
Na+ 1 1.0e-4 1.0e-4 * 0.
Cl- 1 1.0e-4 1.0e-4 * 0.
H4SiO4 2 1.00e-8 1.00e-8 Quartz(alpha) 0.
Cs+ 1 5.66931E-09 5.66931E-09 * 0.
I- 1 4.02957E-08 4.02957E-08 * 0.
HCO3- 2 1.00e-06 1.00e-15 CO2(g) -3.5
O2(aq) 1 3.26297E-06 3.26297E-06 * 0.
ra+2 1 1.77e-12 1.77e-12 * 0.
rn(aq) 1 6.394e-17 6.394e-17 * 0. ! 2200 pCi/liter
*

#INITIAL AND INJECTION WATER TYPES
8 1 !niwtype, nbwtype
-1 16.0 1.0 'rocky' ! assign initial water to elements with rock type 'rocky'
# Equilibrate with amorphous silica
# icon guess ctot constraint log Q/K
h2o 1 1.0 1.0 * 0.0
h+ 0 8. 8. * 0.0
na+ 0 170. 170. * 0.0
k+ 0 2.1 2.1 * 0.0
ca+2 0 100. 100. * 0.0
mg+2 0 88. 88. * 0.0
cl- 0 334. 334. * 0.0
br- 0 3. 3. * 0.0
hco3- 0 140. 140. * 0.0
so4-2 0 423. 423. * 0.0
B(OH)3 0 200. 200. * 0.0
H4SiO4 2 1.e-4 1.e-10 Amorphous_silica 0.0
*
```

### Water-1. Label (a “Skip” record)

Variable: LABEL

Format: A (free format)

LABEL: comments or blank line.

### **Water-2. Header for Water records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Water records.

### **Water-3. Total number of different water compositions in the system**

Variable: NIWTYPE NBWTYPE

Format: 2I (free format)

NIWTYPE: total number of aqueous solutions initially present in the system, excluding waters in injection grid blocks. These are referred to as “initial waters”.

NBWTYPE: total number of aqueous solutions in injection grid blocks. These are often referred to as “injection” or “boundary” waters. Injection waters are not used to set values in large boundary grid blocks. Initial waters are used for that purpose.

### **Aqueous solution compositions**

This section describes the input of “initial” and “injection” water compositions. Records Water-4, Water-5, Water-6, and Water-7 form the ensemble of records necessary to input one water composition. These records must be repeated NIWTYPE times for initial waters, followed by NBWTYPE times for injection waters. Note that “injection water” records must always follow “initial water” records. Each water composition is given a specific index, which is then mapped onto the numerical grid through variables IZIWDF and IZIW (for initial waters) and IZIBDF and IZIB (for injection waters) on Record\_14 and Record\_15, respectively, in file *solute.inp*.

For injection waters, the flux of each chemical component at the injection block is calculated from the given composition (Water-6) multiplied by the water flux given under keyword block ‘GENER’ in the *flow.inp* file (or in the separate GENER file). For a negative water flux (e.g., pumping from a well), a boundary solution composition is not used, because it is determined by the composition of the producing grid block. Note that for negative water fluxes in GENER, the MASS option should be used.

Each “initial” and “injection” water composition defined here undergoes initial speciation computations, with results written to file *chdump.out*.



#### **Water-4. Identification of the aqueous solution**

Variable: IWTYPE TC2 PT 'RKNAM' (optional)

Format: I, F, F, 'A5' (optional) (free format)

IWTYPE : Index of the solution. This index is used to allow a water composition to be assigned to one of the water zone indices specified on Record\_14 and Record\_15 in file *solute.inp*. The value of IWTYPE must start at 1 for the first initial water, then sequentially increase up to NIWTYPE; it is then set again to 1 for the first injection (boundary) water, then increases again sequentially up to NBWTYPE. If IWTYPE is set to a negative integer value, a rock name (from the ROCKS block in *flow.inp*) is expected to be read in (in quotes), allowing an initial water zone to be assigned directly to all grid blocks having that rock type (as assigned to grid blocks in ELEME). In that case, initial water zones assigned to grid blocks in *solute.inp* are ignored.

TC2 : temperature of the solution (°C). Note that TC2 is used only for initial speciation calculations, before the water composition is assigned to specific grid blocks. The initial temperatures and pressures of grid blocks assigned to this water composition are defined in the INCON block of the *flow.inp* file, and are not necessarily the same as TC2.

PT : pressure of the solution (bar). This value can be omitted, in which case PT is assumed to be 1 bar. As for TC2, PT is used only for initial speciation calculations, before the water composition is assigned to specific grid blocks. If PT is 0.0, or is below the water-saturation pressure, it is recalculated as the water saturation pressure at temperature TC2.

'RKNAM' : Optional record read if IWTYPE is set to a negative integer. Corresponds to 5-character rock name in ROCKS block (*flow.inp*). Initial waters will be assigned to all grid blocks having this rock type (as set in ELEME).

#### **Water-5. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: sub-header describing the data that follows.

#### **Water-6. Composition of aqueous solution**

Variable: NAPRI ICON CGUESS CTOT NAMEQ QKSAT

Format: A, I, F, F, A, F (free format, one per primary species)

NAPRI: name of the primary aqueous species, in quotes (truncated after 20 characters). The name of the species must match exactly those previously listed as primary species in the definition of the system, although the order may change. The trailing record (Water-7) must end the list of species.

ICON: flag indicating the units or constraint controlling the aqueous species input concentration:

ICON = 0: input values of CTOT represent total mass (in mg) for aqueous species, pH for H<sup>+</sup>, and total kilograms for liquid H<sub>2</sub>O. Therefore, to input concentrations in mg/kg H<sub>2</sub>O (approximately ppm for dilute solutions), set CTOT = 1.0 for H<sub>2</sub>O.

ICON = 1: input values of CTOT represent total amounts (in moles) for aqueous species, and total kilograms for liquid H<sub>2</sub>O. Thus, to input total molalities, set CTOT = 1.0 for H<sub>2</sub>O.

ICON = 2: the total concentration of the species will be computed such that the saturation index (log(Q/K)) of mineral or gas NAMEQ equals QKSAT at temperature TC2 and pressure PT. Therefore, for equilibrium with a mineral, set ICON=2 with QKSAT = 0.0. For equilibrium with a gas at a given fugacity, set ICON=2 with QKSAT = log(fugacity). With this option, input CTOT values are ignored.

ICON = 3: input values of CTOT represent the known activity of the specific species (i.e., not total concentration) at temperature TC2 and pressure PT. For example, to input a known pH value, use this option and set CTOT = 10<sup>-pH</sup> for H<sup>+</sup> activity.

ICON = 4: the total concentration of the species is adjusted to yield charge balance. Use only with a charged species. If convergence fails, choose a species with an opposite charge. With this option, input CTOT values are ignored.

CGUESS: initial guess (trial) value for the concentration of the individual primary species (not total concentration) in moles/kg H<sub>2</sub>O (molal) for species other than H<sub>2</sub>O and in kg for H<sub>2</sub>O. For ICON=0, CGUESS values are in ppm or pH for H<sup>+</sup>. Input values of CGUESS do not affect results of speciation calculations, but can have a large effect on the number of chemical iterations required for initial speciation.

CTOT: if ICON=1, CTOT is total moles of aqueous species, and total amount (in kg) of liquid water for H<sub>2</sub>O. Molalities are then internally computed as CTOT<sub>i</sub> / CTOT<sub>H<sub>2</sub>O</sub>. If ICON ≠ 1, refer to the discussion of ICON above for the units of CTOT.

NAMEQ: name of mineral or gas to use with option ICON=2. Names must match exactly those previously listed as minerals or gases in the definition of the chemical system. If ICON≠2, this entry is ignored, but cannot be omitted and should be entered as one of more characters (usually as ' ' or \*).

QKSAT: desired value of mineral log(Q/K) or gas log(fugacity) when option ICON=2 is used. For equilibrium with mineral NAMEQ use QKSAT=0.0, and for equilibrium with gas NAMEQ at a given fugacity use QKSAT = log(fugacity). If ICON≠2, this entry is ignored, but cannot be omitted and should be entered as a real number (suggested 0.0).

### Water-7. Trailer for Water records (one record after each water)

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

### 5.3.3 Initial mineral zones (Imin)

---

This section describes the mineral zones initially present in the system. These zones are mapped to the numerical grid through variables IZMIDF (Record\_14) and IZMI (Record\_15) in *solute.inp*. As for water zones, mineral zones may be given in *chemical.inp*, and not necessarily assigned to any grid blocks in *solute.inp* and used in the simulation. An option (starting with sV3.32-OMP) allows mineral zones to be mapped directly to rock names given in *flow.inp*.

```
# INITIAL MINERAL ZONES
1
-1      'rhyol'                ! Altered Rhyolite
calcite  0.0250  1
0.0e+0   10.0  0
dolo-ord  0.0125  1
0.0e+0   10.0  0
Ab80An20-hi  0.105  1
0.0      10.  0
albit-lo  0.0000  1
0.0e+0   1.0  0
microcli  0.1225  1
0.0e+0   1.0  0
quartz   0.485  1
0.0e+0   1.0  0
chalcedo 0.0000  1
0.0e+0   20.0  0
daphnite 0.0050  1
0.0e+0   10.0  0
clchlore 0.0050  1
0.0e+0   10.0  0
epid-ord 0.0000  1
0.0e+0   20.0  0
illite   0.1540  1
0.0e+0   20.0  0
nontr-Mg 0.0156  1
0.0e+0   20.0  0
nontr-Ca 0.0156  1
```

0.0e+0	20.0	0
nontr-Na	0.0156	1
0.0e+0	20.0	0
nontr-K	0.0156	1
0.0e+0	20.0	0
kaolinit	0.0025	1
0.0e+0	20.0	0
laumonti	0.0000	1
0.0e+0	20.0	0
analcite	0.0000	1
0.0e+0	20.0	0
goethite	0.0000	1
0.0e+0	20.0	0
hematite	0.0000	1
0.0e+0	20.0	0
magnetit	0.0075	1
0.0e+0	20.0	0
pyrite	0.0125	1
0.0e+0	20.0	0

\*

### **Imin-1. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments or blank line.

### **Imin-2. Header for Imin records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Imin records.

### **Imin-3.**

Variable: NMTYPE

Format: I (free format)

NMTYPE: Total number of mineral zones in the system.

The following records (Imin-4, Imin-5 and Imin-6, and Imin-7) define each mineral zone, and must be repeated NMTYPE times.

### **Imin-4.**

Variable: IMTYPE, RKNAM (optional)

Format: I (free format), ‘A5’ (optional)

IMTYPE: Index of the mineral zone. It must be 1 for the first zone, increasing sequentially thereafter. If IMTYPE is set to a negative integer value, a rock name (from the ROCKS block in *flow.inp*) is expected to be read in (in quotes), allowing a mineral zone to be assigned directly to all grid blocks having that rock type (as assigned to grid blocks in ELEME). In this case zones assigned to those grid blocks in *solute.inp* are ignored.

#### **Imin-5. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: sub-header describing the data that follow.

#### **Imin-6. Composition of the mineral zone**

Variable: NAMIN VOL2 IKIN4M

Format: A, F, I (free format, one record per mineral)

NAMIN: Name of mineral either present initially or to be considered as a secondary mineral. The name of the mineral must be included among those previously listed in the definition of the system (Miner records). The order need not be the same, and all minerals in the complete list are not required. However, all names of minerals specified to react under equilibrium constraints must precede the names of minerals reacting under kinetic constraints. Minerals defined for the system (Miner records), but excluded from the list, are assumed to take zero values for all input parameters specified below. A trailing record (Imin-7) must end the list of minerals (for each given zone).

VOL2: initial volume fraction or mass fraction of the mineral, excluding porosity. If VOL2 is positive it is volume fraction (mineral volume divided by total volume of solids). If VOL2 is set to a negative number, it is treated as a mass fraction of the mineral in the solid assemblage. The sum of VOL2s need not add up to 1.0. If the sum is less than 1.0, the remaining solid volume fraction is considered nonreactive. Note that some minerals may be given as volume fraction, and others as mass fraction.

IKIN4M: flag for the mineral type:

IKIN4M = 0 for minerals at equilibrium.

IKIN4M = 1 for minerals under kinetic constraints. For minerals under kinetic constraints, an additional record (Imin-6.1, below) is always required.

IKIN4M = 2 to suppress reaction for either kinetic and/or equilibrium minerals.

### **Imin-6.1.**

Variable: RAD, AMIN, IMFLG2

Format: 2F, I (free format)

**RAD:** radius of mineral grain (in m) used to calculate surface area. RAD is used in conjunction with RNUCL (Miner-6) for precipitation of minerals not initially present, and in conjunction with current amounts for minerals initially present, as long as the calculated surface area from RAD is larger than the AMIN value specified below. Suggested values are RAD=1.E-6 to 1.0E-8 with RNUCL=1.0E-6. Using this option, surface areas will be very high when the mineral first precipitates, and then decrease as the mineral abundance increases and the grain size increases. Once the surface area is reduced to the value AMIN specified below, then AMIN will be used. If RAD = 0.0, this option is turned off, and surface areas are calculated using the AMIN value below.

**AMIN:** initial mineral reactive surface area. If a mineral is not initially present, and the option to use mineral grain size is turned off (RAD = 0.0), its surface area will be computed from the value of RNUCL specified on record Miner-6, as long the surface area computed in this way remains below AMIN. The units of AMIN depend on the value of flag IMFLG2 below.

**IMFLG2:** A flag to specify the units of input AMIN values (see Appendix G)

IMFLG2 = 0 for  $\text{cm}^2_{\text{mineral}}/\text{g}_{\text{mineral}}$

IMFLG2 = 1 for  $\text{m}^2_{\text{mineral}}/\text{m}^3_{\text{mineral}}$

IMFLG2 = 2 for  $\text{m}^2_{\text{rock}}/\text{m}^3_{\text{medium (total)}}$

IMFLG2 = 3 for  $\text{m}^2_{\text{rock}}/\text{m}^3_{\text{medium (solids)}}$

IMFLG2 = 3 and RAD=0.0 : the input surface area will remain constant

IMFLG2 = 4 (constant rate is input in mol/sec; surface area is not used)

### **Imin-7. Trailer for Imin records (one record after each zone)**

Variable: LABEL

Format: A (free format)

**LABEL:** character string starting with \* or blank record

### 5.3.4 Initial and injection gas zones (Igas)

---

This section describes the initial and injection gas zones present in the system. These zones are mapped to the numerical grid through variables IZGSDF, IZBGDF, IZGS, and IZBG on Record\_14 and Record\_15, respectively, in file solute.inp. Note that H<sub>2</sub>O gas is not entered in the list of gases here, because H<sub>2</sub>O transport and thermodynamics are treated by the TOUGH2 EOS module selected for any given simulation. The injection gas zone IZBG is a new option for V3-OMP and must be added to files created for earlier TOUGHREACT versions.

```
#INITIAL and INJECTION GAS ZONES
1 1 ! ngtype= number of initial gas zones, injection zones
1 ! igtype
#gas partial pressure
CO2(g) 3.0e-4
He(g) 0.0
Rn(g) 0.0
*
1 ! igtype
#gas mol fraction ! injection gas divided by initial pressure (30 bars)
CO2(g) 3.3333333e-1
He(g) 3.3333333e-4
Rn(g) 3.3333333e-8
*
```

#### **Igas-1. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments or blank line.

#### **Igas-2. Header for Igas records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Igas records.

#### **Igas-3.**

Variable: NGTYPE, NIGASZON

Format: 2I (free format)

NGTYPE: total number of gas zones in the system.

NIGASZON: total number of injection (boundary) gas zones in the system.

The following records Igas-4, Igas-5, Igas-6 and Igas-7 define each gas zone, and must be repeated NGTYPE times.

#### **Igas-4.**

Variable: IGTYPE

Format: I (free format)

IGTYPE: Index of the gas zone. It must be 1 for the first zone, increasing sequentially thereafter. This index must correspond to one of the gas zone indices specified on Record\_14 and Record\_15 in file solute.inp. It is then set again to 1 for the first injection (boundary) gas, then increases again sequentially up to NBGTYPE.

#### **Igas-5. Label**

Variable: LABEL (a “Skip” record)

Format: A (free format)

LABEL: sub-heading describing the data that follow.

#### **Igas-6. Composition of gas zone (partial pressure for initial gas, mole fraction for injected gas)**

Variable: NAGAS GASPP

Format: A, F (free format)

NAGAS: name of the gas species. The name of the gas species must be included among those previously listed in the definition of the system (Gas records). The order may differ, and it is not needed to repeat the complete list. Gases defined for the system (Gas records) but excluded from the list are assumed to take zero values for GASPP below. A trailing record (Igas-7) must end the list of gases (for each given zone).

GASPP: For initial gas zones, it is given as partial pressure of the gaseous species (in bars). If zero, grid blocks corresponding to this zone will be given a partial pressure equal to the fugacity of the gas at equilibrium with the aqueous solution in these blocks, as computed for initial and boundary waters (records Water) during initialization.

For injection (boundary) gas zones, GASPP is given as mole fraction of the injected gas composition. Note that the mole fraction of the injected gas species is always relative to the moles of the carrier gas (e.g. CO<sub>2</sub>, H<sub>2</sub>O, etc.) chosen in GENER.

#### **Igas-7. Trailer for Igas records (one record after each zone)**

Variable: LABEL

Format: A (free format)



LABEL: character string starting with \* or blank record

### 5.3.5 Permeability-porosity law zones (Zppr)

---

This section describes zones where different laws can be applied at individual grid blocks to compute permeability changes as a function of porosity, pore throat diameter, or fracture aperture changes. These zones are mapped to the numerical grid through variables IZPPDF and IZPP on Record\_14 and Record\_15, respectively, in file *solute.inp*.

#### **Zppr-1. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments or blank line.

#### **Zppr-2. Header for Zppr-2 records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Igas records

#### **Zppr-3.**

Variable: NPPZON

Format: I (free format)

NPPZON: Total number of permeability zones defined for the system.

The following records, Zppr-4, Zppr-5, and Zppr-6 define each permeability zone, and must be repeated NPPZON times. Note, in this case, the trailer record (Zppr-7) is required only once at the end of the list of all permeability zones.

#### **Zppr-4.**

Variable: IPPZON

Format: I (free format)

IPPZON: index of the permeability zone. It must be 1 for the first zone, increasing sequentially thereafter. This index must correspond to one of the permeability-porosity zone indices specified on Record\_14 and Record\_15 in file *solute.inp*.

### Zppr-5. Label

Variable: LABEL (a “Skip” record)

Format: A (free format)

LABEL: sub-heading describing the data that follow.

### Zppr-6. Data for permeability-porosity relationships

Variable: ipptyp, aparpp, bparpp

Format: I, 2F (free format)

Ipptyp: the index for the permeability law. Details on permeability-porosity relationships are described in Appendix F.

Ipptyp = 0: No change in permeability. Can be used to turn off permeability changes in specified grid blocks.

Ipptyp = 1: Simplified Carman-Kozeny (Eq. F.7 in Appendix F). The parameter values (aparpp and bparpp) are not used and may be set to 0.0 or any real number.

Ipptyp = 2: Modified Hagen-Poiseuille Model. Permeability calculated from pore throat diameter, number of throats per pore, and number of pores per area using the Hagen-Poiseuille equation (modified from Ehrlich et al. 1991). Cubic packed spheres used to calculate pore throat diameters. The parameter aparpp is the number of effective throats per pore (typically about 2 to 3). Bparpp is the number of pores per  $m^2$  area.

Ipptyp = 3: Cubic law (Eq. F.2). The parameter values (aparpp and bparpp) are not used and may be set to 0.0 or any real number.

Ipptyp = 4: Modified cubic law (Eqs. F.3-F.6). The parameters are: (aparpp) *fracture porosity / fracture-matrix area* (analogous to fracture aperture) ( $m^3/m^2$ ) and (bparpp) fracture spacing ( $m$ )

Ipptyp = 5: Verma-Pruess permeability-porosity relation (Eq. F.8). The parameters are: (aparpp) the fraction of the original porosity at which permeability goes to zero and (bparpp) a power law exponent. The initial porosity,  $\phi_i$ , is taken as the value at  $t = 0$ , rather than the initial value which have changed for a restart simulation. The value of the “critical” porosity  $\phi_c$  at which permeability goes to zero (in Eq. F.8) is then calculated as  $\phi_i \times$  aparpp.

Ipptyp = 6: Matrix fractal pore space geometry (Pape et al., 1999). The parameters are: (aparpp) exponent on  $(\phi/\phi_i)$  for porosity  $\leq 0.1$ , and (bparpp) exponent on  $(\phi/\phi_i)$  for porosity  $\geq 0.1$ .

**Zppr-7. Trailer for Zppr records (one record only, at end zone list)**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

---

### 5.3.6 Surface adsorption zones (Zads)

This part is used to input zones with specific surface areas for surface complexation (adsorption). These zones are mapped to the numerical grid through variables IZADDF and IZAD on Record\_14 and Record\_15, respectively, in file *solute.inp*.

**Zads-1. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments or blank line.

**Zads-2. Header for Zads records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Zads records.

**Zads-3.**

Variable: NDTYPE

Format: I (free format)

NDTYPE: total number of surface adsorption zones defined for the system.

**Zads-4. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: sub-heading describing the data that follow.

The following records, Zads-4, Zads-5, and Zads-6 define each adsorption zone, and must be repeated NDTYPE times. Note, in this case, the trailer record (Zads-6) is required only once at the end of the list of all adsorption zones.

### **Zads-5. Adsorption zone index and type**

Variable: IDZONE IEQUIL

Format: 2 I (free format)

IDZONE: index of the surface adsorption zone. It must be 1 for the first zone, increasing sequentially thereafter. This index must correspond to one of the adsorption zone indices specified on Record\_14 and Record\_15 in file *solute.inp*.

IEQUIL: flag for type of initialization.

= 0 Do not equilibrate the surface with initial aqueous solutions

= 1 Equilibrate the surface with initial aqueous solutions at each model grid block prior to starting flow/transport calculations. In such case, initial sorbed amounts are computed at each grid block, and for each surface, such that initial water compositions remain unchanged after sorption. Results of this initial surface equilibration can be output in file *chdump.out* if *ichdump* is set to 1 or 2 in *solute.inp* (on Record\_2).

### **Zads-6. Adsorption surface area**

Variable: NAME IFLAG S\_AREA

Format: A, I, F (free format)

NAME: name of primary surface species, in quotes. The name must match one of the primary surface complex species entered at the end of the list of primary species at the top of the file (Prim records, species defined with NOTRANS=2).

IFLAG: flag to specify the units of the sorption surface area.

= 0  $\text{cm}^2_{\text{mineral}}/\text{g}_{\text{mineral}}$ . If NAADS\_MIN = 'no\_mineral' (on record Prim-2), internal conversions will assume a generic mineral density of  $2.65 \text{ g/cm}^3$  for this surface.

= 1  $\text{m}^2_{\text{mineral}}/\text{m}^3_{\text{mineral}}$

= 2  $\text{m}^2_{\text{mineral}}/\text{m}^3_{\text{medium_solids}}$

If NAADS\_MIN starts with 'surface' (on record Prim-2), a constant surface area entered in units of  $\text{m}^2/\text{kg}_{\text{H}_2\text{O}}$  will be assumed.

S\_AREA: surface area for sorption, in units as defined by the value of IFLAG and/or NAADS\_MIN (on record Prim-2).

### **Zads-7. Trailer for Zads records (one record only, at end of zone list)**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

## **5.3.7 Linear Kd zones (Zlkd)**

---

This section describes the linear adsorption Kd zones initially present in the system. These zones are mapped to the numerical grid through variables IZKDDF and IZKD on Record\_14 and Record\_15, respectively, in file *solute.inp*.

### **Zlkd-1. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments or blank line.

### **Zlkd-2. Header for Zlkd records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Zads records

### **Zlkd-3.**

Variable: KDTYPE

Format: I (free format)

KDTYPE: total number of Kd zones in the system.

The following records, Zlkd-4, Zlkd-5 and Zlkd-6, define each linear Kd zone, and must be repeated KDTYPE times.

### **Zlkd-4.**

Variable: IDTYPE

Format: I (free format)

IDTYPE: index of the Kd zone. It must be 1 for the first zone, increasing sequentially thereafter. This index must correspond to one of the Kd zone indices specified on Record\_14 and Record\_15 in file *solute.inp*.

#### **Zlkd-5. Label**

Variable: LABEL (a “Skip” record)

Format: A (free format)

LABEL: sub-heading describing the data that follow.

#### **Zlkd-6. Data related to the Kd zone**

Variable: NAME, SDEN2, VKD2

Format: A, F, F (free format)

NAME : the name of primary aqueous species with Kd (in quotes), which can be listed in any order. The species spelling must be the same as defined previously.

SDEN2: the solid density (in kg/dm<sup>3</sup>).

VKD2 is value of Kd (in kg<sup>-1</sup> which is mass/kg solid divided by mass/l solution). If SDEN2=0.0, VKD2 automatically represents retardation factor ( $\geq 1$ ).

#### **Zlkd-7. Trailer for Zlkd records (one record only, at end of zone list)**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

### **5.3.8 Cation exchange zones (Zexc)**

---

This section describes the characteristics of the cation exchange capacity zones present in the system. These zones are mapped to the numerical grid through variables IZEXDF and IZEX on Record\_14 and Record\_15, respectively, in file *solute.inp*.

#### **Zexc-1. Label (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: comments or blank line.

**Zexc-2. Header for Zexc records (a “Skip” record)**

Variable: LABEL

Format: A (free format)

LABEL: header describing Zexc records.

**Zexc-3.**

Variable: NXTYPE

Format: I (free format)

NXTYPE: total number of cation exchange zones.

**Zexc-4. Label**

Variable: LABEL

Format: A (free format)

LABEL: sub-heading describing the data that follow.

**Zexc-5. Data related to the cation exchange zone**

Zexc-5 must be repeated NXTYPE times. If NXTYPE is zero omit this card.

Variable: IXTYPE NXsites(CEC)

Format: I, NXsites(F) (free format)

IXTYPE: index of the cation exchange zone. It must be 1 for the first zone, increasing sequentially thereafter. This index must correspond to one of the exchange zone indices specified on Record\_14 and Record\_15 in file *solute.inp*.

CEC: cation exchange capacity (meq/100 g of solid). Note also that there are NXsites values, each for one exchange site

**Zexc-7. Trailer for Zexc records (one record only, at end of zone list)**

Variable: LABEL

Format: A (free format)

LABEL: character string starting with \* or blank record

## 5.4 Thermodynamic Database

---

TOUGHREACT reads a free format thermodynamic database file (ascii text file). Aqueous species, minerals, and gases read in file *chemical.inp* must be found in the thermodynamic database file. The name of the database file is specified in file *solute.inp*. Values for all input data (even if zero) must be supplied, unless specifically indicated otherwise. If an aqueous species, mineral, or gas is not in the database or the user desires to use different thermodynamic data, they must be added to an existing database, or a new file created. An example of a thermodynamic database file is given in Figure 5-1. The TOUGHREACT distribution files include a utility program for converting databases from other codes (such as EQ3/6 and PHREEQC) to the TOUGHREACT database format. The description of the conversion program is given in Appendix L. Appendix L also gives descriptions of other utility programs for switching basis (primary) species and regressing log(K) data.

This version of TOUGHREACT has options for reading in temperature-dependent coefficients for heat capacity, thermal conductivity, and thermal expansion of minerals as extra lines in the thermodynamic database. Although thermal expansion coefficients can be read in, the calculation of temperature-dependent mineral densities is not yet implemented. Another revision affects the use of the mineral molar volumes that are now read in as initial values that may change owing to swelling/shrinkage. Note that these data are not available in many published thermodynamic databases, and must be added.

### **Spelling convention for reactants/products name**

Names of all reactants and products must be input within quotes. On input, these strings are all converted to lower case characters. In addition, any multiple electronic charges incorporated into the names of cations and anions are converted to one charge sign followed by the number of charges. For example, 'CO3--' is converted to 'co3-2' and 'Al+++ ' is converted to 'al+3'. All names must be no more than 20 characters long. Longer names will be truncated. The use of a consistent spelling in the database is recommended, although the internal conversion to lower case characters and unique style for charge allow for input flexibility.



The following aqueous and gas species require specific spelling for proper internal handling of special functions with some EOS modules:

water	'H2O' or 'h2o'
hydrogen ion	'H+' or 'h+'
hydroxide anion	'OH-' or 'oh-'
carbon dioxide gas	'CO2(g)' or 'co2(g)'
hydrogen gas	'H2(g)' or 'h2(g)'
methane gas	'CH4(g)' or 'ch4(g)'
hydrogen sulfide gas	'H2S(g)' or 'h2s(g)'
sulfur dioxide gas	'SO2(g)' or 'so2(g)'
oxygen gas	'O2(g)' or 'o2(g)'
carbonic acid	'CO2(aq)' or 'co2(aq)'
bicarbonate	'HCO3-' or 'hco3-'
carbonate	'CO3-2' or 'co3-2'
methane (dissolved)	'CH4(aq)' or 'ch4(aq)'
hydrogen sulfide (dissolved)	'H2S(aq)' or 'h2s(aq)'
sulfur dioxide (dissolved)	'SO2(aq)' or 'so2(aq)'
oxygen (dissolved)	'O2(aq)' or 'o2(aq)'

**End-of-header record (first record):**

Variable: 'DUMMY'

Format: A

DUMMY: a label used to indicate the start of the database. This label must start with 'end-of-header', without quotes. All inputs prior to this record are skipped. All records after this record must follow the formatting and record order described below.

**Optional record:**

Variable: 'LABEL', ncoef

Format: A, I

LABEL: a character string (in quotes) that must contain the word *coefficients*

ncoef: an integer specifying the number of regression coefficients used to compute log(K)'s as a function of temperature (see further below Sec-3 and Mineral-3). The default is 5, which is assumed if this record is absent.

**Temperature record:**

'temperature points' 8 0.00 25.0 60.0 100.0 150.0 200.0 250.0 300.0

Variable: 'DUMMY', NTEMP, (TEMPC(i), i=1,NTEMP)

Format: A, I, NTEMP(F)

DUMMY: a label (in quotes) used to describe the data for this record.

NTEMP : the number of TEMPC values to read.

TEMPC : temperatures ( $^{\circ}\text{C}$ ) at which the  $\log(K)$  data are listed in this file, at a given reference pressure  $P_0$  (for databases distributed with TOUGHREACT,  $P_0=1$  bar at  $T<100^{\circ}\text{C}$ , and the saturation pressure of pure water at  $T\geq 100^{\circ}\text{C}$ ). TEMPC values must be listed in order of increasing temperature. These values are used to constrain  $\log(K)$  extrapolation within this temperature range.  $\log(K)$ 's are not extrapolated outside this temperature range. For example, if the maximum TEMPC is  $150^{\circ}\text{C}$  but the computed system temperature is  $250^{\circ}\text{C}$ ,  $\log(K)$ 's will be extrapolated only to  $150^{\circ}\text{C}$  (i.e. the geochemical speciation will be computed at  $150^{\circ}\text{C}$ , not  $250^{\circ}\text{C}$ ). *Therefore, users must make sure that simulation temperatures are within the range of thermodynamic data temperatures.*

### Basis (primary species) records:

All TOUGHREACT versions::

'ca+2'	2.87	2.00	40.078
'cl-'	1.81	-1.00	35.453

Format for TOUGHREACT V3.85-OMP and above with aqueous diffusion coefficients (MOPR(18)=1):

'Al+3'	3.33	3.00	26.982	4.5188E-08	1.0e4	! estimated from Oelkers & Helgeson, 1988 at 25C
'He(aq)'	0.00	0.00	4.003	8.18e-7	1.17e4	! Jahne et al., 1987, JGR 92, 10,767-10,776

### Basis-1.

Variable: 'NAME', A0, Z, MWT, Pre-exp (optional) , Eact (optional)

Format: A, 3F (one record per primary species)

NAME : name or chemical formula of aqueous basis species, in quotes (truncated after 20 characters).

A0 : Ion effective or hydrated radius used to compute the Debye-Hückel  $a_0$  parameter (see Appendix H for details). For neutral species other than typical dissolved gases (see Section H.3 of Appendix H), if  $A_0 > 100$ , the value of  $A_0$  is used to compute a salting-out coefficient  $K_i$  equal to  $A_0 - 100$  (i.e., salting-out coefficients for neutral species can be entered as values of  $A_0$  equal to  $100+K_i$ ; see Equation H.9 for the definition of  $K_i$ ).

Z : the ion electric charge

MWT : Molecular weight of the aqueous species (g/mol).

Pre-exp : Pre-exponential factor in Arrhenius equation for temperature-dependent diffusion coefficients

Eact : Activation energy in Arrhenius equation for temperature-dependent diffusion coefficients

This record is repeated as many times as the number of primary species.

### Trailer record after Basis records:

Variable: 'DUMMY'

Format: A

DUMMY: must spell 'end' or 'null', including quotes. This record indicates the end of the list of basis species, and must appear directly after the last basis species.

### “Skip” records:

Starting from this point, any record beginning with either #, or \* followed by one blank, or any blank record will be skipped on input. These “skip” records can be inserted anywhere in the database (after the first trailer record closing the list of basis species), as long as they are not inserted within records pertaining to the same reaction (i.e., these records can be inserted only between sets of records that pertain to one reaction). These “skip” records can be used for comments, data source references, or simply to clear the appearance of the database.

### Secondary (derived) species records:

Data for individual secondary species are input as a set of 3 records, as follows:

#### Sec-1.

'caf+'                    59.076 2.31 1.00 2 1.0000 'ca+2' 1.0000 'f'

Variable: 'NAME', Xmwt, A0, Z, NCPS, (STQS(i), 'NAM(i)', i=1,NCPS)

Format: A, 3F, I, NCPS(F, A)

NAME : chemical formula of secondary species, in quotes (truncated after 20 characters).

Xmwt : molecular weight of the aqueous species (g/mol).

A0 : ion effective or hydrated radius (Angstrom) used to compute the Debye-Hückel a0 parameter (see Appendix H for details). For neutral species other than typical dissolved gases (see Section H.3 of Appendix H), if  $A0 > 100$ , the value of A0 is used to compute a salting-out coefficient  $K_i$  equal to  $A0 - 100$  (i.e., salting-out coefficients for neutral species can be entered as values of A0 equal to  $100 + K_i$ ; see Equation H.9 for the definition of  $K_i$ ).

Z : ion electric charge.

NCPS : number of basis species defining the secondary species.

STQS : stoichiometric coefficients of component (basis) species NAM included in the dissociation reaction of the derived species (negative and positive values for reactants and products, respectively). The derived species is always assumed to have a stoichiometric coefficient of -1.0, which is not included in STQS.

NAM : name of the reactant or product, in quotes (truncated after 20 characters; must match one of the basis species).

### Sec-2.

'caf+'                    -0.6540 -0.6820 -0.8620 -1.1700 -1.6490 -2.2150 -2.8840 -3.7200

Variable: 'NAME', (AKLOG(i), i=1,ntemp)

Format:    A, ntemp(F)

NAME : name or chemical formula of secondary species, as in Sec-1.

AKLOG : contains the equilibrium constants ( $\log(K)$  in base 10) for the given reaction at each discrete temperature listed in record Temp-1 above (at a reference pressure  $P^0$ ). These data are generally skipped on input if  $\log(K)$  regression coefficients as a function of temperature are entered on record Sec-3 (the discrete  $\log(K)$  values should, however, always be included in the file to provide for easy reference to the data). If no regression coefficients are given on record Sec-3, AKLOG values are used to internally regress  $\log(K)$  as a function of temperature on input. Note that AKLOG values equal to 500 are interpreted as "no data".

### Sec-3.

'caf+'    0.13899322E+03 -0.88384562E+03 -0.14090495E+00 0.50246797E+05 -0.31358951E+07

Variable: 'NAME', (AKCOES(i), i=1,5), (AKCOP(i), i=1,5)

Format:    A, 5(E), 5(E)

NAME : name or chemical formula of secondary species, as in Sec-1.

AKCOES : contains regression coefficients a, b, c, d, and e to calculate  $\log_{10}(K)$  as a function of temperature (at a reference pressure  $P^0$ ) with:

$$\log_{10}(K)_{T,P^0} = a \cdot \ln(T_k) + b + c \cdot T_k + d/T_k + e/T_k^2 \text{ (by default, or if ncoef = 5 is specified in the optional record above the temperature record)}$$

or

$\log_{10}(K)_{T,P0} = a*\ln(T_k) + b + c*T_k + d/T_k + e/T_k^2 + f*T_k^2$  (if ncoef = 6 is specified in the optional record preceding the temperature record)

where  $T_k$  is absolute temperature (K), and  $\ln$  stands for natural logarithm. Values must be entered for all coefficients. If all coefficient values are omitted, the coefficients will be internally computed from AKLOG values input on record Sec-2.

AKCOP : (optional) contains regression coefficients a, b, c, d, and e to calculate the volume change  $\Delta V$  (in  $\text{cm}^3/\text{mol}$ ) for the reaction as a function of temperature (average  $\Delta V$  over the pressure interval  $P^0$  to P), with:

$$\Delta V = a + b*T_k + c*T_k^2 + d/T_k + e/T_k^2$$

This option is enabled with  $a \neq 0$ , in which case all coefficients must be entered. These coefficients are used to correct  $\log(K)$  values as a function of pressure, with  $\log_{10}(K)_{T,P} = \log_{10}(K)_{T,P0} - \Delta V*(P-P^0)/(2.303RT_k)$ , where R is the gas constant.

Records Sec-1, Sec-2, and Sec-3 are repeated as sets of triplets, as many times as the number of secondary species. Each set can be spaced by as many “skip” records as desired.

#### Trailer record after secondary species records:

Variable: 'DUMMY'

Format: A

DUMMY: must spell 'end' or 'null', including quotes. This record indicates the end of the list of secondary species, and must appear anywhere between the last secondary species and first mineral.

#### Mineral Records:

The data for each mineral are input as a set of 3 records, as follows:

##### Mineral-1.

Variable: 'NAME', MOLWT, VMIN0, NCPM, (STQM(i), 'NAM(i)',  $i=1, \text{NCPM}$ )

Format: A, 2F, I, NCPM(F, A)

NAME : name or chemical formula of a mineral, in quotes (truncated after 20 characters).

MOLWT : molecular weight (g/mol).

VMIN0: initial molar volume of mineral ( $\text{cm}^3/\text{mole}$ ). In V3.0-OMP and later, VMIN0 is internally replaced by VMIN which is stored at each grid block and can change during the simulation owing to swelling/shrinkage if invoked. If VMIN) is set to a negative value, a fourth line for temperature-dependent heat capacity coefficients will be read, and VMIN0 will internally be reset to a positive value.

NCPM : the number of component species defining the mineral.

STQM : contains the stoichiometric coefficient of basis species NAM in the dissociation (hydrolysis) reaction of the mineral (negative and positive values for reactants and products, respectively). The mineral species is always assumed to have a stoichiometric coefficient of -1.0, which is not included in STQM.

NAM: name of the reactant or product, in quotes (truncated after 20 characters; must match one of the basis species).

### **Mineral-2.**

Variable: 'NAME', (AKLOG(i), i=1,ntemp)

Format: A, ntemp(F)

NAME : name or chemical formula of the mineral, as in Mineral-1.

AKLOG : contains the equilibrium constants ( $\log(K)$  in base 10) for the reaction at various temperatures. See record Sec-2 for formatting and other details.

### **Mineral-3.**

Variable: 'NAME', (AKCOEM(i), i=1,5), (AKCOP(i), i=1,5)

Format: A, 5(E)

NAME : name or chemical formula of the mineral, as in Mineral-1.

AKCOEM : contains regression coefficients a, b, c, d, and e to calculate  $\log_{10}(K)$  as a function of temperature. See record Sec-3 for formatting and details.

AKCOP : (optional) contains regression coefficients a, b, c, d, and e to calculate  $\Delta V$  for the reaction (in  $\text{cm}^3/\text{mol}$ ) as a function of temperature. See record Sec-3 for formatting and details.

### **Mineral-4. Optional Record, if molar volume (VMIN0) is input as a negative value**

Variable: 'NAME', NITL, (CPMNCF(i), i=1,4)

Format: A, I, 4(E)

NAME : name or chemical formula of the mineral, as in Mineral-1.

NITL : number of additional lines with thermal parameters including this one

CPMNCF : Coefficients for temperature-dependent heat capacity

**Mineral-5. Optional Record, if molar volume (VMIN0) is input as a negative value and NITL ≥2**

Variable: 'NAME', (TCMNCF(i), i=1,2)

Format: A, 2(E)

NAME : name or chemical formula of the mineral, as in Mineral-1.

TCMNCF: Coefficients for temperature-dependent thermal conductivity

**Mineral-5. Optional Record, if molar volume (VMIN0) is input as a negative value and NITL =3**

Variable: 'NAME', (ALPHTM(i), i=1,3)

Format: A, 3(E)

NAME : name or chemical formula of the mineral, as in Mineral-1.

ALPHTM: Coefficients for temperature-dependent thermal expansion

**Trailer record after Mineral records:**

Variable: 'DUMMY'

Format: A

DUMMY: must spell 'end' or 'null', including quotes. This record indicates the end of the list of minerals, and must appear anywhere between the last mineral and first gas.

**Gas records:**

The data for each gas species are input as a set of 3 records, as follows:

**Gas-1.**

Variable: 'NAME', DMOLWT, DMDIAM, NCPG, (STQG(i), 'NAM(i)', i=1,NCPG)

Format: A, 2F, I, NCPG(F, A)

NAME : name or chemical formula of a gas species, in quotes (truncated after 20 characters).

DMOLWT : molecular weight (g/mol)

DMDIAM: molecular diameter (m) used to calculate gas diffusion coefficient (see Eq. (A.1) in Appendix A)

NCPG : the number of basis species defining the gas.

STQG : contains the stoichiometric coefficient of component species NAM in the dissociation reaction of the gas (negative and positive values for reactants and products, respectively). The gas is always assumed to have a stoichiometric coefficient of -1.0, which is not included in STQG.

NAM: name of the reactant or product, in quotes (truncated after 20 characters; must match one of the basis species).

### **Gas-2.**

Variable: 'NAME', (AKLOG(i), i=1,ntemp)

Format: A, ntemp(F)

NAME : name or chemical formula of the gas, as in Gas-1.

AKLOG : contains the equilibrium constants (log(K) in base 10) for the reaction at various temperatures. See record Sec-2 for formatting and other details.

### **Gas-3.**

Variable: 'NAME', (AKCOEG(i), i=1,5), (AKCOPG(i), i=1,5)

Format: A, 5(E)

NAME : name or chemical formula of the gas, as in Gas-1.

AKCOEG : contains regression coefficients a, b, c, d, and e to calculate  $\log_{10}(K)$  as a function of temperature. See record Sec-3 for formatting and details.

AKCOPG : (optional) contains regression coefficients a, b, c, d, and e to calculate  $\Delta V$  for the reaction (in  $\text{cm}^3/\text{mol}$ ) as a function of pressure. See record Sec-3 for formatting and details.

Records Gas-1, Gas-2, and Gas-3 are repeated as sets of triplets, as many times as the number of secondary species. Each set can be spaced by as many "skip" records as desired.

### **Trailer record after Gas records:**

Variable: 'DUMMY'



Format: A

DUMMY: must spell 'end' or 'null', including quotes. This record indicates the end of the list of gases, and must appear anywhere between the last gas and first surface complex.

### Surface complex records:

The data for each surface complex are input as a set of 3 records, as follows:

#### Surface-1.

Variable: 'NAME', Z, NCPS, (STQS(i), 'NAM(i)', i=1,NCPS)

Format: A, F, I, NCPS(F, A)

NAME : chemical formula of surface complex, in quotes (truncated after 20 characters).

Z : electric charge of surface complex.

NCPS : number of basis species defining the surface complex.

STQS: stoichiometric coefficients of component species NAM included in the dissociation reaction of the surface complex (negative and positive values for reactants and products, respectively). The surface complex is always assumed to have a stoichiometric coefficient of -1.0, which is not included in STQS.

NAM: name of the reactant or product, in quotes (truncated after 20 characters; must match one of the basis species).

#### Surface-2.

Variable: 'NAME', (AKLOG(i), i=1,ntemp)

Format: A, ntemp(F)

NAME : name or chemical formula of the surface complex, as in Surface-1.

AKLOG : contains the equilibrium constants ( $\log(K)$  in base 10) for the reaction at various temperatures. See record Sec-2 for formatting and other details.

#### Surface-3.

Variable: 'NAME', (AKCOE(i), i=1,5)

Format: A, 5(E)

NAME : name or chemical formula of the surface complex, as in Surface-1.

AKCOE : contains regression coefficients a, b, c, d, and e to calculate  $\log_{10}(K)$  as a function of temperature. See record Sec-3 for formatting and details.

Records Surface-1, Surface-2, and Surface-3 are repeated as sets of triplets, as many times as the number of surface complexes. Each set can be spaced by as many “skip” records as desired.

**Trailer record after Surface records:**

Variable: 'DUMMY'

Format: A

DUMMY: must spell 'end' or 'null', including quotes. This record indicates the end of the list of secondary species, and must appear anywhere after the last surface complex.

**Figure 5-1 Example of a TOUGHREACT V3-OMP thermodynamic database file. Note addition of thermal parameters (heat capacity, thermal expansion, and thermal conductivity coefficients) for “albit-hi”.**

```
Any text here, for any number of records

!end-of-header      Do not remove this record!
'Temperature points:' 8 0.01 25.0 60.0 100.0 150.0 200.0 250.0 300.0
'H2O'                0.00 0.00      18.015
'Ca++'               2.87 2.00      40.078
'Cl-'                1.81 -1.00     35.453
'Fe++'               2.62 2.00     55.845
'H+'                 3.08 1.00      1.008
'HCO3-'              2.10 -1.00     61.017
'K+'                 2.27 1.00     39.098
'Na+'                1.91 1.00     22.990
'Hfo_sOH'            0.00 0.00      0.000
'null'

#####
# Aqueous species #
#####
'CO2(aq)'            44.010 0.00 0.00   3 -1.00000 'H2O' 1.00000 'H+' 1.00000 'HCO3-'
'CO2(aq)'            -6.5804 -6.3447 -6.2684 -6.3882 -6.7235 -7.1969 -7.7868 -8.5280
'CO2(aq)'            0.10476478E+03 -0.67138541E+03 -0.10862163E+00 0.38868294E+05 -0.26528340E+07
# Data source:      EQ3/6 database data0.ymp.R5 YM Project SN0612T0502404.14

'NaSO4-'            119.053 1.81 -1.00   2 1.00000 'Na+' 1.00000 'SO4--'
'NaSO4-'            -0.6765 -0.7000 -0.8416 -1.0629 -1.3893 -1.7724 -2.2416 -2.8730
'NaSO4-'            0.15443167E+03 -0.98620007E+03 -0.14872193E+00 0.56350439E+05 -0.34707590E+07
# Data source:      EQ3/6 database data0.ymp.R5 YM Project SN0612T0502404.14

'null'

#####
# Minerals #
#####
'Calcite'           100.087 36.934 3 -1.00000 'H+' 1.00000 'Ca++' 1.00000 'HCO3-'
'Calcite'           2.2257 1.8487 1.3330 0.7743 0.0999 -0.5838 -1.3262 -2.2154
'Calcite'           0.14237876E+03 -0.90313945E+03 -0.14436024E+00 0.50619704E+05 -0.29300495E+07
# Data source:      EQ3/6 database data0.ymp.R5 YM Project SN0612T0502404.14

'Carnallite'        277.853 172.580 4 1.00000 'K+' 1.00000 'Mg++' 3.00000 'Cl-' 6.00000 'H2O'
'Carnallite'        500.0000 4.2721 500.0000 500.0000 500.0000 500.0000 500.0000 500.0000
'Carnallite'        0.00000000E+00 0.42721000E+01 0.00000000E+00 0.00000000E+00 0.00000000E+00
```

```

# Data source:      EQ3/6 database data0.ymp.R5 YM Project SN0612T0502404.14

'albit-hi' 262.220 -101.087 5 1.0000 'Na+' 1.0000 'Al+3' 3.0000 'SiO2(aq)' 2.0000
'H2O' -4.0000 'H+'
'albit-hi' 500.0000 2.4190 1.2295 -0.0790 -1.4780 -2.6340 -3.6460 -4.6260
'albit-hi' 0.12199909E+03 -0.81331114E+03 -0.96626546E-01 0.58330172E+05 -0.41063786E+07
'albit-hi' 3 452. -.13364e-1 -1275900. -3953.6
'albit-hi' 0.0 0.0
'albit-hi' 2.762 -1.6329e-5 0.0
# source:      HP98; Cp(T) from Holland and Powell JMG 2011

'null'
#####
# Gases #
#####

'CO2(g)' 44.010 2.5e-10 3 -1.00000 'H2O' 1.00000 'H+' 1.00000 'HCO3-'
'CO2(g)' -7.7695 -7.8257 -8.0437 -8.3390 -8.7356 -9.2136 -9.7552 -10.3962
'CO2(g)' 9.833583157 -59.02305875 -0.026997768 950.3210943 0.0 -30.76062599 0.126305497 -
5.45461E-05 9039.990466 0.0
# Data source:      Regressed from Spycher and Pruess (2009)
# The coefficients for P correction correspond to dV=-32.6 cm3 up to 100C, then
# increase to -39.4 at 300C
# Note, these values are for the CO2(g)=>CO2(aq) reaction, so dV must be zero
# for CO2(aq)=>HCO3- reaction
'null'

#####
# Surface complexes #
#####

'Hfo_sOH2+' 1.000 2 1.00000 'Hfo_sOH' 1.00000 'H+'
'Hfo_sOH2+' 500.0000 -7.2900 500.0000 500.0000 500.0000 500.0000 500.0000
'Hfo_sOH2+' 0.00000000E+00 -0.72900000E+01 0.00000000E+00 0.00000000E+00 0.00000000E+00
# source:      (phreeqc) minteq.v4.dat 85 2005-02-02

'null'

```

## 6 Built-in Error Messages

---

Many execution stops built into TOUGHREACT are accompanied by a message indicating why the execution was aborted. These messages are written to file *runlog.out*. Some error messages do not lead to a program interruption. However, nonconvergence or division-by-zero in some routines may lead to the program crashing without a comprehensible message. In these cases it is useful to check the files for detailed messages and/or examine the files to see which part of the code may have had troubles (e.g., flow, transport, or reaction). It may be necessary to rerun (or restart from the previous *SAVE* and *savechem* files) the simulation writing output (e.g., *iter.out*, *chdump.out*) more frequently. Only messages related to the reactive transport part of the program are reviewed below. Error messages originating from fluid and heat flow calculations are the mostly the same as for TOUGH2 V2 (Pruess et al., 1999).

## 6.1 From Routine: INIT (reads the CHEMICAL.INP file)

---

Most of these messages are self-explanatory and refer to exceeded array dimensions or other errors encountered when reading the chemical.inp file. Array dimension problems can be corrected by reducing the problem size or changing array dimensions in the source file chempar23.inc and recompiling the program. Some examples are given as follows:

*Error: maximum number of component species (MPRI) was exceeded. Current max=(MPRI)*

Execution stop: yes. Self-explanatory.

*Error: maximum number of minerals (MMIN) was exceeded. Current max= (MMIN)*

Execution stop: yes. Self-explanatory.

*error reading aqueous species of the system*

Execution stop: yes. Self-explanatory.

*error reading minerals of the system*

Execution stop: yes. Self-explanatory.

*error reading gases of the system*

Execution stop: yes. Self-explanatory.

*error reading initial water zone= \_\_\_ (iwtype)*

Execution stop: yes. Self-explanatory.

*error reading initial mineral zone= \_\_\_\_ (imtype)*

Execution stop: yes. Self-explanatory.

*error reading initial gas zone= \_\_\_ (imtype)*

Execution stop: yes. Self-explanatory.

## 6.2 From Routine: NRINIT (initial Newton-Raphson iterations)

---

*ERROR (convergence problem in initialization of water composition)  
Please adjust convergence criteria regarding chemical iteration  
and initial guess of concentration of primary species*

Execution stop: yes. Self-explanatory. This error results in calling routine chdump for troubleshooting (i.e. the last chemical speciation data are output in the chdump.out file). This error occurs during the initial geochemical speciation of waters specified in chemical.inp (no minerals, before the first time step). Check the chdump.out file for clues, and also check that water temperatures specified in chemical.inp data are not too different from temperatures assigned to grid blocks in INCON or PARAM.

### 6.3 From Routine: READTHERM (reads thermodynamic database file)

---

Error messages may be written out while reading the thermodynamic database and are generally self-explanatory. These indicate improperly formatted records in the database file. All errors result in a program execution stop. Some examples are:

*Error reading temperature data: stop*

*Error reading primary species: stop*

*Error reading secondary species: stop (followed by the species name)*

*Error reading minerals: stop (followed by the mineral name)*

*Error reading gases: stop (followed by the gas name)*

*Error reading adsorbed species: stop (followed by the species name)*

*Error in opening database file: stop*

*From Routine: READSOLU (reads the file solute.inp)*

There are currently no specific error messages generated while reading the file solute.inp. The unit number of this file is 31. System error messages relating to this I/O number originate while reading this file. Make sure the fixed formats of this file are respected (just the names of grid blocks for writing time interval data). See the file solute.out for the last entry written out to indicate where an error in solute.inp is likely.

### 6.4 From Routine: CR\_CP (kinetic data calculations)

---

*error in data option for mineral (kinetic)= \_\_\_\_\_*

Execution stop: yes. This message occurs if the flag IDEP for any of the kinetic minerals is not set to either 0 or 1. With this program version, IDEP must always be zero (this flag is specified in the mineral section of the chemical.inp file).

From Routine: NEWTONEQ (Newton-Raphson iterations after 1st time step)

*ERROR: chemistry did not converge at node \_\_\_\_\_ (routine NEWTONEQ)*

*Species: \_\_\_\_\_ Error=\_\_\_\_\_ Error limit= \_\_\_\_\_ relative*

*Node temperature (C): \_\_\_\_\_*

*Program execution was not aborted. Check results!*

Execution stop: only if this error occurs at more than fifty grid blocks at any given time step. This error also calls routine chdump for troubleshooting (i.e., the last chemistry calculation data are output in the chdump.out file). This error occurs during the block-by-block geochemical speciation computations after the first time step (complete system, with minerals and gases if any). Check the chdump.out file for clues on why convergence was not reached. In many cases, chemical convergence fails because of errors during transport, resulting in erroneous system compositions that cannot yield a solution to geochemical speciation calculations. In this case, the maximum time step may be decreased (in flow.inp) and/or the Courant number option enabled (RCOUR in solute.inp). If boiling has led to nonconvergence, try increasing SL1MIN or changing STIMAX (specified in solute.inp).

*Error: Negative concentration for species \_\_\_\_\_*

Execution stop: no. Self-explanatory. A concentration may temporarily become negative during the chemical Newton-Raphson iterations, but should not remain negative. This error may indicate problems to come. It is rarely encountered.

## 7 Concluding Remarks

---

TOUGHREACT is a 3-D parallel simulator for non-isothermal multiphase fluid flow and geochemical transport in porous and fractured media. An integral finite difference (IFD) technique is employed for space discretization. The IFD methodology can deal with irregular grids, does not require reference to a global system of coordinates, and includes classical dual-continua, multiple interacting continua, and multi-region models for heterogeneous and fractured rocks. Non-isothermal effects are considered, including water-vapor phase change and air partitioning between the liquid and gas phases, temperature-dependence of thermophysical properties such as phase density and viscosity, and chemical properties such as thermodynamic and kinetic parameters. Chemical reactions considered under the local equilibrium assumption include aqueous complexation, acid-base, redox, gas dissolution/exsolution, cation exchange, and surface complexation. Mineral dissolution/precipitation can proceed either subject to local equilibrium or kinetic conditions. The gas phase is considered active for multiphase fluid flow, species transport, and gas-liquid chemical reactions.

This version of TOUGHREACT is applicable to one-, two-, or three-dimensional geologic domains with physical and chemical heterogeneity, and can be applied to a wide range of subsurface conditions. Temperatures for multiphase flow can reach a maximum of the supercritical

point of water at water saturation pressure ( $\sim 374$  °C ) although the temperature range for equilibrium constants is generally from 0 to 300 °C, limited at present by available geochemical databases such as EQ3/6 (Wolery, 1992). Pressures of 1 bar (atmospheric pressure) to several hundred bars (at several thousand meter depth) can be considered. Water saturation can range from completely dry to fully water saturated. The code can handle ionic strengths from dilute to saline waters with up to 6 mol/kg for an NaCl-dominant solution.

TOUGHREACT applications have been demonstrated for a variety of reactive fluid and geochemical transport systems, including (1) contaminant transport with linear  $K_d$  adsorption and decay, (2) natural groundwater quality evolution under ambient conditions, (3) assessment of nuclear waste disposal sites, (4) sedimentary diagenesis and  $\text{CO}_2$  geological sequestration in deep saline formations, (5) mineral deposition such as supergene copper enrichment, (6) mineral alteration and silica scaling in hydrothermal systems under natural and production conditions, and (7) acidic mine drainage and groundwater contamination. Of course, many other potential geologic, experimental, and engineered systems could be analyzed using similar methodologies as given in these examples.

## 8 References

---

- Ague, J. J., and Brimhall, G. H., Geochemical modeling of steady state and chemical reaction during supergene enrichment of porphyry copper deposits: *Economic Geology*, v. 84, p. 506-528, 1989.
- Ahlers, C. F., and Liu, H. H., Calibrated properties model, MDL-NBS-HS-000003 REV00., Yucca Mountain Project, Lawrence Berkeley National Laboratory, Berkeley, California, 2000.
- Alpers, C. A., and Brimhall, G. H., Paleohydrologic evolution and geochemical dynamics of cumulative supergene metal enrichment at La Escondida, Atacama Desert, Northern Chile: *Economic Geology*, v. 84, p. 229-255, 1989.
- Ananthaswamy, J., and G. J. Atkinson, Thermodynamics of concentrated electrolyte mixtures: 5. A Review of the thermodynamic properties of aqueous calcium chloride in the temperature range 273.15-373.15 K. *J. Chem. Eng. Data*, 30, 120, 1985.
- Appelo, C. A. J., and Postma, D., *Geochemistry, groundwater and pollution*, Rotterdam, The Netherlands, Balkema, 536 pp., 1993.
- Appelo, C. A. J., Cation and proton exchange, pH variations and carbonate reactions in a freshening aquifer, *Water Resour. Res.*, v. 30(10), p. 2793-2805, 1994.
- Apps, J. A., An approach to modeling of the chemistry of waste fluid disposal in deep saline aquifers, In Apps, J. A., and Tsang, C. F. (eds.), *Deep injection disposal of hazardous and industrial waste: Scientific and Engineering Aspects*, p. 465-488, Academic Press, San Diego, California, 1996.
- Aradóttir, E.S.P., B. Sigfussen, E.L. Sonnenthal, G. Björnsson, & H. Jónsson. Dynamics of basaltic glass dissolution - Capturing microscopic effects in continuum-scale models, *Geochimica et Cosmochimica Acta*, 121:311-327.
- Aradóttir, E.S.P., E.L. Sonnenthal, G. Björnsson, & H. Jónsson, 2012. *Multidimensional reactive transport modeling of CO<sub>2</sub> mineral sequestration in basalts at the Hellisheidi geothermal field, Iceland*. *International Journal of Greenhouse Gas Control*, 9:24-40.
- Aradóttir, E.S.P., E.L. Sonnenthal, and H. Jónsson, 2012. *Development and evaluation of a thermodynamic dataset for phases of interest in CO<sub>2</sub> mineral sequestration in basaltic rocks*. *Chemical Geology*, 304-305:26-38.
- Audigane, P., I. Gaus, I. Czernichowski-Lauriol, K. Pruess, and T. Xu, Two-dimensional reactive transport modeling of CO<sub>2</sub> injection in a saline aquifer at the Sleipner Site, *American Journal of Science*, v. 307, p. 974-1008. 2007.
- Bachu, S., Gunter, W. D., and Perkins, E. H., Aquifer disposal of CO<sub>2</sub>: hydrodynamic and mineral trapping, *Energy Convers. Mgmt.*, v. 35, p. 269-279, 1994.
- Balistrieri, L.S., Preliminary estimates of benthic fluxes of dissolved metals in Coeur d'Alene Lake, Idaho 98-793. US Geological Survey, Seattle, WA, 1998.
- Bear, J.: *Dynamics of Fluids in Porous Media*, Dover Publications, Inc., New York, 1972.
- Birkholzer, J. T., and Tsang, Y. W., Pretest analysis of the thermal-hydrological conditions of the ESF Drift Scale Test, Yucca Mountain Project Level 4 Milestone SP9322M4, Lawrence Berkeley National Laboratory, Berkeley, California, 1997.
- Birkholzer, J. T., and Tsang, Y. W., Interpretive analysis of the thermo-hydrological processes of the Drift Scale Test, In Drift Scale Test Progress Report, Chapter 6., Yucca Mountain Project Level 4 Milestone SP2930M4, Lawrence Berkeley National Laboratory, Berkeley, California, 1998.



- Brimhall, G. H., Alpers, C. N., and Cunningham, A. B., Analysis of supergene ore-forming processes and ground water solute transport using mass balance principles: *Economic Geology*, v. 80, p. 1227-1256, 1985.
- Brimhall, G. H., and Dietrich, W. E., Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical systems: Results on weathering and pedogenesis, *Geochim. Cosmochim. Acta*, v. 51, p. 567-588, 1987.
- Burnol A. and Claret, F., Using a generalized power law for simulating the feedback effect of dissolution/precipitation on diffusive transfer in toughreact. Proceedings, TOUGH Symposium 2012, Lawrence Berkeley National Laboratory, Berkeley, California, September 17-19, 2012.
- Carey, J. W., Chipera, S. J., Vaniman, D. T., Bish, D. L., Three-dimensional mineralogic model of Yucca Mountain, Nevada, Rev 2.0., Los Alamos National Laboratory, Los Alamos, New Mexico, 1998.
- Carlos, B. A., Chipera, S. J., Bish, D. L., Calcite and zeolite fracture coating in Topopah Spring Tuff along Drill Hole Wash, Yucca Mountain (Nevada), Proc. 6<sup>th</sup> Intl. Conf. High Level Rad. Waste Mgmt., p. 100-102, 1995.
- Carroll, S., Mroczek, E., Alai, M., and Ebert, M., Amorphous Silica Precipitation (60 to 120°C): Comparison of Laboratory and Field Rates, *Geochim. Cosmochim. Acta*, v. 62, p. 1379–1396, 1998.
- Chapelle, F. H., and Drummond, D. D., Hydrogeology, digital simulation, and geochemistry of the Aquia and Piney Point-Nanjemoy aquifer system in southern Maryland, *Rep. Invest. 38*, Md. Geol. Surv., Baltimore, Maryland, 1983.
- Chapelle, F. H., and Knobel, L. L., Aqueous geochemistry and exchangeable cation composition of glauconite in the Aquia aquifer, Maryland, *Groundwater*, v. 21, p. 343-352, 1983.
- Colin, E., Clarke, W., and Clew, D.N. Evaluation of the thermodynamic functions for aqueous sodium chloride from equilibrium and calorimetric measurements below 154°C. *J. Phys.Chem. Ref. Data* 14, 489-609, 1985.
- Corey, A. T., The interrelation between gas and oil relative permeabilities, *Producers Monthly*, p. 38-41, 1954.
- Dobson, P.F., T.J. Kneafsey, E.L. Sonnenthal, N.F. Spycher, and J.A. Apps, 2003. Experimental and numerical simulation of dissolution and precipitation: Implications for fracture sealing at Yucca Mountain, Nevada. *Journal of Contaminant Hydrology*. 62-63: 459-476.
- Dobson, P. F., Salah, S., Spycher, N., and Sonnenthal, E. L., Simulation of water-rock interaction in the Yellowstone geothermal system using TOUGHREACT, *Geothermics*, v. 33, p. 493-502, 2004.
- Domenico, P. A., and Schwartz, F. W., *Physical and Chemical Hydrogeology*, John Wiley and Sons, New York, 824 pp., 1990.
- Doussan, C., Poitevin, G., Ledoux, E., and Detay, M., River bank filtration: modelling of the changes in water chemistry with emphasis on nitrogen species, *Journal of Contaminant Hydrology*, v. 25, p. 129-156, 1997.
- Drever, J. I., *Geochemistry of Natural Waters*, 3<sup>rd</sup> Edition, Upper Saddle River, New Jersey: Prentice Hall, 436pp., 1997.
- Drummond, J. M., Jr., Boiling and mixing of hydrothermal fluids: Chemical effects on mineral precipitation, Ph.D. thesis, The Pennsylvania State University, University Park, Pennsylvania, 1981.
- Dzombak, D. A., and Morel, F. M. M., *Surface complexation modeling*: New York, Wiley Interscience, 431 pp., 1990.

- Ehrlich R, Etris EL, Brumfield D, Yuan LP, Crabtree SJ. Petrography and reservoir physics III: physical models for permeability and formation factor. *AAPG Bull* 1991; 75(10):1579–92.
- Engesgaard, P., and Kipp, K. L., A geochemical transport model for redox-controlled movement of mineral fronts in groundwater flow systems, A case of nitrate removal by oxidation of pyrite, *Water Resour. Res.*, v. 28, p. 2829-2843, 1992.
- Ennis-King, J., and Paterson, L., Role of convective mixing of the long-term storage of carbon dioxide in deep saline formations, Paper SPE 84344, Presented at Society of Petroleum Engineers Annual Fall Technical Conference and Exhibition, Denver, CO, October 2003.
- Fernández, R., Cuevas, J., Sánchez, L., de la Villa, R.V., Leguey, S., Reactivity of the cement-bentonite interface with alkaline solutions using transport cells, *Appl. Geochem.*, v. 21, p. 977–992, 2006.
- Finsterle, S., E.L. Sonnenthal, and N. Spycher, 2014. *Advances in subsurface modeling using the TOUGH suite of simulators*. Computers & Geosciences, 65:2-12.
- Gaines, G.L. and Thomas, H.C., Adsorption studies on clay minerals. II. A formulation of thermodynamics of exchange adsorption. *Journal of Chemical Physics*, 21, 714-718, 1953.
- Gapon, E.N., On the theory of exchange adsorption in soils. *J. Gen. Chem. USSR* 3: 144-152, 1933 (Chem. Abstr., 28: 4516, 1934)
- García, J.E. Density of Aqueous Solutions of CO<sub>2</sub>, Lawrence Berkeley National Laboratory Report LBNL-49023, Berkeley, CA, 2001.
- Gérard, F., Xu, T., Brimhall, G., and Pruess, K., Modeling reactive chemical transport problems with the codes EQ3/6 and TRANQUI: Lawrence Berkeley Laboratory Report LBL-40505, Berkeley, California, 1997.
- Gherardi, F., Xu, T., and Pruess, K., Numerical modeling of self-limiting and self-enhancing caprock alteration induced by CO<sub>2</sub> storage in a depleted gas reservoir. *Chemical Geology*, 244, (1–2), 103–129, 2007.
- Gu, C., F. Maggi, W. J. Riley, G. M. Hornberger, T. Xu, C. M. Oldenburg, N. Spycher, N. L. Miller, R. T. Venterea, and C. I. Steefel, Aqueous and Gaseous Nitrogen Losses Induced by Fertilizer Application, *J. Geophys. Res.*, doi:10.1029/2008JG000788, 2008.
- Gunnarsson, I. and Arnórsson, S., Amorphous Silica Solubility and the Thermodynamic Properties of H<sub>4</sub>SiO<sub>4</sub> in the Range of 0° to 350°C at P<sub>sat</sub>, *Geochim. Cosmochim. Acta*, v. 64, p. 2295-2307, 2000.
- Gunter W. D., Perkins, E. H., and McCann, T. J., Aquifer disposal of CO<sub>2</sub>-rich gases: Reaction design for added capacity. *Energy Convers. Mgmt.*, v. 34, p. 941-948, 1993.
- Gunter W. D., Bachu, S., Law, D. H. S., Marwaha, V., Drysdale, D. L., MacDonald, D. E., and McCann, T. J., Technical and economic feasibility of CO<sub>2</sub> disposal in aquifers within the Alberta Sedimentary Basin, Canada, *Energy Convers. Mgmt.* v. 37, p. 1135-1142, 1996.
- Gunter W. D., Wiwchar, B., and Perkins, E. H., Aquifer disposal of CO<sub>2</sub>-rich greenhouse gases: extension of the time scale of experiment for CO<sub>2</sub>-sequestering reactions by geochemical modeling, *Mineral. and Petrol.*, v. 59, p. 121-140, 1997.
- Gwo, J. P., Jardine, P. M., Wilson, G. V., and Yeh, G. T., Using a multiregion model to study the effects of advective and diffusive mass transfer on local physical nonequilibrium and solute mobility in a structured soil, *Water Resour. Res.*, v. 32, p. 561-570, 1996.
- Helgeson, H. C., Thermodynamics of hydrothermal systems at elevated temperatures and pressures. *Am.J.Sci.* 267, 729-804, 1969.

- Helgeson, H. C., Kirkham, D. H., Flowers, D. C., Theoretical prediction of the thermodynamic behavior of aqueous electrolytes at high pressures and temperatures: IV. Calculation of activity coefficients, osmotic coefficients, and apparent molal and standard and relative partial molal properties to 600 C and 5 kb. *Am. J. Sci.*, v. 281, p. 1249–1516, 1981.
- Hellmann, R., Tisserand, D., Dissolution kinetics as a function of the Gibbs free energy of reaction: An experimental study based on albite feldspar. *Geochimica et Cosmochimica Acta*, 70, 364-383, 2006.
- Hitchon, B. (ed.), *Aquifer Disposal of Carbon Dioxide*, Geoscience Publishing, Ltd., Sherwood Park, Alberta, Canada, 1996.
- Horowitz, A.J., Elrick, K.A., Robbins, J.A., and Cook, R.B., Effect of mining and related activities on sediment trace element geochemistry of Lake Coeur D'Alene, Idaho, USA Part II. Subsurface sediments: *Hydrol. Process.* 9, 35-54, 1995.
- Javandel, J., Doughty, C., and Tsang, C. F., *Groundwater transport: Handbook of mathematical models*, American Geophysical Union, Washington D. C., pp. 228, 1984.
- JNC, H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, TN1410 2000-001, JNC, Tokai-mura, Japan, 2000.
- Johnson, J. W., Oelkers, E. H., and Helgeson, H. C., SUPCRT92: A software package for calculating the standard molal thermodynamic properties of minerals, gases, aqueous species, and reactions from 1 to 5000 bars and 0 to 1000 degrees C: *Computers and Geosciences*, v. 18, p. 899–948, 1992.
- Johnson, J. W., Nitao, J. J., Steefel, C. I., and Knaus, K. G., Reactive transport modeling of geologic CO<sub>2</sub> sequestration in saline aquifers: The influence of intra-aquifer shales and the relative effectiveness of structural, solubility, and mineral trapping during prograde and retrograde sequestration, In proceedings: First National Conference on Carbon Sequestration, Washington, DC, May 14-17, 2001.
- Kuwabara, J.S., Carter, J.L., Topping, B.R., Fend, S.B., Importance of sediment–water interactions in Coeur d'Alene Lake, Idaho, USA: management implications. *Environ. Manage.* 32, 348–359, 2003.
- Korbol, R., and Kaddour, A., Sleipner vest CO<sub>2</sub> disposal - injection of removed CO<sub>2</sub> into the Utsira Formation, *Energy Convers. Mgmt.*, v. 36(6-9), p. 509-512, 1995.
- Langmuir, D., *Aqueous Environmental Geochemistry*, Prentice Hall, Upper Saddle River, New Jersey, 600pp, 1997.
- Lagneau, V., Influence des processus géochimiques sur le transport en milieu poreux; Application au colmatage de barrières de confinement potentielles dans un stockage en formation géologique. Thèse, CEA, 2002.
- Lasaga, A. C., Chemical kinetics of water-rock interactions, *J. Geophys. Res.*, v. 89, p. 4009-4025, 1984.
- Lasaga, A. C., Soler, J. M., Ganor, J., Burch, T. E., Nagy, K. L., Chemical weathering rate laws and global geochemical cycles. *Geochim. Cosmochim. Acta*, v. 58, p. 2361-2386, 1994.
- Lasaga, A. C., *Kinetic Theory in the Earth Sciences*, Princeton University Press, Princeton, New Jersey, 811pp., 1998.
- Lasaga, A.C., and A. Lutge. 2001. Variation of crystal dissolution rate based on a dissolution stepwave model. *Science* (Washington, DC) 291, 2400-2404.
- Law, D.H.-S., Bachu S., Hydrogeological and numerical analysis of CO<sub>2</sub> disposal in deep aquifers in the Alberta sedimentary basin. *Energy Conversion and Management*, 37, (6–8), 1167–1174, 1996.
- Lichtner, P. C., The quasi-stationary state approximation to coupled mass transport and fluid-rock interaction in a porous medium, *Geochim. Cosmochim. Acta*, v. 52, p. 143-165, 1988.

- Lichtner, P. C., Continuum formulation of multicomponent-multiphase reactive transport, in Lichtner, P. C., Steefel, C. I., and Oelkers, E. H. (eds.), *Reactive transport in porous media*, Reviews in Mineralogy, Mineral Society of America, v. 34, p. 1-79, 1996.
- Liger, E., Charlet L., Van Cappellen, P., Surface catalysis of U(VI) reduction by Fe(II). *Geochim. Cosmochim. Acta*, 63, 2939–2955, 1999.
- Liu, H. H.; Doughty, C.; and Bodvarsson, G. S. An Active Fracture Model for Unsaturated Flow and Transport in Fractured Rocks. *Water Resour. Res.*, v. 34, p. 2633-2646, 1998.
- Lohuis, J. A. O., Carbon dioxide disposal and sustainable development in The Netherlands, *Energy Convers. Mgmt.*, v. 34(9-11), p. 815-821, 1993.
- Maggi, F., C. Gu, W. J. Riley, G.M. Hornberger, R.T. Venterea, T. Xu, N. Spycher, C.I. Steefel, and N.L. Miller, Mechanistic modeling of biogeochemical nitrogen cycling: model development and application in an agricultural system, *J. Geophys. Res. (Biogeosciences)*, *J. Geophys. Res.*, 113, doi:10.1029/2007JG000578, 2008.
- Marshall, B. D., Paces, J. B., Neymark, L. A., Whelan, J. F., and Peterman, Z. E., Secondary minerals record past percolation flux at Yucca Mountain, Nevada, In: Proceedings of the 8th International High-level Radioactive Waste Management Conference, May 11-14, Las Vegas, Nevada, USA, 1998.
- Marshall, B. D., Neymark, L. A., Paces, J. B., Peterman, Z. E., Whelan, J. F., Seepage flux conceptualized from secondary calcite in lithophysal cavities in the Topopah Spring Tuff, Yucca Mountain, Nevada. The society for Mining, Metallurgy, and Exploration, Inc. Annual Meeting 2000, USGS, Denver, Colorado, 1999.
- McPherson, B. J. O. L., and P. C. Lichtner, CO<sub>2</sub> sequestration in deep aquifers, In proceedings: First National Conference on Carbon Sequestration, Washington, DC, May 14-17, 2001.
- Millington, R. J., and Quirk, J. P., Permeability of porous solids, *Trans. Faraday Soc.*, v. 57, p. 1200-1207, 1961.
- Moberly J.G., Borch T., Sani R.K, Spycher N.F., Sengor S., Ginn T.R., Peyton B., 2009. Heavy metal–mineral associations in Coeur d’Alene River sediments: a synchrotron-based analysis. *Water, Air, Soil Pollut.*, 201, 195–208.
- Montazer, P. and Wilson, W. E., Conceptual hydrologic model of flow in the unsaturated zone, Yucca Mountain, Nevada, Water Resources Investigations Report 84-4355, USGS, Denver, Colorado, 1984.
- Moore, D. E., Morrow, C. A., and Byerlee, J. D., Chemical reactions accompanying fluid flow through granite held in a temperature gradient. *Geochim. Cosmochim. Acta*, v. 47, p. 445-453, 1983.
- Moridis, G., and Pruess, K., T2SOLV: An enhanced package of solvers for the TOUGH2 family of reservoir simulation codes, *Geothermics*, v. 27, p. 415-444, 1998.
- Mote T. I., Brimhall, G. H., Tidy-Finch, E., Muller, G., and Carrasco, P., Application of mass-balance modeling of sources, pathways, and sinks of supergene enrichment to exploration and discovery of the Quebrada Turquesa Exotic Copper Orebody, El Salvador District, Chile, *Economic Geology & the Bulletin of the Society of Economic Geologists*, v. 96 (No. 2), p. 367-386, 2001.
- Mukhopadhyay, S., Sonnenthal, E., and Spycher, N., Modeling of coupled heat transfer and reactive transport processes in porous media: Application to seepage studies at Yucca Mountain, Nevada. *Journal of Porous Media*, v. 12, p. 725-748, 2009.
- Mualem, Y., A new model for predicting the hydraulic conductivity of unsaturated porous media, *Water Resour. Res.*, v. 12, p. 513–522, 1976.

- Nagy, K. L., Dissolution and precipitation kinetics of sheet silicates, *Chemical Weathering Rates of Silicate Minerals*, v. 31, p. 291–351, 1995.
- NAGRA, Project Opalinus Clay: Safety Report. Demonstration of Disposal Feasibility (Entsorgungsnachweis) for Spent Fuel, Vitriified High-Level Waste and Long-Lived Intermediate-Level Waste, NAGRA Technical Report NTB 02-05, NAGRA, Wettingen, Switzerland, 2002.
- Narasimhan, T. N., and Witherspoon, P. A., An integrated finite difference method for analyzing fluid flow in porous media, *Water Resour. Res.*, v. 12, p. 57–64, 1976.
- Neymark, L. A., Amelin, Y. V., Paces, J. B., Peterman, Z. E., Whelan, J. F., Age constraints on fluid inclusions in calcite at Yucca Mountain, In: Proceedings of the 9th International High-level Radioactive Waste Management Conference, Las Vegas, Nevada, USA, April 29-May 3, 2001.
- Nordstrom, D. K., and Muñoz, J. L., *Geochemical Thermodynamics*, The Benjamin/Cummings Pub. Co., Menlo Park, California, 477 pp., 1986.
- Nordstrom, D. K., and Alpers, C. N., *The Environmental geochemistry of mineral deposits. Part A. Processes, methods and health Issues*. (Plumlee, G. S., Logsdon, M. J. (Eds) ), Reviews in Economic Geology, v. 6, Society of Economic Geologists, 1997.
- Oldenburg C. M., and Pruess, K., EOS7R: Radionuclide transport for TOUGH2, Lawrence Berkeley National Laboratory Report LBNL-34868, Berkeley, California, 1995.
- Olson, G. J., Rate of pyrite bioleaching by *Thiobacillus ferrooxidans* - Results of an interlaboratory comparison, *Applied and Environmental Microbiology*, v. 57, p. 642-644, 1991.
- Ontoy, Y., Molling, P. L., Xu, T., Spycher, N., Parini, M. and Pruess, K., Scaling of hot brine injection wells: supplementing field studies with reactive transport modeling. In *Proceedings of TOUGH Symposium 2003*, Lawrence Berkeley National Laboratory, Berkeley, California, May 12–14, 2003.
- Paces, J. B., Marshall, B. D., Whelan, J. F., Neymark, L. A., Peterman, Z. E., Summary of subsurface calcite and opal deposits and estimates of the probable distribution and isotopic compositions of hydrogenic minerals along the East-West Cross Drift, Yucca Mountain, Nevada. U.S. Geol. Surv. Open File Rep., Denver, Colorado, 1998.
- Paces, J. B., Neymark, L. A., Marshall, B. D., Whelan, J. F., Peterman, Z. E., Ages and origin of calcite and opal in the Exploratory Studies Facilities tunnel, Yucca Mountain, Nevada. U.S. Geol. Investigations Report, Denver, Colorado, 2001.
- Palandri, J., and Kharaka, Y. K., A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling, US Geol. Surv. Open File Report 2004-1068, 64 pp., 2004.
- Pape, H., Clauser C., and Iffland J., Permeability prediction based on fractural pore-space geometry, *Geophysics*, v. 64(5), p. 1447-1460, 1999.
- Parks, G. A., Surface energy and absorption at mineral-water interfaces: an introduction, *Review of Mineralogy*, v. 23 (Miner.-Water Interface Geochem.), p. 133-75, 1990.
- Parkhurst, D. L., Thorstenson, D. C., and Plummer, L. N., PHREEQE: A computer program for geochemical calculations, US Geol. Surv. Water Resour. Invest. 80-96, 174 pp., 1980.
- Parkhurst, D.L., Appelo, C.A.J., 1999. User's Guide to PHREEQC (Version 2) – a computer program for speciation, batch reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geol. Surv. Water-Resour. Investig. Rep. 99-4259, Denver, CO.
- Peiffer, L., C. Wanner, N. Spycher, E.L. Sonnenthal, B.M. Kennedy, and J. Iovenitti, 2014. *Multicomponent vs. classical geothermometry: insights from modeling studies at the Dixie Valley geothermal area*. *Geothermics*, 51:154–169.

- Perkins, E. H., and Gunter, W. D., Mineral Traps for Carbon Dioxide, in: Hitchon, B. (ed.), *Aquifer Disposal of Carbon Dioxide*, Geoscience Publishing, Ltd., Alberta, Canada, p. 93-113, 1996.
- Pruess, K., and Karasaki, K., Proximity functions for modeling fluid and heat flow in reservoirs with stochastic fracture distributions, in *Proceedings, Eighth workshop on geothermal reservoir engineering*: p. 219-224, Stanford University, Stanford, California, 1982.
- Pruess, K., and Narasimhan, T. N., A practical method for modeling fluid and heat flow in fractured porous media: *Society of Petroleum Engineers Journal*, v. 25, p. 14-26, 1985.
- Pruess, K., TOUGH user's guide, Nuclear Regulatory Commission, report NUREG/CR-4645 (also Lawrence Berkeley Laboratory Report LBL-20700, Berkeley, California), 1987.
- Pruess, K., TOUGH2: A general numerical simulator for multiphase fluid and heat flow, Lawrence Berkeley Laboratory Report LBL-29400, Berkeley, California, 1991.
- Pruess, K., Oldenburg, C., and Moridis, G., TOUGH2 user's guide, Version 2.0, Lawrence Berkeley Laboratory Report LBL-43134, Berkeley, California, 1999.
- Pruess, K., and García, J., Multiphase flow dynamics during CO<sub>2</sub> disposal into saline aquifers, *Environmental Geology*, v. 42, p. 282-295, 2002.
- Pruess, K., Xu, T., Apps, J., and García, J., Numerical modeling of aquifer disposal of CO<sub>2</sub>, Paper SPE-83695, *SPE Journal*, p. 49-60, 2003.
- Pruess, K., ECO2N: A TOUGH2 Fluid Property Module for Mixtures of Water, NaCl, and CO<sub>2</sub>, Lawrence Berkeley National Laboratory Report LBNL-57592, Berkeley, California, 2005.
- Raffensperger, J. P., Numerical simulation of sedimentary basin-scale hydrochemical processes, In *Advances in Porous Media*, Corapcioglu, Y. C., (ed.), Amsterdam, The Netherlands, Elsevier Science, 440 pp., 1996.
- Reed, M. H., Calculation of multicomponent chemical equilibria and reaction processes in systems involving minerals, gases and aqueous phase, *Geochim. Cosmochim. Acta*, v. 46, p. 513-528, 1982.
- Reed M.H., 1998. Calculation of simultaneous chemical equilibria in aqueous-mineral-gas systems and its application to modeling hydrothermal processes. In: *Techniques in Hydrothermal Ore Deposits Geology*, Reviews in Economic Geology, Volume 10. Richards J, Larson P (eds), 109–124.
- Richards, L. A., Capillary conduction of liquids through porous mediums, *Physics*, v. 1, p. 318-333, 1931.
- Rickard, D., Kinetics of FeS precipitation: Par 1. Competing reaction mechanisms. *Geochim. Cosmochim. Acta* 59, 4367–4379, 1995.
- Rimstidt, J. D. and Barnes, H. L., The kinetics of silica–water reactions, *Geochim. Cosmochim. Acta*, v. 44, p. 1683-1699, 1980.
- Robinson, R. A., and Stokes, R. H., *Electrolyte Solutions, the Measurement and Interpretation of Conductance, Chemical Potential and Diffusion in Solutions of Simple Electrolytes*, 2<sup>nd</sup> Edition, London, England: Butterworths & Company, 1965.
- Senger, R., T. Xu, P. Marschall, and S. Finsterle, Modeling approaches of two-phase flow phenomena associated with corrosion of SF/HLW canisters in a proposed repository in Opalinus clay, Switzerland, *Physics and Chemistry of the Earth*, v. 33, S317–S326, 2008.
- Senger, R., Ewing, J., Evolution of temperature and water content in the bentonite buffer: Detailed modelling of two-phase flow processes associated with the early closure period – complementary simulations. Report NAB 08-53 for NAGRA, INTERA Inc., Austin, Texas 78758, 2008.

- Sengör, S.S., Spycher N., Ginn T.R., Sani R.K., Peyton B., Biogeochemical reactive-diffusive transport of heavy metals in Lake Coeur d'Alene sediments, *Applied Geochemistry*, 22, 2569-2594, 2007a.
- Sengör, S.S., Spycher, N.F., Ginn, T.R., Moberly, J., Peyton, B., & Sani, R.K., Reductive dissolution and metal transport in Lake Coeur d'Alene sediments. In *Water-Rock Interaction, WRI-12* (Bullen T. and Wang Y., eds.), Taylor & Francis, New York, Vol. 2, 895-899, 2007b.
- Shock, E. L., Helgeson, H. C., and Sverjensky, D. A., Calculation of the thermodynamic and transport properties of aqueous species at high pressures and temperatures: Standard partial molal properties of inorganic neutral species, *Geochim. Cosmochim. Acta*, v. 53 (9), p. 2157-2183, 1989.
- Simunek, J., and Suarez, D. L., Two-dimensional transport model for variably saturated porous media with major ion chemistry, *Water Resour. Res.*, v. 30, p. 1115-1133, 1994.
- Singer, P. C., and Stumm, W., Acid mine drainage - The rate determining step: *Science*, v. 167, p. 1121-1123, 1970.
- Singleton, M.J., E.L. Sonnenthal, M.E. Conrad, D.J. DePaolo, and G.W. Gee, 2004. Multiphase reactive transport modeling of stable isotope fractionation in unsaturated zone pore water and vapor: Application to seasonal infiltration events at the Hanford Site, WA. *Vadose Zone Journal*, 3: 775-785.
- Slider, H. C., Practical petroleum reservoir engineering methods, An Energy Conservation *Science*. Tulsa, Oklahoma, Petroleum Publishing Company, 1976.
- Sonnenthal, E. L., and Bodvarsson, G. S., Percolation flux estimates from geochemical and thermal modeling. Proceedings of the Eighth International Conference on High-Level Radioactive Waste Management, American Nuclear Society, p. 130-132, 1998.
- Sonnenthal, E. L., Bodvarsson, G. S. Constraints on the hydrology of the unsaturated zone at Yucca Mountain, NV from three-dimensional models of chloride and strontium geochemistry. *J. Contam. Hydrol.*, v. 38, p. 107-156, 1999.
- Sonnenthal, E., A. Ito, N. Spycher, M. Yui, J. Apps, Y. Sugita, M. Conrad, and S. Kawakami, Approaches to modeling coupled thermal, hydrological, and chemical processes in the Drift Scale Heater Test at Yucca Mountain, *International Journal of Rock Mechanics and Mining Sciences*, v. 42, p. 698-719, 2005.
- Sonnenthal, E.L. and A.R. McBirney, 1998. *The Skaergaard Layered Series. Part IV. Reaction-transport simulations of foundered blocks*. *Journal of Petrology*, 39(4): 633-661.
- Sonnenthal, E. and Ortoleva, P. J., Numerical simulations of overpressured compartments in sedimentary Basins, *Basin Compartments and Seals*. Ortoleva, P.J., ed., AAPG Memoir v. 61, p. 403-416, Tulsa, Oklahoma, American Association of Petroleum Geologists, 1994.
- Sonnenthal, E., Spycher, N., Apps, J. A., and Simmons, A., 1998, Thermo-hydro-chemical predictive analysis for the Drift-Scale Heater Test, Yucca Mountain Project Level 4 Milestone SPY289M4, Lawrence Berkeley National Laboratory, Berkeley, California, 1998.
- Sonnenthal, E. L., Spycher, N., Drift-Scale coupled processes (DST and THC seepage) models. AMR N0120/U0110 Rev.01, Yucca Mountain Project, Lawrence Berkeley National Laboratory, Berkeley, California, 2001.
- Sonnenthal, E. L., Spycher, N., Callahan, O., Cladouhos, T., Petty, S., 2012. *A thermal-hydrological-chemical model for the enhanced geothermal system demonstration project at Newberry Volcano, Oregon*. Proceedings, Thirty-Seventh Workshop on geothermal reservoir engineering, Stanford University, Stanford, Ca, January 30 - February 1. SGP-TR-194.
- Sonnenthal, E.L., N.F. Spycher, M. Conrad, and J. Apps, 2004. *A conceptual and numerical model for thermal-hydrological –chemical processes in the Yucca Mountain Drift Scale Test*. In: Stephansson, O.,

J.A. Hudson, and L. Jing, ed., Coupled Thermo-Hydro-Mechanical-Chemical Processes in Geo-Systems, Fundamentals, Modelling, Experiments and Applications. Elsevier Geo-Engineering Book Series, volume 2, p. 347-352.

Sonnenthal, E., N. Spycher, and T. Xu, 2003. Linking reaction, transport, and hydrological parameters in unsaturated fractured rock: TOUGHREACT implementation and application. Proceedings, TOUGH Symposium, 2003.

Sonnenthal, E., T. Xu, and G. Bodvarsson, Reply to “Commentary: Assessment of past infiltration fluxes through Yucca Mountain on the basis of the secondary mineral record – is it a viable methodology?”, by Y.V. Dublyansky and S.Z. Smirnov, *Journal of Contaminant Hydrology*, v. 77, p. 225-231, 2005.

Spycher, N. F., and Reed, M. H., Fugacity coefficients of H<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O and of H<sub>2</sub>O-CO<sub>2</sub>-CH<sub>4</sub> mixtures: A virial equation treatment for moderate pressures and temperatures applicable to calculations of hydrothermal boiling, *Geochim. Cosmochim. Acta*, v. 52, p. 739-749, 1988.

Spycher N. F., Sonnenthal, E. L., and Apps, J. A., Fluid flow and reactive transport around potential nuclear waste emplacement tunnels at Yucca Mountain, Nevada, *J. Contam. Hydrol.*, v.62-63, p. 653-673, 2003a.

Spycher, N., Sonnenthal, E. L., Dobson, P. F., Kneafsey, T., and Salah, S., Drift-scale coupled processes (DST and THC seepage) models, MDL-NBS-HS-000001 REV02, BSC: Las Vegas, NV, Report number LBID-2478, Lawrence Berkeley National Laboratory, Berkeley, California, 2003b.

Spycher, N., and Pruess, K., CO<sub>2</sub>-H<sub>2</sub>O mixtures in the geological sequestration of CO<sub>2</sub>: II. Partitioning in chloride brines at 12–100°C and up to 600 bar, *Geochimica et Cosmochimica Acta*, v. 69, p. 3309-3320, 2005.

Spycher, N., Zhang, G., Sengor, S., Issarangkun, M., Barkouki, T., Ginn, T., Wu, Y., Smith, R., Hubbard, S., Fujita, Y., Sani, R., and Peyton, K., Application of TOUGHREACT V2.0 to environmental systems, In Proceedings of TOUGH Symposium 2009 Lawrence Berkeley National Laboratory, Berkeley, California, September 14-16, 2009.

Steefel, C. I., and van Cappellen, P., A new kinetic approach to modeling water-rock interaction: The role of nucleation, precursors and Ostwald ripening, *Geochim. Cosmochim. Acta*, v. 54, p. 2657-2677, 1990.

Steefel, C. I., and Lasaga, A. C., A coupled model for transport of multiple chemical species and kinetic precipitation/dissolution reactions with applications to reactive flow in single phase hydrothermal system, *Am. J. Sci.*, v. 294, p. 529-592, 1994.

Steefel, C. I., and MacQuarrie, K. T. B., Approaches to modeling of reactive transport in porous media, In Lichtner, P. C., Steefel, C. I., and Oelkers, E. H. (eds.), *Reactive transport in porous media*, Reviews in Mineralogy, Mineral Society of America, v. 34, p. 83-129, 1996.

Steefel, C. I., CRUNCH, Lawrence Livermore National Laboratory, pp. 76, 2001.

Stumm, W., and Morgan, J. J., *Aquatic chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters*, John Wiley & Sons, New York, 780 pp., 1981.

Toevs, G.R., Morra, M.J., Polizzotto, M.L., Strawn, D.G., Bostick, B.C., Fendorf, S., Metal(loid) diagenesis in mine-impacted sediments of Lake Coeur d’Alene, Idaho. *Environ. Sci. Technol.* 40, 2537–2543, 2006.

Todaka, N., C. Akasaka, T. Xu and K. Pruess. Reactive geothermal transport simulation to study the formation mechanism of impermeable barrier between acidic and neutral fluid zones in the Onikobe geothermal field, Japan, *J. Geophys. Res. Solid Earth*, Vol. 109(B5):5209, doi: 10.1029/2003JB002792, 2004.



Van Cappellen, P., Gaillard, P., Biogeochemical dynamics in aquatic sediments. In: Lichtner, P.C., Steefel, C.I., Oelkers, E.H. (Eds.), *Reactive Transport in Porous Media*, vol. 34. Mineralogical Society of America, pp. 335–376 (Chapter 8), 1996.

Vanselow, A.P. 1932. Equilibria of the base-exchange reactions of bentonites, permutites, soil colloids, and zeolites. *Soil Sci.* 33: 95-113.

Van Genuchten, M. T., A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.*, v. 44, p. 892-898, 1980.

Vaniman, D. T., Chipera, S. J., Paleotransport of lanthanides and strontium recorded in calcite compositions from tuffs at Yucca Mountain, Nevada, USA. *Geochim. Cosmochim. Acta*, v.60(22), p.4417-4433, 1996.

Vaniman, D. T., Chipera, S. J., Bish, D. L., Carey, J. W., and Levy, S. S., Quantification of unsaturated-zone alteration and cation exchange in zeolitized tuffs at Yucca Mountain, Nevada, USA. *Geochim. Cosmochim. Acta*, v. 65(20), p. 3409-3433, 2001.

Vaughan, P. J., Analysis of permeability reduction during flow of heated, aqueous fluid through Westerly Granite, in C.F. Tsang (ed.), *Coupled processes associated with nuclear waste repositories*, pp. 529-539, Academic Press, New York, 1987.

Verma, A., and Pruess, K., Thermohydrological conditions and silica redistribution near high-level nuclear wastes emplaced in saturated geological formations, *J. Geophys. Res.*, v. 93, p. 1159-1173, 1988.

Vinsome, P. K. W. and Westerveld, J., A simple method for predicting cap and base rock heat losses in thermal reservoir simulators, *J. Canadian Pet. Tech.*, v. 19 (3), p. 87–90, 1980.

von Gunten, U. and Zobrist, J., Biogeochemical changes in groundwater infiltration systems: column studies, *Geochim. Cosmochim. Acta*, v. 57, p. 3895-3906, 1993.

Walter, A. L., Frind, E. O., Blowes, D. W., Ptacek, C. J., and Molson, J. W., Modeling of multicomponent reactive transport in groundwater: 1, Model development and evaluation, *Water Resour. Res.*, v. 30, p. 3137-3148, 1994.

Wanner, C., L. Peiffer, E. Sonnenthal, N. Spycher, J. Iovenitti, and B.M. Kennedy, 2014. *Reactive transport modeling of the Dixie Valley geothermal area: Insights on flow and geothermometry*. *Geothermics*, 51:130-141.

Wanner C. and E.L. Sonnenthal. *Assessing the control on the effective kinetic Cr isotope fractionation factor: A reactive transport modeling approach*, 2013. *Chemical Geology*, 337-338: 88-98.

Weir, G. J., White, S. P., and Kissling, W. M., Reservoir Storage and Containment of Greenhouse Gases, in: K. Pruess (ed.), *Proceedings of the TOUGH Workshop '95*, Lawrence Berkeley National Laboratory Report LBL-37200, p. 233-238, Berkeley, CA, 1995.

White, S. P., Multiphase non-isothermal transport of systems of reacting chemicals, *Water Resour. Res.*, v. 31, p. 1761-1772, 1995.

Winowiecki, L., 2002. Geochemical cycling of heavy metals in the sediment of Lake Coeur d'Alene, Idaho. Masters Thesis, University of Idaho, Moscow, Idaho.

Wolery, T. J., EQ3/6: Software package for geochemical modeling of aqueous systems: Package overview and installation guide (version 8.0), Lawrence Livermore National Laboratory Report UCRL-MA-110662 PT I, Livermore, California, 1992.

Wu, Y.-S., and Mishra, A.,K., Modifications and additions to the selected TOUGH2 modules. Lawrence Berkeley National Laboratory Report LBNL-41870, Berkeley, California, 58 pp., 1998.

- Wu, Y.-S., Haukwa, C., and Mukhopadhyay, S., TOUGH2 V1.4 and T2R3D V1.4: Verification and Validation Report, Rev.00, Revised 10/11/99, 1999. MOL.20000216.0111.
- Xu, T., and Pruess, K., Coupled modeling of non-isothermal multiphase flow, solute transport and reactive chemistry in porous and fractured media: 1. Model development and validation, Lawrence Berkeley National Laboratory Report LBNL-42050, Berkeley, California, 38 pp., 1998.
- Xu, T., Samper, J., Ayora, C., Manzano, M., and Custodio, E., Modeling of non-isothermal multi-component reactive transport in field-scale porous media flow system, *J. Hydrol.*, v. 214, p. 144-164, 1999a.
- Xu, T., Pruess, K., and Brimhall, G., An improved equilibrium-kinetics speciation algorithm for redox reactions in variably saturated flow systems, *Computers & Geosciences*, v. 25, p. 655-666, 1999b.
- Xu, T., White, S. P., Pruess, K., Brimhall, G. H., and Apps, J., Modeling of pyrite oxidation in saturated and unsaturated subsurface flow systems, *Transport in Porous Media*, v. 39, p. 25-56, 2000.
- Xu, T., and Pruess, K., On fluid flow and mineral alteration in fractured caprock of magmatic hydrothermal systems, *J. Geophys. Res.*, v. 106, p. 2121-2138, 2001a.
- Xu, T., and Pruess, K., Modeling multiphase fluid flow and reactive geochemical transport in variably saturated fractured rocks: 1. Methodology, *Am. J. Sci.*, v. 301, p. 16-33, 2001b.
- Xu, T., Sonnenthal, E., Spycher, N., Pruess, K., Brimhall, G., Apps, J., Modeling multiphase fluid flow and reactive geochemical transport in variably saturated fractured rocks: 2. Applications to supergene copper enrichment and hydrothermal flows, *Am. J. Sci.*, v. 301, p. 34-59, 2001.
- Xu, T., Sonnenthal, E., and Bodvarsson G., A reaction-transport model for calcite precipitation and evaluation of infiltration-percolation fluxes in unsaturated fractured rock, *J. Contam. Hydrol.*, v. 64(1-2) p. 113 - 127, 2003a.
- Xu, T., Apps, J. A., and Pruess, K., Reactive geochemical transport simulation to study mineral trapping for CO<sub>2</sub> disposal in deep arenaceous formations, *J. Geophys. Res.*, v. 108 (B2), 2071, doi:10.1029/2002JB001979, 2003b.
- Xu, T., Apps, J. A., and Pruess, K., Numerical simulation of CO<sub>2</sub> disposal by mineral trapping in deep aquifers, *Applied Geochemistry*, v. 19, p. 917-936, 2004a.
- Xu, T., Ontoy, Y., Molling, P., Spycher, N., Parini, M., and Pruess, K., Reactive transport modeling of injection well scaling and acidizing at Tiwi Field Philippines, *Geothermics*, v. 33(4), p. 477-491, 2004b.
- Xu, T., E.L. Sonnenthal, N. Spycher, and K. Pruess, TOUGHREACT - A simulation program for non-isothermal multiphase reactive geochemical transport in variably saturated geologic media: Applications to geothermal injectivity and CO<sub>2</sub> geological sequestration, *Computer & Geoscience*, v. 32/2 p. 145-165, 2006.
- Xu, T., J. A. Apps, K. Pruess, and H. Yamamoto, Numerical modeling of injection and mineral trapping of CO<sub>2</sub> with H<sub>2</sub>S and SO<sub>2</sub> in a sandstone formation, *Chemical Geology*, v. 242/3-4, p. 319-346, 2007.
- Xu, T., Incorporation of aqueous reaction kinetics and biodegradation into TOUGHREACT: Application of a multi-region model to hydrobiogeochemical transport of denitrification and sulfate reduction, *Vadose Zone Journal*, v. 2008-7, p. 305-315, 2008.
- Xu, T., R. Senger, and S. Finsterle, Corrosion-induced gas generation in a nuclear waste repository: Reactive geochemistry and multiphase flow effects, *Appl. Geochem.*, v. 23, 3423-3433, 2008.
- Xu, T., Rose, P., Fayer, S., Pruess, On modeling of chemical stimulation of an enhanced geothermal system using a high pH solution with chelating agent. *Geofluid*, v. 9, p. 167-177, 2009a.

Xu, T., Sonnenthal, E., Spycher, N., Zhang, G., Zheng, L., and Pruess, K., TOUGHREACT Version 2.0, In Proceedings of TOUGH Symposium 2009 Lawrence Berkeley National Laboratory, Berkeley, California, September 14-16, 2009b.

Xu, T., Spycher N., Sonnenthal E., Zhang G., Zheng L. and Pruess, K., TOUGHREACT Version 2.0: A simulator for subsurface reactive transport under non-isothermal multiphase flow conditions, *Computers & Geosciences* 37, 763–774, 2011.

Xu, T., Senger, R., and Finsterle, S., Bentonite alteration due to thermal-hydro-chemical processes during the early thermal period in a nuclear waste repository, *Nuclear Technology*, v.174, p. 438-451, 2011.

Yeh, G. T., and Tripathi, V. S., A model for simulating transport of reactive multispecies components: model development and demonstration, *Water Resour. Res.*, v. 27, p. 3075-3094, 1991.

Zhang, W., Li, Y., Xu, T., Cheng, H., Zheng, Y., and Xiong, P., Long-term variations of CO<sub>2</sub> trapped in different mechanisms in deep saline formations: A case study of the Songliao Basin, China, *Greenhouse Gas Control Technologies*, v3(2), p. 161-180, 2009.

Zheng, L., Apps, J.A., Zhang, Y., Xu, T., and Birkholzer, J., On mobilization of lead and arsenic in groundwater in response to CO<sub>2</sub> leakage from deep geological storage, *Chemical Geology*, v. 268, p. 281-297, 2009.

Zysset, A., Stauffer, E., and Dracos, T., Modelling of reactive groundwater transport governed by biodegradation, *Water Resour. Res.*, v. 30, p. 2423-2434, 1994.

## Appendix A Mathematical Equations for Flow and Transport

All flow and transport equations have the same structure, and can be derived from the principle of mass (or energy) conservation. Table A-1 summarizes these equations and Table A-2 gives the meaning of symbols used. The models for fluid and heat flow are discussed in detail by Pruess (1987 and 1991) and Pruess et al. (1999). Aqueous species are subject to transport in the liquid phase and local chemical interaction with the solid and gaseous phases. Chemical transport equations are written in terms of total dissolved concentrations of chemical components comprised of concentrations of their basis species plus their associated aqueous secondary species (Yeh and Tripathi, 1991; Steefel and Lasaga, 1994; Walter et al., 1994). Transport of total chemical concentrations can be by advection and diffusion. Detailed description of aqueous and gaseous species transport equations are presented in Appendix C.

**Table A-1 Governing equations for fluid and heat flow, and chemical transport, using EOS3 and EOS4 equation-of-state modules for example. Symbol meanings are given in Table 8-2. For EOS2 and ECO2N, component 'Air' in the table should be replaced with "CO<sub>2</sub>". For EOS1, the equation for air is not used. For EOS9 (Richard's equation), equations for air and heat are not used.**

**General governing equations:** 
$$\frac{\partial M_k}{\partial t} = -\nabla F_k + q_k$$

Water: 
$$M_w = \varphi(S_l \rho_l X_{wl} + S_g \rho_g X_{wg}) \quad F_w = X_{wl} \rho_l u_l + X_{wg} \rho_g u_g$$
  

$$q_w = q_{wl} + q_{wg}$$

Air: 
$$M_c = \varphi(S_l \rho_l X_{cl} + S_g \rho_g X_{cg}) \quad F_c = X_{cl} \rho_l u_l + X_{cg} \rho_g u_g \quad q_c = q_{cl} + q_{cg} + q_{cr}$$

Heat: 
$$M_h = \varphi(S_l \rho_l U_l + S_g \rho_g U_g) + (1 - \varphi) \rho_s U_s \quad F_h = \sum_{\beta=l,g} h_\beta \rho_\beta u_\beta - \lambda \nabla T \quad q_h$$

where 
$$u_\beta = -k \frac{k_{r\beta}}{\mu_\beta} (\nabla P_\beta - \rho_\beta g) \quad \beta=l,g \text{ (multiphase Darcy's Law)}$$

**Chemical components in the liquid phase (j=1,2,...,N<sub>l</sub>):**

$$M_j = \varphi S_l C_{jl} \quad F_j = u_l C_{jl} - (\tau \varphi S_l D_l) \nabla C_{jl} \quad q_j = q_{jl} + q_{js} + q_{jg}$$

$$\tau_\beta = \varphi^{1/3} S_\beta^{10/3} \quad \text{(Millington and Quirk, 1961)}$$

**Table A-2 Symbols used in Table A-1.**

<b>C</b>	Component concentration, mol L <sup>-1</sup>	$\rho$	density, kg m <sup>-3</sup>
<b>D</b>	diffusion coefficient, m <sup>2</sup> s <sup>-1</sup>	$\mu$	viscosity, kg m <sup>-1</sup> s <sup>-1</sup>
<b>F</b>	mass flux, kg m <sup>-2</sup> s <sup>-1</sup> (*)	$\lambda$	thermal conductivity, W m <sup>-1</sup> K <sup>-1</sup>
<b>k</b>	permeability, m <sup>2</sup>		
<b>k<sub>r</sub></b>	relative permeability	Subscripts:	
<b>g</b>	gravitational acceleration, m s <sup>-2</sup>	<b>c</b>	air
<b>M</b>	mass accumulation, kg m <sup>-3</sup>	<b>g</b>	gas phase
<b>N</b>	number of chemical components	<b>h</b>	heat
<b>p</b>	pressure, Pa	<b>j</b>	aqueous chemical component
<b>q</b>	source/sink	<b>l</b>	liquid phase
<b>S</b>	saturation	<b>r</b>	reaction
<b>T</b>	temperature, °C	<b>s</b>	solid phase
<b>U</b>	internal energy, J kg <sup>-1</sup>	<b>w</b>	water
<b>u</b>	Darcy velocity, m s <sup>-1</sup>	$\kappa$	governing equation index
<b>X</b>	mass fraction	$\beta$	phase index
$\phi$	porosity	$\tau$	medium tortuosity

(\*) For chemical transport and reaction calculations, molar units are used instead of kg.

The primary governing equations given in Table A-1 must be complemented with constitutive relationships that express all parameters as functions of thermophysical and chemical variables. The expressions for non-isothermal multiphase flow are given by Pruess et al. (1999). The expressions for chemical reactions are given in Appendix B.

## Appendix B Mathematical Formulation of Chemical Reactions

To represent a geochemical system, it is convenient to select a subset of  $N_C$  aqueous species as basis species (or component or primary species). All other species are called secondary species that include aqueous complexes, precipitated (mineral) and gaseous species (Reed, 1982; Yeh and Tripathi, 1991; Steefel and Lasaga, 1994). The number of secondary species must be equal to the number of independent reactions. Any of the secondary species can be represented as a linear combination of the set of basis species such as

$$S_i = \sum_{j=1}^{N_C} v_{ij} S_j \quad i = 1, \dots, N_R \quad (\text{B.1})$$

where S represents chemical species, j is the basis species index, i is the secondary species index,  $N_R$  is the number of reactions (or secondary species), and  $v_{ij}$  is the stoichiometric coefficient of j-th basis species in the i-th reaction.

## B.1 Kinetic reactions among primary species

---

These type of reactions include aqueous and sorption reaction kinetics and biodegradation. A general-rate law is used,

$$r_i = \sum_{s=1}^M \left[ \begin{array}{l} k_{i,s} \quad \text{rate constant} \\ \times \prod_{j=1}^{N_l} (\gamma_j^{v_{i,j}} C_j^{v_{i,j}}) \quad \text{product terms} \\ \times \prod_{k=1}^{N_m} \frac{C_{i,k}}{K_{M_i,k} + C_{i,k}} \quad \text{Monod terms} \\ \times \prod_{p=1}^{N_p} \frac{I_{i,p}}{I_{i,p} + C_{i,p}} \quad \text{inhibition terms} \end{array} \right] \quad (\text{B.2})$$

where  $r_i$  is the reaction rate of the i-th reaction, M is the number of mechanisms or pathways and s is the mechanism counter, k is a rate constant, (often denoted  $v_{\max}$ , maximum specific growth constant for biodegradation),  $\gamma_j$  is the activity coefficient of species j,  $C_j$  is the concentration of species j (with biodegradation the product term is usually biomass concentration),  $v_{i,j}$  is a stoichiometric coefficient,  $N_l$  is the number of reacting species in the forward rate term (called product terms),  $N_m$  is the number of Monod factors (Monod terms),  $C_{i,k}$  is the concentration of the k-th Monod species,  $C_{i,p}$  is the concentration of the p-th inhibiting species,  $K_{M_i,k}$  is the k-th Monod half-saturation constant of the i-th species,  $N_p$  is the number of inhibition factors (inhibition terms), and  $I_{i,p}$  is the p-th inhibition constant. Equation (B.2) accounts for multiple mechanisms and multiple products, Monod, and inhibition terms, which can cover many rate expressions (examples of rate expression are given in Samples 9 and 10).

## B.2 Aqueous complexation

---

These reactions are assumed to be at local equilibrium. By making use of the mass action equation to the dissociation of the i-th aqueous complex (Equation B.1), concentrations of aqueous complexes can be expressed as functions of the concentrations of basis species:

$$c_i = K_i^{-1} \gamma_i^{-1} \prod_{j=1}^{N_c} c_j^{v_{ij}} \gamma_j^{v_{ij}} \quad (\text{B.3})$$

where  $c_i$  is molal concentration of the  $i$ -th aqueous complex, and  $c_j$  is molal concentration of the  $j$ -th basis species,  $\gamma_i$  and  $\gamma_j$  are thermodynamic activity coefficients (details on calculation of activity coefficients are given in Appendix H), and  $K_i$  is the equilibrium constant.

### B.3 Equilibrium mineral dissolution/precipitation

---

The mineral saturation ratio can be expressed as

$$\Omega_m = K_m^{-1} \prod_{j=1}^{N_c} c_j^{v_{mj}} \gamma_j^{v_{mj}} \quad m = 1 \dots N_p \quad (\text{B.4})$$

where  $m$  is the equilibrium mineral index, and  $K_m$  is the corresponding equilibrium constant. At equilibrium, we have

$$SI_m = \log_{10} \Omega_m = 0 \quad (\text{B.5})$$

where  $SI_m$  is called the mineral saturation index. The treatment for mineral solid solutions is given in Appendix I.

### B.4 Kinetic mineral dissolution/precipitation

---

Dissolution and/or precipitation of minerals kinetically can be described using some different forms based on Transition-State-Theory, as given by Lasaga et al. (1994):

$$r_n = f(c_1, c_2, \dots, c_{N_c}) = \pm k_n A_n |1 - \Omega_n^\theta|^\eta \quad n = 1 \dots N_q \quad (\text{B.6})$$

where positive values of  $r_n$  indicate dissolution, and negative values precipitation,  $k_n$  is the rate constant (moles per unit mineral surface area and unit time) which is temperature dependent,  $A_n$  is the specific reactive surface area per kg H<sub>2</sub>O (details on  $A_n$  calculations are given in Appendix G),  $\Omega_n$  is the kinetic mineral saturation ratio defined in (B.4). The parameters  $\theta$  and  $\eta$  must be determined from experiments; usually, but not always, they are taken equal to one. The temperature dependence of the reaction rate constant can be expressed reasonably well via an

Arrhenius equation (Lasaga, 1984; Steefel and Lasaga, 1994). Because many rate constants are reported at 25°C, it is convenient to approximate rate constant dependency as a function of temperature, thus

$$k = k_{25} \exp \left[ \frac{-E_a}{R} \left( \frac{1}{T} - \frac{1}{298.15} \right) \right] \quad (\text{B.7})$$

where  $E_a$  is the activation energy,  $k_{25}$  is the rate constant at 25°C,  $R$  is gas constant,  $T$  is absolute temperature. Kinetic rates can be functions of non-basis species as well. Usually the species appearing in rate laws happen to be basis species.

Carroll et al. (1998) noted that the rates of amorphous silica precipitation based on Rimstidt and Barnes (1980) are about three orders of magnitude lower than those observed in geothermal systems. Carroll et al. (1998) presented experimental data on amorphous silica precipitation for more complex geothermal fluids at higher degrees of supersaturation, and also for a near-saturation simple fluid chemistry. Under conditions far from equilibrium, the rate law for amorphous silica precipitation has been expressed as:

$$r = kA(\Omega)^\theta \quad (\text{B.8})$$

This rate does not tend to zero as  $\Omega$  goes to one, and therefore, in TOUGHREACT, a modification was made to this law so that it tends to zero as  $\Omega$  approaches one

$$r = kA \left[ (\Omega)^\theta - \frac{1}{\Omega^{2\theta}} \right] \quad (\text{B.9})$$

The pH dependence of mineral precipitation and dissolution rates is calculated using the following expressions:

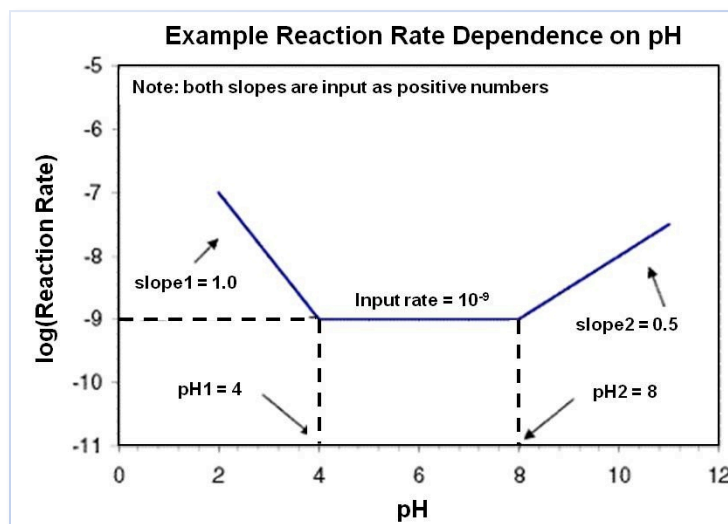
$$k_{adj} = k (10^{-pH_c}/10^{-pH1})^{slope1} \quad \text{if } pH_c < pH1 \quad (\text{B.10})$$

$$k_{adj} = k (10^{-pH_c}/10^{-pH2})^{-slope2} \quad \text{if } pH_c > pH2 \quad (\text{B.11})$$

where  $k_{adj}$  is the rate adjusted for pH,  $k$  is the original rate (Equation B.6),  $pH_c$  is the current (calculated) pH,  $pH1$  is the pH below which the rate is adjusted by  $slope1$  and  $pH2$  is the pH above which the rate is adjusted by  $slope2$ . Parameters  $slope1$  and  $slope2$  are the absolute values (both positive numbers) of the  $\log(k)$  versus pH slopes below  $pH1$  and above  $pH2$ , respectively (Figure B-1). Between these two pH values, the rate is assumed to remain independent of pH.



Figure B-1 Variation of reaction rate with pH. Slopes shown are for the dissolution of silicate and aluminosilicate minerals (After Drever, 1997).



The kinetic rate constant ( $k$ ) in Eqs. (B.6) and (B.7) only considers the most well-studied mechanism in pure  $H_2O$  (at neutral pH). Dissolution and precipitation of minerals are often catalyzed by  $H^+$  (acid mechanism) and  $OH^-$  (base mechanism). For many minerals, the kinetic rate constant  $k$  includes each of these three mechanisms (Lasaga et al., 1994; Palandri and Kharaka, 2004), or

$$k = k_{25}^{nu} \exp \left[ \frac{-E_a^{nu}}{R} \left( \frac{1}{T} - \frac{1}{298.15} \right) \right] + k_{25}^H \exp \left[ \frac{-E_a^H}{R} \left( \frac{1}{T} - \frac{1}{298.15} \right) \right] a_H^{n_H} + k_{25}^{OH} \exp \left[ \frac{-E_a^{OH}}{R} \left( \frac{1}{T} - \frac{1}{298.15} \right) \right] a_{OH}^{n_{OH}} \quad (B.12)$$

where superscripts or subscripts nu, H, and OH indicate neutral, acid and base mechanisms, respectively;  $a$  is the activity of the species; and  $n$  is power term (constant). Notice that parameters  $\theta$  and  $\eta$  (see Eq. B.6) are assumed the same for each mechanism. The rate constant  $k$  can be also dependent on other species such as  $Al^{3+}$  and  $Fe^{3+}$ . Two or more species may be involved in one mechanism. A general form of species dependent rate constants (extension of Eq. B.12) is coded in TOUGHREACT, or,

$$k = k_{25}^{nu} \exp \left[ \frac{-E_a^{nu}}{R} \left( \frac{1}{T} - \frac{1}{298.15} \right) \right] + \sum_i k_{25}^i \exp \left[ \frac{-E_a^i}{R} \left( \frac{1}{T} - \frac{1}{298.15} \right) \right] \prod_j a_{ij}^{n_{ij}} \quad (B.13)$$

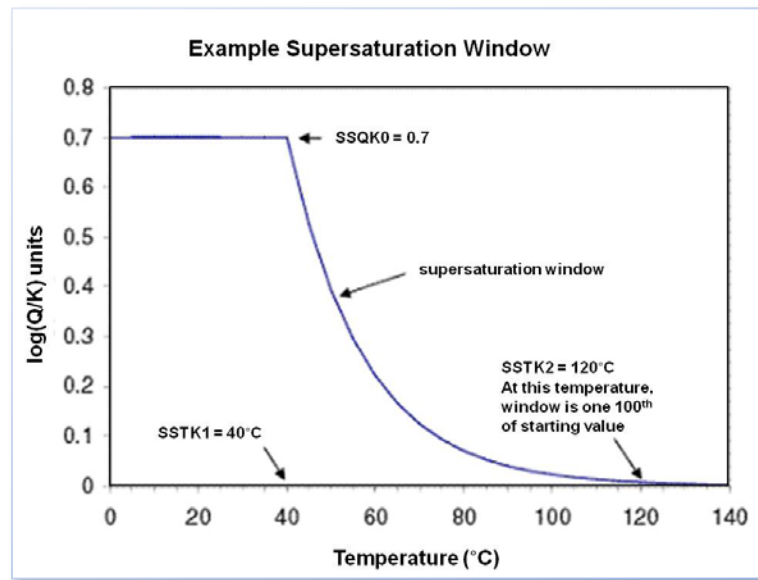
where superscripts or subscripts  $i$  is the additional mechanism index, and  $j$  is species index involved in one mechanism that can be primary or secondary species. TOUGHREACT considers up to five additional mechanisms and up to five species involved in each mechanism. An application of multiple mechanisms (Eq. B.13) can be found in the CO<sub>2</sub> disposal sample problem (see TOUGHREACT Sample Problem Guide).

The precipitation of a mineral can be suppressed up to a given, positive saturation index value,  $\log(\Omega)_w$ . Within this "supersaturation window", the mineral is not allowed to precipitate. The mineral precipitates if its saturation index  $\log(\Omega) \geq \log(\Omega)_w$ , and dissolves if  $\log(\Omega) < 0$ . The size of the window can be set to decrease exponentially with temperature as follows:

$$(\Omega)_{w,T} = \log(\Omega)_{w,T_0} \exp(-4.61(T - T_0)/(T_1 - T_0)) \quad (\text{B.14})$$

where  $\log(\Omega)_{w,T}$  is the window at the current temperature  $T$  and  $\log(\Omega)_{w,T_0}$  is the initial (input) window at temperature  $T_0$ .  $T_1$  is the temperature at which the window is one-hundredth the size of the initial window (thus the temperature at which the effect of the window essentially disappears, see Figure B-2). Values of  $\log(\Omega)_{w,T_0}$ ,  $T_0$ , and  $T_1$  are provided as input parameters.

**Figure B-2 Supersaturation window dependence on temperature.**



## B.5 Gas dissolution/exsolution

Reactions involving aqueous and gaseous phases are usually assumed to be at equilibrium. According to the Mass-Action Law, one has:

$$P_f \Gamma_f K_f = \prod_{i=1}^{N_i} C_i^{v_i} \gamma_i^{v_i} \quad (\text{B.15})$$

where subscript f is gas index, p is the partial pressure (in bar),  $\Gamma$  is the gas fugacity coefficient. For low pressures (in the range of atmospheric pressure), the gaseous phase is assumed to behave like an ideal mixture, and the fugacity coefficient  $\Gamma$  is assumed equal to one. At higher temperatures and pressures, such as boiling conditions in hydrothermal systems and CO<sub>2</sub> disposal in deep aquifers, the assumption of ideal gas and ideal mixing behavior is not valid, and the fugacity coefficients should be corrected according to temperatures and pressures (Spycher and Reed, 1988). For example, for H<sub>2</sub>O-CO<sub>2</sub> mixtures in boiling conditions, we assume that H<sub>2</sub>O and CO<sub>2</sub> are real gases, but their mixing is ideal. Following Spycher and Reed (1988), the fugacity coefficients is calculated from

$$\ln \Gamma = \left(\frac{a}{T^2} + \frac{b}{T} + c\right)P + \left(\frac{d}{T^2} + \frac{e}{T} + f\right)\frac{P^2}{2} \quad (\text{B.16})$$

where P is the total gas pressure (vapor and CO<sub>2</sub>), T is absolute temperature, and a, b, c, d, e, and f are constants fitted from experimental data. For P-T ranges, 50-350°C, up to 500 bars, the fitted constants for CO<sub>2</sub> have the following values: a = -1430.87, b = 3.598, c = -2.27376×10<sup>-3</sup>, d = 3.47644, e = -1.04247×10<sup>-2</sup>, and f = 8.36271×10<sup>-6</sup>. Examples of equilibrium calculations between aqueous and gas phases show that ideal mixing of real gases is a reasonable approximation near the water saturation pressure curve (Spycher and Reed, 1988). Details on fugacity correction are given in Section H.4 of Appendix H.

For low ionic strength solution, the CO<sub>2</sub>(aq) activity coefficient  $\gamma$  can be assumed equal to one. For a high ionic strength sodium chloride solution,  $\gamma$  should be corrected (salting out effect). Here we use an activity coefficient expression of Drummond (1981) for CO<sub>2</sub>(aq):

$$\ln \gamma = \left(C + FT + \frac{G}{T}\right)I - (E + HT)\left(\frac{I}{I+1}\right) \quad (\text{B.17})$$

where T is the absolute temperature, I is ionic strength (or sodium chloride molality), C, F, G, E, and H are constants (C=-1.0312, F=0.0012806, G=255.9, E=0.4445, and H=-0.001606). A similar expression is used in other geochemical modeling codes such as in EQ3/6 (Wolery, 1992). The ionic strength, I, is defined by

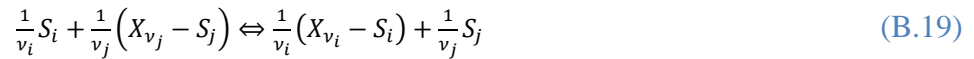
$$I = \frac{1}{2} \sum_i c_i z_i^2 \quad (\text{B.18})$$

where the summation is over all aqueous species, and  $c_i$  and  $z_i$  are concentration (mol/kg H<sub>2</sub>O) and electrical charge of species i.

## B.6 Cation exchange

---

Cation exchange takes place when free cations in solution exchange with interlayer cations. This process can be described as an equilibrium reaction between an exchangeable cation and an exchange site. The equilibrium constant is usually known as the exchange coefficient because its value depends on the ionic strength of the solution. A general expression for cation exchange reactions according to the Gaines-Thomas convention is (Appelo and Postma, 1993):



where  $v_i$  and  $v_j$  are the stoichiometric coefficients (equal to their charges) of dissolved and interlayer cations, respectively;  $S_i$  and  $S_j$  denote dissolved cationic species and  $(X_{v_i} - S_i)$  and  $(X_{v_j} - S_j)$  represent exchange sites or exchange interlayer cations. Let's have an example:



The equilibrium equation for cation exchange is obtained from the Mass Action Law:

$$K_{ij}^* = \frac{\bar{w}_i^{1/v_i} \cdot a_j^{1/v_j}}{\bar{w}_j^{1/v_j} \cdot a_i^{1/v_i}} \quad (\text{B.20})$$

where  $K_{ij}^*$  is the exchange coefficient or selectivity,  $a_j$  is the activity of the j-th dissolved species and  $\bar{w}_i$  is the activity of the i-th interlayer cation. For the example of (B.19a), we have:

$$K_{Na/Ca}^* = \frac{\bar{w}_{Na} \cdot a_{Ca}^{0.5}}{\bar{w}_{Ca}^{0.5} \cdot a_{Na}} \quad (\text{B.20a})$$

Activities of dissolved cations are related to concentrations as given in Appendix H. Activities of interlayer cations are approximated by (1) their equivalent fractions of the number of exchange sites, which is commonly referred as the *Gaines-Thomas* convention (Appelo and Postma, 1993), after Gaines and Thomas (1953) who was among the first to give a rigorous definition of a thermodynamic standard state of interlayer cations; or (2) their molar fractions of the number of exchange sites, which follows *Vanselow* convention (Vanselow, 1932). Thus, the activity of the interlayer cation  $\bar{w}_i$  is assumed to be equal to its fraction  $\beta_i$  of equivalent (Gaines-Thomas convention) or mole (Vanselow convention), and is calculated as:

$$\bar{w}_i \cong \beta_i = \frac{w_i}{\sum_{i=1}^{N_w} w_i} \quad (\text{B.21})$$

where  $w_i$  is the concentration of the  $i$ -th interlayer cation and  $N_w$  is the total number of such interlayer cations. The sum of concentrations of exchange sites or interlayer cations is the so-called cation exchange capacity (CEC). Substituting (B.21) into (B.20) yields the general equation for cation exchange:

$$K_{ij}^* = \frac{\beta_i^{1/v_i} \cdot (c_j \gamma_j)^{1/v_j}}{\beta_j^{1/v_j} \cdot (c_i \gamma_i)^{1/v_i}} \quad (\text{B.22})$$

where the activity of each dissolved species  $a_i$  has been expressed as the product of its concentration  $c_i$  time its activity coefficients  $\gamma_i$ . The Na/Ca exchange example becomes

$$K_{Na/Ca}^* = \frac{\beta_{Na}^{1/1} \cdot (c_{Ca} \gamma_{Ca})^{1/2}}{\beta_{Ca}^{1/2} \cdot (c_{Na} \gamma_{Na})^{1/1}} \quad (\text{B.22a})$$

From Eq. (B.22),  $\beta_j$  can be expressed as

$$\beta_j = (K_{ij}^*)^{-v_j} c_j \gamma_j \left( \frac{\beta_i}{c_i \gamma_i} \right)^{v_j/v_i} \quad j = 1, 2, \dots, N_w \quad (\text{B.23})$$

For Na/Ca exchange example, we have:

$$\beta_{Ca} = (K_{Na/Ca}^*)^{-2} c_{Ca} \gamma_{Ca} \left( \frac{\beta_{Na}}{c_{Na} \gamma_{Na}} \right)^{2/1} \quad (\text{B.23a})$$

From the definition of Eq. (B.21), one has:

$$\sum_{j=1}^{N_w} \beta_j = 1 \quad (\text{B.24})$$

Substituting Equation B.23 into B.24 results in:

$$\sum_{j=1}^{N_w} (K_{ij}^*)^{-v_j} c_j v_j \left( \frac{\beta_i}{c_i v_i} \right)^{v_j/v_i} = 1 \quad (\text{B.25})$$

which for given dissolved concentrations  $c_j$  can be solved for the single unknown  $\beta_i$ . This equation is quadratic when cation exchange involves only homovalent and divalent cations. However, when cation exchange involves also trivalent cations a cubic equation is obtained. Once the equivalent fraction  $\beta_i$  is known the rest of exchange fractions can be calculated from Equation B.21. According to Equation B.21, the concentration of the  $i$ -th exchanged cation  $w_j$  (in moles per liter of fluid) can be obtained from

$$w_j = \beta_j \sum_{j=1}^{N_w} w_j \rho_s \frac{(1-\varphi)}{100\varphi z_j} \quad \text{for Gaines-Thomas convention} \quad (\text{B.26a})$$

$$w_j = \beta_j \sum_{j=1}^{N_w} w_j \rho_s \frac{(1-\varphi)}{100\varphi} \quad \text{for Vanselow convention} \quad (\text{B.26b})$$

For the commonly used Gaines-Thomas convention,  $\sum_{j=1}^{N_w} w_j$  is also referred as CEC, the cation exchange capacity (usually measured as the number of milli equivalents of cations per 100 gram of solid),  $\varphi$  is the porosity,  $\rho_s$  is the density of the solids (kg of solids per  $\text{dm}^3$  of solids), and  $z_j$  is the cation charge.

A third cation exchange convention implemented is **Gapon** convention (Gapon, 1933). In this convention, the activities of the adsorbed ions are expressed as a fraction of the number of exchange sites ( $X^-$ ). When cation exchange involves homovalent and divalent cations, the reaction should be written as



with

$$K_{\text{Na/Ca}}^* = \frac{[\text{Na-X}][\text{Ca}^{2+}]^{0.5}}{[\text{Ca}_{0.5}\text{-X}][\text{Na}^+]} = \frac{\beta_{\text{Na}}[\text{Ca}^{2+}]^{0.5}}{\beta_{\text{Ca}}[\text{Na}^+]} \quad (\text{B.28})$$

In this case, molar and equivalent fractions become identical since both are based on a single exchange site with charge -1.

Under variably water-saturated condition, exchangeable surface sites depend on water saturation. Assuming an ideal-wetting condition, using a correct with water saturation  $S_l$ , Eq. B.26a becomes (a similar form for B.26b):

$$w_j = \beta_j \sum_{j=1}^{N_w} w_j \rho_s \frac{(1-\phi)}{100\phi z_j S_l} \quad (\text{B.29})$$

In Eq. B.29, as  $S_l$  goes to zero, the surface sites (concentration) would tend to infinity. Clearly, at a very low liquid saturation, the exchangeable (reactive or effective) sites of the soil contacted by water are likely much smaller than the total sites.

The dependence of the surface sites on water saturation is very complex in field-scale conditions. Two methods (models) have been implemented to address this phenomenon. The first method considers that the surface sites contacted by water diminish proportionately to the saturation (Model 1), or ideal-wetting condition. The second method considers multiplying a (correction) factor  $f$  that depends on liquid saturation,  $f(S_l)$ , or

$$w_j = \beta_j \sum_{j=1}^{N_w} w_j \rho_s \frac{(1-\phi)}{100\phi z_j S_l} f(S_l) \quad (\text{B.30})$$

Values of the factor  $f$  range from zero to one, or  $0 \leq f \leq 1$ . One  $f(S_l)$  function could be adopted from the reactive surface area calculations for dissolution and precipitation of minerals (Model 2; see Appendix K).

The above equations (B.19 to B.30) are formulated for a single-site exchange of cations. Multi-site exchanges are implemented. Each site is assumed to be independent. Eqs. B.19 to B.30 are applied for each site.

## B.7 Surface Complexation

---

### *Surface Electric Potential Model*

The sorption of solutes on solid surfaces can be described as a chemical reaction between the aqueous species and the specific surface sites (surface complexation). These surface reactions

include proton exchange, cation binding and anion binding via ligand exchange at surface hydroxyl sites (represented here as XOH to avoid confusion with other chemical species). For example, the sorption of a metal could be represented as:



At equilibrium, the sorption reactions can be described by the mass law equation:

$$K_{app} = \frac{[\text{XOM}^{z-1}]a_{\text{H}^+}}{[\text{XOH}]a_{\text{M}^{z+}}} \quad (\text{B.32})$$

where  $K_{app}$  is referred to as the apparent equilibrium constant, because it includes surface charge effects and hence is dependent on the extent of surface ionization (Dzombak and Morel, 1990),  $a$  is the thermodynamic activity of the aqueous species, and the terms in brackets represent the concentration of surface complexes (mol/kg).

In aqueous complexation reactions, the electric charge is assumed to be homogeneous in the solution. However, surface reactions take place on a fixed charged surface creating an electrostatic field. An additional energetic term accounting for the work needed for the aqueous species to travel across the surface electric field is required:

$$\Delta G_{ads} = \Delta G_{intr} + \Delta G_{coul} = \Delta G_{intr} + (\Delta G_{\psi=0} - \Delta G_{\psi=\psi_0}) = \Delta G_{intr} - zF\psi_0 \quad (\text{B.33})$$

where  $\Delta G_{ads}$  is the free enthalpy change of the overall adsorption reaction,  $\Delta G_{intr}$  and  $\Delta G_{coul}$  are the free enthalpy change due to chemical bonding and to the electrostatic work, respectively,  $z$  is the charge of the surface species,  $F$  the Faraday's constant (96485 C/mol), and  $\psi_0$  is the mean surface potential (V). Since

$$\Delta G = -RT \ln K, \quad (\text{B.34})$$

Equation (B.33) can be rewritten as:

$$K_{app} = K_{int} e^{\frac{zF\psi_0}{RT}}, \quad (\text{B.35})$$



where  $R$  is the gas constant (8.354 J/mol/K),  $T$  is the absolute temperature (K), and  $K_{int}$  is the intrinsic equilibrium constant which does not depend on the surface charge.

### *Diffuse Layer Model*

The diffuse layer model has been described in great detail by Dzombak and Morel (1990) and was applied to adsorption of metals on iron oxide surfaces. In the diffuse layer model, the solid-water interface is composed of two layers: a layer of surface-bound complexes and a diffuse layer of counter ions in solution. The surface charge is calculated from the total surface species adsorbed on the layer:

$$\sigma_p = \frac{F}{A} \sum_{k=1}^{N_s} z_k y_k \quad (\text{B.36})$$

According to the Gouy-Chapman theory, the surface charge density  $\sigma_p$  (C/m<sup>2</sup>) is related to the potential at the surface (volt) by:

$$\sigma_d = (8RT \varepsilon \varepsilon_0 I \times 10^3)^{1/2} \sinh(zF\psi_0/2RT), \quad (\text{B.37})$$

where  $R$  is the molar gas constant (8.354 J mol<sup>-1</sup> K<sup>-1</sup>),  $T$  is the absolute temperature (K),  $\varepsilon$  is the relative dielectric constant of water ( $\varepsilon = 78.5$  at 29°C),  $\varepsilon_0$  is the permittivity of free space (8.754 10<sup>-12</sup> C V<sup>-1</sup> m<sup>-1</sup> or 8.754 10<sup>-12</sup> C<sup>2</sup> J<sup>-1</sup> m<sup>-1</sup>), and  $C$  is the molar electrolyte concentration (M). Equation (B.37) is only valid for a symmetrical electrolyte ( $Z$ =ionic charge). It is common to use the linearized version of Equation (B.37) for low values of the potential:

$$\sigma_p = \varepsilon \varepsilon_0 \kappa \psi_0, \quad (\text{B.38})$$

where  $1/\kappa$  (m) is the double-layer thickness defined as:

$$\frac{1}{\kappa} = \left( \frac{\varepsilon \varepsilon_0 RT}{2F^2 \cdot 1000I} \right)^{1/2} \quad (\text{B.39})$$

Equations (B.37) can be simplified by rewritten  $(8RT \varepsilon \varepsilon_0 I \times 10^3)^{1/2}$  for 29°C:

$$\sigma_p = 0.1174 I^{1/2} \sinh(zF\psi_0/2RT) \quad (\text{B.40})$$

Therefore, in the diffuse-layer model, the value of the capacitance  $C$  relating the surface charge and the potential can be calculated based on theoretical considerations (Equation B.38) instead of being an experimental fitting parameter.

### *Constant Capacitance Model*

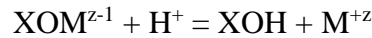
Similar to the diffused-layer, the constant capacitance model is based on the assumption that all the species are adsorbed in the same layer and a diffuse layer of counterions constitutes the transition to homogenous solution. However, differently from the diffuse-layer model, the relationship between the surface charge and the potential is assumed to be linear:

$$\sigma = C\psi \quad (\text{B.41})$$

where  $C$  is a constant value to be obtained from fitting experimental data.

### *Mathematical Formulation of Adsorption Reactions*

Lets us consider the following surface desorption reaction:



with the equilibrium constant of the reaction given as:

$$K_{int} = \frac{[\text{XOH}]a_M}{[\text{XOM}]a_{\text{H}^+}} e^{\left(\frac{-zF\psi_0}{RT}\right)} \quad (\text{B.42})$$

Usually, the neutral surface complex  $\text{XOH}$  is included in the  $N_C$  aqueous primary species. The new unknown is the potential term

$$\tilde{\psi} = \frac{-F\psi_0}{RT} \quad (\text{B.43})$$

The concentration of a surface complex,  $y_j$ , ( $\text{mol}/\text{m}^3$ ), can be expressed in terms of the concentration of the primary species and the potential term:

$$y_j = K_j^{-1} \prod_{i=1}^{N_C} c_i^{v_{ji}^y} \gamma_i^{v_{ji}^y} e^{z_j \tilde{\psi}} \quad j = 1 \dots N_Y \quad (\text{B.44})$$

where  $K_j$  is the intrinsic equilibrium constant of the desorption reaction.

In order to solve for the potential term, an additional equilibrium equation is needed. For the double diffuse layer model, we obtain Equation (B.45), if the Guoy-Chapman double-layer theory is used to relate surface charge and the potential (Equation (B.37)). If the linearized Equation (B.38) is used, we obtain Equation (B.46). If a constant capacity model is used, we obtain Equation (B.47).

$$(8RT \varepsilon \varepsilon_0 I \times 10^3)^{1/2} \sinh(-\tilde{\psi}/2) - \frac{F}{A} \sum_{k=1}^{N_s} z_k y_k = 0 \quad (\text{B.45})$$

$$\frac{F^2}{A \varepsilon \varepsilon_0 \kappa RT} \sum_{k=1}^{N_s} z_k y_k + \tilde{\psi} = 0 \quad (\text{B.46})$$

$$\frac{F^2}{ACRT} \sum_{k=1}^{N_s} z_k y_k + \tilde{\psi} = 0 \quad (\text{B.47})$$

## Appendix C Solution Method for Solute Transport Equations

---

Most chemical species are only subject to transport in the liquid phase. A few species can be transported in both liquid and gas phases such as O<sub>2</sub> and CO<sub>2</sub>. We first derive the numerical formulation of reactive transport in the liquid phase. This will then be extended to transport in the gas phases for some gaseous species.

### C.1 Transport in the Aqueous Phase

---

In the sequential iteration approach (SIA), the mass transport equations and chemical reaction equations are considered as two relatively independent subsystems. They are solved separately in a sequential manner following an iterative procedure. If reactions taking place in the liquid phase are assumed to be at local equilibrium, mass transport equations can be written in terms of total dissolved component concentrations. By lumping all mass accumulation terms due to mass transfer between aqueous and solid phases including precipitated (kinetics and equilibrium), exchanged and sorbed species, and by using Equation (4.1) (in Chapter 4), we can write equations for multi-component chemical transport in the liquid phase as

$$\frac{\Delta t}{V_n} \sum_m A_{nm} \left[ u_{nm}^{k+1} C_{nm}^{(j),k+1,s+1/2} + D_{nm} \frac{C_m^{(j),k+1,s+1/2} - C_n^{(j),k+1,s+1/2}}{d_{nm}} \right] = \Delta M_n^{(j),k+1} - q_n^{(j),k+1} \Delta t - R_n^{(j),k+1,s} \Delta t \quad j=1,2,\dots,N_C \quad (C.1)$$

where n labels the grid block, m label the adjacent grid blocks connected to n, j labels the chemical component,  $N_C$  is the total number of chemical components, l labels liquid phase (for simplicity, the liquid phase index l is neglected), k labels the number of the time step, s labels the number of the transport-chemistry iteration (details is given later),  $u_{nm}$  is the liquid volumetric flux or the Darcy velocity (m/s),  $D_{nm}$  is the effective diffusion coefficient (including effects of porosity, phase saturation, tortuosity and weighting factors between the two grid blocks),  $d_{nm}$  is the nodal distance,  $R_n^{(j),k+1}$  are the overall chemical reaction source/sink terms.

The concentrations in the advective and diffusive flux terms of Equation (C.1) can be evaluated by

$$\begin{aligned} C_{nm}^{(j),k+1,s+1/2} &= \theta \left[ \varepsilon_{nm} C_n^{(j),k+1,s+1/2} + (1 - \varepsilon_{nm}) C_m^{(j),k+1,s+1/2} \right] \\ &\quad (1-\theta) \left[ \varepsilon_{nm} C_n^{(j),k} + (1 - \varepsilon_{nm}) C_m^{(j),k} \right] \\ C_n^{(j),k+1,s+1/2} &= \theta C_n^{(j),k+1,s+1/2} + (1-\theta) C_n^{(j),k} \\ C_m^{(j),k+1,s+1/2} &= \theta C_m^{(j),k+1,s+1/2} + (1-\theta) C_m^{(j),k} \end{aligned} \quad (C.2)$$

where  $\theta$  is the time weighting factor, with values in the range from 0 to 1;  $\theta = 1$  indicates a fully implicit calculation; and

$$\varepsilon_{nm} = \begin{cases} 0 & \text{if } u_{nm} \geq 0 \text{ inflow} \\ 1 & u_{nm} < 0 \text{ outflow} \end{cases}$$

Fully upstream weighting is used for advective flux calculations. The mass accumulation terms can be evaluated as

$$\Delta M_n^{(j),k+1} = S_{l,n}^{k+1} \varphi_n^{k+1} C_n^{(j),k+1,s+1/2} - S_{l,n}^k \varphi_n^k C_n^{(j),k} \quad (C.3)$$

By substituting Equations (C.2) and (C.3) into (C.1), and then rearranging them in terms of unknowns,  $C_n^{(j),k+1,s+1/2}$  (total dissolved component concentrations), one has

$$\begin{aligned}
& \left[ S_{l,n}^{k+1} \varphi_n^{k+1} + \frac{\theta \Delta t}{V_n} \sum_m A_{nm} \left( -u_{nm}^{k+1} \varepsilon_{nm} + \frac{D_{nm}}{d_{nm}} \right) \right] C_n^{(j),k+1,s+1/2} + \\
& \frac{\theta \Delta t}{V_n} \sum_m A_{nm} \left[ u_{nm}^{k+1} (\varepsilon_{nm} - 1) - \frac{D_{nm}}{d_{nm}} \right] C_m^{(j),k+1,s+1/2} = \\
& \frac{(1-\theta) \Delta t}{V_n} \sum_m A_{nm} \left( u_{nm}^{k+1} \varepsilon_{nm} - \frac{D_{nm}}{d_{nm}} \right) C_n^{(j),k} - \\
& \frac{(1-\theta) \Delta t}{V_n} \sum_m A_{nm} \left[ u_{nm}^{k+1} (\varepsilon_{nm} - 1) + \frac{D_{nm}}{d_{nm}} \right] C_m^{(j),k} \\
& S_{l,n}^k \varphi_n^k C_n^{(j),k} + q_n^{(j)k+1} \Delta t + R_n^{(j),k+1,s} \Delta t \quad j=1,2,\dots,N_C \quad (C.4)
\end{aligned}$$

For the sequential iteration approach, the iteration index  $s$  is essential. A new transport-chemistry iteration consists of two parts, transport part denoted by,  $s+1/2$ , (it should be noted that  $1/2$  does not mean  $\Delta t/2$ ), and chemistry part denoted by,  $s+1$ . Equation (C.4) for each chemical component  $j$  is linear if  $R_n^{(j),s}$  is known, and has the same structure as the non-reacting (conservative) solute transport equation. The chemical reaction source/sink term  $R_n^{(j),s}$  represents mass transfer of component  $j$  between aqueous and solid phases. The values of these source/sink terms at the new transport iteration,  $s+1/2$ , are evaluated at the previous chemistry iteration,  $s$ . The resulting new values of  $C_n^{(j),s+1/2}$ , obtained by solving transport Equations (C.1), are substituted into chemical reaction subroutines and one can compute new values of  $R_n^{(j),s+1}$ . Transport and chemical reaction equations are solved iteratively until the prescribed convergence criteria are satisfied. The essence of this sequential iteration approach is therefore the sequential solution of two independent sets of equations: the transport equations and the chemical equations. The transport equations are solved on a component-by-component basis, whereas the chemical equations are solved on a grid block by grid block basis. These two sets of equations are coupled by updating chemical source/sink terms.

For kinetic mineral dissolution-precipitation, the terms  $R_n^{(j)}$  can be calculated directly from kinetic expressions. For equilibrium, these terms can be obtained indirectly from component mass

balance equations. The solution of chemical equilibrium system and calculation of the source/sink terms  $R_n^{(j)}$  are presented in Appendix D. From the chemistry point of view, equilibrium mineral dissolution-precipitation does not appear in an explicit rate expression. To avoid confusion, we write the last term in Equation (C.4) as

$$R_n^{(j),k+1,s} \Delta t = -\Delta P_n^{(j),k+1,s} \quad (\text{C.5})$$

where  $\Delta P_n^{(j),k+1,s}$  means mass transfer of component  $j$  from the aqueous phase to the mineral phase at iteration  $s$ , grid block  $n$  and time step  $k+1$  (or called mass accumulation in mineral phases; negative values indicate mass transfer from the mineral phase to the aqueous phase).

Returning to Equation (C.4), we can see that the coefficient matrix is the same for all chemical components as long as diffusion coefficients are the same for all aqueous species. The matrix depends on space and time discretization, and flow conditions. The equations for different components only differ in right-hand side terms.

The mathematical treatment of adding  $K_d$  linear adsorption and first-order decay effects in the model follows the work by Oldenburg and Pruess (1995, EOS7R), but no gas phase partitioning is considered. The mass accumulation term for any species (for simplification, the species index is not appeared in the following equations) with  $K_d$  adsorption on the solid matrix is

$$M = \phi S_l C + (1 - \phi) \rho_s C K_d \quad (\text{C.6})$$

where  $\phi$  is porosity,  $S_l$  is the liquid saturation,  $C$  is the aqueous concentration (mol/l),  $\rho_s$  is the solid density (kg/dm<sup>3</sup>),  $K_d$  is the distribution coefficient (l/kg = mass/kg solid divided by mass/l solution) and is species-dependent. The accumulation also term can be written in terms of a retardation factor

$$M = \phi S_l R C \quad (\text{C.7})$$

and

$$R = 1 + \frac{(1-\phi)\rho_s}{\phi S_l} K_d \quad (\text{C.8})$$

The input can be optionally by  $K_d$  and  $R$ , depending on user convenience and data availability.

The first-order decay of a species is handled by the discretized equation (Oldenburg and Pruess, 1995)

$$M_n^{k+1}(1 + \lambda\Delta t) - M_n^k = \frac{\Delta t}{V_n} (\sum_m A_{nm} F_{nm}^{k+1} + V_n q_n^{k+1}) \quad (\text{C.9})$$

where  $\lambda$  is decay constant (1/s) which is species-dependent, subscript  $n$  labels grid block, superscript  $k$  labels time step, subscript  $m$  labels the grid block connected to grid block  $n$ ,  $\Delta t$  is time step size,  $M_n$  is the average mass per unit volume, surface integrals are approximated as a discrete sum of averages over surface segments  $A_{nm}$ ,  $F_{nm}$  is the average mass flux over the surface segment  $A_{nm}$  between volume elements  $V_n$  and  $V_m$ , and  $q$  is the average value of source/sink term per unit volume and unit time.

## C.2 Transport in the Gas Phase

---

TOUGHREACT has the option to transport trace gas species within the primary gas phase considered in multiphase flow calculations. We will denote the primary gas phase as the "carrier" gas, in contrast to the "gaseous species" or "trace gas species" that are considered only in the reactive-transport calculations. Gaseous species can be transported via advection and/or diffusion. Trace gas diffusion coefficients can be calculated based on the gaseous species molecular diameter and mass, the temperature, and the total pressure. Data for individual gaseous species are entered in the thermodynamic database.

In TOUGHREACT V2 and earlier, the trace gas species concentrations in the gas phase were calculated assuming that the carrier gas had ideal gas properties (Xu et al., 2011). Starting with V3.0-OMP, gas species concentrations are calculated using the nonideal carrier gas properties derived directly from those determined in the EOS module at the current time step. In addition to improved accuracy, this allowed for a rigorous implementation of trace gas species injection with various carrier gases, such as CO<sub>2</sub>, air, water vapor, and gas mixtures. Improvements and extensions to EOS module EWASG were implemented since V3.32-OMP. The revised equations are given below.

The concentration  $C_{g,i}$  (mol/liter medium) of gas species  $i$  is calculated from the gas species partial pressure  $P_{g,i}$  (bars), as follows:

$$C_{g,i} = P_{g,i} \phi S_g / [MW_g P_{tot} 10^{-5} / \rho_g] \quad (\text{C.10})$$

where  $P_{tot}$  is the total pressure (Pa),  $\rho_g$  the "carrier" gas density,  $MW_g$  is the molecular weight of the carrier gas mixture,  $\phi$  is the porosity, and  $S_g$  the gas saturation.

Gaseous species concentrations for ideal gases can be related to partial pressures by

$$C_g = \frac{10^2}{RT} P_g \quad (\text{C.11})$$

where  $C_g$  are gaseous species concentrations (in mol/l),  $P_g$  is the gaseous species partial pressure (in bar),  $R$  is the gas constant ( $8.3144 \text{ J mol}^{-1} \text{ K}^{-1}$ ) and  $T$  is the absolute temperature.

By following the same principle as used for transport in liquid phase and by considering Equation (C.10), the numerical formulation of gaseous transport in the gas phases can be expressed as

$$\begin{aligned} & \left[ \frac{10^2}{RT} S_{g,n}^{k+1} \varphi_n^{k+1} + \frac{\Delta t}{V_n} \sum_m A_{nm} \frac{10^2}{RT} \left( -u_{g,nm}^{k+1} \varepsilon_{g,nm} + \frac{D_{g,nm}}{d_{nm}} \right) \right] P_{g,n}^{(j),k+1,s+1/2} + \\ & \frac{\Delta t}{V_n} \sum_m A_{nm} \frac{10^2}{RT} \left[ u_{g,nm}^{k+1} (\varepsilon_{g,nm} - 1) - \frac{D_{g,nm}}{d_{nm}} \right] P_{g,m}^{(j),k+1,s+1/2} = \\ & \frac{10^2}{RT} S_{g,n}^k \varphi_n^k P_{g,n}^{(j),k} + q_n^{(j),k+1} \Delta t + R_n^{(j),k+1,s} \Delta t \quad j=1,2,\dots,N_g \end{aligned} \quad (\text{C.11})$$

where  $N_g$  is number of gaseous species. The structure of Equations (C.11) is the same as that of (C.4) for transport only in liquid phase. The same solution method can be applied for solving Equations (C.11).

Gas species diffusion coefficients are computed as a function of temperature, pressure, molecular weight, and molecular diameter. Assuming ideal gas behavior, the tracer diffusion coefficient of a gaseous species can be expressed as follows (Lasaga, 1998):

$$D = \frac{RT}{3\sqrt{2}\pi P N_A d_m^2} \sqrt{\frac{8RT}{\pi M}} \quad (\text{A. 1})$$

where:



$D$  = diffusion coefficient ( $\text{m}^2\text{s}^{-1}$ )  
 $R$  = molar gas constant ( $8.31451 \text{ m}^2\text{kg s}^{-2}\text{mol}^{-1} \text{ K}^{-1}$ )  
 $T$  = temperature in Kelvin units  
 $\pi = 3.1415926536$   
 $P$  = pressure ( $\text{kg m}^{-1} \text{ s}^{-2}$ )  
 $N_A$  = Avogadro's number ( $6.0221367 \times 10^{23}$  molecules/mol)  
 $D_m$  = molecular diameter (m)  
 $M$  = molecular weight (kg/mol)

## Appendix D Solution Method for Mixed Equilibrium-Kinetics Chemical System

Aqueous complexation and gas dissolution/exsolution proceed according to local equilibrium, while mineral dissolution/precipitation are subject to equilibrium and/or kinetic conditions. Gas dissolution/exsolution is included in the model and treated in a similar way as equilibrium mineral dissolution/precipitation but fugacity correction. The formulation is based on mass balances in terms of basis species as used by Parkhurst et al. (1980) and Reed (1982) for the equilibrium chemical system. The kinetic rate expressions for mineral dissolution/precipitation are included in the equations along with the mass balances of basis species. At time zero (initial), the total concentrations of basis species  $j$  in the system are assumed to be known, and are given by

$$T_j^0 = c_j^0 + \sum_{k=1}^{N_x} v_{kj} c_k^0 + \sum_{m=1}^{N_p} v_{mj} c_m^0 + \sum_{n=1}^{N_q} v_{nj} c_n^0 + \sum_{z=1}^{N_z} v_{zj} c_z^0 + \sum_{s=1}^{N_s} v_{sj} c_s^0 \quad j = 1 \dots N_C \quad (\text{D.1})$$

where superscript 0 represents time zero;  $c$  denotes concentration; subscripts  $j, k, m, n, z$  and  $s$  are the indices of the primary species, aqueous complexes, minerals at equilibrium, minerals under kinetic constraints, and exchanged and surface complexes, respectively;  $N_C, N_x, N_p, N_q, N_z$  and  $N_s$  are the number of corresponding species and minerals; and  $v_{kj}, v_{mj}, v_{nj}, v_{zj}$  and  $v_{sj}$  are stoichiometric coefficients of the primary species in the aqueous complexes, equilibrium, kinetic minerals, and exchanged and surface complexes, respectively.

After a time step  $\Delta t$ , the total concentration of primary species  $j$  ( $T_j$ ) is given by

$$T_j = c_j + \sum_{k=1}^{N_x} v_{kj} c_k + \sum_{m=1}^{N_p} v_{mj} c_m + \sum_{n=1}^{N_q} v_{nj} (c_n^0 - r_n \Delta t) + \sum_{z=1}^{N_z} v_{zj} c_z + \sum_{s=1}^{N_s} v_{sj} c_s \quad j = 1 \dots N_C \quad (\text{D.2})$$

where  $r_n$  is the kinetic rate of mineral dissolution (negative for precipitation, units used here are mole per kilogram of water per time), for which a general multi-mechanism rate law can be used.  $\Delta t$  and  $T_j$  are related through generation of  $j$  among primary species as follows

$$T_j - T_j^0 = \sum_{l=1}^{N_a} v_{lj} r_l \Delta t \quad j = 1, \dots, N_C \quad (D.3)$$

where  $l$  is the aqueous kinetic reaction (including biodegradation) index,  $N_a$  is total number of kinetic reactions among primary species, and  $r_l$  is the kinetic rate which is in terms of one mole of product species.

By substituting Equations (D.1) and (D.2) into Equation (D.3), and denoting residuals as  $F_j^c$  (which are zero in the limit of convergence), we have

$$\begin{aligned} F_j^c = & (c_j - c_j^0) && \text{primary species} \\ & + \sum_{k=1}^{N_x} v_{kj} (c_k - c_k^0) && \text{equilibrium aqueous complexes} \\ & + \sum_{z=1}^{N_z} v_{zj} (c_z - c_z^0) && \text{exchanged complexes} \\ & + \sum_{s=1}^{N_s} v_{sj} (c_s - c_s^0) && \text{surface complexes} \\ & + \sum_{m=1}^{N_p} v_{mj} (c_m - c_m^0) && \text{equilibrium minerals} \\ & - \sum_{n=1}^{N_q} v_{nj} r_n \Delta t && \text{kinetic minerals} \\ & - \sum_{l=1}^{N_a} v_{lj} r_l \Delta t && \text{kinetics among primary species} \\ = & 0 && j = 1 \dots N_C \end{aligned} \quad (D.4)$$

According to mass-action equations, the concentrations of aqueous and exchanged complexes  $c_k$  and  $c_z$  can be expressed as functions of concentrations of the primary species  $c_j$ . Kinetic rates  $r_n$  and  $r_l$  are functions of  $c_j$ . The expression for  $r_n$  is given in Eq. B.6 in Appendix B, and  $r_l$  will be presented in Eq. B.2. Surface complexes are expressed as the product of primary species and an additional potential term  $\Psi$ . Additional equilibrium equations (Equation (B.42) or (B.43) depending on the surface complexation model have to be solved together with Equation (D.4). No

explicit expressions relate equilibrium mineral concentrations  $c_m$  to  $c_j$ . Therefore,  $N_P$  additional mass action equations (one per mineral) are needed, which are provided by Equation (B.5). At equilibrium we have the residual functions

$$F_m^p = SI_m = 0 \quad m = 1, \dots, N_P \quad (\text{D.5})$$

where  $SI_m$  is the  $m$ -th equilibrium mineral saturation index which is a function of  $c_j$  (see Equations B.4 and B.5 in Appendix B).  $N_C$  equations in (D.4) and  $N_P$  in (D.5) constitute a complete set of equations needed for  $N_C+N_P$  primary variables,  $(c_1, c_2, \dots, c_{N_C}, c_1, c_2, \dots, c_{N_P})$ . Denoting the set of primary variables collectively as  $X_i$  ( $i=1, 2, \dots, N_C+N_P$ ), using Newton-Raphson iteration we have

$$\sum_{i=1}^{N_C+N_P} \frac{\partial F_j}{\partial X_i} \Delta X_i = -F_j \quad j = 1, \dots, N_C + N_P \quad (\text{D.6})$$

where  $j$  is a row index and  $i$  is a column index (here  $j$  as a row index can be thought of as also representing an “extended” basis set including the equilibrium minerals). In matrix form Eqs. (D.6) reduce to

$$\mathbf{J} \Delta \mathbf{X} = -\mathbf{F} \quad (\text{D.7})$$

where  $\mathbf{J}$  is the so-called Jacobian matrix. The matrix elements are evaluated in Appendix E. The values of  $\Delta X_i$  are used to update the primary variables:

$$X_i^{s+1} = X_i^s + \Delta X_i^s \quad (\text{D.8})$$

where  $s$  labels iteration number. The  $|\Delta X_i|$  are expected to decrease in successive iterations. The system of equations is considered satisfactorily solved when

$$\max_j \left( \frac{|F_j^c|}{T_j^0} \right) \leq \tau \quad j = 1, \dots, N_C \quad (\text{D.9})$$

where  $\tau$  is specified tolerance limit. In order to avoid negative values for concentrations of the basis species, the relative change is restricted to one (called under-relaxation), or

$\frac{|\Delta X_i|}{X_i} < 1 \quad i = 1 \dots N_C + N_P + N_S \quad (i = 1 \dots N_C)$ . As a consequence, although the iteration method

becomes more robust, the rate of convergence may slow down in some cases. When a negative value of  $X_i$  ( $i = N_C + 1, \dots, N_C + N_P$ ) is obtained, the corresponding mineral is considered exhausted and must be removed from the chemical system, and its corresponding equation disappears (Reed, 1982). In this case, the speciation in solution may change drastically. This might have a strong effect on kinetic rate laws. So when a change occurs in the mineral assemblage, one might have to limit the time step to retain accuracy in rate law integration. In addition, for a given time step the code checks that dissolution of a mineral cannot be greater than the amount present in the medium, in order to avoid “over-dissolution”.

The solution of the reaction system requires knowing initial total concentrations of basis species  $j$  in the equilibrium system (aqueous and mineral), and the time step  $\Delta t_r$ . Adding kinetic mineral dissolution/precipitation processes does not require additional primary equations, because the reaction rate is a function of the concentrations of the basis species. Once the concentrations of the basis species are obtained, all other secondary variables can be computed in a straightforward manner.

## Appendix E Evaluation of the Jacobian Matrix for the Chemical Equations

The final Jacobian matrix has  $N_C + N_P + N_\psi$  rows and  $N_C + N_P + N_\psi$  columns, as follows:

$$\begin{array}{ccc}
 & N_C & N_P & N_\psi \\
 N_C & \frac{\partial F_j^c}{\partial c_i} & \frac{\partial F_j^c}{\partial p_i} & \frac{\partial F_j^c}{\partial \tilde{\psi}} \\
 N_P & \frac{\partial F_j^p}{\partial c_i} & \frac{\partial F_j^p}{\partial p_i} & \frac{\partial F_j^p}{\partial \tilde{\psi}} \\
 N_\psi & \frac{\partial F_j^{\tilde{\psi}}}{\partial c_i} & \frac{\partial F_j^{\tilde{\psi}}}{\partial p_i} & \frac{\partial F_j^{\tilde{\psi}}}{\partial \tilde{\psi}}
 \end{array} \quad (\text{E.1})$$

The entries of the Jacobian matrix are

$$J^{cc} = \frac{\partial F_j^c}{\partial c_i} = \delta_{ji} + \sum_{k=1}^{N_x} \nu_{kj} \nu_{ik} \frac{c_k}{c_i} + \sum_{n=1}^{N_q} \nu_{nj} \nu_{in} \frac{k_n A_n \Omega_n}{c_i} + \sum_{s=1}^{N_S} \nu_{sj} \nu_{is} \frac{c_s}{c_i} \quad (\text{E.2})$$

$$J^{cp} = \frac{\partial F_j^c}{\partial p_i} = v_{mj} \quad (\text{E.3})$$

$$J^{pc} = \frac{\partial F_j^p}{\partial c_i} = \frac{v_{mj}}{c_i} \quad (\text{E.4})$$

$$J^{pp} = \frac{\partial F_j^p}{\partial p_i} = 0 \quad (\text{E.5})$$

$$J^{c\tilde{\psi}} = \frac{\partial F_j^c}{\partial \tilde{\psi}} = \sum_{s=1}^{N_s} v_{sj} z_s c_s \quad (\text{E.6})$$

$$J^{\tilde{\psi}c} = \frac{\partial F^{\tilde{\psi}}}{\partial c_i} = - \sum_{s=1}^{N_s} z_s v_{is} \frac{c_s}{c_i} \quad (\text{E.7})$$

or

$$J^{\tilde{\psi}c} = \frac{\partial F^{\tilde{\psi}}}{\partial c_i} = \frac{F^2}{A \varepsilon \varepsilon_0 \kappa R T} \sum_{s=1}^{N_s} z_s v_{is} \frac{c_s}{c_i} \quad (\text{E.8})$$

or

$$J^{\tilde{\psi}c} = \frac{\partial F^{\tilde{\psi}}}{\partial c_i} = \frac{F^2}{ACRT} \sum_{s=1}^{N_s} z_s v_{is} \frac{c_s}{c_i} \quad (\text{E.9})$$

$$J^{\tilde{\psi}\tilde{\psi}} = \frac{\partial F^{\tilde{\psi}}}{\partial \tilde{\psi}} = -\frac{1}{2} (\delta R T \varepsilon \varepsilon_0 I \times 10^3)^{1/2} \cosh(-\tilde{\psi}/2) - \frac{F}{A} \sum_{k=1}^{N_s} z_k z_k y_k \quad (\text{E.10})$$

or

$$J^{\tilde{\psi}\tilde{\psi}} = \frac{\partial F^{\tilde{\psi}}}{\partial \tilde{\psi}} = \frac{F^2}{A \varepsilon \varepsilon_0 \kappa R T} \sum_{s=1}^{N_s} z_s z_s c_s + 1 \quad (\text{E.11})$$

or

$$J^{\tilde{\psi}\tilde{\psi}} = \frac{\partial F^{\tilde{\psi}}}{\partial \tilde{\psi}} = \frac{F^2}{ACRT} \sum_{s=1}^{N_s} z_s z_s c_s + 1 \quad (\text{E.12})$$

## Appendix F Effects of Mineral Precipitation/Dissolution on Hydrologic Properties

---

### F.1 Porosity Changes

---

Porosity changes in matrix and fractures are directly tied to the volume changes as a result of mineral precipitation and dissolution. The molar volumes of minerals created by hydrolysis reactions (i.e., anhydrous phases, such as feldspars, reacting with aqueous fluids to form hydrous minerals such as zeolites or clays) are often larger than those of the primary reactant minerals;

therefore, constant molar dissolution-precipitation reactions may lead to porosity reductions. Porosity changes are taken into account in the code as follows:

The porosity  $\phi$  of the medium (fracture or matrix) is given by

$$\phi = 1.0 - \sum_{m=1}^{nm} \phi_m - \phi_u \quad (\text{F.1})$$

where  $nm$  is the number of minerals,  $\phi_m$  is the volume fraction of mineral  $m$  in the rock ( $V_{\text{mineral}}/V_{\text{medium}}$ , including porosity), and  $\phi_u$  is the volume fraction of unreactive rock. As the  $\phi_m$  of each mineral changes, the porosity is recalculated at each time step. The porosity is not allowed to go below zero.

Several options are available in TOUGHREACT to compute permeability changes as a result of mineral precipitation and/or dissolution. Some options depend solely on porosity changes, whereas others employ options related to, for example, fracture aperture changes or pore throat diameter changes.

## F.2 Fracture Permeability Changes

---

Option 3: Fracture permeability changes can be approximated using the porosity change and an assumption of plane parallel fractures of uniform aperture (cubic law; e.g., Steefel and Lasaga, 1994). The modified permeability,  $k$ , is then given by

$$k = k_i \left( \frac{\phi}{\phi_i} \right)^3 \quad (\text{F.2})$$

where  $k_i$  and  $\phi_i$  are the initial permeability and porosity, respectively. This law yields zero permeability only under the condition of zero fracture porosity.

Option 4: In most experimental and natural systems, permeability reductions to values near zero occur at porosities significantly greater than zero. This generally is the result of mineral precipitation in the narrower interconnecting apertures. The hydraulic aperture, as calculated from the fracture spacing and permeability (as determined through air-permeability measurements) assuming a cubic law relation, is a closer measure of the smaller apertures in the flow system. Using the hydraulic aperture, a much stronger relationship between permeability and porosity can be developed. This relationship can be approximated as follows:

The initial hydraulic aperture  $b_{0,h}$  (m) is calculated using the following cubic law relation:

$$b_{0,h} = [12k_0s]^{1/3} \quad (\text{F.3})$$

where  $k_0$  is the initial fracture permeability ( $\text{m}^2$ ) and  $s$  is the fracture spacing (m). The permeability ( $k'$ ) resulting from a change in the hydraulic aperture, is given by

$$k' = \frac{(b_{0,h} + \Delta b)^3}{12s} \quad (\text{F.4})$$

where  $\Delta b$  is the aperture change resulting from mineral precipitation/dissolution.

The aperture change resulting from a calculated volume change can be approximated by assuming precipitation of a uniform layer over the entire geometric surface area of the fracture, assuming also that this area as well as the fracture spacing remains constant. The actual distribution of mineral alteration is much more heterogeneous and depends on many processes that are active at scales much smaller than the resolution of the model; however, the combined effect of the initial heterogeneities and localized precipitation processes can only be treated through model sensitivity studies and experiments.

For a dual permeability model, changes in the fracture porosity are calculated based on the porosity of the fracture medium, so that  $\Delta b$  can be approximated by

$$\Delta b = \frac{(\phi'_{fm} - \phi_{fm,0})}{\phi_{fm,0}} b_g \quad (\text{F.5})$$

Equations (F.3), (F.4), and (F.5) were implemented in TOUGHREACT with input parameters of  $b_g$  and  $s$ . An example of this type of porosity and permeability relationship is given in Sample Problem 4 (Section 8.11: Heater Test).

In this example problem, the initial aperture available for precipitation ( $b_g$ , the geometric aperture, rather than the hydraulic aperture) was estimated from the ratio of the initial fracture porosity ( $\phi_{f,0}$ ) to the fracture surface area ( $A_f$ ), as follows:

$$b_g = \phi_{f,0} / A_f \quad (\text{F.6})$$

However, the user can, of course, use any methodology to calculate the geometric aperture.

### F.3 Matrix Permeability Changes

---

Option 1: Matrix permeability changes are calculated from changes in porosity using ratios of permeabilities calculated from the Carman-Kozeny relation (Bear, 1972), and ignoring changes in grain size, tortuosity and specific surface area as follows:

$$k = k_i \frac{(1-\phi)^2}{(1-\phi_i)^2} \left( \frac{\phi}{\phi_i} \right)^3 \quad (\text{F.7})$$

Option 2: Modified Hagen-Poiseuille Law. Studies on predicting the permeability of clastic rocks commonly found in sedimentary basins (e.g., sandstones and carbonate rocks) have shown that the permeability can be predicted using a form of the Hagen-Poiseuille equation and knowledge of the pore size distribution, pore throat size, and pore type (Ehrlich et al. 1991). In this study, pore throat sizes and distributions were obtained through a combination of mercury intrusion porosimetry, petrographic image analysis, and image processing.

Option 5: The simple cubic law (Eq. F.2) and the Kozeny-Carman (Eq. F.7) porosity-permeability equations may not reflect the complex relationship of porosity and permeability in geologic media that depends on an interplay of many factors, such as pore size distribution, pore shapes, and connectivity (Verma and Pruess, 1988). Laboratory experiments have shown that modest reductions in porosity from mineral precipitation can cause large reductions in permeability (Vaughan, 1987). Detailed analysis of a large set of field data also indicated a very strong dependence of permeability on small porosity changes (Pape et al., 1999). This is explained by the convergent-divergent nature of natural pore channels, where pore throats can become clogged by precipitation while disconnected void spaces remain in the pore bodies (Verma and Pruess, 1988). The permeability reduction effects depend not only on the overall reduction of porosity, but on the details of the pore space geometry and the distribution of precipitates within the pore space. These may be quite different for different media, which makes it difficult to achieve generally applicable predictions. To evaluate the effects of a more sensitive coupling of permeability to porosity, we also implemented a porosity-permeability relationship presented by Verma and Pruess (1988):



$$\frac{k}{k_i} = \left( \frac{\phi - \phi_c}{\phi_i - \phi_c} \right)^n \quad (\text{F.8})$$

where  $\phi_c$  is the value of “critical” porosity at which permeability goes to zero, and  $n$  is a power law exponent. Parameters  $\phi_c$  and  $n$  are medium-dependent. An example of this porosity-permeability relationship is given in Sample problem 8 (Section 8.8: Injection well scaling).

#### F.4 Effects of Permeability and Porosity Changes on Capillary Pressures

---

Permeability and porosity changes will likely result in modifications to the unsaturated flow properties of the rock. For cylindrical pore throats changes to unsaturated flow properties are approximated by modification of the calculated capillary pressure ( $P_c$ ) using the Leverett scaling relation (Slider, 1976) to obtain a scaled  $P_c'$  as follows:

$$P_c' = P_c \sqrt{\frac{k_i \phi}{k \phi_i}} \quad (\text{F.9})$$

For fractures, the capillary pressures are scaled assuming channel flow,

$$P_c' = P_c \left( \frac{k_i \phi}{k \phi_i} \right)^{1/3} \quad (\text{F.10})$$

Since many problems may involve fractures and rock matrix (e.g., dual-permeability), a third option allows for a linear porosity-dependent scaling between capillaries and channels (fractures), as follows:

$$P_c' = P_c \left( \frac{k_i \phi}{k \phi_i} \right)^{[0.5(1 - \phi) + (1/3)\phi]} \quad (\text{F.11})$$

This relation assumes that grid blocks having porosities equal to 1.0 are solely fractures, and in the limit that the porosity goes to 0.0, solely matrix. Porosities between 0.0 and 1.0 are considered to be "equivalent continua", composed of fractures and matrix.

Scaled capillary pressures are subject to the maximum capillary pressure prescribed in the capillary pressure function in the ROCKS or RPCAP blocks (see TOUGH2 V.2 users manual).

#### Appendix G Mineral Reactive Surface Areas

---

This appendix describes how input values of surface areas are used to calculate the reactive surface area needed for kinetic rate laws (e.g., in equations B.6 and B.9). The general methodology

implemented into TOUGHREACT is presented first (Section G.1), followed by suggestions on how to calculate and input surface areas for fractures (Section G.2) and a porous rock matrix (Section G.3). Surface areas are input as variable AMIN on record Imin-6.1 (in file chemical.inp), using a choice of units defined by flag IMFLG on the same input record. Note that any approach may be used to calculate input surface areas as long as the correct units are entered for the specified value of IMFLG.

## G.1 General Methodology

---

The following general relationship is implemented into TOUGHREACT to compute reactive surface areas of minerals:

$$A_r = (V_{frac} A_m + A_{prc}) / C_w \quad (G.1)$$

with:

$A_r$	Effective reactive surface area of minerals in units of $m^2_{\text{mineral}}/kg_{\text{water}}$ for input into kinetic rate laws (e.g. equations B.6 and B.9)
$A_m$	Surface area of minerals in units of $m^2_{\text{mineral}}/m^3_{\text{mineral}}$
$A_{prc}$	Precursor surface area (optional) in units of $m^2_{\text{surface}}/m^3_{\text{medium}}$
$V_{frac}$	Mineral volume fraction in units of $m^3_{\text{mineral}}/m^3_{\text{medium}}$
$C_w$	Wetted-surface conversion factor in units of $kg_{\text{water}}/m^3_{\text{medium}}$

The values of  $A_m$ ,  $V_{frac}$ , and  $C_w$  change in the course of a simulation as minerals dissolve and precipitate, and as the liquid saturation of the medium fluctuates.  $A_m$  is computed, in part, from input surface areas.  $A_{prc}$ , however, is an input parameter that remains constant in the course of a simulation. Various approaches are followed to compute  $A_m$ ,  $V_{frac}$ , and  $C_w$  from input parameters and/or model assumptions, depending on whether a mineral is present or not, which type of surface area model is selected, which type of medium is considered (fractures or matrix), and which units are chosen to input surface areas. Approaches followed to compute these variables are described below.

**Mineral volume fraction  $V_{frac}$ .** For all minerals (initially present or not) included in a simulation, a minimum value of  $V_{frac}$  is calculated as

$$V^0_{frac} = \text{maximum} ( \text{RNUCL}(1-\phi_{med}); 10^{-15} ) \quad (G.2)$$

where RNUCL is an assumed minimum volume fraction (in  $\text{m}^3_{\text{mineral}}/\text{m}^3_{\text{solids}}$ ) (entered on record Miner-2.2 in file chemical.inp) and  $\phi_{med}$  is the porosity of the medium. When a mineral is not initially present (i.e., case of a secondary phase that forms during a simulation),  $V_{frac}$  in Equation (G.1) always takes the value of  $V_{frac}^0$ . For minerals that are present in the modeled system,  $V_{frac}$  is initially computed from input mineral volume fractions  $f_m$  (in  $\text{m}^3_{\text{mineral}}/\text{m}^3_{\text{solids}}$ ) (VOL on record Imin-6 in file chemical.inp) and porosity of the medium ( $\phi_{med}$ , read in flow.inp or INCON files) as:

$$V_{frac} = f_m (1 - \phi_{med}) \quad (\text{G.3})$$

The values of  $V_{frac}$  are then continuously updated from the computed amounts of minerals, as these dissolve and/or precipitate. Note that if, at any time,  $V_{frac}$  is less than  $V_{frac}^0$ , the value of  $V_{frac}^0$  is used instead of  $V_{frac}$  in equation (G.1).

**Surface area  $A_m$ .** Values of  $A_m$  are calculated as

$$A_m = A_m^0 + A_{nucl} \quad (\text{G.4})$$

$A_m^0$  is the input mineral surface area (AMIN, if IMFLG $\neq$ 3, on record Imin-6.1 in chemical.inp). It is always internally converted to units of  $\text{m}^2_{\text{mineral}}/\text{m}^3_{\text{mineral}}$ .  $A_{nucl}$  is a surface area used to approximate nucleation effects (this is not a nucleation model!) By default,  $A_{nucl}$  is always set to zero if the value of RAD (on record Imin-6.1 in file chemical.inp) is set to zero. If RAD  $\neq$  0, a simple model is implemented to compute  $A_{nucl}$  as a function of mineral grain size, with RAD entered as the initial grain radius (in m). This is done by assuming simple cubic packing of spherical grains of radius  $r$ . This cubic arrangement of spheres yields, in a cube of side  $4r$  and volume  $(4r)^3$ , a total of 8 spheres, each of radius  $r$ , volume  $4/3 \pi r^3$ , and area  $4\pi r^2$ . Thus the surface area  $A_{nucl}$  (as the area of the spheres divided by the volume of the cube) is computed as

$$A_{nucl} = 0.5/r \quad (\text{G.5})$$

For minerals not initially present,  $r$  is initially taken as the value of RAD (in m). Only on precipitation, the value of  $r$  is increased as the mineral forms, such that  $A_{nucl}$  decreases with increasing mineral amounts. This is accomplished by tying the increase of  $V_{frac}$  to  $r$  through a variable,  $n_{grain}$ , expressing the number of mineral grains per volume medium as follows

$$n_{grain} = 0.125 V_{frac} / r^3 \quad (G.6)$$

Equation (G.6) is also derived assuming simple cubic packing of spherical grains. For minerals not initially present, the number of mineral grains is initially calculated using Equation (G.6) with  $V_{frac} = V_{frac}^0$  and  $r = RAD$ . At subsequent time steps, as  $V_{frac}$  increases with mineral precipitation,  $n_{grain}$  is decreased proportionally to  $V_{frac} / V_{frac}^0$  (an assumption) and the grain radius is recomputed by re-expressing Equation (G.6) to yield values of  $r$ :

$$r = \sqrt[3]{\frac{0.125 V_{frac}}{n_{grain}}} \quad (G.7)$$

As  $r$  grows and  $n_{grain}$  diminishes,  $A_{nucl}$  decreases to a point when  $A_{nucl} \ll A_m^0$  and  $A_m \approx A_m^0$  in Equations (G.4) and (G.1). On precipitation, because  $n_{grain}$  is forced to decrease,  $A_r$  also decreases as  $r$  grows, as long as  $A_{nucl} > A_m^0$ . In contrast, on dissolution,  $n_{grain}$  is kept constant (i.e., not recomputed), such that if  $A_{nucl} > A_m^0$ ,  $A_r$  always keeps decreasing with decreasing  $r$  (as seen by substituting Equations G.3, G.4, and G.5 into Equation G.1).

**Wetted-surface conversion factor  $C_w$ .** This conversion factor (in units of  $\text{kg}_{\text{water}}/\text{m}^3_{\text{medium}}$ ) usually takes the form

$$C_w = \rho_w \phi_{med} S_w \quad (G.8)$$

where  $\rho_w$  is the water density (kg/L),  $\phi_{med}$  is the porosity of the medium, and  $S_w$  is liquid saturation. For a fully saturated system,  $S_w = 1$ . For an unsaturated system,  $S_w < 1$ . However, as  $S_w$  goes to zero,  $C_w$  goes to zero, and therefore the wetted reactive surface area  $A_r$ , which is proportional to  $1/C_w$  (Equation G.1), tends to infinity. Clearly, at a very low liquid saturation, the surface area of the rock contacted by water is likely much smaller than the total area. Two methods are implemented to address this problem. The first method assumes that the wetted surface area diminishes proportionately to the liquid saturation. This behavior is achieved by multiplying the right side of Equation (G.1) by  $S_w$ . This cancels out  $S_w$  in Equation (G.8), such that the quantity  $C_w$  in Equation (G.1) becomes, in effect

$$C_w = \rho_w \phi_{med} \quad (G.9)$$

This method is implemented for both porous media and fractured systems. However, an other method is applied for fractured systems if the active-fracture model is enabled (which is done by specifying non-zero active-fracture parameters (CP(6), in the third record of the ROCKS block in file flowinp). This method employs the active-fracture-model of Liu et al. (1998) modified to consider water-rock reactions taking place below the residual saturation in fractures. The form of the active fracture parameter for reaction is given by the following set of equations:

$$S_{ar} = (S_w - S_m)/(1-S_m) \quad (\text{G.10})$$

$$a_{fmr} = S_{ar}^{(1+\gamma)} \quad (\text{G.11})$$

where  $S_m$  is the minimum liquid saturation for which water-rock reactions are considered (input parameter SL1MIN on Record-3 in file solute.inp),  $S_{ar}$  is an effective saturation for reaction, and  $\gamma$  is the active fracture parameter. The factor that reduces the surface area contacted by water is given by  $a_{fmr}$ . Generally,  $S_m$  is set to a small value (e.g.,  $1 \times 10^{-4}$ ), to ensure that reactions take place until virtually no water is left (e.g., during dryout via ventilation or heating). Using this model, the quantity  $C_w$  is computed as

$$C_w = \rho_w \phi_{med} S_w / a_{fmr} \quad (\text{G.12})$$

## G.2 Estimation of Surface Areas for Fractures

---

In the dual permeability method, the porosity of the fracture medium could be taken as 1.0. However, for modeling of mineral dissolution and precipitation, there would then be no rock to dissolve. Therefore, a non-zero fracture-medium porosity ( $\phi_{med}$ ) must always be assumed for input into simulation (typically  $0.5 < \phi_{med} < 0.9$ ; this porosity is not to be confused with the true fracture porosity  $\phi_f$ ). If the dissolution rates of minerals are small (which is the case for many minerals at temperatures below 100°C), only a small volume of rock adjoining the open space of the fracture needs to be considered as the starting rock fraction (i.e.,  $\phi_{med}$  can be large, as long as  $< 1$ ).

Reactive surface areas of minerals on fracture walls can be calculated from the fracture-matrix interface area/volume ratio, the fracture porosity, and the derived mineral volume fractions. These areas can be calculated based on the fracture densities, fracture porosities, and mean fracture diameter. The wall of the fracture can be treated as a surface covered by mineral grains having the

form of uniform hemispheres. The grain diameter and spatial density are not considered in this method, so that the area is actually only marginally greater than the fracture geometric surface area. Using this approach, the geometric surface area of the fracture wall can be approximated by:

$$A = \frac{\pi A_{f-m}}{2\phi_f} \quad (\text{G.13})$$

where  $A$  is the “reactive” surface area (in units of  $\text{m}^2_{\text{reactive surface}}/\text{m}^3_{\text{fracture medium}}$ ),  $A_{f-m}$  is the fracture-matrix interface area/volume ratio (in units of  $\text{m}^2_{\text{reactive surface}}/\text{m}^3_{\text{total fracture+matrix medium}}$ ), and  $\phi_f$  is the true fracture porosity of the rock. The factor of  $\pi/2$  is a roughness factor equal to the actual surface area of solid grains on the fracture plane, divided by the fracture plane surface, given by cubic packing of spherical grains.

Surface areas calculated using Equation (G.13) are input as AMIN with IMFLG=3 on record Imin-6.1 in file chemical.inp. In this case, input AMIN values correspond to  $A_{prc}$  in Equation (G.1), and values of  $A_m^0$  in Equation (G.4) are internally set to zero (therefore  $A_m = A_{nucl}$  in Equation G.1). In this scenario,  $A$  in Equation G.13 is assumed to be the same for all minerals.

An alternative is to consider mineral proportions in the surface coverage of fractures. Assuming that the fracture coverage for each mineral is proportional to the mineral volume fraction,  $V_{frac}$ , the surface area for each mineral,  $A'$  (in units of  $\text{m}^2_{\text{mineral}}/\text{m}^3_{\text{fracture medium}}$ ) can be calculated as

$$A' = A V_{frac} \quad (\text{G.13})$$

Values of  $A'$  calculated in this way are input as AMIN with IMFLG=2 on record Imin-6.1 in file chemical.inp. For minerals not initially present,  $V_{frac}$  in Equation (G.13) must be taken as  $V_{frac}^0$  (Equation G.2) for internal consistency. In this case, the input AMIN values correspond to  $A_m^0$  in Equation (G.1), and  $A_{prc}$  in this equation is internally set to zero.

### **G.3 Estimation of Surface Areas in the Rock Matrix (Porous Medium)**

---

One method to calculate the reactive surface areas of minerals in a rock or granular material is to use a geometric area of a cubic array of truncated spheres to make up the framework of the rock (Sonnenthal and Ortoleva, 1994). Clay minerals can be considered as coatings of plate-like grains. The mineral surface areas of framework grains (truncated spheres) in contact with the open

pore space can be calculated using an initial grain diameter, followed by successive truncation of the grains in the vertical direction until the porosity of this system is close to the measured porosity of the rock. The abundance of secondary phases (i.e., those that formed as alteration products or low-temperature coatings on the primary assemblage), such as clay minerals, can be used to reduce the free surface area of the framework grains. The surface areas of the secondary phases can be calculated based on their size and morphology.

A more approximate but very simple method is to consider geometric surface areas for either single sphere, simple cubic packing of untruncated spheres, or cubic-centered packing of untruncated spheres. The surface area is obtained by dividing the area of the spheres by the volume of the spheres (for the various packing arrangements) as shown below.

Single sphere – area  $4\pi r^2$ , volume  $4/3 \pi r^3$ :

$$A = 3/r \quad (\text{G.14})$$

Simple cubic packing – 8 spheres of total area  $8 \times 4\pi r^2$ , in a cube of volume  $(4r)^3$ :

$$A = 0.5/r \quad (\text{G.15})$$

Cubic-close packing – 4 spheres of total area  $4 \times 4\pi r^2$ , in a cube of volume  $(2\sqrt{2}r)^3$ :

$$A = \pi / (\sqrt{2}r) = 2.22/r \quad (\text{G.16})$$

Note that differences in the constant terms in these equations are much smaller than the typical order-of-magnitude uncertainty of surface areas. If the grain radius  $r$  is in units of m, values of  $A$  calculated in this way are in units of  $\text{m}^2_{\text{mineral}}/\text{m}^3_{\text{mineral}}$  and can be input directly as AMIN with flag IMFLG=1 in record Imin-6.1 (in file chemical.inp). Surface areas in units of  $\text{cm}^2/\text{g}$  can be calculated from

$$A' = 100 A / \rho_m = 100 A M_m / V_m \quad (\text{G.17})$$

where  $\rho_m$ ,  $M_m$  and  $V_m$  are the mineral density in  $\text{g}/\text{cm}^3$ , molecular weight in mol/g, and molar volume in  $\text{cm}^3/\text{mol}$  ( $M_m$  and  $V_m$  can be taken from record Mineral-1 in the thermodynamic database). In this case,  $A'$  is entered (in file chemical.inp) as AMIN with flag IMFLG=0 on record Imin-6.1.

## Appendix H Calculation of Activity and Fugacity Coefficients

---

### H.1 Extended Debye-Hückel Model for Ionic Species and Water

---

Activity coefficients of charged aqueous species and the water activity are computed using the extended Debye-Hückel model presented by Helgeson et al. (1981), often referred to as the HKF model (for Helgeson, Kirkham, and Flowers). We will use this acronym, below, to refer to the model, its authors, or their published paper.

The HKF model is applied making the assumption that the dominant cation and anion in solution are sodium and chloride, respectively, which entails limits on the model applicability. In addition, the Debye-Hückel model, even if extended, technically only applies to dilute solutions. For this reason, for applications at elevated ionic strengths ( $> \sim 1$  molal), the model should be very carefully applied, with full knowledge its limitations, as discussed further below. Note that at ionic strength  $< \sim 1$  molal, the HKF model yields results very close to the more commonly used “b-dot” extended Debye-Hückel model (Helgeson, 1969). Details on the formulation of activity coefficients for charged species, water activity, and the HKF model applicability are presented below in Sections H.1.1, H.1.2, and H.1.3, respectively.

#### H.1.1 Activity Coefficients of Charged Aqueous Species

---

The assumption is made that the dominant cation and anion in solution are sodium and chloride, respectively, so that HKF Equation (298) can be used directly, as follows:

$$\log(\gamma_j) = -\frac{A_\gamma z_j^2 I^{0.5}}{\Lambda} + \log(1 + 0.0180153 \text{ m}^*) - [\omega_j b_{\text{NaCl}} + b_{\text{Na}^+, \text{Cl}^-} - 0.19 (|z_j| - 1)] I \quad (\text{H.1})$$

and

$$\Lambda = 1 + a B_\gamma \bar{I}^{1/2} \quad (\text{H.2})$$

$$\omega_j = \eta \frac{z_j^2}{r_{e,j}} \quad (\text{H.3})$$

where the subscript  $j$  refers to each ion,  $\gamma$  is the activity coefficient of the ion, Debye-Hückel parameters  $b_{\text{Na}^+, \text{Cl}^-}$ ,  $b_{\text{NaCl}}$ ,  $A_\gamma$  and  $B_\gamma$  are given in HKF Tables 1, 29, and 30, Debye-Hückel



parameter  $\text{\AA}$  is calculated as discussed below,  $z$  is the ion electric charge,  $I$  is taken as the true ionic strength of the solution,  $\omega$  is the Born coefficient,  $\eta$  is a constant equal to 1.66027 ( $\text{\AA cal/mol}$ ), and  $r_{e,j}$  is the effective ionic radius given in HKF Table 3 or estimated as shown on Table H-1 when not available.

Debye-Huckel parameters  $b_{\text{Na}^+, \text{Cl}^-}$ ,  $b_{\text{NaCl}}$ ,  $A\gamma$  and  $B\gamma$  were regressed as a function of temperature and the resulting functions and regression coefficients are currently built into TOUGHREACT. Values of  $\text{\AA}$  are calculated by TOUGHREACT using effective ionic radii  $r_{e,j}$ . Making the assumption that NaCl is the dominant electrolyte, and using the ion charge to determine stoichiometry coefficients, HKF Equation (125) simplifies to (as implemented in models by Reed, 1982):

$$\text{\AA}_j = 2 (r_{e,j} + 1.91 |z_j|) / (|z_j| + 1) \text{ for anions} \quad (\text{H.4})$$

$$\text{\AA}_j = 2 (r_{e,j} + 1.81 |z_j|) / (|z_j| + 1) \text{ for cations} \quad (\text{H.5})$$

where the subscript  $j$  refers to each ion and other parameters are as defined above. The values of 1.91 and 1.81 in the above equations correspond to  $r_{e,\text{Na}^+}$  and  $r_{e,\text{Cl}^-}$ , respectively. Values of  $r_{e,j}$  are input from the TOUGHREACT database and can be changed as deemed necessary in this database.

**Table H-1** Estimated values of effective ionic radii ( $r_{e,j}$ ) currently in the TOUGHREACT thermodynamic database for species that are not reported in HKF Table 3. When available, values from HKF Table 3 are used directly instead of those shown here.

Ionic Charge	$r_{e,j}$	Source
-1	1.81	Cl- value
-2	3.00	Rounded average of CO3-- and SO4-- values
-3	4.2	Estimated from straight line fit with charge
+1	2.31	NH4+ value
+2	2.8	Rounded average for +2 species in HKF Table 3
+3	3.6	Rounded average for +3 species in HKF Table 3
+4	4.5	Estimated using HKF Equation 142 and average crystallographic radii of +4 species in CRC Handbook
< -3		Linear Extrapolation (charge $\times$ 4.2/3.0)
> +3		Linear Extrapolation (charge $\times$ 4.5/4.0)

## H.1.2 Activity of Water

---

First, a simplification of HKF Equation (190) is used to compute the osmotic coefficient of the solution,  $\Phi$ , as follows:

$$\Phi = -\frac{2.303}{m^*} \sum_j \left[ m_{t,j} \left[ \frac{A_\gamma z_j^2 \bar{I}^{0.5} \sigma}{3} + \frac{\log(1 + 0.0180153 m^*)}{0.0180153 m^*} - 0.5 (\omega_j b_{\text{NaCl}} \bar{I}) + (b_{\text{Na}^+, \text{Cl}^-} - 0.19 (|z_j| - 1)) \frac{mchr}{2} \right] \right] \quad (\text{H.6})$$

with

$$\sigma = \frac{3}{\text{a} B_\gamma \bar{I}^{3/2}} \left[ \Lambda - \frac{1}{\Lambda} - 2 \ln(\Lambda) \right]$$

and with

$$\Lambda = 1 + \text{a} B_\gamma \bar{I}^{1/2} \quad \text{and} \quad \omega_j = \eta \frac{z_j^2}{r_{e,j}}$$

where the subscript  $j$  refers to each charged species in solution,  $m^*$  is taken as the sum of the molalities of all species in solution,  $m_t$  is the total molality of each charged species,  $mchr$  is the sum of the molalities of all charged species, and  $\bar{I}$  is taken as the stoichiometric ionic strength. Other parameters are as defined for Equation (H.1). The simplifications made in Equation (H.6) assume dominance of NaCl in solution, and are essentially the same as the simplifications made to derive Equation (H.1). Two differences are the use of the stoichiometric ionic strength instead of the true ionic strength, and the use of  $mchr/2$  instead of true ionic strength. These modifications were made because they seemed to reproduce water activity data reported by Robinson and Stokes (1965) better than without these modifications. Once the osmotic coefficient is calculated, the water activity is then given by the HKF Equation (126), as:

$$\ln(a_w) = -\Phi m^* \frac{1}{55.51} \quad (\text{H.7})$$

## H.1.3 Applicability of the HKF Extended Debye-Hückel Model

---

It is recommended that users understand the HKF model and its limitations before applying it at ionic strengths greater than about  $\sim 1$  molal. The limits of applicability of this model depend,

in part, on how well the assumption of NaCl-dominance in solution is satisfied. Also, consistency between the activity coefficient model and the types of ion pairs included in the thermodynamic database is critical. Good examples are the  $\text{NaCl}^0$  and  $\text{CaCl}_2^0$  (and  $\text{CaCl}^+$ ) ion pairs. HKF fitted their Debye-Hückel parameters assuming that no significant formation of these ion pairs took place (i.e., the effect of these ion pairs are implicitly taken into account in the model parameters). Therefore, for applications at elevated ionic strengths ( $> \sim 1$  molal), good results are obtained only after removing these ion pairs from the thermodynamic database.

With careful testing for each particular system, including determination of which ion pairs to include (or not) into the thermodynamic database, this model can be applied to ionic strengths up to about 2 molal, and possibly up to 4 molal for simple salt systems. However, no general rule can be made as to the limits of applicability, except that we do not recommend using this model at ionic strengths greater than  $\sim 2$  molal, especially at higher temperatures. It should be noted that for salt mixtures, the model limit should be evaluated by the user on a case-by-case basis, taking into consideration the overall reactive transport model uncertainty and the goals of the modeling work. As a general guideline, an ionic strength limit of 2 molal may be appropriate for many applications, and values greater than 4 molal should not be considered.

To evaluate the range of model applicability for single salt systems, speciation calculations (one grid block, no transport) were run for solutions of various single salts. Results were then compared with published experimental data (Robinson and Stokes 1965; Colin et al. 1985; and Ananthaswamy and Atkinson, 1985). Only electrolyte activity can be measured, from which mean activity coefficients can be derived (individual activity coefficients cannot be measured). For this reason, individual activity coefficients activities calculated with the HKF model need to be converted for comparisons to measured data (or vice versa). For an electrolyte  $k$  (e.g., NaCl) consisting of ionic species  $j$  (e.g.,  $\text{Na}^+$  and  $\text{Cl}^-$ ), the mean activity coefficient,  $\gamma_{k\pm}$ , and electrolyte activity,  $a_k$ , can be related to the activity coefficients  $\gamma_j$  and activities  $a_j$  of individual ionic species using the following relationships (e.g., Robinson and Stokes, 1965, Equations 2.12, 2.8, and 2.13, respectively):

$$\gamma_{k\pm} = \left( \prod_j \gamma_j^{\nu_{j,k}} \right)^{1/\nu_k} \tag{H.8}$$

$$a_k = \prod_j (a_j)^{v_{j,k}} \quad (\text{H.9})$$

$$a_k = \prod_j (v_{j,k}^{v_{j,k}})(m_k \gamma_{k\pm})^{\sum_j v_{j,k}} \quad (\text{H.10})$$

where  $v_{j,k}$  are stoichiometric coefficients of ionic species  $j$  in electrolyte  $k$ , and  $m_k$  is the electrolyte molality. For comparison with literature data, computed activity coefficients for individual ions (output in file *chdump.out*) were converted to mean activity coefficients using Equation (H.8). Activities for individual ions were also calculated from individual molalities ( $m_j$ ) and activity coefficients ( $\gamma_j$ ) (using the relationship  $a_j = \gamma_j m_j$ ), then converted to mean activities using Equation (H.9). As necessary, Equation (H.10) was also used to convert mean activity coefficients from the literature data to mean activities. Finally, osmotic coefficients ( $\Phi$ ) from the literature were converted to water activities ( $a_{\text{H}_2\text{O}}$ ) using Equation (H.7). After these conversions, computed and measured data could be compared, with results summarized in Figure H-1 through Figure H-5, and in Table H-2. As noted above, computations without including the secondary species  $\text{NaCl}_{(\text{aq})}$ ,  $\text{CaCl}^+$ , and  $\text{CaCl}_2(\text{aq})$  in the thermodynamic database provide best results, because the HKF model was developed assuming no explicit ion association for these salts. At elevated ionic strengths ( $> 1$  molal), the model reproduces fairly well the mean activity coefficients of  $\text{NaCl}$  solutions up to at least 6M  $\text{NaCl}$  (ionic strength 6) (Figure H-1 and Figure H-4). The reverse is true for species like  $\text{MgSO}_4$  and  $\text{Na}_2\text{SO}_4$ , for which accurate activities cannot be computed without including the  $\text{MgSO}_4$  and  $\text{NaSO}_4^-$  species in the thermodynamic database, because the significant association of  $\text{Mg}$  and  $\text{Na}$  with  $\text{SO}_4$  was considered in the HKF model. In this case, using dissociation constants from Shock et al. (1989) for these species, mean activities determined by Robinson and Stokes (1965) at 25°C can be reproduced fairly well up to 2M  $\text{MgSO}_4$  (ionic strength = 8) and 1M  $\text{Na}_2\text{SO}_4$  (ionic strength = 3) (Figure H-2). Activity coefficients and activities in  $\text{CaCl}_2$  solutions are also reasonably reproduced up to about 1.5 m  $\text{CaCl}_2$  (ionic strength = 4.5 molal) (Figure H-5).

Figure H-1 Mean-ion activity coefficients of NaCl and CaCl<sub>2</sub> at 25°C derived from individual activity coefficients calculated with Equation (H.1). Symbols represent data from measurements by Robinson and Stokes (1965).

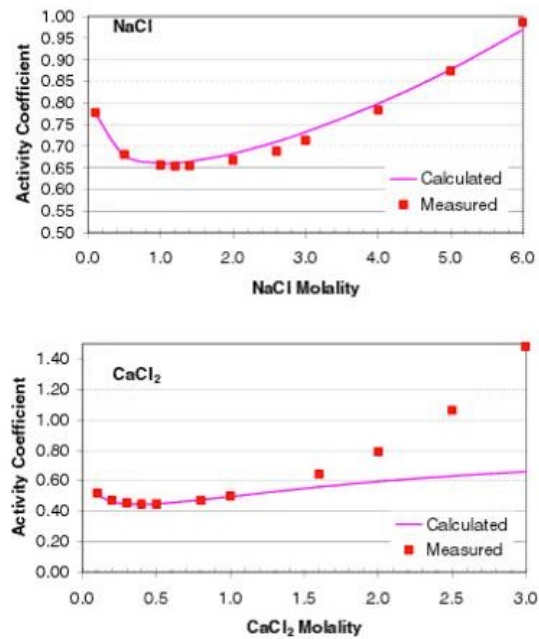


Figure H-2 Activities of MgSO<sub>4</sub> and Na<sub>2</sub>SO<sub>4</sub> at 25°C derived from individual activity coefficients calculated with Equation (H.1). Symbols represent data from measurements by Robinson and Stokes (1965). Actual activities, rather than activity coefficients, are compared here because significant ion association takes place.

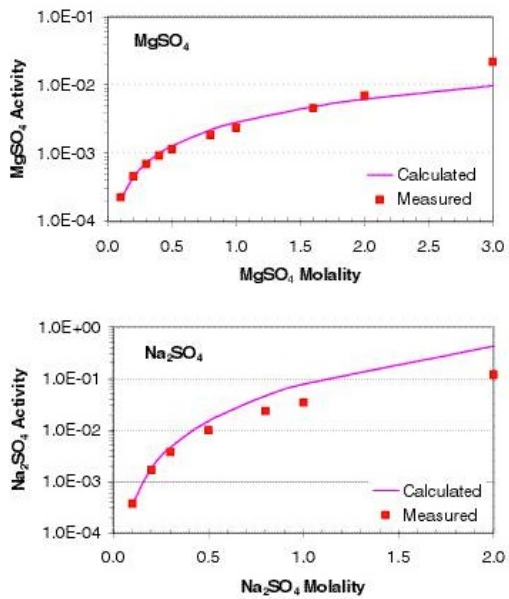


Figure H-3 Activities of water in NaCl and CaCl<sub>2</sub> solutions at 25°C calculated with Equations (H.6) and (H.7). Symbols represent data from measurements by Robinson and Stokes (1965).

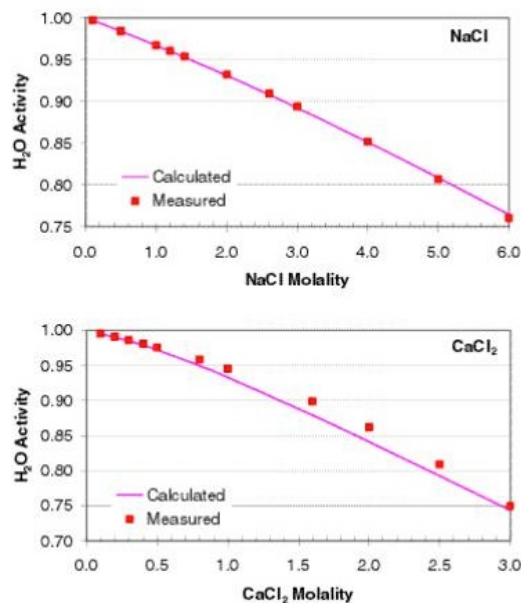


Figure H-4 Comparison of measured (Colin et al. 1985) and computed activities for NaCl solutions. Note that the NaCl<sub>(aq)</sub> species is excluded from the simulation for consistency with the activity coefficient model.

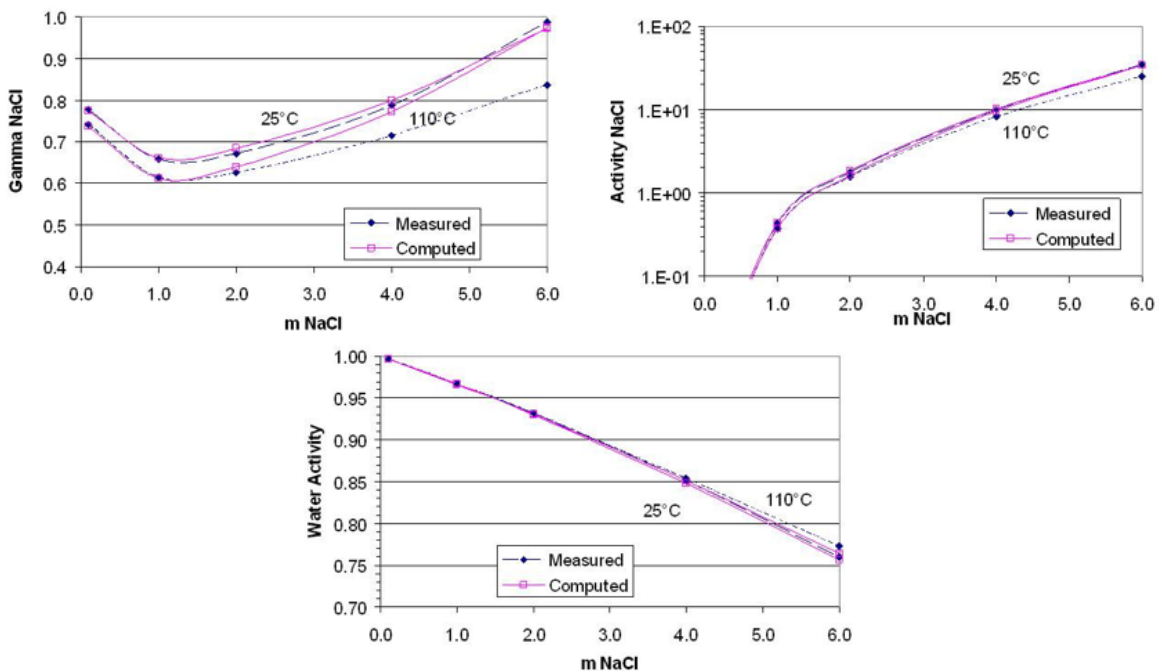


Figure H-5 Comparison of measured (Ananthaswamy and Atkinson, 1985) and computed activities for  $\text{CaCl}_2$  solutions. Note that the  $\text{CaCl}_{2(\text{aq})}$  and  $\text{CaCl}^+$  species are excluded from the simulation for consistency with the activity coefficient model.

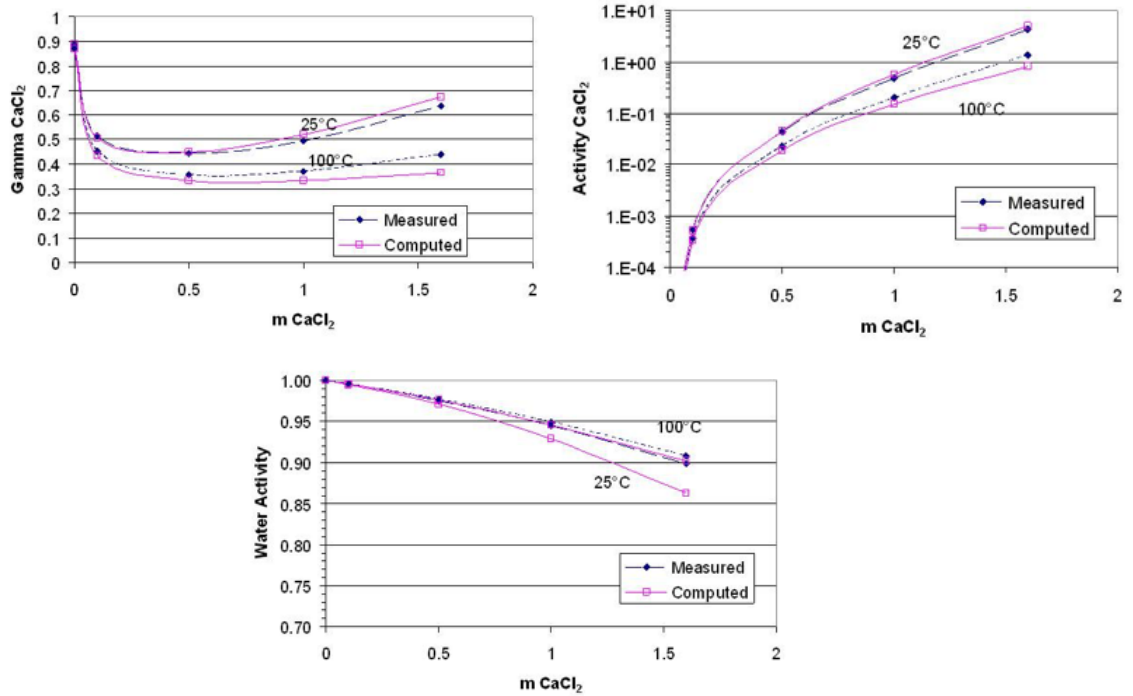


Table H-2 Comparison of measured and computed activity data for NaCl and CaCl<sub>2</sub> solutions. Note that the NaCl<sub>(aq)</sub>, CaCl<sup>+</sup>, and CaCl<sub>2(aq)</sub> secondary species are excluded from the simulation for consistency with the activity coefficient model.

			Mean activity coefficient			Mean activity			Water activity		
Temp (°C)	m NaCl	Ion. Str.	$\gamma_{NaCl\pm}$	$\gamma_{NaCl\pm}$	%Diff	$a_{NaCl}$	$a_{NaCl}$	%Diff	$a_{H2O}$	$a_{H2O}$	%Diff
			Meas <sup>1</sup>	Comp		Meas <sup>1</sup>	Comp		Meas <sup>1</sup>	Comp	
25	0.1	0.1	0.77753	0.775	-0.4	6.05E-03	6.00E-03	-0.7	0.9966	0.997	0.0
25	1	1	0.65805	0.661	0.5	4.33E-01	4.37E-01	0.9	0.9668	0.967	0.0
25	2	2	0.67131	0.684	1.8	1.80E+00	1.87E+00	3.7	0.934	0.930	-0.1
25	4	4	0.78809	0.800	1.5	9.94E+00	1.02E+01	2.9	0.8512	0.851	0.0
25	6	6	0.98882	0.972	-1.7	3.52E+01	3.40E+01	-3.3	0.7601	0.764	0.5
110	0.1	0.1	0.74109	0.736	-0.7	5.49E-03	5.41E-03	-1.4	0.9967	0.997	0.0
110	1	1	0.61371	0.612	-0.2	3.77E-01	3.75E-01	-0.4	0.9670	0.967	0.0
110	2	2	0.62566	0.639	2.1	1.57E+00	1.63E+00	4.3	0.9317	0.930	-0.1
110	4	4	0.71514	0.772	7.9	8.18E+00	9.53E+00	17	0.8542	0.848	-0.8
110	6	6	0.83637	0.974	17	2.52E+01	3.42E+01	36	0.7727	0.756	-2.1
			Mean activity coefficient			Mean activity			Water activity		
Temp (°C)	m CaCl <sub>2</sub>	Ion. Str.	$\gamma_{CaCl2\pm}$	$\gamma_{CaCl2\pm}$	%Diff	$a_{CaCl2}$	$a_{CaCl2}$	%Diff	$a_{H2O}$	$a_{H2O}$	%Diff
			Meas <sup>2</sup>	Comp		Meas <sup>2</sup>	Comp		Meas <sup>2</sup>	Comp	
25	0.001	0.003	0.8881	0.888	0.0	2.80E-09	2.80E-09	0.0	0.9999	1.000	0.0
25	0.1	0.3	0.5164	0.507	-1.8	5.51E-04	5.21E-04	-5.4	0.9954	0.995	0.0
25	0.5	1.5	0.4453	0.450	1.2	4.41E-02	4.57E-02	3.5	0.9756	0.971	-0.4
25	1	3	0.4959	0.522	5.3	4.88E-01	5.69E-01	17	0.9451	0.929	-1.7
25	1.6	4.8	0.6367	0.675	6.1	4.23E+00	5.04E+00	19	0.8989	0.863	-4.0
100	0.001	0.003	0.8695	0.869	-0.1	2.63E-09	2.62E-09	-0.2	0.9999	1.000	0.0
100	0.1	0.3	0.4530	0.438	-3.4	3.72E-04	3.35E-04	-9.9	0.9956	0.996	0.0
100	0.5	1.5	0.3568	0.334	-6.3	2.27E-02	1.87E-02	-18	0.9770	0.976	-0.1
100	1	3	0.3703	0.334	-9.7	2.03E-01	1.50E-01	-26	0.9493	0.946	-0.4
100	1.6	4.8	0.4381	0.366	-16	1.38E+00	8.04E-01	-42	0.9079	0.902	-0.7

<sup>1</sup>Data from, Colin et al., 1985; <sup>2</sup>Data from Ananthaswamy and Atkinson, 1985

### Activity Coefficients of Neutral Aqueous Species

For dissolved gases with the following exact names in the thermodynamic database, activity coefficients are computed using an equation derived from correlations developed by Drummond (1981) for CO<sub>2</sub> gas dissolution in NaCl solutions up to 6 molal (see also Section B.4 in Appendix B):

'co2(aq)' or 'CO2(aq)'

'ch4(aq)' or 'CH4(aq)'

'h2(aq)' or 'H2(aq)'

'h2s(aq)' or 'H2S(aq)'

'o2(aq)' or 'O2(aq)'

'so2(aq)' or 'SO2(aq)'



$$\ln(\gamma) = (C + F T + G/T) I - (E + H T) I/(I + I) \quad (\text{H.11})$$

where  $I$  and  $T$  are the true ionic strength and absolute temperature, respectively, and  $C$ ,  $E$ ,  $F$ ,  $G$ , and  $H$  are fit coefficients as follows:

<b>C</b>	-1.0312
<b>E</b>	0.4445
<b>F</b>	0.0012806
<b>G</b>	255.9
<b>H</b>	-0.001606

For other uncharged molecular species activity coefficients are set to one by default or can be optionally computed as (e.g. Langmuir 1997):

$$\log(\gamma_i) = K_i I \quad (\text{H.12})$$

where  $K_i$  are salting-out coefficients and  $I$  is the true ionic strength of the solution. Currently, values of  $K_i$  are assumed to be independent of temperature. These salting-out coefficients are input from the TOUGHREACT thermodynamic database (A0 in the primary and secondary species blocks, see Section 6.4), and default to zero (unit activity coefficients).

#### H.1.4 Fugacity Coefficients of Gases

---

When TOUGHREACT is compiled with the TOUGH2 module ECO2N, the fugacity coefficients of  $\text{CO}_2$  are computed within the ECO2N module as a function of pressure, temperature, and composition, using the  $\text{H}_2\text{O}$ - $\text{CO}_2$  mutual solubility model of Spycher et al. (2005) for pure water and saline solutions (for temperature and pressure ranges of 10–110°C and 1–600 bar).

When TOUGHREACT is compiled with other EOS modules, or for initial speciation calculations, fugacity coefficients of  $\text{CO}_2$ ,  $\text{H}_2$ , and  $\text{CH}_4$ , are computed as a function of pressure and temperature only (ideal mixing of real gases) using the correlations of Spycher and Reed (1988) (for temperature and pressure ranges of ~50–300°C and 1–500 bar for  $\text{CO}_2$ ; 0–1000°C and 1–3000 bar for  $\text{H}_2$ ; and 25–300°C and 1–500 bar for  $\text{CH}_4$ ). Fugacity coefficients of other gases (besides  $\text{H}_2\text{O}$  gas) are assumed equal to 1 (ideal gas behavior and ideal mixing). The calculation

of fugacity coefficients can be turned on or off for various EOS modules (except ECO2N) by setting flag iFugaC to 0 (off) or 1 (on) in subroutine Gas\_Fuga\_Coe (in treat\_v2.f).

The behavior of H<sub>2</sub>O gas (ideal or non-ideal), and computation of H<sub>2</sub>O gas fugacity, is always taken into account by the selected TOUGH2 EOS module compiled with TOUGHREACT.

## Appendix I Treatment for Mineral Solid Solutions

---

Currently, TOUGHREACT considers only an ideal solid solution model. The solid solution model is only available for minerals that react kinetically.

The condition of equilibrium for a solid solution is

$$\left( Q_{ss} / K_{ss} a_{ss} \right) = 1 \quad (\text{I.1})$$

where the subscript *ss* refers to the solid solution, and *Q* and *K* are the ion activity product and equilibrium constant for that solid solution, respectively, and *a* is the activity of the solid solution. By convention,  $a_{ss} = 1.0$ .

A similar expression can be written for the condition of equilibrium for each end-member of the solid solution:

$$\left( Q_i / K_i a_i \right) = 1 \quad (\text{I.2})$$

In this case, the subscript *i* refers to each end member, and  $a_i \neq 1.0$ .

In the case of an ideal solid solution, the activity of each endmember,  $a_i$ , is assumed to equal its mole fraction  $x_i$  in the solid solution. Making this assumption and combining Equations (I.1) and (I.2) (with  $a_{ss} = 1.0$ ) yields:

$$\left( Q_i / K_i x_i \right) = \left( Q_{ss} / K_{ss} \right) \quad (\text{I.3})$$

For a solid solution composed of *n* end-members, Equation (I.3) is consistent with the relation (e.g. Reed, 1982):

$$\left(Q_{ss}/K_{ss}\right) = \sum_{i=1}^n \left(Q_i/K_i\right) \quad (\text{I.4})$$

Alternatively, combining Equations (I.3) and (I.4) yields, at equilibrium

$$x_i = \frac{\left(Q_i/K_i\right)}{\sum_{i=1}^n \left(Q_i/K_i\right)} \quad (\text{I.5})$$

For a solid solution reacting under kinetic constraints we can then write a rate law similar to Equation (B.5) in Appendix B.

$$R_{ss} = k_{ss}A_{ss} \left[ 1 - \left(Q_{ss}/K_{ss}\right) \right] \quad (\text{I.6})$$

where  $R$ ,  $A$ , and  $k$  stand for the reaction rate, surface area, and rate constant of the whole solid solution  $ss$ . To treat the solid solution as a function of only individual endmembers,  $i$ , we write:

$$R_{ss} = \sum_{i=1}^n (x_i R_i) \quad (\text{I.7})$$

with  $x_i$  and  $R_i$  being the mole fraction and rate, respectively, for each endmember of the solid solution. The rate of each endmember can be expressed as

$$R_i = k_i A_{ss} \left[ 1 - \left(Q_i/K_i a_i\right) \right] \quad (\text{I.8})$$

where  $k_i$  is the rate constant of each endmember. Assuming ideal behavior ( $a_i = x_i$ ) and substituting Equation (I.8) into Equation (I.7) we get:

$$R_{ss} = \sum_{i=1}^n (x_i R_i) = \sum_{i=1}^n \left( x_i k_i A_{ss} \left[ 1 - \left(Q_i/K_i x_i\right) \right] \right) \quad (\text{I.9})$$

which can be further expanded as

$$R_{ss} = \sum_{i=1}^n \left( k_i A_{ss} \left[ x_i - \left(Q_i/K_i\right) + 1 - 1 \right] \right) = \sum_{i=1}^n \left( k_i A_{ss} \left[ 1 - \left(Q_i/K_i\right) \right] + k_i A_{ss} [x_i - 1] \right) \quad (\text{I.10})$$

Equation (I.10) leads to the final relationship

$$R_{ss} = \sum_{i=1}^n [ R_i' + k_i A_{ss} (x_i - 1) ] \quad (\text{I.11})$$

where  $R_i'$  is the rate of the endmember as a pure mineral (that is, with  $a_i = 1$  in Equation (I.8)).

This approach is implemented in TOUGHREACT by adding a term equal to  $k_i A_{ss} (x_i - 1)$  to the rates  $R_i'$  computed for each individual mineral that is part of a solid solution. In doing so, Equation (I.11) is implicitly treated by the total effect of the precipitation or dissolution of all endmembers. For precipitation, mole fractions  $x_i$  are computed using Equation (I.5), which technically only applies at equilibrium. For dissolution, values of  $x_i$  are calculated from the actual abundances of each endmember present.

It should be noted that this method is currently valid only for rate expressions without exponents on the affinity term (i.e. with exponents  $m$  and  $n$  set to 1 in Equation B.5), and close to equilibrium for precipitation. This approach also implies that

$$k_{ss} = \sum_{i=1}^n (x_i k_i) \quad (\text{I.12})$$

and that

$$A_{ss} = \sum_{i=1}^n (A_i) \quad (\text{I.13})$$

where  $A_i$  is the surface area computed from the abundance of each endmember. Note that stoichiometric dissolution is obtained by using identical  $k_i$  values for all endmembers in a given solid solution.

## Appendix J Implementation of the Hellmann and Tisserand (2006) Rate Law for Mineral Dissolution and Precipitation

---

### J.1 Rate Expression

---

Hellmann and Tisserand (2006) published an improved rate equation for low albite dissolution in the aqueous phase;

$$r = kA \left( 1 - e^{ng^m} \right) \quad (\text{J.1})$$

where  $n$  and  $m$  are fitted parameters, and

$$g = \ln \frac{Q}{K} \quad (\text{J.2})$$

They used an extensive and continuous set of experimental data relating the dissolution rate of low albite to the affinity of the reaction. The highly non-linear behavior of the rate equation precludes use of a classical TST rate law embodied in Eq. J.1, except when the affinity is less than  $\approx 15$  kJ/mol (Lasaga, 1998, p. 678 *ff*). Hellmann and Tisserand's equation better describes the dissolution rate of albite in the transition region between TST control and the generalized dissolution rate established far from equilibrium and independent of the affinity of reaction, a region characterized by most laboratory studies of aluminosilicate dissolution. Similar complex dissolution rate behavior has been observed for other minerals, e.g., gibbsite, labradorite and smectite (Lasaga and Luttge, 2001).

Although a theoretical basis exists for calculating the transition in dissolution rate between TST control, and control by etch pits for each mineral (Lasaga and Luttge, 2001), parameters are not available for many minerals. Hellmann and Tisserand (2006) reported the parameters  $n$  and  $m$  for albite,  $n = 9.75 \times 10^{-5}$  and  $m = 3.74$ . We implemented this new rate law in TOUGHREACT, but it has not been well-tested. For some user's interest, we document the implementation below.

## J.2 Implementation

---

Compared to TST rate law, only two records Miner-2 and Miner-2.1 in file chemical.inp needs to be modified as follows:

### **Miner-2**

Variable: NAMIN, IKIN, IDISPRE, ISS, M1

Format: A, 4I (free format)

IKIN: =2 for this new rate law (=1 for TST rate law).

Other variables: are the same as the TST rate law

### **Miner-2.1**

Variable: RKF, IDEP, CK1, CK2, EA, ACFDISS, BCFDISS, CCFDISS

Format: F, I, 6F (free format)

CK1 and CK2: the exponents n and m, respectively in Eq. (J.1) above.

Other variables: are the same as the TST rate law

An example for 'albite~low' is given below:

```
'albite~low'      2      3      0      0
                  2.7542e-13      2      9.75E-5      3.74      69.80      0.0      0.0      0.0
mechnism          1
                  6.9183e-11      65.0      1      'h+'      0.457 ! acid
0
0.0      0.      000.00
```

## Appendix K Treatment of Cation Exchange under Water Unsaturated Conditions

---

Two models are used for cation exchange under water unsaturated conditions. The first model assumes cation exchange sites (CEC) remain constant as water saturation changes. In fact, the number of available exchange sites decreases as water saturation decreases. TOUGHREACT provides another option, the second model. The variation of exchange sites is addressed by simply scaling CEC by a factor, which is a function of water saturation. TOUGHREACT can use a function  $f(S_l)$  proposed by Liu et al. (1998) and is based on the change in reactive surface area with a change in saturation for fracture networks (see Appendix G):

$$f(S_l) = S_l^{(1+\gamma)} \quad (\text{K.1})$$

where  $\gamma$  is an empirical coefficient. Both these functional forms are constrained in the range  $0 \leq f(S_l) \leq 1$ , and approach 0 as  $S_l$  approaches 0, and approach 1 as  $S_l$  approaches 1. Saturation values approaching 0 are usually not encountered, and are limited by the residual saturation in the capillary pressure curve. TOUGHREACT is, however, a nonisothermal code, and for boiling conditions, rocks can completely dry out. During complete dryout, Equations (K.1) become undefined at  $S_l = 0$ , and a lower limit must be placed on  $S_l$  to prevent this. For application under this condition, Sonnenthal et al. (2005) defined an effective residual saturation for reaction ( $S_{ar}$ ), which is used in Equation (K.1) instead of  $S_l$ , and is expressed as

$$S_{ar} = \frac{S_l - S_m}{1 - S_m} \quad (\text{K.2})$$

where  $S_m$  is the minimum liquid saturation for which reactions are considered and is generally set to a small saturation (such as  $1 \times 10^{-4}$ ), to ensure that reactions take place until virtually no water is left (e.g., during dryout). Clearly, at a very low liquid saturation, the reactive exchange contacted by water is likely much smaller than the total sites. The dependence of reactive surface sites on water saturation is very complex in field-scale conditions. Additional investigations are needed to define the functional form of this relation.

## Appendix L Heat Capacities and Thermal Conductivities of Rocks and Minerals

---

In TOUGHREACT V3.0-OMP and later, temperature-dependent rock grain heat capacity coefficients (for use in the energy conservation equations) can be entered either directly into the ROCKS block of the flow input file, or calculated from individual mineral heat capacity coefficients obtained from the thermodynamic database. Bulk rock thermal conductivities can also be entered as terms in temperature-dependent relations in the ROCKS block or calculated from data on minerals in the thermodynamic database. Several thermal conductivity relations are available. It is important to recognize that the thermal diffusivity is proportional to the ratio of the thermal conductivity to the heat capacity, with both parameters typically varying with temperature. Therefore, in many cases, both parameters should be calculated using a temperature-dependent function to obtain reasonable thermal diffusivities. Starting in V3.85-OMP, thermal diffusivities are written to the output file *flowdata.tec*.

### L.1 Rock Grain Heat Capacities

---

For the rock grain heat capacity ( $C_{p,grain}$ ), entered in the ROCKS block (*flow.inp*), two options are available. Option 1 (ihcplaw=1) uses the Holland and Powell (2011) polynomial, with units of J/kg/K instead of J/mol/K:

$$C_{p,grain} = a + bT + cT^{-2} + dT^{0.5}, \quad (\text{L.1})$$

where  $a$ ,  $b$ ,  $c$ , and  $d$  are fitting constants.

Option 2 (ihcplaw=2) uses a logarithmic expression for  $C_{p,grain}$ , as used in Hadgu et al. (2007), with  $T(^{\circ}\text{C})$  as follows:

$$C_{p,grain} = a \ln [T(C)] + b, \quad (\text{L.2})$$

where  $a$  and  $b$  are fitting constants.

## L.2 Mineral Heat Capacities

---

To calculate the rock grain heat capacity directly from the mineral abundances in each grid block, including changes as a result of mineral precipitation/dissolution,  $C_{p,min}$  coefficients ( $a$ ,  $b$ ,  $c$ ,  $d$ ) for individual minerals are entered in an optional fourth line in the input thermodynamic data file (in J/mol/K). The format of this entry is given in the "Mineral" section of the thermodynamic data file input format description in the main section of this document. Mineral heat capacities ( $C_{p,m}$  in J/mol/K) as a function of temperature ( $T$  in K) are calculated using the polynomial expression from Holland and Powell (2011):

$$C_{p,m} = a + bT + cT^{-2} + dT^{0.5}. \quad (\text{L.3})$$

## L.3 Rock Grain Heat Capacities Derived from Mineral Heat Capacities

---

In TOUGHREACT, rock grain heat capacities ( $C_{p,grain}$ ) have units of J/kg/K, and therefore  $C_{p,m}$  in J/mol/K must be converted to J/kg/K. Conveniently, all data necessary for the conversion are already present in the thermodynamic database. First, the total moles of minerals ( $M_m$ ) in each grid block ( $M_{tot}$ , moles/m<sup>3</sup> medium) are calculated from the sum of the moles of individual minerals, as follows ( $nm$  is the total number of minerals present):

$$M_{tot} = \sum_{m=1}^{nm} M_m. \quad (\text{L.4})$$

The mole fraction of each mineral ( $X_m$ ) in the solid assemblage is then given by:

$$X_m = \frac{M_m}{M_{tot}}. \quad (\text{L.5})$$

Prior to calculating the rock grain heat capacities, the rock grain heat capacity coefficients ( $cf_{Cp,grain}$ ) are calculated from the mineral coefficients ( $cf_{Cp,m}$ ), so they can be written to file *thermalparam.tec*, as follows:



$$cf_{Cp,grain} = \sum_{m=1}^{nm} \left[ cf_{Cp,m} \frac{X_m}{MW_m} \right] \quad (L.6)$$

where  $MW_m$  is the molecular weight of the mineral (kg/mol). Rock grain heat capacities are then given by:

$$C_{p,grain} = \sum_{m=1}^{nm} \left[ C_{p,m} \frac{X_m}{MW_m} \right] \quad (L.7)$$

The coefficients for the rock grain heat capacities can then be used as input (in ROCKS) for employing temperature-dependent heat capacities in thermal-hydrological simulations without performing reactive chemistry or reading the thermodynamic database. Additionally, starting in TOUGHREACT V3.85-OMP, rock grain heat capacities are written out at every grid block in the file *flowdata.tec*.

## L.4 Bulk Rock Thermal Conductivities

---

Temperature-dependent bulk rock thermal conductivities can be calculated in TOUGHREACT V3.0-OMP (and later), without invoking reactive transport. Currently, three options are available, based primarily on fits of experimental and field data for geothermal systems:

$$k_{T,rock} = \frac{a}{(350 + T(C))} + b \quad (\text{Zoth and Hanel, 1988}) \quad (L.8)$$

$$k_{T,rock} = \left( \frac{k_{Tref,rock}}{a + bT(C) \left( 1 - \frac{c}{k_{Tref,rock}} \right)} \right) \quad (\text{Williams and Sass, 1996}) \quad (L.9)$$

$$k_{T,rock} = \left( \frac{k_{Tref,rock}}{a + T(C) \left( b - \frac{c}{k_{Tref,rock}} \right)} \right) \quad (\text{Vosteen and Schellschmidt, 2003}) \quad (L.10)$$

where  $k_{Tref,rock}$  is the saturated thermal conductivity at the reference temperature, entered in the usual location in file *flow.inp* on line ROCKS.1. In TOUGHREACT V3.32-OMP and later, bulk rock thermal conductivities are written out at every grid block in the file *flowdata.tec*.

## L.5 Mineral Thermal Conductivities

---

Mineral thermal conductivities ( $k_{T,min}$  in W/m/K) can be calculated using coefficients ( $D$  and  $E$ ) read from the thermodynamic database, using the relation from Clauser and Huenges (1995):

$$k_{T,min} = 1/(D + E*T(K)) \quad (L.11)$$

## L.6 Bulk Rock Thermal Conductivities Calculated from Mineral Values

---

Bulk rock thermal conductivities are calculated from the mineral values ( $k_{T,min}$ ) and the mineral volume fractions. First, the current mineral volumes (in liters, or dm<sup>3</sup>) per liter medium ( $V_{min}$ ) are calculated from the updated mineral moles per liter medium ( $m_{min}$ ) and mineral molar volume ( $\bar{v}_{min}$ ), as follows:

$$V_{tot,min} = m_{min}\bar{v}_{min} \quad (L.12)$$

The mineral volume fractions in the solid phase assemblage are then given by

$$V_{f,min} = V_{tot,min} / \sum_{m=1}^{nm} V_{tot,min} \quad (L.13)$$

Bulk rock thermal conductivities  $k_{T,rock}$  are then given by the relation by Woodside and Mesmer (1961):

$$k_{T,rock} = \prod_{m=1}^{nm} k_{T,min}^{V_{f,min}} \quad (L.14)$$

## L.7 Effect of Porosity Changes on Bulk Rock Thermal Conductivities

---

To capture the effect of porosity ( $\phi$ ) changes on bulk rock thermal conductivity, a variation of Eqtn. L-14 is employed:

$$\dot{k}_{T,rock} = k_{T,rock} \left[ \frac{k_{T,rock}^{(1-\phi)}}{k_{T,rock}^{(1-\phi_0)}} \right] \quad (L.15)$$

## Appendix M Heats of Reaction

---

The heats of reaction can be calculated by taking the derivative of  $\Delta G$  with respect to temperature (T), starting with the free energy equation:

$$\Delta G = RT \ln K, \quad (\text{M.1})$$

where R is the gas constant (J/mol/K) and  $\ln K$  is the natural logarithm of the equilibrium constant, The derivative of the free energy with respect to temperature is:

$$\frac{d\Delta G}{dT} = RT \frac{d \ln K}{dT}. \quad (\text{M.2})$$

Equilibrium constants as a function of temperature are given in the thermodynamic database as follows:

$$\log_{10} K = a \ln T_K + b + c T_K + d/T_K + e/T_K^2, \quad (\text{M.3})$$

where a, b, c, d, and e are the coefficients. Substituting the  $\log(K)$  equilibrium constant equation M.3 gives:

$$\frac{d(\Delta G)}{dT} = RT \left[ \frac{d(\ln K)}{dT} + \ln K/T \right]. \quad (\text{M.4})$$

## Appendix N Single-Phase Wellbore Flow Model

---

A simple single phase liquid wellbore flow model was added to TOUGHREACT V3.0-OMP, and was revised since then. Although it is limited to single phase liquid flow, neglecting energy conservation terms, it has some advantages for users compared to other more complex wellbore simulators (e.g., T2WELL; Pan). It is independent of the EOS module employed, can be used easily with very minor modification of ISOT values for connections, and can be turned on/off with a simple MOP parameter option. It is also solved during the Newton-Raphson flow iterations, rather than using velocities from the previous time step.

The basic model considers wall friction and turbulence to calculate an effective permeability in the wellbore, and is based loosely on Marcolini et al. (2011). The effective permeability is recalculated during the Newton-Raphson flow iterations based on the fluid flow

velocity, and is not lagged in time. Because the flow velocity is dependent on the pressure gradient, which depends on the permeability that is recalculated based on the flow velocity, the number of Newton-Raphson (NR) iterations needed for flow convergence is usually higher (~7-9) than in a "normal" flow simulation (~2-4). Therefore, MOP(16), which controls the increase in the time step length as a function of the number of NR iterations for convergence, usually needs to be set to 8 or 9 if wellbore flow is enabled.

The only numerical input parameter needed for the wellbore flow model is the initial permeability of the wellbore, calculated assuming laminar Poiseuille flow in a pipe. It is input as the third permeability value  $per(3)$  in the ROCKS block in *flow.inp*. The wellbore flow model is then active if the MOP(17) parameter = 1 or 2, and only for connections with ISOT = 5.

Using the permeability  $k_3$  (derived from  $per(3)$ ), the wellbore diameter is calculated at each grid block ( $n$ ) in a connection (with ISOT = 5), as follows:

$$d_{wb,n} = 2\sqrt{8k_3} \quad . \quad (N.1)$$

The mean wellbore diameter at the connection is then calculated from the average of the wellbore diameters in the connected grid blocks:

$$\bar{d}_{wb,c} = (d_{wb,1} + d_{wb,2})/2 \quad . \quad (N.2)$$

The Reynolds number  $Re$  for pipe flow at the connection is given by:

$$Re = (v_l \bar{\rho}_{l,c} \bar{d}_{wb,c}) / \bar{\nu}_{l,c} \quad , \quad (N.3)$$

where the distance-weighted liquid density at the interface is:

$$\bar{\rho}_{l,c} = (\rho_{l,1} d_1 + \rho_{l,2} d_2) / (d_1 + d_2) \quad . \quad (N.4)$$

and the distance-weighted liquid viscosity at the interface is:

$$\bar{\nu}_{l,c} = (\nu_{l,1} d_1 + \nu_{l,2} d_2) / (d_1 + d_2) \quad . \quad (N.5)$$

Assuming the roughness  $r_{wb}$  is proportional to the wellbore diameter, with a factor of  $10^{-3}$ , gives:

$$r_{wb} = 10^{-3} \bar{d}_{wb,c} \quad , \quad (N.6)$$

The Reynolds number cutoff for turbulent flow, is approximately

$$Re_{turb} = 3500 / (\bar{d}_{wb,c} r_{wb}) . \quad (N.7)$$

If  $Re > 1$  and  $Re \geq Re_{turb}$ , then the friction factor in each element of a connection is calculated from the Swamee-Jain equation:

$$fr_{SJ,1} = \frac{0.25}{\left[ \log_{10} \left( r_{wb} / (3.7 \bar{d}_{wb,1}) + 5.74 / (Re^{0.9}) \right) \right]^2} \quad , \quad (N.8)$$

and similarly for grid block 2. If  $Re > Re_{turb}$ , then the friction factor in each element of a connection is calculated from the Colebrook-White equation for turbulent flow at an infinite Reynolds number, as follows:

$$fr_{CW,1} = \frac{1.0}{\left[ 1.14 - 2 \log_{10} (r_{wb} / \bar{d}_{wb,1}) \right]^2} \quad , \quad (N.9)$$

and similarly for grid block 2. The distance-weighted average friction factor at the interface is then given by:

$$\bar{fr}_c = (fr_1 d_1 + fr_2 d_2) / (d_1 + d_2) \quad . \quad (N.10)$$

The mass flux  $\omega_m$  at the interface, with connection area  $A_c$ , revised from Marcolini et al. (2011) is:

$$\omega_m = A_c \sqrt{\left| \left[ (-dP/dl + \bar{\rho}_{l,c} \bar{g}) / \left( (\bar{fr}_c / (2 \bar{d}_{wb,c} \bar{\rho}_{l,c})) + (1/\rho_{l,2} - 1/\rho_{l,1}) / (d_1 + d_2) \right) \right] \right|} . \quad (N.11)$$

The effective permeability at each element of a wellbore connection is calculated from friction and turbulent pressure drop, as follows:

$$k_{wb,n} = v_{l,n} d_{wb,n} 2 A_c / (\bar{fr}_c \omega_m) \quad . \quad (N.12)$$

Note that several levels of averaging at the connection interfaces are carried out. In some cases, the averaging is probably not necessary, however, given the changes in fluid velocity along a wellbore having different diameter sections, and the potential for flow direction reversals at fracture intersections along open or perforated sections, the averaging allows for greater numerical stability.

## Appendix O Aqueous Species Diffusion

---

In TOUGHREACT versions starting with V3.32-OMP, the basic structure and inputs for solving multicomponent aqueous species diffusion were added. However, charge and mass balance constraints have not yet been implemented. Hence, although species- and temperature-dependent diffusion coefficients can be calculated and used for diffusive transport of total concentrations, the current formulation is only accurate for trace neutral species, and trace charged isotopes of the same species. It is especially usefully for simulating diffusion of neutral isotopologues and dissolved gaseous species.

## Appendix P Utility Programs for the Thermodynamic Database

---

### P.1 Converting from other databases

---

#### *Description*

Program DBCONV2 reads the thermodynamic database of either EQ3/6 v7.2b (data0.dat; Wolery, 1992), PHREEQC (phreeqc.dat; Parkhurst and Appelo, 1999), or SOLVEQ/CHILLER (soltherm.xxx; Reed, 1982 and 1998) formats the data for input into TOUGHREACT. The source code (dbconv2.f) is provided with the distribution files. For the most part, the conversion requires only reformatting of the same data values. However, the program also regresses input equilibrium constant values as a function of temperature in the form:  $\log(K)_T = a * \ln(Tk) + b + c*Tk + d/Tk + e/Tk^2$  where Tk is temperature in degrees K. The program also assigns values of effective ionic radii to aqueous species by reading these values in a special input file (rej.dat). Currently, this file contains effective ionic radii from Helgeson et al. (1981; AJS, 1249-1516, Table 3). Radii of species for which data listed in rej.dat are computed as a function of ionic charge as shown in Table H-1 in Appendix H.

#### *Input and output files:*

The program needs to read in two input files and generates four output files. The names of input and output files are entered interactively when running the program. File contents and default names are as follows:

<i>data0.dat</i>	Main input file - original EQ3/6, PHREEQC or SOLVEQ/CHILLER thermodynamic database (the converter automatically detects the original file format).
<i>rej.dat</i>	Input data file containing effective ionic radii from Helgeson et al. (1981, AJS, 1249-1516, Table 3). The species listed in this file must have the same spelling as the species in the input thermodynamic database. If no match is found, rej values are computed based on ionic charge (see Table H-1 in Appendix H).
<i>mvm0.dat</i>	Mineral densities, used to compute molar volumes if these data are not available in the input database. References for these data are listed at the top of this file.
<i>dbconv2.out</i>	Main output file - converted database (for the file format, see Section 6.4 of this manual).
<i>dump_aux.out</i>	Separate subset of main output file containing converted data for auxiliary species only. To complete the conversion of the database, this file is to be manually inserted in dbconv2.out at the location indicated in that file.
<i>checkfit.out</i>	Print-plot file to visually check the quality of the log(K) regression. A user should always look at this file before using the output data.
<i>checkdat.out</i>	Printout of species for which one or more regressed log(K) value exceeds 0.1 log(K) units (generally, but not necessarily, indicating some problems with the regression).

For EQ3/6 conversions, the input file must have the format of EQ3/6 thermodynamic databases, with the following successive blocks of data. All these blocks are required in the input file and these data blocks must occur in the same order as shown below, otherwise input errors will occur:

```
+-----  
basis species  
  
+-----  
auxiliary species  
  
+-----  
aqueous species
```

+-----  
solid species

+-----  
gases

+-----  
solid solutions

To convert EQ3/6 files, the program will work only with input log(K) grids composed of eight values, at the following temperatures: 0, 25, 60, 100, 150, 200, 250, and 300°C. A log(K) value of 500 is interpreted as “no available data” and regression of log(K) values is not performed if at least one of log(K) value is set to 500. With PHREEQC databases, log(K) values are extrapolated only between 0 and 60°C using the van’t Hoff equation and given enthalpy values, unless log(K) regression entries (*-analytic*) are present in the file. With SOLVEQ/CHILLER databases, log(K) values are regressed between 25 and 350°C, although log(K) values in the converted database are shown only up to 300°C. Note that additional parameters such as Arrhenius constants for aqueous diffusion, molecular diameters for gas species diffusion, heat capacity and thermal conductivity coefficients are not available in standard geochemical thermodynamic databases, and must be added after conversion.

## P.2 Switching Basis (Primary) Species

---

### *Description*

The program KSWITCH reads TOUGHREACT thermodynamic database entries and creates another identical set of entries with one of the component species "switched" with a derived species. For example, use KSWITCH to replace Al+++ (as a basis species) with new component species such as AlO<sub>2</sub><sup>-</sup>.

### *Input data files and formats*

One input file is needed (with default name thermok.dat, but any name can be chosen and input interactively). This file contains component species data, reaction stoichiometries and log(K) data entries that must have the same format as the entries for aqueous species, gases, and minerals in the TOUGHREACT thermodynamic database, including the same structure as the thermodynamic database (with a top record specifying temperature values for the log(K) data, then



component (basis) species, derived species, minerals, and gases separated by records starting with 'null'). The entire thermodynamic database, or a subset of it, can be used as an input file. Also, any number of headers can appear at the top of the file before the temperature header. The remaining input is done interactively with self-explanatory prompts that ask for the names of input and output files, the species to switch (use the exact same spelling as in the input file), and the molecular weight of the switched species. The latter is used only for inclusion in the new component species entry and is not used in calculations. Note that the new component species must always be a derived species that is present in the input file. Also, only one switch is allowed for each run. For multiple switches, run the program more than once, reading the output of each run as input for the following run.

### **P.3 Regression of log(K) Data**

---

#### *Description*

Program KREG is used to regress log(K) data in the thermodynamic database of TOUGHREACT as a function of temperature, and to generate records for aqueous species, minerals, and/or gases including the log(K) regression coefficients formatted for input into this thermodynamic database.

#### *Input data files and formats*

The names of input and output files are entered interactively when running the program. One input file (default name: kreg.dat) is required, containing: the first record identical to the first record of the thermodynamic database indicates the temperatures for which log(K) data are given, followed by records identical to those in the thermodynamic database for derived aqueous species, minerals, and/or gases. (3 records per entry: the first for stoichiometry, second for individual log(K) values, and the third for regression coefficients. The regression coefficients can be left blank, but the name of the species, mineral, or gas preceding the regression coefficients must be present). The entire thermodynamic database, with component (primary) species removed, can also be used as an input file.

## P.4 Checking Mass and Charge Balances

---

### *Description*

Program THERMOCHK reads the thermodynamic database of TOUGHREACT and checks the mass and charge balances of all reactions entered in that database. It does so by adding the molecular weights multiplied by stoichiometric coefficients (mass balance) and adding ionic charges multiplied by stoichiometric coefficients (charge balance) of each specified reaction. The program then flags non-zero charge balances and mass balances greater than  $5 \times 10^{-5}$  times the molecular weight of the species/mineral/gas to which the reaction pertains.

### *Input data files and formats*

The program needs to read in two input files and generates two output files. The names of input and output files are entered interactively when running the program. File contents and default names are as follows:

thermok.dat (default)	Main input file (TOUGHREACT database to check)
molwt_aq.dat	Input file with molecular weights of aqueous species, used only if this information is not already provided in the thermok.dat input file (i.e., as in earlier versions of the database).
thermochk.out	Output file listing charge and mass balances for all reactions.
error.out	Output file listing only those species, minerals, and gases for which reactions have non-zero charge balances and mass balances exceeding $5 \times 10^{-5}$ times the molecular weight of the species, mineral, or gas in question.

## INDEX

---

### A

Accumulation terms · 124, 125  
Accuracy · 20, 133  
Acidizing · 107  
Activation energy · 54, 58, 59, 113  
Activity coefficient · 37, 39, 100, 111, 112, 116, 118, 145, 148, 149, 150, 151, 152, 153, 154  
Adsorption · 14, 15, 23, 47, 48, 50, 51, 62, 76, 77, 78, 96, 121, 122, 127  
Advection · 14, 21, 28  
Air · 5, 14, 17, 95, 109, 135  
Aqueous · 4, 5, 14, 15, 16, 22, 23, 25, 26, 27, 28, 35, 39, 40, 41, 42, 45, 49, 50, 52, 53, 56, 62, 65, 66, 67, 73, 77, 79, 81, 82, 83, 84, 93, 95, 100, 103, 104, 106, 107, 109, 110, 111, 112, 116, 117, 120, 121, 123, 124, 126, 127, 130, 131, 133, 134, 145, 157, 167, 168, 169, 170, 171  
Aqueous species · 15, 22, 23, 25, 26, 28, 35, 42, 45, 49, 50, 52, 56, 67, 79, 81, 83, 84, 93, 100, 104, 110, 117, 120, 121, 127, 145, 167, 168, 169, 170, 171  
Aquifer · 97, 98, 100, 103  
Arrays · 12  
automatic · 21  
Automatic time stepping · 21

---

### B

Balance equations · 17, 127  
Balances · 23, 130, 171  
Block · 19, 20, 21, 23, 25, 27, 31, 32, 33, 35, 37, 40, 43, 47, 48, 52, 56, 57, 61, 65, 66, 77, 95, 125, 126, 127, 128, 142, 148  
Boiling · 21, 26, 38, 95, 105, 116, 159  
Boundary conditions · 13, 21, 26  
Brine · 5, 102

---

### C

Calcite · 101, 102, 106, 107  
Capillary · 5, 14, 16, 27, 32, 38, 138, 159  
Cation exchange · 14, 16, 53, 63, 79, 80, 95, 106, 117, 118, 119, 159  
Change · 31, 33, 34, 41, 67, 70, 73, 75, 86, 95, 121, 132, 135, 136, 139, 159  
*chdump.out* · 23, 65, 77, 93, 95, 149  
Chemical · 5, 13, 14, 15, 17, 20, 21, 22, 23, 24, 26, 27, 28, 29, 33, 35, 37, 38, 39, 41, 42, 44, 45, 46, 47, 49, 55, 56, 65, 67, 68, 81, 83, 84, 85, 86, 87, 88, 89, 90, 93, 94, 95, 97, 98, 99, 103, 104, 105, 107, 108, 109, 110, 111,

120, 121, 124, 125, 126, 127, 130, 133, 139, 140, 143, 144, 158  
Chemical property zone · 46  
chemical reaction · 15, 20, 21, 23, 26, 27, 95, 97, 110, 120, 124, 125, 126  
Chemical transport · 15, 17, 99, 109, 110, 124  
Chemical zone · 23  
CO<sub>2</sub> · 2, 5, 14, 38, 59, 82, 91, 92, 96, 97, 99, 100, 101, 103, 105, 107, 108, 109, 115, 116, 124, 153, 154  
Code installation · 1  
Coefficient · 4, 26, 40, 53, 54, 58, 63, 83, 84, 85, 86, 87, 89, 90, 110, 111, 116, 117, 125, 127, 129, 130, 146, 147, 148, 151, 152, 153, 159  
Compilation · 102  
Complexation · 4, 14, 51, 53, 76, 95, 98, 120, 121, 130, 131  
Components · 15, 16, 17, 32, 42, 108, 109, 125, 127  
Concentration · 41, 42, 55, 56, 67, 93, 95, 110, 111, 112, 117, 118, 119, 120, 121, 122, 123, 127, 130  
Conduction · 14, 103  
Conductivity · 33, 34, 101, 106, 110  
Constant · 15, 26, 28, 37, 51, 53, 54, 55, 56, 58, 59, 62, 71, 77, 86, 111, 112, 113, 114, 117, 121, 122, 123, 124, 128, 129, 130, 135, 136, 139, 141, 144, 146, 155, 156, 159, 167  
Constitutive relations · 110  
Coordinates · 25, 95  
Copper deposits · 97  
Corrosion · 103  
criteria · 13, 23, 41, 93, 126

---

### D

Database · 14, 22, 23, 39, 44, 45, 46, 50, 56, 57, 60, 61, 81, 82, 84, 91, 92, 94, 144, 146, 148, 149, 153, 154, 167, 168, 169, 170, 171  
Decay · 14, 15, 23, 50, 62, 96, 127, 128  
Defaults · 39  
Density · 5, 14, 17, 19, 43, 51, 77, 79, 95, 98, 110, 119, 122, 127, 141, 143, 144  
Diffusion · 14, 15, 21, 22, 33, 35, 39, 40, 89, 110, 125, 127, 129, 130  
Diffusive flux · 125  
Discretization · 17, 19, 20, 95, 127  
Dispersion · 16  
disposal · 1, 5, 14, 59, 96, 97, 99, 100, 101, 103, 107, 115, 116  
Domain · 17, 29  
Dual · 95, 136, 142  
Dual permeability · 136, 142

---

## **E**

Elements · 13, 19, 128, 132  
EOS1 · 5, 109  
EOS2 · 5, 38, 109  
EOS3 · 5, 109  
EOS4 · 5, 109  
EOS9 · 5, 33, 109  
EQ3/6 database · 91, 92  
Equations · 13, 15, 17, 19, 20, 21, 39, 109, 120, 124, 126,  
127, 130, 131, 132, 133, 137, 138, 139, 142, 144, 146  
Equilibrium · 14, 20, 23, 53, 54, 57, 60, 67, 68, 70, 71,  
73, 85, 87, 89, 90, 95, 107, 111, 112, 113, 116, 117,  
121, 122, 123, 124, 126, 130, 131, 132, 133, 155, 157,  
158, 167  
Error message · 23, 92, 94  
Exchange · 4, 14, 16, 42, 46, 47, 53, 63, 79, 80, 95, 97,  
106, 117, 118, 119, 120, 121, 159, 160  
Executable · 6, 12  
Execution · 6, 92, 94  
Explicit · 28, 37, 39, 127, 132, 149  
Exsolution · 14, 95, 130

---

## **F**

Field · 26, 29, 33, 102, 107, 120, 121, 137, 160  
Files · 1, 6, 12, 13, 21, 22, 23, 24, 26, 27, 29, 38, 39, 42,  
43, 140, 167, 168, 169, 170, 171  
Finite differences · 17, 19  
Flow · 1, 12, 13, 14, 15, 16, 17, 19, 20, 21, 23, 24, 25, 26,  
27, 29, 30, 33, 38, 39, 40, 41, 43, 46, 47, 48, 57, 65, 66,  
77, 92, 95, 99, 101, 102, 103, 105, 106, 107, 109, 110,  
127, 135, 138, 140, 142  
Flux · 19, 23, 57, 65, 101, 104, 110, 125, 128  
FORTRAN · 6, 36  
Fraction · 29, 43, 59, 70, 118, 119, 135, 139, 140, 142,  
143, 155, 156  
Fracture · 16, 32, 75, 98, 103, 135, 136, 142, 143, 159  
Fractured rock · 19, 26, 105, 107  
Function · 14, 15, 22, 32, 40, 53, 54, 85, 86, 87, 89, 91,  
100, 113, 120, 129, 132, 133, 138, 140, 146, 154, 156,  
159, 167, 170

---

## **G**

Gas · 4, 14, 21, 23, 25, 26, 32, 33, 37, 38, 39, 40, 47, 48,  
60, 67, 68, 72, 73, 81, 82, 86, 88, 89, 90, 93, 94, 95, 98,  
107, 110, 113, 116, 122, 124, 127, 129, 130, 153, 154,  
155, 170, 171  
Generation · 34, 107, 131  
Geometry · 102, 137  
Governing equations · 15, 110  
Gradient · 19, 37  
Gravity · 14

---

## **H**

Heterogeneity · 13, 95  
Hydrothermal · 5, 14, 21, 96, 98, 105, 107, 116

---

## **I**

Ideal gas · 116, 129, 154  
Implicit · 39, 40, 125  
*inchem* · 24  
*INCON* · 24, 26, 32, 33, 66, 140  
Initial conditions · 23, 31  
Initial water · 23, 47, 65, 66, 77, 93  
Initialization · 73, 77, 93  
Injection · 47, 65, 97, 100, 102, 107  
Injectivity · 107  
Input · 1, 13, 21, 22, 23, 24, 25, 26, 29, 31, 32, 34, 35, 36,  
39, 40, 42, 43, 49, 51, 52, 53, 54, 56, 59, 61, 65, 67, 70,  
71, 76, 81, 84, 85, 86, 88, 90, 115, 127, 136, 138, 139,  
140, 142, 143, 144, 146, 154, 167, 168, 169, 170, 171  
Input (flow.inp) · 40  
Input file · 13, 23, 24, 25, 26, 29, 36, 39, 43, 95, 167, 168,  
169, 170, 171  
Integration · 133  
Interface · 99, 122, 142, 143  
Ionic strength · 14, 38, 96, 116, 117, 145, 146, 147, 148,  
149, 154  
Irregular · 19, 95  
Iteration · 19, 20, 27, 36, 37, 39, 41, 93, 124, 125, 126,  
127, 132, 133

---

## **K**

Kinetics · 4, 15, 49, 100, 102, 103, 107, 111, 124

---

## **L**

law · 16, 31, 40, 58, 59, 75, 111, 113, 121, 131, 133, 135,  
136, 137, 138, 156, 158, 159  
Leverett · 16, 27, 32, 138  
Linear equations · 19  
Linear Kd · 14, 78, 96  
*Linking* · 12  
Liquid · 14, 21, 23, 25, 32, 38, 40, 43, 57, 63, 67, 95, 109,  
110, 120, 124, 125, 127, 129, 139, 141, 142, 160

---

## **M**

Mass · 15, 17, 19, 23, 24, 26, 28, 41, 53, 54, 79, 98, 99,  
100, 101, 109, 110, 111, 121, 124, 125, 126, 127, 128,  
130, 131, 171  
Matrix · 26, 75, 127, 132, 133, 134, 135, 139, 142, 143  
*min\_Sl.out* · 24

Mineral · 4, 5, 14, 16, 24, 25, 26, 27, 28, 29, 32, 38, 39, 42, 43, 47, 51, 53, 57, 59, 67, 68, 69, 70, 71, 77, 81, 86, 87, 88, 93, 94, 96, 97, 98, 99, 100, 102, 105, 107, 110, 112, 113, 115, 126, 127, 130, 131, 132, 133, 134, 135, 136, 137, 139, 140, 141, 142, 143, 144, 157, 158, 170, 171  
Mixture · 116  
Molecular · 14, 15, 21, 40, 84, 86, 89, 129, 130, 144, 154, 170, 171  
Multiphase · 5, 13, 15, 17, 21, 25, 95, 101, 103, 107, 110

---

## N

NaCl · 6, 14, 39, 96, 103, 146, 147, 148, 149, 150, 151, 153  
Nodal distance · 125  
Nonisothermal · 159  
Nuclear waste · 1, 2, 5, 14, 96, 105, 106, 107, 108  
Numerical solution · 13, 17

---

## O

Output · 22, 23, 24, 25, 26, 27, 28, 30, 33, 38, 39, 42, 43, 44, 45, 46, 50, 77, 93, 95, 149, 167, 168, 170, 171

---

## P

Parameter · 12, 31, 32, 33, 39, 62, 75, 83, 84, 123, 139, 142, 146  
Parameter · 12, 26  
Partial · 21, 25, 73, 100, 104, 116, 129  
Partitioning · 95, 127  
Permeability-porosity relationship · 75  
Phase · 5, 15, 17, 20, 21, 23, 25, 38, 40, 57, 95, 103, 105, 109, 110, 116, 124, 125, 127, 129, 140, 157  
Plot · 168  
Porosity · 4, 16, 27, 31, 32, 38, 40, 47, 48, 74, 75, 98, 119, 125, 127, 135, 136, 137, 138, 140, 141, 142, 143, 144  
Porosity-permeability · 16, 27, 47, 137, 138  
Porosity-permeability relationship · 137, 138  
Porous medium · 21, 100, 103  
Pressure · 5, 13, 14, 16, 21, 22, 23, 26, 27, 32, 38, 40, 66, 67, 73, 83, 85, 86, 96, 110, 116, 129, 130, 138, 154, 159  
Primary species · 15, 42, 44, 50, 53, 55, 56, 62, 66, 67, 77, 83, 84, 93, 94, 110, 123, 130, 131  
Primary variables · 132  
Printout · 5, 22, 23, 25, 27, 37, 39, 42, 43  
Pyrite · 21, 99, 102, 107

---

## R

Radius · 71, 83, 84, 140, 141, 144, 146

Rate · 5, 16, 19, 22, 24, 28, 41, 49, 53, 54, 58, 59, 71, 100, 102, 104, 111, 112, 113, 114, 127, 130, 131, 133, 138, 139, 156, 157, 158, 159  
Reaction · 4, 5, 15, 20, 22, 24, 26, 28, 36, 37, 38, 39, 52, 53, 54, 59, 63, 71, 84, 85, 86, 87, 89, 90, 92, 97, 100, 103, 105, 107, 110, 111, 112, 114, 117, 119, 120, 121, 123, 124, 125, 126, 131, 133, 142, 156, 158, 159, 169, 171  
Reactive surface area · 4, 24, 28, 71, 112, 120, 138, 139, 141, 143, 159  
Redox · 14, 15, 16, 95, 99, 107  
Reduction · 21, 106, 107, 137  
Relative · 14, 32, 41, 43, 94, 98, 100, 110, 122, 132  
Reservoir · 99, 101, 103, 104, 106  
Residual · 32, 37, 132, 142, 159  
Retardation factor · 79  
*runlog.out* · 23, 26, 27, 92

---

## S

Salinity · 5  
Salting out · 116  
Sample problems · 1, 6, 13, 36, 49, 53  
Saturation · 13, 23, 24, 27, 31, 32, 38, 40, 55, 57, 63, 66, 67, 83, 96, 111, 112, 113, 115, 116, 120, 125, 127, 132, 139, 141, 142, 159, 160  
Saturation · 20, 25, 32  
*savechem* · 23  
Secondary · 15, 37, 55, 56, 59, 84, 85, 86, 89, 91, 94, 101, 105, 109, 110, 111, 115, 133, 140, 144, 149, 153, 154  
Selectivity · 63, 117  
Sequential iteration · 19, 37, 39, 41, 124, 126  
Solid solution · 4, 57, 112, 155, 156, 157, 169  
Solubility · 100, 154  
Solution method · 20, 129  
source/sink · 15, 19, 38, 125, 126, 127, 128  
*speciation* · 23, 26, 37, 38, 41, 65, 66, 67, 83, 93, 95, 107, 133, 148, 154  
*Speciation data* · 23, 93  
Species · 67, 94, 111  
Specific · 12, 23, 25, 30, 39, 47, 48, 51, 54, 65, 67, 76, 82, 94, 111, 112, 120, 137  
Stability condition · 20  
State variables · 19  
Stepping · 21, 33  
Supergene copper · 14, 96, 107  
Supersaturation window · 60, 115

---

## T

Temperature · 5, 13, 14, 16, 22, 23, 25, 26, 32, 33, 40, 43, 54, 58, 60, 62, 66, 67, 83, 85, 86, 87, 89, 91, 93, 94, 95, 101, 103, 110, 112, 113, 115, 116, 117, 122, 129, 130, 144, 146, 154, 167, 169, 170  
Templates · 1  
Thermodynamic database · 13, 22, 23, 39, 44, 45, 46, 50, 56, 57, 60, 61, 81, 94, 144, 146, 148, 149, 153, 154, 167, 168, 169, 170, 171

Thermophysical properties · 17, 95  
Time · 13, 19, 20, 21, 23, 24, 25, 26, 27, 28, 30, 33, 34,  
37, 38, 39, 40, 41, 42, 43, 93, 95, 99, 112, 118, 125,  
127, 128, 130, 131, 133, 135, 140, 141  
Tortuosity · 31, 40, 125, 137  
Total dissolved concentration · 15, 109  
TOUGH2 V2 · 1, 6, 13, 21, 23, 27, 29, 30, 31, 37, 92  
Tracer · 129  
Transport · 5, 13, 15, 16, 17, 19, 20, 21, 22, 23, 24, 25,  
26, 27, 36, 37, 38, 39, 41, 51, 60, 72, 77, 92, 95, 96, 97,  
98, 99, 100, 101, 102, 104, 105, 106, 107, 108, 109,  
110, 124, 125, 126, 129, 148

---

## ***U***

Units · 42, 43, 52, 53, 71, 77, 78, 110, 130, 131, 139, 140,  
141, 143, 144, 168  
Upstream weighting · 40, 125  
Utility programs · 81

---

## ***V***

Vadose zone · 5

Vapor · 5, 14, 95, 104, 116  
Vapor pressure lowering · 5  
Variables · 15, 19, 32, 34, 35, 41, 49, 51, 62, 64, 65, 68,  
72, 74, 76, 78, 79, 110, 132, 133, 139, 158, 159  
Verma-Pruess · 75  
Viscosity · 5, 14, 17, 95, 110  
Void space · 137

---

## ***W***

Water · 4, 5, 13, 14, 17, 21, 22, 23, 26, 43, 47, 49, 57, 63,  
64, 65, 66, 67, 68, 77, 82, 83, 93, 95, 96, 98, 100, 102,  
103, 104, 105, 116, 120, 122, 131, 141, 142, 145, 147,  
149, 151, 154, 159, 160  
Weathering · 1, 98, 100  
Weighting · 40, 125  
Well · 19, 107, 112, 113, 114, 136, 138, 148, 149, 158

---

## ***Y***

Yucca Mountain · 97, 98, 101, 102, 104, 105, 106