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Acknowledgments

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by

D.M. Diodato

Abstract

The report is designed to be used as a decision-making aid for individuals who need to simulate fluid flow in fractured porous media. Fracture flow codes of varying capability in the public and private domain were identified in a survey of government, academia, and industry. The selection and use of an appropriate code requires conceptualization of the geology, physics, and chemistry (for transport) of the fracture flow problem to be solved. Conceptual models that have been invoked to describe fluid flow in fractured porous media include explicit discrete fracture, dual continuum (porosity and/or permeability), discrete fracture network, multiple interacting continua, multipermeability/multiporosity, and single equivalent continuum. The explicit discrete-fracture model is a "near-field" representation, the single equivalent continuum model is a "far-field" representation, and the dual-continuum model is intermediate to those end members. Of these, the dual-continuum model is the most widely employed. The concept of multiple interacting continua has been applied in a limited number of examples. Multipermeability/multiporosity provides a unified conceptual model. The ability to accurately describe fracture flow phenomena will continue to improve as a result of advances in fracture flow research and computing technology. This improvement will result in enhanced capability to protect the public environment, safety, and health.

1 Introduction

1.1 Background

This report contains summaries of numerical models describing fluid flow in fractured porous media. In addition, a brief overview of the pertinent concepts relating to fracture flow modeling is provided. The emphasis is on applications that support field-scale problem solving. The intent is to provide a stand-alone document as an aid to the individual confronted with a problem that requires fracture flow modeling. Identifying pertinent physical and chemical processes, developing a conceptual hydrogeologic model, and recognizing appropriate field data requirements are critical to successful modeling. Having accomplished those fundamental tasks, the investigator will be able to identify which of the codes herein most nearly satisfies the required simulation criteria.
Government, academia, and industry were surveyed to identify all available fracture flow codes. The capabilities, assumptions, limitations, and availability of fracture flow codes from these entities are outlined in Table 1 (pages 10–13) and summarized in Appendix A. Appendix B lists codes sorted by custodian. Appendix C describes code custodians, their support policies, and pricing structures (where variable). Appendix D lists select references sorted by code. Appendix E lists codes that were identified but unavailable.

1.2 How to Use This Document

Follow the procedure outlined below to identify fracture flow codes that will satisfy your required simulation criteria.

1. After completing hydrogeologic data acquisition and site characterization and identifying all physical and chemical processes of interest, identify an appropriate conceptual model of fracture flow.

2. Read this document.

3. Identify potentially suitable codes from Table 1.

4. Consult Appendix A for expanded descriptions of the codes identified in step 3.

5. Of the codes that remain suitable, consult the code custodian to verify that the code satisfies the required simulation criteria. Because the availability, capabilities, and limitations of many of these codes may change, this final check is important.
2 Overview of Fracture Flow Models

Research into the nature of fluid flow in fractures and multiphase fluid flow has been conducted by petroleum engineers, mining engineers, and hydrogeologists. In the past, economic resource evaluation and production were the motivation for these studies. Today, that motivation is fueled by worldwide concerns about radioactive waste isolation and migration.

Research on fluid flow in fractures and in fractured porous media has a history that spans nearly four decades (Barenblatt et al. 1960; Warren and Root 1963). This research has focused on four principal aspects of fracture flow: (1) development of conceptual models, (2) development of analytical and numerical solution schemes, (3) description of fracture hydraulic characteristics in static and deforming media, and (4) development of stochastic techniques to describe fracture flow and hydrogeologic parameter distributions. Bear et al. (1993) extensively review the research on fracture flow phenomena.

2.1 Conceptual Models of Fracture Flow

Researchers have developed several conceptual models describing fluid flow in fractured porous media. Fundamentally, each method can be distinguished on the basis of the storage and flow capabilities of the porous medium and the fracture. The storage characteristics are associated with porosity, and the flow characteristics are associated with permeability. Four conceptual models have dominated the research: (1) explicit discrete fracture, (2) dual continuum, (3) discrete fracture network, and (4) single equivalent continuum. In addition, multiple-interacting continua and multiporosity/multipermeability conceptual models have been recently introduced in the literature.

Further distinctions can be drawn on the basis of the spatial and temporal scales of integration or averaging of the flow regime. Bear and Berkowitz (1987) describe four scales of concern in fracture flow: (1) the very near field, where flow occurs in a single fracture and porous medium exchange is possible; (2) the near field, where flow occurs in a fractured porous medium and each fracture is described in detail; (3) the far field, where flow occurs in two overlapping continua with mass exchanged through coupling parameters; and (4) the very far field, where fracture flow occurs, on average, in an equivalent porous medium.

2.1.1 Explicit Discrete Fracture Formulation

Several investigators have published numerical models incorporating explicit discrete representations of fractures. TRACR3D (Travis 1984) incorporates fractures explicitly, but this model is restricted to fractures with vertical or horizontal orientation. The most recent version of the Sandia Waste Isolation Flow and Transport (SWIFT) model incorporates options for discrete fractures or dual porosity (Intercomp 1976; Ward et al. 1993). The advantage of explicit
Discrete-fracture models is that they allow for explicit representation of fluid potential gradients and fluxes between fractures and porous media with minimal non-physical parameterization. However, data acquisition can become onerous where large numbers of fractures occur. Also, as the complexity of the model domain increases with increasing numbers of fractures, the computational burden increases significantly.

2.1.2 Dual-Continuum Formulation

Dual-continuum approaches were introduced by Barenblatt et al. (1960) and later extended by Warren and Root (1963). Dual-continuum models are based on an idealized flow medium consisting of a primary porosity created by deposition and lithification and a secondary porosity created by fracturing, jointing, or dissolution (Warren and Root 1963). The basis of these models is the observation that unfractured rock masses account for much of the porosity (storage) of the medium, but little of the permeability (flow). Conversely, fractures may have negligible storage, but high permeability. The porous medium and the fractures are envisioned as two separate but overlapping continua. Fluid mass transfer between porous media and fractures occur at the fracture-porous medium interface. In some numerical approaches, the mass transfer is lumped at the nodes common to the fracture and porous medium grids. The transfer occurs according to a fluid-potential-dependent coupling parameter. This approach averages or "smears" the transient response between fracture and porous medium (Elsworth, D., pers. comm.). Huyakorn et al. (1983) describe a number of different formulations of the coupling parameter.

2.1.3 Discrete-Fracture Network

Discrete-fracture-network models describe a class of dual-continuum models in which the porous medium is not represented. Instead, all flow is restricted to the fractures. This idealization reduces computational resource requirements. Fracture "legs" are often represented as lines or planes in two or three dimensions. Some codes allow for variable coupling at the fracture-leg intersections and for multiple legs to connect at a single location. For contaminant transport, some network models allow for diffusion between the fracture and porous medium.

2.1.4 Single Equivalent Continuum Formulation

The volume of interest is considered to be large enough that, on average, permeability is a sum of fracture and porous media permeability. This approximation substantially simplifies the flow problem. Pruess et al. (1986) presented a model for a single equivalent continuum in unsaturated fractured rock in which hydraulic conductivity was taken as a sum of hydraulic conductivity from the porous medium and the fracture. Pruess et al. (1990a,b) found that this approach was unacceptable in the presence of rapid flow transients, large fracture spacings, or with a very low permeability rock matrix. In broad terms, where the scales of integration are sufficiently large, the single equivalent continuum approximation will do a fair job of conserving
fluid mass. It may, however, be a poor predictor of spatial and temporal distributions of contaminant fluxes.

2.1.5 Alternative Conceptual Models

Recently, Bai et al. (1993) introduced a unified multiporosity/multipermeability approach to modeling flow in fractured porous media. They illustrate that single porosity/single permeability, dual porosity/single permeability, dual porosity/dual permeability, dual porosity/triple permeability, and triple porosity/triple permeability are all just special cases of a generalized multiporosity/multipermeability description. Consistent with Bai et al. (1993), Bear (1993) pointed out that different geologic and environmental processes can produce multiple distinct fracture subsystems in a common domain. In that case, each distinct subsystem might be modeled as a separate continuum within a single numerical model, provided a common representative elementary volume (REV) exists. A multiple-interacting continua approach has been proposed and implemented by Pruess and Narasimhan (1982, 1985) and Pruess (1991). In their approach, matrix grid blocks are divided into nested subdomains to accommodate slow changes in fluid pressures, temperatures, and phase compositions, which are strongly a function of distance from the fracture. One-dimensional calculations are then used to determine the solution within the porous block domain.

2.2 Fracture Flow in Deforming Media

Iwai (1976), Witherspoon, et al. (1980), Elsworth (1989), and Bai et al. (1993) have developed models describing fluid flow in fractured media undergoing deformation. SANGRE (Anderson 1986) simulates fluid flow and heat transport in a grid that can rotate, translate, and deform over time. The ductile and brittle deformation processes are simulated where faulting can occur on pre-defined slip-planes. SANGRE was designed to simulate the formation of petroleum reservoir traps over tens of millions of years. At high rates of media deformation, or over long periods, changing material properties can significantly impact fluid potential fields and fluxes.

2.3 Unsaturated and Multiphase Flow

Several of the codes in this review can simulate unsaturated flow. In this report, unsaturated or variably saturated is used to mean flow of a single phase (usually water) where that phase does not fully saturate the fractured porous media. Often, the mathematical equation solved takes the form of the well-known Richards equation. Multiphase is used to mean miscible or immiscible coupled flow of two or more phases.

The TOUGH family of codes (Pruess 1987, 1991) simulates nonisothermal multiphase flow in fractured porous media by using one of five equations of state, depending upon the
phases present. TRACER3D (Travis and Birdsell 1991) supports saturated, unsaturated, and multiphase flow. PORFLOW (Runchal 1994) also supports saturated, unsaturated, and multiphase flow. Huyakorn and Pinder (1978) and Kaluarachi and Parker (1989) evaluated how effectively several numerical approaches solve porous media multiphase flow equations by using finite elements. Diodato and Filley (1989), Filley et al. (1991), and Filley and Diodato (1993) employed the Implicit Pressure-Explicit Saturation (IMPES) finite-difference numerical technique (Aziz and Settari 1979) and analytical equations of state (van Genuchten 1980) to investigate multiphase fluid flow and contaminant transport in two-dimensional, anisotropic, heterogeneous porous media.

Diodato (1994) proposed a simulator for multiphase flow in fractured porous media on the basis of an explicit discrete fracture conceptual model. The code allows for fractures and geologic units at any orientation and provides built-in grid visualization capabilities. Reitsma and Kueper (1994) quantified capillary pressure as a function of saturation in a fracture in the laboratory. They found the Brooks-Corey (Brooks and Corey 1964, 1966) porous-media capillary pressure-saturation relationship to be suitable for describing this phenomenon in a fracture. Glass (1993) and Nicholl and Glass (1993) investigated in-fracture unsaturated flow instabilities by using physical and numerical models. They observed viscous fingering and zones of persistent entrapped air in a series of vertical and horizontal imbibition and drainage experiments.

2.4 Stochastic Methods

As an alternative to deterministic models, some investigators have used stochastic methods of characterizing fracture occurrence and flow in fractures. For example, de Marsily (1986) describes stochastic partial differential equations in which one or more of the parameters is a random variable. In addition, he gives several approaches to solutions. Given a sufficient data set and an appropriate distribution, the statistical moments of fracture occurrence, orientation, spacing, and aperture can be described. From these values, equivalent statistical models of fracture fields can be generated. Shimo and Long (1987) and Long (1989) have generated stochastic fracture fields by working from several different conceptual models. Neuman (1982) summarizes statistical approaches to aquifer characterization. Rouleau (1988) used the codes NETFLO/NETTRANS to simulate flow and transport in a stochastically generated discrete-fracture network. The FracMan/MAFIC code package includes stochastic fracture-network generators.
3 Numerical Methods

Research on solving fracture flow problems has included both analytical and numerical solution schemes. Because this document is not a mathematical reference, equations and solution schemes employed are not listed. Streltsova-Adams (1978) describes several analytical solutions for flow in fractured rock. Elsworth (1984) describes several analytic solutions to particular flow geometries and laminar or turbulent flow. A summary of some of the numerical approaches used can be found in Ababou (1991). Amadei and Illangasekare (1992) employed integral transforms to generate continuous expressions for fluid potential in rectangular joints. Their approach allowed for anisotropy and heterogeneity in fracture aperture and roughness and provided an analytical vehicle for the study of the cubic law. Because of the integral transform, the fracture volume did not have to be discretized. The volume itself, however, was restricted to simple geometries. More recently, Amadei and Illangasekare (1994) have expanded the method to investigate solute transport phenomena. Pinder et al. (1993) provide several analytical and numerical formulations describing fracture flow.

Differential and integral numerical methods for solving the material balance equations describing mass flow and transport in fractured porous media have been employed. For the spatial derivatives, integral methods have enjoyed more widespread use than the differential approach of the finite difference method (FDM), partly because they are amenable to irregular domain geometries. Integral methods used in fracture flow modeling include the finite-element (FEM) method and the boundary-element method (BEM). Elsworth (1984, 1987) presented a hybrid BEM-FEM procedure for simulating fracture flow problems. Rasmussen (1987) used BEM to simulate unsaturated flow in discrete fracture networks. Additionally, integrated finite-difference methods (IFDM) have been presented and applied (Edwards 1972; Narasimhan and Witherspoon 1976; Pruess 1987, 1991). Temporal derivatives are commonly treated implicitly by using a Crank-Nicholson approximation. To eliminate problems of instability at high Peclet numbers, Sudicky and McLaren (1992) used a Laplace transform technique to explicitly solve for any desired time.
4 Review Criteria

Fracture flow codes were reviewed with respect to their availability, capabilities, and limitations. Because many of the codes have the capability of modeling contaminant transport, categories describing those capabilities are included in the review. Fundamental capabilities with respect to flow and transport are summarized in Table 1. Detailed descriptions of the flow and transport capabilities and other information are included in Appendix A. The meaning of the categories and responses in Table 1 is described below.

**Availability**
Cost in U.S. or Canadian (where indicated) dollars. The Energy Science and Technology Software Center (ESTSC) pricing varies by customer and is indicated with an "E." Some of their codes may not be available to non-U.S. citizens. "Yes" means that the code is available for a nominal charge, in some cases at no cost. Consult the custodian descriptions in Appendix C for more information about individual pricing policies.

**Flow Model**

**Dimensionality**
The number of spatial dimensions modeled.

**Conceptual Model**
"EX" explicit discrete fracture,
"DU" dual continuum,
"NE" discrete fracture network, and
"EQ" equivalent porous medium.

**Steady-State**
"Yes" means that steady-state flow can be simulated.

**Transient**
"Yes" means that transient flow can be simulated.

**Heterogeneous**
"Yes" means that the conductive medium can be heterogeneous.

**Anisotropic**
"Yes" means that the conductive medium can be anisotropic.

**Unsaturated**
"Yes" means that the model can simulate unsaturated flow.

**Multiphase**
"Yes" means that the model can simulate multiphase flow.
Transport Model

Types

"S" Solute

"H" Heat

"R" Radionuclides

Advection

"Yes" means that the model can simulate advection.

Dispersion

"Yes" means that the model can simulate dispersion.

Diffusion

"Yes" means that the model can simulate diffusion.

Retardation

"Yes" means that the model can simulate retardation.

Sorption

"Yes" means that the model can simulate sorption.

Decay

"Yes" means that the model can simulate decay.

If a "?" appears in any category, the code vendor did not supply the information.
## TABLE 1 Capabilities of the Fracture Flow Codes (see page 8 for explanation of categories)

<table>
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<tr>
<th>Parameter</th>
<th>3-D FE DUAL</th>
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5 Conclusions

To select an appropriate flow code, one should carefully consider the geology, physics, and, if appropriate, chemistry of the problem to be solved. Careful consideration of the conceptual model of fluid flow in a fractured rock setting is critical to successful fracture flow modeling. Inherent in this conceptualization is the determination of spatial and temporal scales relevant to the problem. Near-field problems may require explicit discrete fracture flow models, while far-field problems may appropriately employ a single continuum model. For the large number of intermediate situations, dual-continuum models may be used. For cases of chemical or radioisotope transport, pertinent physical and chemical processes must be identified and considered as to their relative importance in describing mass transport of the constituents of concern. These processes may include advection, dispersion, adsorption/desorption, diffusion, retardation, chemical reactions, phase partitioning, decay, and radioactive decay product series.

The custodianship and the availability of all of the codes identified in this survey were confirmed. Of the 35 codes identified in an initial screening, 7 are no longer available.

Research into improved representations of fluid flow and contaminant transport in fractured rock continues at an exciting pace. Driving much of this research is interest in fractured low-permeability geologic media as repositories of high-level radioactive waste in the United States and abroad. With advances in fracture flow and contaminant transport research, as well as in computing technology, the ability to accurately model the geology, physics, and chemistry of the natural settings and processes will continue to improve. Enhanced modeling capabilities will aid groundwater protection and remediation, thereby improving the capability to protect the safety and health of the populace.
6 References


Appendix A:

Detailed Descriptions of the Fracture Flow Codes
Appendix A: Detailed Descriptions of the Fracture Flow Codes

This appendix contains detailed descriptions of fracture flow codes identified in this survey. The categories are described below.

**Code Name:** Name of the fracture flow code.

**Author(s):** Author(s) of the code.

**Year:** Year the version of the code was created.

**Revision:** Revision level of the code.

### A.1 Capabilities, Limitations, and Assumptions

Capabilities, limitations, and assumptions in the categories of flow modeling, transport modeling, and numerical methods are described. Note that the absence of a feature implies a limitation with respect to that feature. Assumptions are inherent in the different conceptual models for fracture flow and in the processes that are and are not simulated.

**Flow Model:** Fluid-flow-simulation capabilities including, but not limited to, dimensionality, fractured/unfractured porous media, single phase/multiphase flow, saturated/unsaturated flow, isothermal/nonisothermal flow, state-variable dependencies.

**Transport Model:** Radionuclide, energy, and/or solute transport processes simulated including, but not limited to, single/multiple decay chains, convection, diffusion, advection, dispersion, sorption, adsorption, reaction series, stochastic representations.

**Numerical Model:** Fracture flow conceptual model: explicit discrete fracture, dual continuum, discrete fracture network, single equivalent continuum, multiple interacting continua. Spatial discretization: finite difference, finite element, integral finite difference, boundary integral. Solution procedures, especially where unique. Abbreviations include Incomplete Cholesky Conjugate Gradient (ICCG) and Generalized Minimal Residual (GMRES) matrix solvers.
A.2 Quality Assurance/Quality Control

A number of categories have been identified that pertain to quality assurance and quality control with respect to the accuracy, reliability, and dependability of supplied codes.

Peer Review: "Yes" means that theory and application of theory has been subject to peer review either through professional journal publication or outside agency review.

Benchmarking: "Yes" means that the code has been benchmarked against analytical solutions of test problems.

Field Testing: "Yes" means that the code has been field tested and been shown to successfully simulate the processes encountered at field test sites.

Code Documentation: "Yes" means that the code algorithms are documented on paper and that the code is commented.

User Documentation: "Yes" means that documentation describing the use of the code exists.

I/O Check files: "Yes" means that example input files are provided. It is recommended that electronic copies of output files also be provided. A new installation test run with a supplied input file should generate an output file identical in size and content to the one supplied.

A.3 Support and Enhancements

Code Support: "Yes," if available; amount in dollars per annum if not included.

Pre-Processor: "Yes" if a pre-processor is available.

Post-Processor: "Yes" if a post-processor is available.

A.4 Other

Availability: Cost of proprietary or public domain codes. In some cases, code prices vary or codes are available for free by written request.
**Custodianship:** Current code custodian.

**Hardware Requirements:** Platform(s) on which code runs.

**Source Availability:** "Yes" if source code is supplied.

**Source Language:** Language of source code, if supplied.

**References:** Number of references to the code listed in Appendix D. The number is followed by a plus (+) where more references have been identified than are listed in Appendix D.

Blank entries indicate that the information is not available or that the category is not applicable. For example, the transport category is blank for a code that does not have that capability.
### A.5 The Codes

#### 3-D FE DUAL-POROSITY FLOW & TRANSPORT MODEL

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#### Capabilities, Limitations, and Assumptions

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#### Quality Assurance/Quality Control

- Peer Review: Yes
- Benchmarking
- Field Testing
- Code Documentation
- User Documentation: Yes
- I/O Check Files

#### Support and Enhancements

- User Support
- Pre-processor
- Post-processor

#### Other

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BIM/BIM2D/BIM3D/FRACGEN

Author(s) Rasmussen, T.C., and D.D. Evans
Year 1989
Revision

Capabilities, Limitations, and Assumptions
Flow Model Two- or three-dimensional steady-state saturated, unsaturated, or multiphase flow in fractured, porous or non-porous media.
Transport Model Solute transport by advection, and diffusion.
Numerical Methods Dual-continuum (multiporosity) conceptual model. Boundary Integral Method. Includes synthetic fracture network generator, FRACGEN.

Quality Assurance/Quality Control
Peer Review Yes
Benchmarking Yes
Field Testing Laboratory testing only.
Code Documentation Limited
User Documentation Yes
I/O Check Files No

Support and Enhancements
User Support No
Pre-processor No
Post-processor No

Other
Availability Research code available free upon request.
Custodianship T.C. Rasmussen
Hardware Requirements Any platform with a FORTRAN compiler.
Source Included Yes
Source Language FORTRAN
References 3
DCM3D

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**Capabilities, Limitations, and Assumptions**

- **Flow Model**: Three-dimensional, transient, variably saturated flow in fractured, heterogeneous, anisotropic porous media.
- **Transport Model**: None
- **Numerical Methods**: Dual-continuum conceptual model. Integrated finite-difference method. Block-centered orthogonal grid. Temporally variable boundary conditions.

**Quality Assurance/Quality Control**

- **Peer Review**: Yes
- **Benchmarking**: Yes
- **Field Testing**: No
- **Code Documentation**: Yes
- **User Documentation**: Yes
- **I/O Check Files**: Yes

**Support and Enhancements**

- **User Support**: Limited support provided by custodian. See custodian description.
- **Pre-processor**: No
- **Post-processor**: Yes, of limited capability.

**Other**

- **Availability**: Yes
- **Custodianship**: U.S. Nuclear Regulatory Commission
- **Hardware Requirements**: Double-precision version available for 32-bit machines (INTEL-based, DEC VAX, etc.)
  - Single-precision version available for 64-bit machines (Cray)
  - Modifications to Cray system time/date/cpu time calls may be required.
- **Source Included**: Yes
- **Source Language**: FORTRAN
- **References**: 2
**FRACSDVS**

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### Capabilities, Limitations, and Assumptions

**Flow Model**
- Three-dimensional, steady-state or transient, saturated or unsaturated flow in fractured or unfractured porous media.

**Transport Model**
- Solute or radionuclide transport by advection, dispersion, diffusion, retardation, multi-species transport, straight/branching first-order decay chains, linear adsorption/desorption.

**Numerical Methods**
- Explicit discrete-fracture conceptual model. Control volume finite element (FE) (also known as IFDM), Galerkin FE finite difference (FD). Spatial discretization as 8- or 6-point FE or 7-point FD. Richard’s equation used for unsaturated flow. Optional NAPL source term. Adaptive time-stepping. ORTHOMIN solver.

### Quality Assurance/Quality Control

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### Support and Enhancements

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### Other

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<td>R. McLaren</td>
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<td>Hardware Requirements</td>
<td>80386 or better, or IBM RS/6000 (AIX OS w/X)</td>
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<td>Source Included</td>
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<td>Source Language</td>
<td>FORTRAN77</td>
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<td>References</td>
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FRACFLO

Author(s)        Gureghian, A.B.
Year             1990

Capabilities, Limitations, and Assumptions

Flow Model       Two-dimensional steady-state flow in fracture network.
Transport Model  Radionuclide transport by advection, dispersion, diffusion into rock matrix, decay. Source configurations variable in space and time.

Quality Assurance/Quality Control

Peer Review      Yes
Benchmarking     
Field Testing    
Code Documentation
User Documentation Yes
I/O Check Files 

Support and Enhancements

User Support     Limited; see custodian description.
Pre-processor    FRACGRF, FRACGRF2D, require CA-DISSPLA 10.5
Post-processor   

Other

Availability      Yes. See custodian description for pricing scheme.
Custodianship    Energy Science and Technology Software Center (ESTSC)
Hardware Requirements DEC VAX8700 (VMS 5.0)
Source Included  Yes
Source Language  VMS FORTRAN
References       2
FRACFLOW

Author(s)  GeoTrans, Inc.
Year  1988
Revision  1.15

Capabilities, Limitations, and Assumptions

Flow Model Two-dimensional transient fluid flow in heterogeneous fractured porous media.
Transport Model
Numerical Methods Dual-continuum conceptual model. Finite-element discretization.

Quality Assurance/Quality Control

Peer Review  Yes
Benchmarking  Yes
Field Testing  Yes
Code Documentation  Yes
User Documentation  Yes
I/O Check Files  Yes

Support and Enhancements

User Support  Yes
Pre-processor
Post-processor

Other

Availability
Custodianship  GeoTrans, Inc.
Hardware Requirements  80486
Source Included  Yes
Source Language  FORTRAN
References  1
FracMan/MAFIC

Author(s) Golder Associates, Inc.
Year 1994
Revision 2.306/1.3

Capabilities, Limitations, and Assumptions

Flow Model Three-dimensional steady-state or transient, variably saturated, density- and temperature-dependent flow in fractured porous media.

Transport Model Transport of solutes, heat, and radionuclides by particle tracking; advection, dispersion, matrix diffusion, retardation, radionuclide decay.


Quality Assurance/Quality Control

Peer Review Yes
Benchmarking Yes
Field Testing Yes
Code Documentation Yes
User Documentation Yes
I/O Check Files Yes

Support and Enhancements

User Support On a consulting basis. Annual maintenance for consultation, $10,000.
Pre-processor Fractures can be generated on the basis of a variety of geostatistical models, including box fractal and Poisson, or by conditioning and projection onto convex sets. Interface to TOUGH available.
Post-processor Yes

Other

Availability $1,000 per annum. Generally no license fee for U.S. government and academia.
Custodianship Golder Associates, Inc.
Hardware Requirements MAFIC: SUN, HP9000, Silicon Graphics, IBM RS/6000
Source Included No
Source Language C, FORTRAN
References 8+
FRACTRAN

Author(s)        Sudicky, E.A., and R.G. McLaren
Year             1992
Revision         3.07

Capabilities, Limitations, and Assumptions

Flow Model       Two-dimensional steady-state flow in fractured or unfractured porous media.
Transport Model  Solute and radionuclide transport by advection, dispersion, diffusion, retardation, and first-order decay.

Quality Assurance/Quality Control

Peer Review      Yes
Benchmarking     Yes
Field Testing    No
Code Documentation Yes
User Documentation Yes
I/O Check Files  Yes

Support and Enhancements

User Support     Yes
Pre-processor    Yes
Post-processor   Yes

Other

Availability      $2,500 (Canadian)
Custodianship    R. McLaren
Hardware Requirements 80386 or better
Source Included   Yes
Source Language   FORTRAN77
References       2
FRANET

Author(s)                 Kanehiro, B.Y., and C.H. Lai
Year                      1987
Revision                  2.0

Capabilities, Limitations, and Assumptions

Flow Model
Steady-state or transient, slightly compressible flow in a
fracture network of arbitrary orientation.

Transport Model
None

Numerical Methods
Discrete-fracture-network conceptual model. Finite-element
spatial discretization.

Quality Assurance/Quality Control

Peer Review                Yes
Benchmarking               Yes
Field Testing              No
Code Documentation         Yes
User Documentation         Yes
I/O Check Files            No

Support and Enhancements

User Support               Limited
Pre-processor              No
Post-processor             No

Other

Availability               Small charge
Custodianship             Berkeley Hydrotechnique, Inc.
Hardware Requirements     Any platform with FORTRAN77
Source Included           Yes
Source Language           FORTRAN
References                1
FTRANS

Author(s)       Huyakorn, P.S.
Year            1982

Capabilities, Limitations, and Assumptions

Flow Model       Two-dimensional, transient, density-dependent flow in
fractured or unfractured anisotropic, heterogeneous, porous
media.

Transport Model  Solute, heat, and radionuclide transport by advection,
conduction, dispersion, diffusion, sorption, and first-order
decay with decay chains.

Numerical Methods Dual-continuum conceptual model. Finite-element spatial
discretization.

Quality Assurance/Quality Control

Peer Review      Yes
Benchmarking     Yes
Field Testing    
Code Documentation
User Documentation Yes
I/O Check Files  Yes

Support and Enhancements

User Support
Pre-processor
Post-processor

Other

Availability      Yes. See custodian description for pricing scheme.
Custodianship    Energy Science and Technology Software Center (ESTSC)
Hardware Requirements
Source Included
Source Language
References       1
MAGNUM2D

Author(s)  England, R.L., N.W. Kline, K.J. Ekblad, and R.G. Baca
Year       1985

Capabilities, Limitations, and Assumptions

Flow Model  Two-dimensional, transient or steady-state, flow in
fractured anisotropic, heterogeneous, porous media.
Transport Model  Solute and heat transport by advection, dispersion,
diffusion, sorption, and multi-species decay. Can be linked
with the radionuclide transport code CHAINT.
Numerical Methods  Explicit discrete-fracture, dual-continuum, or equivalent
porous-medium conceptual models. Finite-element spatial
discretization.

Quality Assurance/Quality Control

Peer Review  Yes
Benchmarking  Yes
Field Testing  Yes
Code Documentation
User Documentation  Yes
I/O Check Files  Yes

Support and Enhancements

User Support  Limited, see custodian description.
Pre-processor  Yes
Post-processor  Requires CA-DISSPLA

Other

Availability  Yes. See custodian description for pricing scheme.
Custodianship  Energy Science and Technology Software Center (ESTSC)
Hardware Requirements
Source Included
Source Language
References  4
MOTIF

Author(s)  Guvanasen, V., and T. Chan
Year  1991
Revision

Capabilities, Limitations, and Assumptions

Flow Model  One-, two-, or three-dimensional, variably saturated flow in fractured, deformable, porous media.
Transport Model  Solute, heat, and single-species radionuclide transport by convection, advection, dispersion, diffusion, adsorption, decay.

Quality Assurance/Quality Control

Peer Review  Yes
Benchmarking  Yes
Field Testing  Yes
Code Documentation  Yes
User Documentation  Yes
I/O Check Files  Yes

Support and Enhancements

User Support  Yes
Pre-processor  Third party only
Post-processor  Third party only

Other

Availability  $20,000 (Canadian)
Custodianship  Atomic Energy Canada, Ltd.
Hardware Requirements  Wide variety of UNIX (including AIX and UNICOS), VMS, and CMS platforms.
Source Included  By special arrangement.
Source Language  FORTRAN77
References  4
NEFTRAN II

Author(s) Olague, N.E., and D.E. Longsine
Year 1991
Revision

Capabilities, Limitations, and Assumptions

Flow Model One-dimensional saturated or unsaturated flow along discrete fractures of arbitrary orientation. Fractures are treated as discrete "legs" of uniform hydrogeologic properties in a network. Components of the fluid velocity field may be supplied as user input. For transient flow simulations, multiple velocity fields must be input.

Transport Model Radionuclide transport along flow paths with matrix diffusion, dispersion, sorption, and multiple decay chains.


Quality Assurance/Quality Control

Peer Review Yes
Benchmarking Yes
Field Testing Yes
Code Documentation Minimal
User Documentation Yes
I/O Check Files Yes

Support and Enhancements

User Support Limited
Pre-processor No
Post-processor No

Other

Availability Yes
Custodianship U.S. Nuclear Regulatory Commission
Hardware Requirements CPU with FORTRAN compiler
Source Included Yes
Source Language Microsoft FORTRAN77
References 1
NETFLO/NETRANS

Author(s) Rouleau, A.
Year 1988
Revision

Capabilities, Limitations, and Assumptions

Flow Model Two-dimensional steady-state flow in fracture network in impermeable non-porous media.

Transport Model Transport by advection simulated by stochastic particle tracking in virtual network based on selected directional parameters: relative flow rate, mean flow velocity, and mean length of fracture segment.

Numerical Methods Discrete-fracture-network conceptual model. Solution to conductance network flow in domain of fractures generated stochastically by using the results of Monte Carlo realizations of fields based on statistics from field data.

Quality Assurance/Quality Control

Peer Review Yes
Benchmarking Not applicable (analytical model)
Field Testing Yes
Code Documentation Yes
User Documentation Yes
I/O Check Files Yes

Support and Enhancements

User Support None
Pre-processor NETWORK code
Post-processor

Other

Availability $30 Canadian
Custodianship A. Rouleau
Hardware Requirements SUN workstation, FORTRAN Compiler, IMSL Subroutines
Source Included Yes
Source Language FORTRAN
References 4
PORFLO-3

Author(s)          Runchal, A.K., B. Sagar, and N.W. Kline
Year               1992
Revision           1.2

Capabilities, Limitations, and Assumptions

Flow Model         Three-dimensional, Cartesian or radial, steady-state or transient, nonisothermal, variably saturated flow in fractured porous media.
Numerical Methods  Equivalent porous media or lower dimensional explicit discrete fracture conceptual models. Integrated finite-difference method. PSOR, ADI, Cholesky, conjugate gradient, and other solvers.

Quality Assurance/Quality Control

Peer Review        Yes
Benchmarking       Yes
Field Testing      Yes
Code Documentation Yes
User Documentation Yes
I/O Check Files    Yes

Support and Enhancements

User Support       Kline, N.W.
Pre-processor      Yes
Post-processor     

Other

Availability       Yes
Custodianship     Akshai K. Runchal. Technical Contact: N.W. Kline
Hardware Requirements  80386, 80486, SUN, Silicon Graphics, IBM RS/6000, Cray, Application Dependent
Source Included    Yes
Source Language    FORTRAN77
References         4+
PORFLOW

Author(s) Runchal, A.K.
Year 1994
Revision 2.50

Capabilities, Limitations, and Assumptions

Flow Model Two- or three-dimensional, cartesian or radial, steady-state or transient, variably saturated or multiphase flow in fractured or unfractured, anisotropic, heterogeneous porous media. Supports freezing/thawing and evaporation/condensation.

Transport Model Solute, heat, or radionuclide transport by advection, dispersion, diffusion, sorption, retardation, convection, conduction, dispersion, decay. Highly variable source configuration.

Numerical Methods Equivalent porous media or lower dimensional explicit discrete-fracture conceptual models. Integrated finite-difference spatial discretization. PSOR, ADI, Cholesky, conjugate gradient, and other solvers.

Quality Assurance/Quality Control

Peer Review Yes
Benchmarking Yes
Field Testing Yes
Code Documentation Yes
User Documentation Yes
I/O Check Files Yes

Support and Enhancements

User Support $1,000–5,000
Pre-processor Yes
Post-processor $495–7,495 (platform-dependent)

Other

Availability $995–14,995 without source (platform-dependent)
Custodianship Akshai K. Runchal
Hardware Requirements Any system with a FORTRAN77 compiler.
Source Included $995–14,995 with source (see vendor description)
Source Language FORTRAN77
References 6+ (>100)
SANGRE

Author(s)  Anderson, C.A.
Year       1986
Revision

Capabilities, Limitations, and Assumptions

Flow Model  Two-dimensional flow in deformable and translatable geologic media. Accommodates fractures and the simulation of ductile-brittle discontinuity-developing deformation processes, such as faulting.
Transport Model  Convective energy transport

Quality Assurance/Quality Control

Peer Review  Yes
Benchmarking  Yes
Field Testing
Code Documentation  Yes
User Documentation  Yes
I/O Check Files  Yes

Support and Enhancements

User Support  No
Pre-processor  No
Post-processor  Yes (SANGPL).

Other

Availability  Yes
Custodianship  C.A. Anderson
Hardware Requirements  CPU with FORTRAN Compiler
Source Included  Yes
Source Language  FORTRAN
References  1
**SEFTRAN**

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Huyakorn, P.S., D.S. Ward, J.O. Rumbaugh, and R.W. Broome</th>
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**Capabilities, Limitations, and Assumptions**

<table>
<thead>
<tr>
<th>Flow Model</th>
<th>Two-dimensional transient flow in fractured or unfractured, anisotropic, heterogeneous porous media.</th>
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<tbody>
<tr>
<td>Transport Model</td>
<td>Solute transport by advection, dispersion, equilibrium adsorption, and first-order decay.</td>
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<tr>
<td>Numerical Methods</td>
<td>Explicit discrete-fracture conceptual model. Finite-element spatial discretization. Line elements used to represent either discrete fractures or rivers.</td>
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**Quality Assurance/Quality Control**

<table>
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<td>I/O Check Files</td>
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**Support and Enhancements**

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**Other**

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<td>References</td>
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STAFF2D

Author(s)          Huyakorn, P.S.
Year               1988
Revision

Capabilities, Limitations, and Assumptions

Flow Model          Two-dimensional, steady-state or transient, flow in
                    fractured or unfractured porous media. Real, cross-
                    sectional, or radial-grid orientations.

Transport Model     Solute and radionuclide transport by advection, dispersion,
                    sorption, and first-order degradation, including chain decay
                    of multiple species.

Numerical Methods   Explicit discrete-fracture and dual-continuum (or a
                    combination of the two) conceptual models. Finite-element
                    spatial discretization with porous media represented as
                    quadrilaterals and fractures as line elements. Galerkin
                    solution technique.

Quality Assurance/Quality Control

Peer Review         Yes
Benchmarking        Yes
Field Testing       Yes
Code Documentation  Yes
User Documentation  Yes
I/O Check Files     Yes

Support and Enhancements

User Support        Yes (~$60/h)
Pre-processor       Yes
Post-processor      Yes

Other

Availability        $3,000
Custodianship      HydroGeoLogic Software Sales
Hardware Requirements Many platforms; PCs, workstations, mainframes
Source Included    Yes
Source Language     FORTRAN77
References          3
STAFF3D

Author(s) HydroGeoLogic, Inc.
Year
Revision

Capabilities, Limitations, and Assumptions

Flow Model Two- or three-dimensional, cartesian or radial, steady-state or transient, flow in fractured or unfractured, anisotropic, heterogeneous porous media.

Transport Model Single species or decay-chain transport by advection, dispersion, linear equilibrium sorption, and first-order degradation.

Numerical Methods Explicit discrete-fracture and dual-continuum (or a combination of the two) conceptual models. Finite-element spatial discretization. Fractures represented by one-dimensional elements in discrete fracture model. Porous matrix represented by one-dimensional elements in dual-continuum model. PCG and ORTHOMIN solvers.

Quality Assurance/Quality Control

Peer Review Yes
Benchmarking Yes
Field Testing
Code Documentation
User Documentation Yes
I/O Check Files Yes

Support and Enhancements

User Support Yes (~$60/h)
Pre-processor Yes
Post-processor

Other

Availability $4,000 first year, $2,000 subsequent years.
Custodianship HydroGeoLogic Software Sales
Hardware Requirements Personal computers, workstations, minicomputers
Source Included No
Source Language
References Same as Staff2D
### SWIFT II

<table>
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<tr>
<th>Author(s)</th>
<th>Intercomp, Intera</th>
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#### Capabilities, Limitations, and Assumptions

<table>
<thead>
<tr>
<th>Flow Model</th>
<th>Three-dimensional transient flow in fractured or unfractured, anisotropic, heterogeneous porous media. Viscosity dependency as a function of temperature and brine concentrations.</th>
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<tbody>
<tr>
<td>Transport Model</td>
<td>Solute, heat, and radionuclide transport by advection, dispersion, diffusion.</td>
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<tr>
<td>Numerical Methods</td>
<td>Explicit discrete-fracture or dual-continuum conceptual models. Finite-difference spatial discretization.</td>
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#### Quality Assurance/Quality Control

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<td>Field Testing</td>
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<td>Code Documentation</td>
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#### Support and Enhancements

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#### Other

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SWIFT/486

Author(s)  Intercomp, GeoTrans
Year  1994
Revision  2.54

Capabilities, Limitations, and Assumptions

Flow Model  Three-dimensional transient flow in fractured or unfractured, anisotropic, heterogeneous porous media. Viscosity dependency as a function of temperature and brine concentrations.

Transport Model  Solute, heat, and radionuclide transport by advection, dispersion, diffusion. Freundlich and linear adsorption isotherms.

Numerical Methods  Explicit discrete-fracture or dual-continuum conceptual models. Finite-difference spatial discretization.

Quality Assurance/Quality Control

Peer Review  Yes
Benchmarking  Yes
Field Testing  Yes
Code Documentation  Yes
User Documentation  Yes
I/O Check Files  Yes

Support and Enhancements

User Support  $1,000 per annum
Pre-processor
Post-processor  Two

Other

Availability  $800
Custodianship  GeoTrans, Inc.
Hardware Requirements  80386 or better with 4 megabytes of extended memory
Source Included  Yes
Source Language  FORTRAN
References  7+
TOUGH2

Author(s)         Pruess, K.
Year              1991
Revision

Capabilities, Limitations, and Assumptions

Flow Model       One-, two-, or three-dimensional, transient, nonisothermal multiphase, multicomponent fluid and coupled heat flow in fractured, anisotropic, heterogeneous porous media. Five different equations of state available, depending on phases present.

Transport Model  Multicomponent advection and heat conduction.

Numerical Methods Dual-continuum conceptual model with multiple interacting continua (MINC) option. Integral finite-difference method. Solution is achieved through Newton-Raphson iteration on the residual by using the Harwell MA-28 solver. Requires 64-bit arithmetic for successful execution.

Quality Assurance/Quality Control

Peer Review      Yes
Benchmarking     Yes
Field Testing    Yes
Code Documentation Yes
User Documentation Yes
I/O Check Files  Yes

Support and Enhancements

User Support     K. Pruess, Lawrence Berkeley Laboratory; ESTSC
Pre-processor    Mesh generator
Post-processor   

Other

Availability      Yes. See custodian description for pricing scheme.
Custodianship    Energy Science and Technology Software Center (ESTSC)
Hardware Requirements Cray X-MP, IBM RS/6000 workstation, PCs
Source Included  Yes
Source Language  FORTRAN
References       8
TRACR3D

Author(s)           Travis, B.J.
Year                1984
Revision

Capabilities, Limitations, and Assumptions

Flow Model          One-, two-, or three-dimensional, steady-state or transient, flow in fractured or unfractured, deformable, anisotropic, heterogeneous porous media. Flow options include single-phase saturated, single-phase unsaturated, two-phase immiscible, and others.

Transport Model     Multicomponent transport in air and/or water phases by advection, dispersion, diffusion, equilibrium or kinetic adsorption/desorption, up to n chains of radioactive decay, and biological transformation.

Numerical Methods   Orthogonal, explicit, discrete fractures occurring at edges of grid blocks or equivalent continuum-conceptual models. Integrated finite-difference method. Newton-Raphson iteration with ICCG and GMRES matrix solvers.

Quality Assurance/Quality Control

Peer Review         Yes
Benchmarking        Yes
Field Testing       Yes
Code Documentation  Yes
User Documentation  Yes
I/O Check Files     Yes

Support and Enhancements

User Support        Yes
Pre-processor       
Post-processor      

Other

Availability        Yes
Custodianship      B. Travis
Hardware Requirements Apple, IBM, SUN, HP, Vax, Cray
Source Included    Does not include biological transformation capabilities.
Source Language    FORTRAN
References          2
TRAFRAP-WT PC/EXT

Author(s)                  Huyakorn, P.S., H.O. White, and T.D. Wadsworth
Year                       1991
Revision                   1.3

Capabilities, Limitations, and Assumptions

Flow Model
Two-dimensional, transient, fractured or unfractured, anisotropic, heterogeneous porous media.

Transport Model
Solute or radionuclide transport by convection, dispersion, diffusion, sorption, radionuclide decay.

Numerical Methods
Explicit discrete-fracture or dual-continuum conceptual models. Finite-element spatial discretization.

Quality Assurance/Quality Control

Peer Review               Yes
Benchmarking              Yes
Field Testing             Yes
Code Documentation
User Documentation        Yes
I/O Check Files           Yes

Support and Enhancements

User Support              Yes
Pre-processor
Post-processor

Other

Availability              $100
Custodianship            IGWMC
Hardware Requirements    80386 or better with extended memory.
Source Included
Source Language
References                1
TRINET

Author(s) Karasaki, K.
Year 1986
Revision 0.1

Capabilities, Limitations, and Assumptions

Flow Model Three-dimensional transient flow in fracture network or porous media. Designed for well-test analysis in fractured hydrogeologic systems.
Transport Model Solute transport by advection, dispersion.

Quality Assurance/Quality Control

Peer Review Yes
Benchmarking Yes
Field Testing Yes
Code Documentation Yes
User Documentation Yes
I/O Check Files Yes

Support and Enhancements

User Support Limited
Pre-processor Yes
Post-processor Yes

Other

Availability Limited
Custodianship K. Karasaki
Hardware Requirements Requires f77 compiler, SUN, DEC, CRAY. Parallel processing capable.
Source Included Yes
Source Language FORTRAN77
References 5
TRUMP

Author(s)  Edwards, A.L., A. Rasmuson, I. Neretneiks, and T.N. Narasimhan
Year  1980
Revision

Capabilities, Limitations, and Assumptions

Flow Model  One-, two-, or three-dimensional, steady-state or transient, flow in fractured heterogeneous porous media.
Transport Model  Solute or heat transport by advection, dispersion, diffusion, conduction.
Numerical Methods  Integral finite-difference method.

Quality Assurance/Quality Control

Peer Review  Yes
Benchmarking  Yes
Field Testing  
Code Documentation  
User Documentation  Yes
I/O Check Files  Yes

Support and Enhancements

User Support  
Pre-processor  Yes. FED (see TRUMP references).
Post-processor  

Other

Availability  Yes. See custodian description for pricing scheme.
Custodianship  Energy Science and Technology Software Center (ESTSC)
Hardware Requirements  IBM 360 or IBM 370
Source Included  Yes
Source Language  FORTRAN IV (95%), BAL (5%)
References  3
TRUST84

Author(s) Narasimhan, T.N.
Year 1984
Revision

Capabilities, Limitations, and Assumptions

Flow Model One-, two-, or three-dimensional, steady-state or transient, variably saturated flow in fractured or unfractured, anisotropic, heterogeneous deformable porous media.

Transport Model
Numerical Methods Integral finite-difference method.

Quality Assurance/Quality Control

Peer Review Yes
Benchmarking
Field Testing
Code Documentation
User Documentation
I/O Check Files

Support and Enhancements

User Support Limited, see custodian description.
Pre-processor
Post-processor

Other

Availability Yes. See custodian description for pricing scheme.
Custodianship Energy Science and Technology Software Center (ESTSC)
Hardware Requirements DEC Vax
Source Included Yes
Source Language FORTRAN 77
References 5
Appendix B:

Custodians of Fracture Flow Codes
Appendix B: Custodians of Fracture Flow Codes

<table>
<thead>
<tr>
<th>Custodian</th>
<th>Code(s)</th>
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<td>C.A. Anderson, ESA-13, MS-J576, Los Alamos National Laboratory, Los Alamos, NM 87545, (505) 667-5150, <a href="mailto:canderson@lanl.gov">canderson@lanl.gov</a></td>
<td>SANGRE</td>
</tr>
<tr>
<td>Atomic Energy Canada, Ltd., Whiteshell Nuclear Research Establishment, Pinawa, Manitoba, ROE 1L0 Canada, Attn: Sales &amp; Marketing, (416) 592-5296, (416) 592-4485 (FAX)</td>
<td>MOTIF</td>
</tr>
<tr>
<td>Energy Science and Technology Software Center, P.O. Box 1020, Oak Ridge, TN 37831, (615) 576-2606, <a href="mailto:estsc@adonis.osti.gov">estsc@adonis.osti.gov</a></td>
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<td>TRUMP</td>
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<td>FracMan/MAFIC</td>
</tr>
<tr>
<td>4104 148th Ave NE</td>
<td></td>
</tr>
<tr>
<td>Redmond, WA 98052</td>
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</tr>
<tr>
<td>(206) 883-0777</td>
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<td><a href="mailto:fracman@golder.com">fracman@golder.com</a></td>
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<tr>
<td>HydroGeoLogic, Inc.</td>
<td>STAFF2D</td>
</tr>
<tr>
<td>1165 Herndon Parkway, Suite 900</td>
<td>STAFF3D</td>
</tr>
<tr>
<td>Herndon, VA 22070</td>
<td></td>
</tr>
<tr>
<td>(703) 478-5186</td>
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<td>IGWMC</td>
<td>TRAFRAP-WT PC/EXT</td>
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<td>Colorado School of Mines</td>
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<tr>
<td>Golden, CO 80401-1887</td>
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</tr>
<tr>
<td>(303) 273-3103</td>
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<tr>
<td><a href="mailto:igwmc@mines.colorado.edu">igwmc@mines.colorado.edu</a></td>
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<tr>
<td>K. Karasaki</td>
<td>TRINET</td>
</tr>
<tr>
<td>MS 50E</td>
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<tr>
<td>Earth Sciences Division</td>
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<tr>
<td>Lawrence Berkeley Laboratory</td>
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<tr>
<td>Berkeley, CA 94720</td>
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</tr>
<tr>
<td>(510) 527-6759</td>
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<tr>
<td>N.W. Kline</td>
<td>PORFLO-3</td>
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<tr>
<td>Westinghouse Hanford Co.</td>
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<tr>
<td>P.O. Box 1970, MS HO-36</td>
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<tr>
<td>Richland, WA 99352</td>
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<tr>
<td>(509) 376-8080</td>
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<tr>
<td>R. McLaren</td>
<td>FRAC3DVS</td>
</tr>
<tr>
<td>U. of Waterloo</td>
<td>FRACTRAN</td>
</tr>
<tr>
<td>Waterloo, Ontario, N2L 3G1 Canada</td>
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</tr>
<tr>
<td><a href="mailto:mclaren@sciborg.uwaterloo.ca">mclaren@sciborg.uwaterloo.ca</a></td>
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</tr>
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</table>
Custodian

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trasmuss@uga.cc.uga.edu

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Reston, VA 22092
Attn: O.A. Holloway
(703) 648-5695 (Program Information Line)
(703) 648-5295 (FAX)

U.S. Nuclear Regulatory Commission
Office of Research, Waste Management Branch
Washington, D.C. 20555
Attn: T.J. McCarten
(301) 492-3847 or 492-7000
tjm3@nrc.gov

Code(s)

BIM/BIM2D/BIM3D/FRACGEN

NETFLO/NETRANS

PORFLOW

TRACR3D

3-D FE DUAL-POROSITY FLOW & TRANSPORT MODEL

DCM3D

NEFTRAN II
Appendix C:

Annotated List of Custodians of Fracture Flow Codes
Appendix C: Annotated List of Custodians of Fracture Flow Codes

Charles A. Anderson, ESA-13, MS-J576, Los Alamos National Laboratory, Los Alamos, NM 87545, telephone: (505) 667-5150, internet: canderson@lanl.gov

Charles Anderson is a staff scientist at the Los Alamos National Laboratory. He will supply a copy of SANGRE upon request. SANGRE is available in a wide variety of media formats, or by e-mail.

Atomic Energy Canada, Ltd., Whiteshell Nuclear Research Establishment, Pinawa, Manitoba, R0E1J0 Canada, att: Sales & Marketing, fax: (416) 592-4485.

MOTIF is available from Atomic Energy Canada, Ltd. (AECL), for $20,000 Canadian per year lease for the executable code only. Source code is available only through special arrangement with Sales & Marketing. Limited technical support may be available from Tin Chan, senior staff scientist at AECL Research. He can be reached at (416) 592-5296 or chant@wl.aecl.ca

Berkeley Hydrotechnique, Inc., 2039 Shattuck Ave., Suite 401, Berkeley, CA 94704

Att: B.Y. Kanehiro, telephone: (510) 549-9570, fax: (510) 549-1713.

Brian Kanehiro will supply FRANET with limited support for a nominal charge.

Energy Science and Technology Software Center (ESTSC), P.O. Box 1020, Oak Ridge, TN 37831, telephone: (615) 576-2606, internet: estsc@adonis.osti.gov

The ESTSC is the repository for much of the software produced by U.S. government laboratories. It replaces the National Energy Software Center, which no longer exists. The ESTSC provides limited support for code installation only. The ESTSC provides a responsive staff to assist with software searches and acquisition. Not all of the codes that the ESTSC provides are available to non-U.S. citizens.

The ESTSC has variable pricing scale (Table C.1). Prices are in U.S. dollars for products in ESTC's "AS IS" and "SCREENED" categories. Add 20% for products categorized as "TESTED."

In addition to being a repository of largely historical codes, ESTSC has a suite of analytical solutions for verifying fracture flow and other codes called VERTPAK1. M.J. Golis of Battelle Columbus Division authored the package, which includes solutions for flow and
TABLE C.1 Cost of ESTSC Products by Platform and Customer

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<th>Customer</th>
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<td>400</td>
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<td>510</td>
<td>1,305</td>
<td>1,835</td>
<td>4,560</td>
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<tr>
<td>Foreign</td>
<td>940</td>
<td>2,000</td>
<td>2,715</td>
<td>6,700</td>
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transport in many different geometries. Software from a number of pertinent U.S. government agencies, such as the Geological Survey and the Environmental Protection Agency, is not archived at the ESTSC.

**GeoTrans, Inc.**, 46050 Manekin Plaza, Suite 100, Sterling, VA 20166, att: David Ward, telephone: (703) 444-7000, internet: geotran1@access.digex.net

GeoTrans, Inc., is a consulting firm that specializes in groundwater analysis. GeoTrans has extensive experience in computer code research, development, and end-user training. The research of GeoTrans staff often appears in well-respected refereed journals. In addition to code sales and training courses, GeoTrans offers extensive client-support services.

**Golder Associates, Inc.**, 4104 148th Ave. NE, Redmond, WA 98052, telephone: (206) 883-0777, internet: fracman@golder.com

Golder Associates is an international group of consulting companies. Since 1960, Golder Associates has provided services in soil mechanics, rock mechanics, engineering geology, and fluid flow. The FracMan/Mafic package is distributed on the basis of licensing agreements for U.S. government, academic users, and private companies. There is generally no cost for U.S. government and academic licenses.

**HydroGeoLogic Software Sales**, 1165 Herndon Parkway, Suite 900, Herndon, VA 22070, telephone: (703) 478-5186.

HydroGeoLogic is a groundwater consulting firm with many years of experience in modeling groundwater flow and transport processes. In addition to software sales, it provides modeling support for approximately $60 per hour or on a contractual consulting basis.
International Ground Water Modeling Center (IGWMC), Colorado School of Mines, Golden, CO 80401-1887, telephone: (303) 273-3103, internet: igwmc@mines.colorado.edu

The IGWMC is a repository and distribution center for a large number of ground-water-related computer programs. The IGWMC sells software that runs on IBM PC-compatible machines under the MS-DOS operating system. Support of individual codes varies. In some cases, support for non-current versions of codes does not exist (the user is required to upgrade to receive support). In addition to software distribution, the IGWMC organizes many short courses, workshops, seminars, conferences. The IGWMC also has an extensive library of ground-water-related publications available for purchase.

K. Karasaki, MS 50E, Earth Sciences Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720, telephone: (510) 527-6759.

K. Karasaki is a staff scientist at the Lawrence Berkeley Laboratory. He will supply a copy of TRINET upon request, with some conditions.

Niall W. Kline, Westinghouse Hanford Co., PO Box 1970, MS HO-36, Richland, WA 99352, telephone: (509) 376-8080.

Niall W. Kline is a staff scientist for the Westinghouse Hanford Company and serves as a technical contact for PORFLO-3. By the agreement between the U.S. Department of Energy (DOE) and ACRi, Inc., copyright of PORFLO-3 has been waived by DOE, so that ACRi may claim that right. However, the U.S. Government retains a paid-up, nonexclusive, irrevocable worldwide license for use of PORFLO-3 by the government.

Rob McLaren, U. of Waterloo, Waterloo, Ontario, N2L 3G1 Canada, telephone: (519) 885-1211, ext. 2257, internet: mclaren@sciborg.uwaterloo.ca

Rob McClaren is a Research Technologist at the Waterloo Centre for Groundwater Research. Free limited support of FRACTRAN and FRAC3DVS is available. More extensive support, if required, may be arranged on a contractual basis.

Todd C. Rasmussen, School of Forest Resources, University of Georgia, Athens, GA 30602-2152, telephone: (706) 542-4300, internet: trasmuss@uga.cc.uga.edu

Todd Rasmussen is a faculty member at the University of Georgia. He will supply copies of the research codes BIM/BIM2D/BIM3D upon request.

Alain Rouleau, Dept. de Science Appliquees, University du Quebec a Chicoutimi Chicoutimi, Quebec G7H 2B1 Canada
Alain Rouleau is a professor at the University du Quebec a Chicoutimi. NETFLO/NETRANS is in the public domain and is provided as is for a nominal fee.

Akshai K. Runchal, Analytical and Computational Research, Inc., 1931 Stradella Rd., Bel Air, CA 90077, telephone: (310) 471-3023, internet: runchal@netcom.com

ACRI is an international consulting organization providing mathematical modeling and computer analysis of environmental pollution and engineering processes involving fluid dynamics, heat and mass transfer, turbulence, and combustion. The prices of the software distributed by this vendor vary according to the memory capabilities, single user and multiuser, source supplied or not supplied, and annual lease or "paid-up license." These prices are applicable to both the PORFLOW code and the arcPLOT post-processor. For example, a single-user, 16-MB version of the executable code can be purchased for $2,995. The same code, with source code, can be leased annually for the same amount, or purchased for $8,995. Installation fees are applied to all but IBM PC licenses. Educational discounts of 40% are available. Training is available for $1,250 per day, with 3-5-day workshops recommended. Unlimited telephone support is provided at a cost of $1,000 per year. The cost of unlimited telephone support, problem solving, and enhancement consultations is $5,000 per year and includes product upgrades. Additional consulting is charged on the basis of time and materials.

Technical support for PORFLO 1.3, a precursor to PORFLOW, is available from N.W. Kline (see earlier entry).

Bryan Travis, EES-5, MS-F665, Los Alamos National Laboratory, Los Alamos, NM 87545, telephone: (505) 667-1254, internet: bjt@vega.lanl.gov

Bryan Travis is a staff scientist at the Los Alamos National Laboratory. He will provide a copy of TRACR3D upon receipt of a written request describing the proposed application and platform. Source code is unavailable for the most recent version of TRACR3D, which incorporates biological degradation capabilities.

U.S. Nuclear Regulatory Commission, Office of Research, Waste Management Branch, Washington, DC 20555, Att: Tim McCarten, telephone: (301) 492-3847 or 492-7000, internet: tjm3@nrc.gov

Tim McCarten is the U.S. Nuclear Regulatory Commission (NRC) sponsor and contact for DCM3D and NEFTRAN2. He will provide copies of those codes, with sample input data sets, upon request. Generally, the codes are provided as source only on diskettes formatted for DOS machines. Technical support for installation is available, at the discretion of the U.S. NRC. Distribution of these codes is limited to U.S. citizens. Eventually, the codes will be available from the ESTSC.
Write to this office to obtain 3D FE Dual-Porosity Flow & Transport Model. The code is supplied on 3.5-in. or 5 1/4-in. diskettes as source code. Code cost includes documentation, in this case the Water Resources Investigation Report. The code is supplied "as is" and no support is available. All requests must be provided in writing, either by mail or fax. The USGS accepts money orders or checks as prepayment. Alternatively, the USGS will ship a product with a bill in response to a purchase request.

This is also the distribution office for all USGS Water Resource Division (WRD) codes. All USGS WRD codes cost $40.
Appendix D:

Selected References by Fracture Flow Code
Appendix D: Selected References by Fracture Flow Code

3-D FE DUAL-POROSITY FLOW & TRANSPORT


BIM/BIM2D/BIM3D/FRACGEN


DCM3D


FRACFLO


FRACFLOW


FracMan/MAFIC


FRACTRAN


FRANET

**FTRANS**


**GREASE2**


**MAGNUM2D**


**MOTIF**


Conference of the International Association for Computer Methods and Advances in Geomechanics, Cairns, Australia, Balkema Press, Rotterdam, pp. 1547–1552, May 6–10.

**NEFTRAN II**


**NETFLONETRANS**


**PORFLO-3**


PORFLOW


SANGRE


SEFTRAN


SHALT


**STAFF2D and STAFF3D**


**SWIFT II**


**SWIFT/486**


**TOUGH/TOUGH2**

Antunex, A., G. Moridis, and K. Pruess, 1994, *Large-Scale Geothermal Reservoir Simulation on PCs*, LBL-35192, Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, presented at 19th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, January.


TRACR3D

TRAFRAP-WT PC/EXT

TRINET

TRUMP
TRUST


Appendix E:

Codes That Are Unavailable
Appendix E: Codes That Are Unavailable

This appendix lists codes that are either superseded by codes listed in Appendix A or are no longer available.

### 3D FRACTURE GENERATOR

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<th>Author(s)</th>
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<tr>
<td>Huang, C., D.D. Evans</td>
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### FLASH

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### FRACT

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<td>Pruess, K.</td>
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### NETFLOW

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### SHALT

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### STAFAN/STAFAN2

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<tr>
<td>Huyakorn, P.S.</td>
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Appendix F:

Distribution List
Appendix F: Distribution List

C.A. Anderson
ESA-13, MS-J576
Los Alamos National Laboratory
Los Alamos, NM 87545

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Geraghty & Miller Environmental Services
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46050 Manekin Plaza, Suite 100
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Robert J. Glass, Jr.
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Argonne, IL 60439

GRAM, Inc. (2)
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Albuquerque, NM 87112

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The Pennsylvania State University
University Park, PA 16801

IGWMC
Colorado School of Mines
Golden, CO 80401-1887

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Berkeley, CA 94720

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Washington, D.C. 20555

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Wakefield, MA 01880

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Bethesda, MD 20814-3620

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Bel Air, CA 90077

B. Sagar  
Southwest Research Institute  
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San Antonio, TX 28510

Sandia National Laboratories (3)  
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Dave Gallegos  
Nataly Olague  
Albuquerque, NM 87185-1345

Steve Sayko  
ERM, Inc.  
855 Springdale Drive  
Exton, PA 19341

B. Travis  
EES-5, MS-F665  
Los Alamos National Laboratory  
Los Alamos, NM 87545

Richard Wardrop  
Nittany Geoscience, Inc.  
101 Radnor Road  
State College, PA 16801

Jim Wilson  
U.S. Geological Survey  
P.O. Box 1125  
Cheyenne, WY 82003