SWIFT II SELF-TEACHING CURRICULUM: ILLUSTRATIVE PROBLEMS FOR THE SANDIA WASTE-ISOLATION FLOW AND TRANSPORT MODEL FOR FRACTURED MEDIA

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ABSTRACT

Several documents have been written describing SWIFT II, the most current version of the SWIFT Model. One, Reeves et al [1984a], describes the theory and implementation, and another, Reeves et al [1984b], describes the data input. Two others, Ward et al [1984a] and Ward et al [1984b] deal with code assessment through verification and field application and through benchmarking, respectively. This document, however, has an entirely different function. It, like the work of Finley and Reeves [1981] for an earlier version, is devoted to assisting the analyst who desires to use the SWIFT Code. This code is quite general in terms of both the processes (flow, heat, brine and radionuclide transport) and the media (single and/or dual porosity, confined or unconfined) which it considers. Consequently a document such as this one is necessary. Nine examples are presented to illustrate the use of SWIFT II in doubly porous and unconfined aquifers. Each problem and its numerical solution are described. Then several exercises are presented in order to assist the reader with the input and the output and, occasionally, with the interpretation of the results. For each case a printed input listin and a microfiche output listing are provided.

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1 INTRODUCTION

The SWIFT Model (Sandia Waste-Isolation Flow and Transport Model) has been developed for the evaluation of repository-site performance. It is a fully-coupled, transient, three-dimensional model, and it is implemented by a finite-difference code, which solves the equations for flow, heat, brine and radionuclide transport in geologic media. Having evolved from the U.S. Geological Survey Code, SWIP (Survey Waste Injection Program [INTERCOMP, 1976]), this code has experienced continuous improvements since 1977 [Dillon et al, 1978, and Reeves and Cranwell, 1981]. SWIFT II marks a significant extension of the development in that the model can now treat three additional types of media in a cost-effective manner. Two are confined dual-porosity systems and include a fractured porous material and an aquifer with conductive confining beds. The other is an unconfined aquifer with a free-water surface. As such, the model has become a very comprehensive and effective tool for evaluating the processes envisioned for a repository of high-level nuclear wastes. Furthermore, its applications extend beyond nuclear-waste isolation to, for example, aquifer thermal-energy storage, liquid-waste disposal by deep-well injection and migration of contaminants from surface disposal sites.

At the same time, however, the use of SWIFT does make rather heavy demands on the analyst. He must have a familiarity not only with the basic science but also with the mathematical model*, the numerical model*, the code*, its input and its output. Current documentation [Reeves et al, 1984a,b] is available covering each of these items. Nevertheless, probably the easist way to learn the SWIFT Model, or any other model, is through a meaningful set of worked problems. Such is the basic premise for both this report and its precursor, SWIFT Self-Teaching Curriculum [Finley and Reeves, 1981]. As a matter of fact, that earlier report is appropriate for SWIFT II. A total of 11 problems are presented there in the input format used by SWIFT, Release 4.81. However, with only minor changes, as described in the

* See Silling [1983] for a definition of these terms.

Appendix of this report, the input data sets listed there may be used to illustrate the application of SWIFT II, Release 12.83, to single-porosity media.

In this document 9 problems are presented. Fracture/matrix problems are presented first, followed by aquifer/confining-bed and unconfined-aquifer problems. In each case the discussion proceeds from a description of the problem to a description of the numerical simulation. For convenience, a definition of the symbols is reserved for Section 6. Further, the oft-referenced documents of Reeves et al [1984a,b] are referenced simply as the Theory and Implementation and the Data-Input Guide, respectively. Several exercises are placed at the end of the discussion for each problem, which are directed at two different levels of expertise. The more basic Level 1 familiarizes the reader with the input, which is printed, and the output, which appears in microfiche affixed to the back cover. For these exercises the only necessary resources, other than this document itself, are the Data-Input Guide and the Theory and Implementation. The more advanced Level 2 tests the reader's ability to extend or interpret the basic results. Here a computer and the SWIFT II Code may also be necessary.

2 SOLUTE TRANSPORT THROUGH DUAL-POPOSITY MEDIA

2.1 PROBLEM 1. TRANSPORT OF A DECAYING RADIONUCLIDE IN A FRACTURED POROUS MEDIA [TANG ET AL, 1981].

2.1.1 Objective

- To illustrate fracture/matrix transport with a prismatic characterization of the rock matrix.

2.1.2 Description of the Problem

Problem Statement. A thin rigid fracture is situated within a saturated porous rock matrix as shown in Figure 2.1-1. Both fracture and matrix are semi-infinite in their extent. Radionuclides, which derive from a source of constant strength, are convected and dispersed through the fracture by a constant velocity field and are diffused into the rock matrix.

Transport Equations. Mathematically the transport within the fractures is governed by the equations

$$-\frac{\partial}{\partial x}(\rho C u) + \frac{\partial}{\partial x}\left(\rho D \frac{\partial C}{\partial x}\right) - \Gamma - \lambda K \phi \rho C = \frac{\partial}{\partial t}(K \phi \rho C) \qquad (2.1\text{-}1)$$

Transport within the rock matrix is assumed to occur in a direction perpendicular to the fracture and is governed by the equation

$$\frac{\partial}{\partial s}\left(\rho' D'_m \frac{\partial C'}{\partial s}\right) + \Gamma - \lambda K' \phi' \rho' C' = \frac{\partial}{\partial t}(K' \phi' \rho' C') \qquad (2.1\text{-}2)$$

Coupling then arises through the flux at the fracture/matrix interface:

$$\Gamma = -A_V \rho' D'_m \frac{\partial C'}{\partial s}(s=0) \qquad (2.1\text{-}3)$$

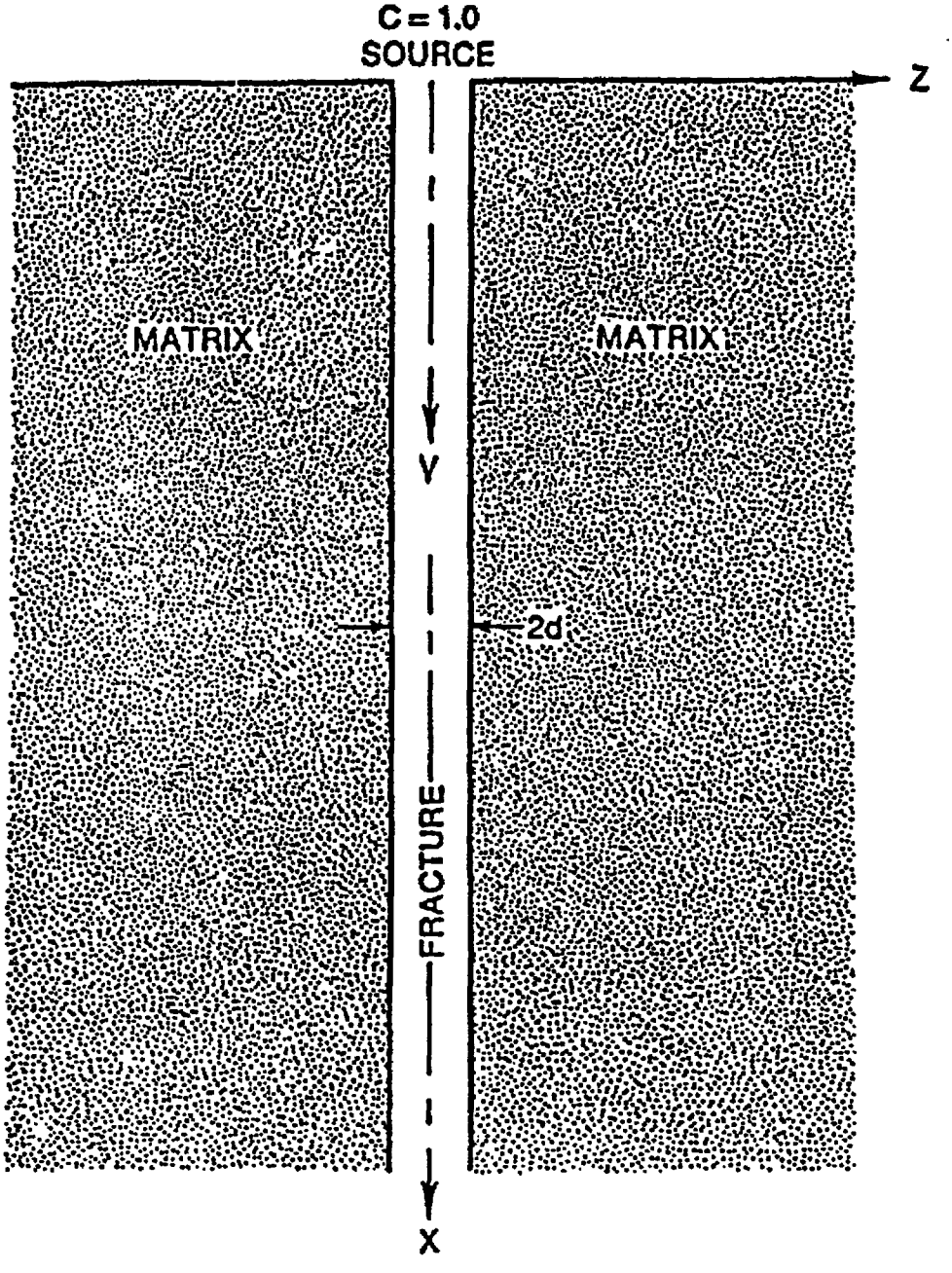


Figure 2.1-1. Problem 1. Schematic Diagram.

The composite parameters are defined here in terms of the basic parameter set. They are the dispersion/diffusion of the fracture:

$$D = \alpha_L u + D_m \tag{2.1-4a}$$

the diffusivity of the fractures:

$$D_m = \phi D^* \tag{2.1-4b}$$

and the diffusivity of the rock matrix:

$$D'_m = \bar{\tau}\phi' D^* \tag{2.1-4c}$$

The remainder of the parameters are defined in Section 6.

Initial/Boundary Conditions. Within the rock matrix the initial concentration is zero:

$$C'(x,s,t=0) = 0 \quad , \quad s > 0 \quad , \quad x > 0 \tag{2.1-5a}$$

and fracture and matrix concentrations are identical at the interface:

$$C'(x,s=0,t) = C(x,t) \quad , \quad t > 0 \tag{2.1-5b}$$

Within the fracture, the initial concentration is also zero:

$$C(x,t=0) = 0 \quad , \quad x > 0 \tag{2.1-6a}$$

and the boundary concentration is unity:

$$C(x=0,t) = 1 \quad , \quad t > 0 \tag{2.1-6b}$$

Input/Output Specifications. The input data for this problem, given in Table 2.1-1, is the same as that prescribed by Tang et al for their low-velocity case (p. 561 ff). The desired output consists of two sets of spatial

Table 2.1-1. Problem 1. Input Specifications.

Parameter	Symbol	Value
Fracture Width	$2d$	10^{-4} m
Matrix Porosity	ϕ'	0.01
Matrix Tortuosity	$\bar{\tau}$	0.1
Fracture Dispersivity	α_L	0.5 m
Molecular Diffusion in Water	D^*	1.6×10^{-5} cm^2/s
Half Life	τ	12.35 y
Decay Constant	λ	0.0561 y^{-1}
Matrix Retardation	K'	1.0
Fracture Retardation	K	1.0
Fracture Velocity	v	0.0[illegible] m/d
Fracture Porosity	ϕ	1.0

distributions. Curves of concentration versus distance within the fracture are called for at the values of time, t = 100, 1000 and 10,000 d. Then a single curve of concentration versus distance within the rock matrix is called for at the time t = 10,000 d and the position x = 1.5 m.

2.1.3 Numerical Simulation

Discussion of Code Input. Two items are of interest here. Specifically they are: (1) representing a semi-infinite domain with a finite domain and (2) specifing the flow and diffusion within the system. For the first of these, the steady-state solution of Tang et al is most helpful. This solution provides one characteristic length for penetration into the fracture and another for penetration into the rock matrix:

$$\tilde{L} = \left\{(1/2)\alpha_L - \left[(1/4)\alpha_L^2 + \psi/D\right]^{1/2}\right\}^{-1} \qquad (2.1\text{-}7)$$

and

$$\tilde{a} = (D'/\lambda)^{1/2} \qquad (2.1\text{-}8)$$

where

$$D = \alpha_L v + D^* \qquad (2.1\text{-}9a)$$

$$D' = \tau D^* \qquad (2.1\text{-}9b)$$

$$\psi = \lambda + \phi'(D'\lambda)^{1/2}/d \qquad (2.1\text{-}9c)$$

With values taken from Table 2.1-1, these expressions yield

$$\tilde{L} = 1.4 \text{ m} \qquad (2.1\text{-}10)$$

and

$$\tilde{a} = 0.30 \text{ m} \qquad (2.1\text{-}11)$$

The domains of simulation are taken to be somewhat larger than these characteristic lengths, i.e.,

$$L = 10.24 \text{ m} \tag{2.1-12}$$

for the fracture (Figure 2.1-2) and

$$a = 1.2 \text{ m} \tag{2.1-13}$$

for the rock matrix (Figure 2.1-3a).

Spatial increments in the fracture and matrix domains are then taken to be significantly smaller than the characteristic lengths. Nevertheless, some numerical experimentation is necessary for gridding both the spatial and the temporal domains. There is, however, one consistency check:

$$\Delta s \sim (2D'\Delta t)^{1/2} \tag{2.1-14}$$

for the matrix, which is a useful guide. Figures 2.1-2 and 2.1-3 show pictorially the gridding adopted for the two spatial regimes. Figure 2.1-4, then exhibits this information as it is specified in the data input. As shown, the globally connected mesh of SWIFT II is used to simulate the composite fracture/matrix system with the individual increments specified in Cards R1-17 (Δx), R1-18 (Δy) and R1-19 (Δz). The one-dimensional mesh, locally connected to only one global grid block, is then used to simulate the rock matrix, which is here imbedded within the global mesh. Gridding, in this case, is specified by the three parameter values provided in Cards ROD-2 (n_s) and R1D-2-2 (a and Δs). Given the number of increments n_s and the increment Δs at the fracture/matrix interface, the code generates the local mesh automatically.

Continuing on to the second item, the flow within the global system is maintained using injection and production wells in the end blocks of the global system, the common rate being

$$q = 2d\Delta yv = 1.157 \times 10^{-11} \text{ m}^3/\text{s} \quad , \quad \text{R2-6} \tag{2.1-15}$$

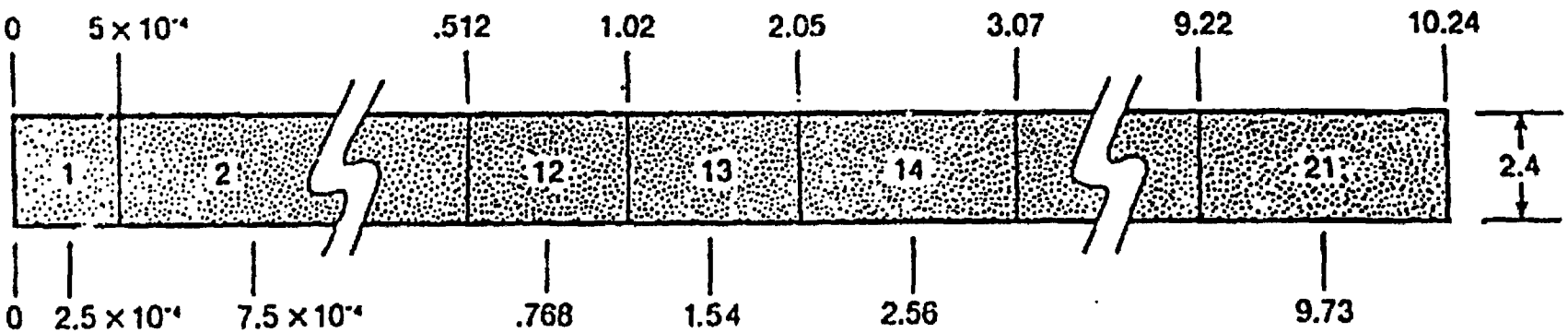
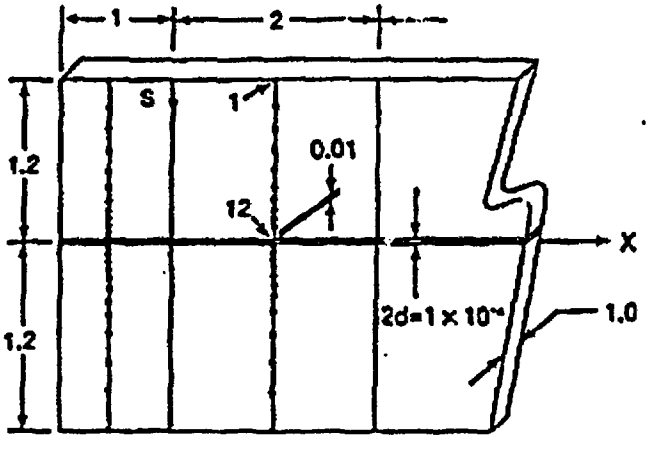
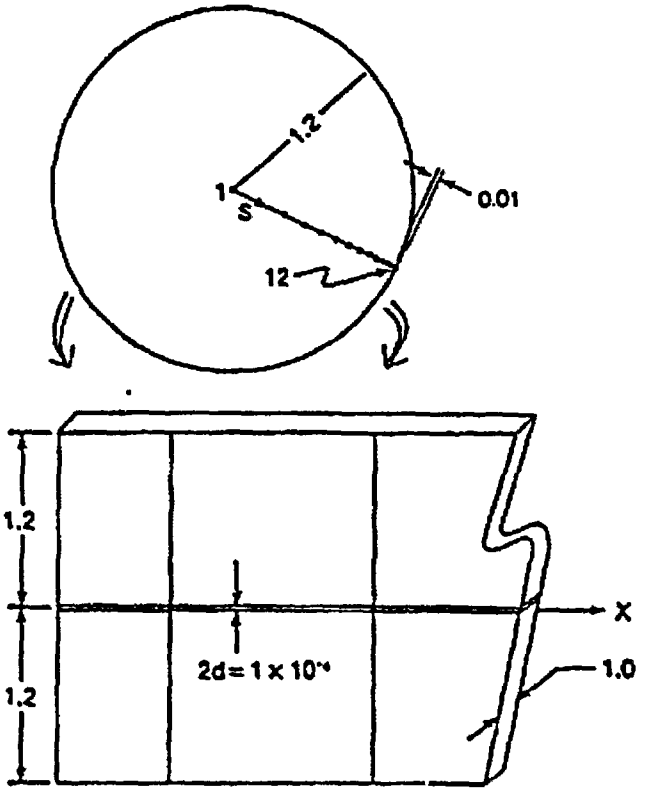


Figure 2.1-2. Gridding of the Fracture.



(a) Prismatic Characterization.



(b) Spherical Characterization.

Figure 2.1-3. Gridding of the Rock Matrix.

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```
          1         2         3         4         5         6         7         8
 12345678901234567890123456789012345678901234567890123456789012345678901234567890
 +---------+---------+---------+---------+---------+---------+---------+---------+
 I                                                                                I
 I PROBLEM NO. 1, THREE-COMPONENT NUCLIDE TRANSPORT IN FRACTURED MEDIA,   M-1-1   I
 I                                                                                I
 I 12/81, COMPARISON WITH ANALYTICAL SOL'N - PRISMATIC REPRESENTATION     M-1-2   I
 I+++++                                  +++++                                    I
 I+(1)+    0    0    0    0    0    0+(2)+    0                            M-2   I
 I+++++                                  +++++                                    I
 I   21    1    1    2    1    2    0    2    1    0    1    0    0    OM-3-1   I
 I     +++++                                                                      I
 +    0+(3)+    1    0                                                     M-3-2   +
 I     +++++                                                                      I
 I100RAD TRAC        1    0    0     12.35                                RO-1   I
 I                                                                                I
 I       0.0                                                              RO-2-1   I
 I                                  ********************************              I
 I       0.0                        * "***" REFERENCED IN TEXT     *      RO-2-1   I
 I                                  * "***" REFERENCED IN EXERCISE *              I
 I       1.0                        ********************************      RO-2-2   I
 I                                                                                I
 +       1.0                                                              RO-2-2   +
 I+++++                                                                           I
 I+(4)+                                                                    ROD-1   I
 I+++++                                                                           I
 I   12                                                                    ROD-2   I
 I+++++                                  +++++                                    I
 I    2   21    1    1    1    1    1+(5)+                                ROD-3   I
 I                                       +++++                                    I
 I                                                                      ROD-3-BLN  I
 I                                                                                I
 +       0.0       0.0       0.0    4186.0       1.0                       R1-1   +
 I                                                                 **********     I
 I       0.0       0.0       0.0       0.0      0.50        0.06.6671E-14R1-2     I
 I                                                                 **********     I
 I       0.0       0.0       0.0                                           R1-2.5   I
 I+++++++++                                                                       I
 I+   (6)  +       0.0                                                     R1-2.5   I
 I+++++++++                                                                       I
 I       0.0       0.0       0.0                                           R1-2.5   I
 I                                                                                I
 +   4.00E03       0.0                                                     R1-2.5   +
 I                                                                                I
 I    2700.0  1.013E05      20.0    1000.0    1000.0                        R1-3   I
 I                                                                                I
 I    2    2    2    2                                                       R1-6   I
 I                                                                                I
 I      20.0     0.001      20.0     0.001                                   R1-7   I
 I                                                                                I
 I      0.20     0.001      0.80     0.001                                   R1-8   I
 I                                                                                I
 +     100.0     0.001     200.0     0.001                                   R1-9   +
 I                                                                                I
 +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.1-4. Listing of the SWIFT II Input Data.

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```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
I                                                                                 I
26 I     100.0     0.001     200.0     0.001                            R1-10    I
I                                                                                 I
27 I       0.0      20.0                                               R1-11    I
I                                                                                 I
28 I     100.0      20.0                                               R1-11    I
I                                                                                 I
29 I    0    0                                                         R1-12    I
I                                                                                 I
30 +      20.0  1.013E05       0.0       0.0                            R1-16    +
I**********                                                                      I
31 I  2*5.0L-4    1.0E-3    2.0E-3    4.0E-3    8.0E-3    1.6E-2    3.2E-2       I
I**********                                                                      I
32 I    6.4E-2     0.128     0.256     0.512   9*1.024                          I
I**********                                                                      I
33 I       1.0                                                                   I
I**********                                                                      I
34 I       2.4                                                                   I
I**********                        **********                                    I
35 + 3.4052E-7 3.4052E-7 3.4052E-7  4.167E-5       0.0       0.0       0.0R1-20   +
I                                  **********                                    I
36 I                                                                     R1-21    I
I                                                                                 I
37 I    1    1    1    1    1    1                                       R1-26-1  I
I                                                                                 I
38 I       1.0       1.0       1.0       1.0       0.0       0.01.91985E09R1-26-2 I
I                                                                                 I
39 I       0.0       0.0       0.0                                       R1-26-3  I
I                                                                                 I
40 +                                                                     R1-26-BLN +
I                                                                                 I
41 I    0    0                                                         R1-27    I
I                                                                                 I
42 I  1.00E-20                                                           R1D-I    I
I**********          **********                                                  I
43 I+   (7)  +       0.0+   (8).  +   1.5E-15       0.0       1.0       1.0R1D-2-1 I
I*****************************                                                  I
44 I    1    1       1.2     0.010       0.0                            R1D-2-2  I
I           ********************                                                 I
45 +                                                                     R1D-3-BLN +
I                                                                                 I
46 I       0.0                                                           R1D-4    I
I                                                                                 I
47 I                                                                     R1D-5-BLN I
I                                                                                 I
48 I    0    0    1                                                      I-1      I
I                                                                                 I
49 I    1    1    1    1    1    1       1.0                            I-4      I
I                                                                                 I
50 +                                                                     I-4-BLN  +
I                                                                                 I
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.1-4 Continued.

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```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
I                                                                                I
I    2   21    1    1    1    1    1                                   R1A-1     I
I                                                                                I
I    1    1    1    1    1    1    2                                   R1A-1     I
I                                                                                I
I                                                                      R1A-1-BLN I
I                                                                                I
I        0.0                                                           R1A-2     I
I*****                                                                           I
*    2    1    1    0    0    0    0    0    0                         R2-1      *
I*****                                                                           I
I   +1       0.50                                                       R2-2      I
I                                                                                I
I    2                                                                  R2-4      I
I     **********                                                                 I
I    1-1.157E-11                                                        R2-6-1    I
I     **********                                                                 I
I    2+1.157E-11                                                        R2-6-2    I
I     **********                                                                 I
*                                                                       R2-6-BLN  *
I                                                                                I
I    1    1    1    1    1    1                                        R2-7-1    I
I                                                                                I
I        1.0       0.0      20.0       0.0                              R2-7-2    I
I                                                                                I
I    2   21    1    1    1    1                                        R2-7-3    I
I                                                                                I
I        1.0       0.0      20.0       0.0                              R2-7-4    I
I                                                                                I
*                                                                       R2-7-BLN  *
I                                                                                I
I        1.0       1.0                                                           I
I                                                                                I
I    1    1    1    1    1    1  000    0 0000    0   13    1  000   12R2-13    I
I                                                                                I
I    0    0    0    0    1   -0    0    0    1                         R2-1      I
I                                                                                I
I    1                                                                  R2-9      I
I                                                                                I
*    1    1    1    1                                                  R2-10-1   *
I                                                                                I
I        0.0       0.0-7.1212E-5                                        R2-10-2   I
I                                                                                I
I                                                                      R2-10-BLN I
I                                                                                I
I    3                                                                  R2-11.5   I
I                                                                                I
I  3.456E06  3.456E06                                                            I
I                                                                                I
*    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13    *
I                                                                                I
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.1-4 Continued.

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```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
      +---------+---------+---------+---------+---------+---------+---------+---------+
      I                                                                                 I
   76 I   0    0    0    0    0    0    0    0    0                        RZ-1       I
      I                                                                                 I
   77 I  8.64E06  5.184E06                                                              I
      I                                                                                 I
   78 I   1   -1   -1   -1    1   -1  000    0 0000    0   10    1  000   10RZ-13      I
      I                                                                                 I
   79 I   0    0    0    0    0    0    0    0    0    0                        RZ-1       I
      I                                                                                 I
   80 + 1.525E07  6.910E06                                                              +
      I                                                                                 I
   81 I   1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10RZ-13      I
      I                                                                                 I
   82 I   0    0    0    0    0    0    0    0    0    0                        RZ-1       I
      I                                                                                 I
   83 I 2.50:E07  9.771E06                                                              I
      I                                                                                 I
   84 I   1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10RZ-13      I
      I                                                                                 I
   85 +   0    0    0    0    0    0    0    0    0    0    0                        RZ-1       +
      I                                                                                 I
   86 I 3.884E07  1.382E07                                                              I
      I                                                                                 I
   87 I   1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10RZ-13      I
      I                                                                                 I
   88 I   0    0    0    0    0    0    0    0    0    0                        RZ-1       I
      I                                                                                 I
   89 I 5.838E07  1.954E07                                                              I
      I                                                                                 I
   90 +   1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10RZ-13      +
      I                                                                                 I
   91 I   0    0    0    0    0    0    0    0    0    0                        RZ-1       I
      I                                                                                 I
   92 I 8.640E07  2.802E07                                                              I
      I                                                                                 I
   93 I   1   -1   -1   -1    1   -1  000    0 0000    0   10    1  000   10RZ-13      I
      I                                                                                 I
   94 I   0    0    0    0    0    0    0    0    0    0                        RZ-1       I
      I                                                                                 I
   95 + 1.251E08  3.906E07                                                              +
      I                                                                                 I
   96 I   1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10RZ-13      I
      I                                                                                 I
   97 I   0    0    0    0    0    0    0    0    0    0                        RZ-1       I
      I                                                                                 I
   98 I 1.803E08  5.522E07                                                              I
      I                                                                                 I
   99 I   1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10RZ-13      I
      I                                                                                 I
  100 +   0    0    0    0    0    0    0    0    0    0                        RZ-1       +
      I                                                                                 I
      +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.1-4 Continued.

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```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
101  2.564E08  7.810E07
102    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13
103    0    0    0    0    0    0    0    0    0    0                   R2-1
104  3.448E08  8.64E07
105    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13
106    0    0    0    0    0    0    0    0    0    0                   R2-1
107  4.312E08  8.64E07
108    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13
109    0    0    0    0    0    0    0    0    0    0                   R2-1
110  5.176E08  8.64E07
111    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13
112    0    0    0    0    0    0    0    0    0    0                   R2-1
113  6.040E08  8.64E07
114    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13
115    0    0    0    0    0    0    0    0    0    0                   R2-1
116  6.904E08  8.64E07
117    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13
118    0    0    0    0    0    0    0    0    0    0                   R2-1
119  7.767E08  8.64E07
120    1   -1   -1   -1   -1   -1  000    0 0000    0   10   -1  000   10R2-13
121    0    0    0    0    0    0    0    0    0    0                   R2-1
122  8.640E08  8.730E07
123    1   -1   -1   -1    1   -1  000    0 0000    0   10    1  000   10R2-13
124    0    0    0    0    0    0    0    0    0    0                   R2-1
125  1.728E09  1.728E08
```

Figure 2.1-4 Continued.

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```
          1         2         3         4         5         6         7         8
  12345678901234567890123456789012345678901234567890123456789012345678901234567890
 +---------+---------+---------+---------+---------+---------+---------+---------+
 |                                                                                |
126|    1   -1   -1   -1    1   -1  000    0 0000    0   10    1  000   10R2-13  |
 |                                                                                |
127|    0    0    0    1                                                R2-1-STOP |
 |                                                                                |
 +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.1-4 Continued.

Since both fracture and matrix are included within the global blocks (IFD = 0 in Card ROD-3), the global porosity is specified by

$$\phi = d/(a+d) = 4.167 \times 10^{-5} \quad , \quad \text{R1-20} \qquad (2.1\text{-}16)$$

This yields, then, from Equation (2.1-4a), the value

$$D_m = 6.6672 \times 10^{-14}\ m^2/s \quad , \quad \text{R1-2} \qquad (2.1\text{-}17a)$$

for the diffusion of the global system. The corresponding relation for the rock matrix is, from Equation (2.1-4b):

$$D'_m = 1.6 \times 10^{-12}\ m^2/s \qquad (2.1\text{-}17b)$$

Results. Figures 2.1-5 and 2.1-6 show the results obtained from the SWIFT Code plotted alongside the analytic results of Tang et al. Both within the fracture and within the matrix, the two show reasonable agreement.

Discussion of the Code Output. The numerical results exhibited in these figures are presented in much more detail by the microfiche listing (inside the back cover). At this point, the reader is encouraged to scan the listing for a general familarity, but with only one specific purpose, i.e., to locate the data used in these figures. The tables which are denoted there by the words "dual porosity" or "rock matrix" refer, in this case, to the rock matrix of a fracture/matrix problem. In Problems 6 and 7, however, these tables acquire a new meaning in that they there refer to the confining beds of an aquifer.

In order to examine the concentration distributions, the reader should note specifically three tables. The first of these tables is entitled "X-Direction Distance to Grid-Block Center". It provides distances along the fracture to the centers of the grid blocks. As shown, the distance x = 1.5 m lies in Global Block 13. The second, "Dual-Porosity Block Numbers," then identifies, with a unique number, the local one-dimensional rock matrix units which are imbedded in the global blocks. Note that such a unit is not imbedded in Block 1. This block, as discussed under Problem 2, is used only for the purpose of establishing a constant-concentration boundary within the fracture. Note also that Local Unit 12 is associated with Global Block 13 ar

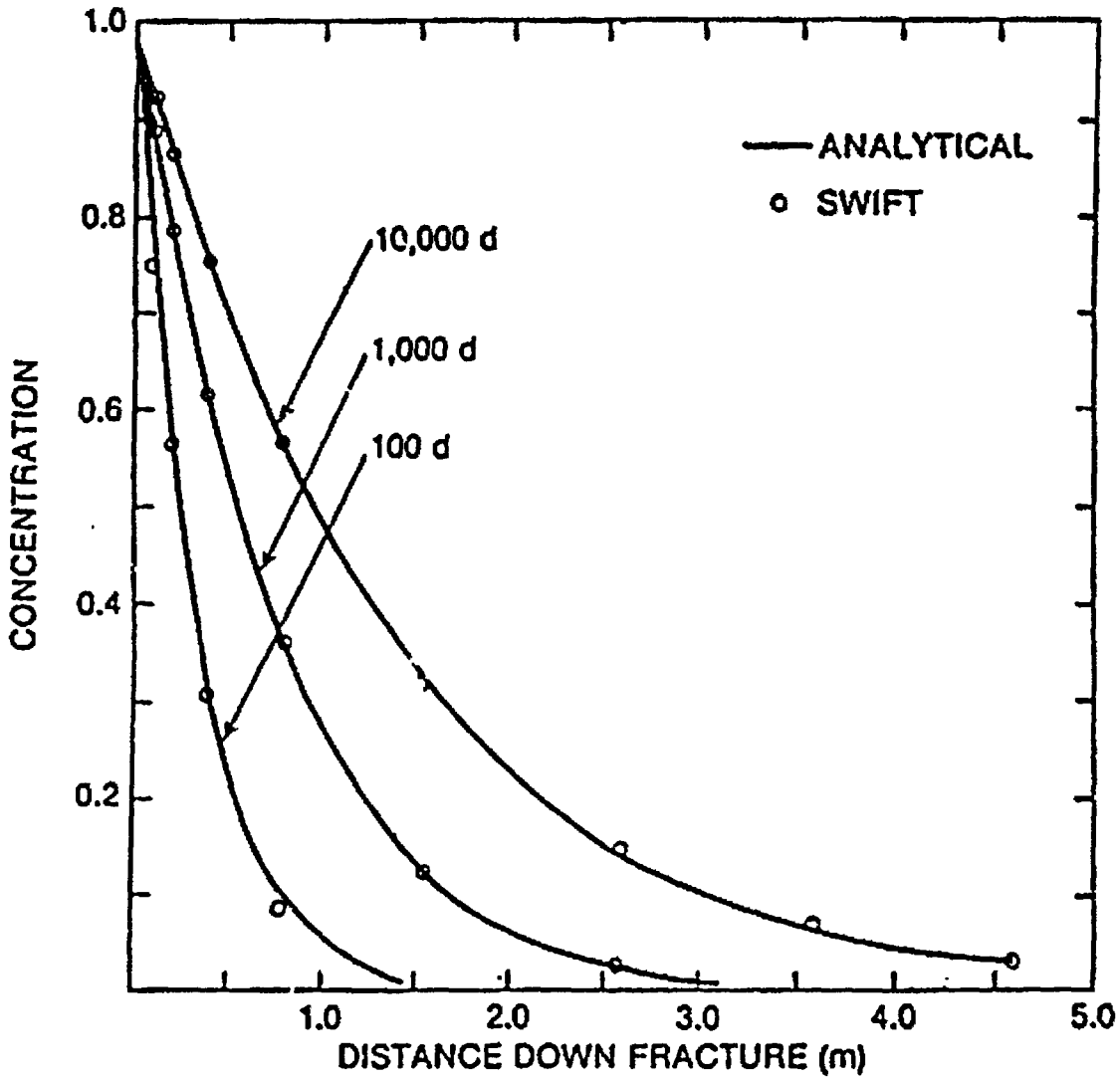

Figure 2.1-5. Radionuclide Concentrations Within the Fracture for a Prismatic Characterization of the Rock Matrix.

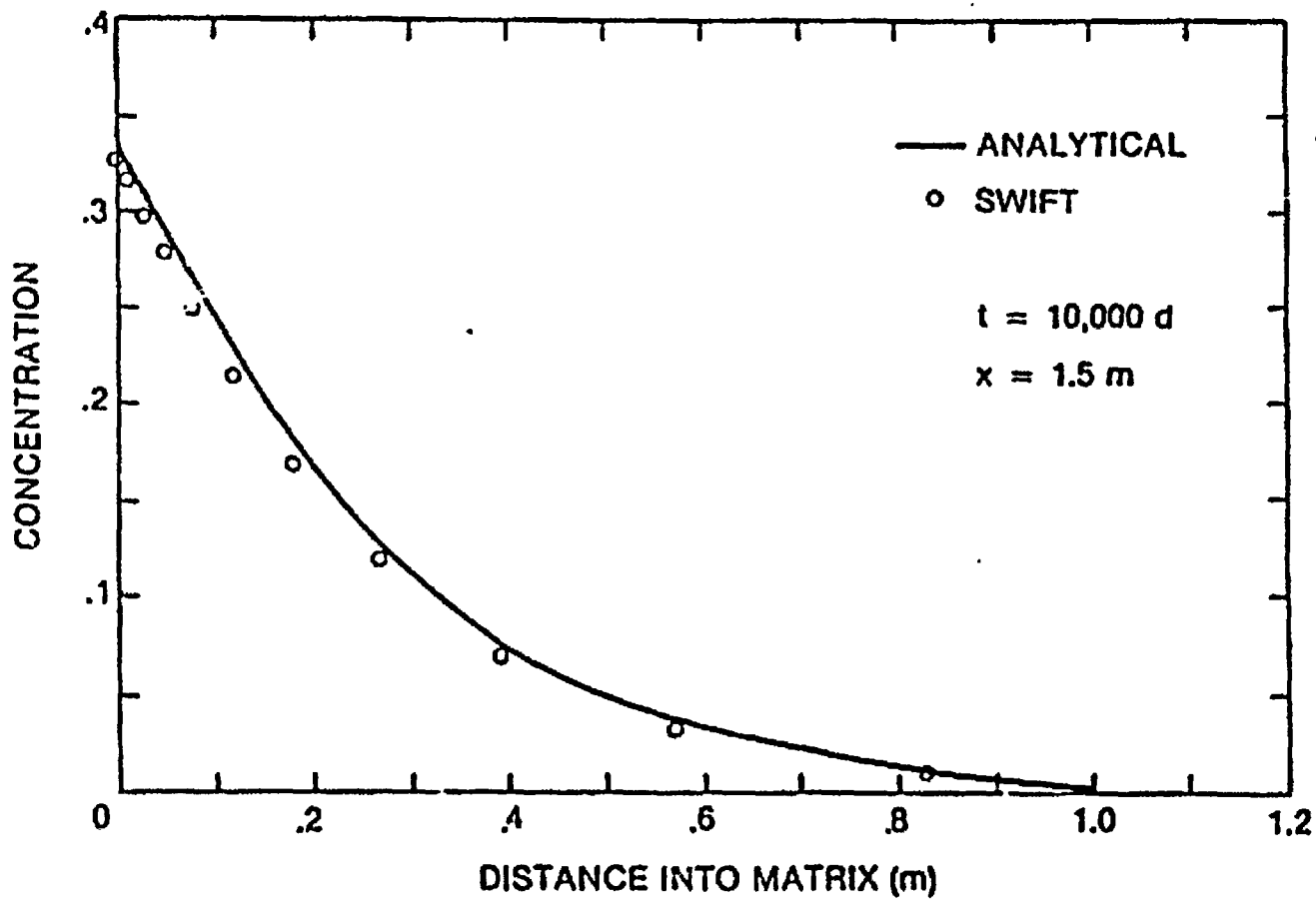

Figure 2.1-6. Radionuclide Concentrations Within the Rock Matrix for a Prismatic Characterization of the Rock Matrix.

hence, with the distance x = 1.5 m measured within the fracture. The third table "Specific Matrix Discretization Parameters" gives nodal locations within the rock-matrix units. Note that Node 12 is located at the fracture/matrix interface. Thus, for example, Node 4 is located at a distance of about 0.4 m from that interface.

Tables of fracture concentrations, labelled "Component-1 Concentration," and matrix concentrations, labelled "Component-1 Radionuclide Concentration Within the Rock Matrix," appear at selected time intervals, with the last such tables corresponding to 10,000 d. The calculated fracture concentration C = 0.318 for Global Block 13 (x = 1.5 m) does agree with Figure 2.1-5. Also, the matrix concentration C' = 0.068 for Local Unit 12 and Local Block 4 (s = 0.4 m from interface) is consistent with Figure 2.1-6. Other values may be checked, as desired.

2.1.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1: From Table 2.1-1 and Equations (2.1-16) and (2.1-17), what data are required for the blanks labelled "1" through "5" in the input-data set?

The control parameters called for here should specify steady-state flow, the international SI system of units, transient-state radionuclide transport and no convection within the rock matrix (the local system). In this case convection within the matrix is of negligible importance, and, for computational efficiency, the proper control parameter should be set to indicate "no convection".

Exercise 2: From the physical properties specified in Table 2.1-2, what are the data required for the blanks labelled "6" through "8" in the input-data set?

Exercise 3 Check the answers for Exercises 1 and 2 by referring to the output listing, specifically to the echo of the input data which appears at the beginning.

Level 2. The reader who wants to develop a deeper understanding of the code should also consider the following exercise*:

Exercise 4: A basic assumption of the foregoing analyses, both analytical and numerical, is that diffusion in a direction parallel to the fracture may be neglected. Evaluate this assumption for the problem of Tang et al.

In most applications where fracture transport (convection and dispersion) dominates over matrix diffusion, it is safe to say that this assumption is valid. In some applications, however, it may be necessary to check this assumption. One approach is simultaneous discretization of both fracture and matrix, which involves the gridding of a two dimensional plane. Such a simulation has been performed by one of the authors with the basic assumption found to be valid.

---

* For the reader with no previous exposure to the SWIFT Code this exercise will likely be too difficult at this point and should be postponed.

2.2 PROBLEM 2. TRANSPORT OF A DECAYING RADIONUCLIDE IN A FRACTURED POROUS MEDIA [HUYAKORN, 1983]

2.2.1 Objective

- To illustrate fracture/matrix transport with a spherical characterization of the rock matrix.

2.2.2 Description of the Problem

This problem is identical to Problem 1 with only two exceptions. Firstly, it is assumed that the exposed surface area between fracture and matrix, per unit fracture length, is greater here and may be more realistically approximated by a spherical surface (Figure 2.1-3b) for the rock matrix. Thus, Equation (2.1-2) of the previous section is replaced by

$$\frac{1}{s}\frac{\partial}{\partial s}\left(s\rho' D_m' \frac{\partial C'}{\partial s}\right) + \Gamma - \lambda K'\phi'\rho'C' = \frac{\partial}{\partial t}(K'\phi'\rho'C') \qquad (2.2\text{-}1)$$

The radius for the spherical units is chosen to be identical to that used in Problem 1 for the length of the prismatic units:

$$a = 1.2 \text{ m} \qquad (2.2\text{-}2)$$

Secondly, the matrix diffusion is reduced by a factor of approximately three relative to that of Equation (2.1-17):

$$D_m' = 5.787 \times 10^{-13} \text{ m}^2/\text{s} \qquad (2.2\text{-}3)$$

The desired output, as in the previous problem, consists of two sets of spatial distributions. However, the values of time are changed to t = 441, 3619 and 90,615 d for the distributions within the fracture and the rock matrix. The position for the latter is also changed to x = 1.0 m.

2.2.3 Numerical Simulation

Discussion of the Code Input. To simulate the semi-infinite fracture, two boundary conditions are specified here, just as they are for Problem 1. At the maximum extent of the system (10.24 m), a convection-only condition

$$\frac{\partial c}{\partial x}(x=L) = 0 \qquad (2.2\text{-}1)$$

is easily specified in the code input (Figure 2.2-1) by default.

At the origin, however, the specification of unit concentration (Equation 2.1-6b) is considerably more complicated. Since SWIFT is designed to evaluate repository-site performance, only facilities for radionuclide sources have been provided. However, a constant-concentration boundary condition may still be used by taking the boundary block (Block 1, in this case) to be an essentially infinite well-stirred reservoir. In fact, this is a basic physical definition for a constant-concentration condition. Distances, of course, are measured by taking x = 0 at the interface between Blocks 1 and 2, and the dual-porosity region begins with Block 2 (see Card ROD-3). To implement the concept of a well-stirred reservoir, four separate steps are taken here.

Firstly, the thickness of Block 1 is increased to

$$\Delta z_1 = (1.91985 \times 10^9 + 2.4)\ \text{m} \quad , \quad \text{R1-26 and R1-19} \qquad (2.2\text{-}2a)$$

using the modification cards. Secondly, the concentration of this block is specified as

$$C_1 = 1 \quad , \quad \text{I-4} \qquad (2.2\text{-}2b)$$

Thirdly, provision is made to replace, with a source, the mass lost from the reservoir by both decay and convection:

$$q = C_1\rho(\lambda\phi\Delta x_1\Delta y_1\Delta z_1 + q) = 7.12 \times 10^{-5}\ \text{kg/s} \quad , \quad \text{R2-10} \qquad (2.2\text{-}2c)$$

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
PROBLEM NO. 2, THREE-COMPONENT NUCLIDE TRANSPORT IN FRACTURED MEDIA,   M-1-1
12/83, COMPARISON WITH 'FTRANS' -- SPHERICAL REPRESENTATION            M-1-2
   4    0    0    0    0    0    0    1    0                          M-2
  21    1    1    2    1    2    0    2    1    0    1    0    0     OM-3-1
   0    2    1    0                                                   M-3-2
                          **********
100RAD  001         1    0    0    12.350                             RO-1
                          **********
       0.0                                                             RO-2-1
       0.0                          ******************************     RO-2-1
                                    * "***" REFERENCED IN TEXT     *
       1.0                          * "***" REFERENCED IN EXERCISE *   RO-2-2
                                    ******************************
       1.0                                                             RO-2-2
   0    0                                                              ROD-1
  12                                                                   ROD-2
*****
   2   21    1    1    1    1    1    0                               ROD-3
*****
                                                                       ROD-3-BLN
       0.0       0.0       0.0    4186.0       1.0                    R1-1
       0.0       0.0       0.0       0.0      0.50       0.0  1.00E-50R1-2
       0.0       0.0       0.0                                         R1-2.5-1
      0.50       0.0                                                   R1-2.5-2
       0.0       0.0       0.0                                         R1-2.5-1
* ********
   4.00E08       0.0                                                   R1-2.5-2
**********
                          ********************
    2700.0  1.013E05      20.0    1000.0    1000.0                    R1-3
                          ********************
    2    2    2    2                                                   R1-6
      20.0     0.001      20.0     0.001                              R1-7
      0.20     0.001      0.80     0.001                              R1-8
     100.0     0.001     200.0     0.001                              R1-9
```

Figure 2.2-1. Problem 2. Listing of SWIFT II Input Data.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
      +---------+---------+---------+---------+---------+---------+---------+---------+
      I                                                                                 I
 26   I     100.0     0.001     200.0     0.001                                R1-10   I
      I                                                                                 I
 27   I       0.0      20.0                                                     R1-11   I
      I                                                                                 I
 28   I     100.0      20.0                                                     R1-11   I
      I                                                                                 I
 29   I    0    0                                                               R1-12   I
      I                                                                                 I
 30   +      20.0  1.013E05       0.0       0.0                                 R1-16   +
      I**********                                                                       I
 31   I  2*5.0E-4    1.0E-3    2.0E-3    4.0E-3    8.0E-3    1.6E-2    3.2E-2           I
      I**********                                                                       I
 32   I    6.4E-2     0.128     0.256     0.512   9*1.024                               I
      I**********                                                                       I
 33   I       1.0                                                                      I
      I**********                                                                       I
 34   I       2.4                                                                      I
      I**********                          **********                                   I
 35   +3.4052E-07 3.4052E-7 3.4052E-7  4.167E-5       0.0       0.0       0.0R1-20      +
      I                                   **********                                   I
 36   I                                                                       R1-21   I
      I                                                                                 I
 37   I    1    1    1    1    1    1                                         R1-26-1 I
      I                                                          **********             I
 38   I       1.0       1.0       1.0       1.0       0.0       0.01.91985E09R1-26-2 I
      I                                                          **********             I
 39   I       0.0       0.0       0.0                                         R1-26-3 I
      I                                                                                 I
 40   +                                                                       R1-26-BLN +
      I                                                                                 I
 41   I    0    0                                                               R1-27   I
      I                                                                                 I
 42   I  1.00E-20                                                              R1D-1   I
      I**********                                                                       I
 43   I+   (1)  +       0.0     0.010       0.0       0.0       1.0       1.0R1D-2-1 I
      I*******************                                                              I
 44   I+(2)+    1+   (3)  +    0.0100                                          R1D-2-2 I
      I*****     **********                                                            I
 45   +                                                                       R1D-3-BLN +
      I**********                                                                       I
 46   I+   (4)  +                                                             R1D-4   I
      I**********                                                                       I
 47   I                                                                       R1D-5-BLN I
      I                                                                                 I
 48   I    0    0    1                                                          I-1   I
      I                                   **********                                   I
 49   I    1    1    1    1    1    1       1.0                                   I-4   I
      I                                   **********                                   I
 50   +                                                                       I-4-BLN   +
      I                                                                                 I
      +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.2-1 Continued.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
       +---------+---------+---------+---------+---------+---------+---------+---------+
       I                                                                                 I
 51    I   2   21   1   1   1   1   1                                   R1A-1           I
       I                                                                                 I
 52    I   1   1   1   1   1   1   2                                   R1A-1           I
       I                                                                                 I
 53    I                                                               R1A-1-BLN       I
       I                                                                                 I
 54    I       0.0       0.0                                           R1A-2           I
       I                                                                                 I
 55    +   2   1   1   0   0   0   0   0   0                           R2-1            +
       I                                                                                 I
 56    I  +1       0.50                                                R2-4            I
       I                                                                                 I
 57    I   2                                                           R2-4            I
       I    **********                                                                   I
 58    I   1-1.157E-11                                                 R2-6-1          I
       I    **********                                                                   I
 59    I   2+1.157E-11                                                 R2-6-2          I
       I    **********                                                                   I
 60    +                                                               R2-6-BLN        +
       I                                                                                 I
 61    I   1   1   1   1   1   1                                       R2-7-1          I
       I                                                                                 I
 62    I       1.0       0.0       20.0       0.0                      R2-7-2          I
       I                                                                                 I
 63    I   2   21   1   1   1   1                                       R2-7-1          I
       I                                                                                 I
 64    I       1.0       0.0       20.0       0.0                      R2-7-2          I
       I                                                                                 I
 65    +                                                               R2-7-BLN        +
       I                                                                                 I
 66    I       0.0       0.0                                                             I
       I                                                                                 I
 67    I   0   0   0   0   0   0  000   0 0000   0   13   11  000   12R2-13             I
       I                                                                                 I
 68    I   0   0   0   0   1   0   0   0   1                           R2-1            I
       I                                                                                 I
 69    I   1                                                           R2-9            I
       I                                                                                 I
 70    +   1   1   1   1                                               R2-10-1         +
       I                **********                                                       I
 71    I       0.0       0.0-7.1212E-5                                 R2-10-2         I
       I                **********                                                       I
 72    I                                                               R2-10BLN        I
       I                                                                                 I
 73    I   3                                                           R2-11.5         I
       I                                                                                 I
 74    I  8.64E06   8.64E06                                                              I
       I                                                                                 I
 75    +   1  -1  -1  -1  -1  -1  000   0 0000   0   00  -1  111   00R2-13             +
       I                                                                                 I
       +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.2-1 Continued.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
       +---------+---------+---------+---------+---------+---------+---------+---------+
       I                                                                                I
  76   I   0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                I
  77   I 2.086E07  1.222E07                                                            I
       I                                                                                I
  78   I  -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     I
       I                                                                                I
  79   I   0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                I
  80   + 3.813E07  1.727E07                                                            +
       I                                                                                I
  81   I   1   -1   -1   -1    1   -1  000    0 0000    0   00    1  111   00R2-13     I
       I                                                                                I
  82   I   0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                I
  83   I 6.256E07  2.443E07                                                            I
       I                                                                                I
  84   I  -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     I
       I                                                                                I
  85   +   0    0    0    0    0    0    0    0    0                        R2-1       +
       I                                                                                I
  86   I 9.710E07  3.454E07                                                            I
       I                                                                                I
  87   I   1   -1   -1   -1    1   -1  000    0 0000    0   00    1  111   00R2-13     I
       I                                                                                I
  88   I   0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                I
  89   I 1.459E08  4.884E07                                                            I
       I                                                                                I
  90   +  -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     +
       I                                                                                I
  91   I   0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                I
  92   I 2.150E08  6.906E07                                                            I
       I                                                                                I
  93   I  -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     I
       I                                                                                I
  94   I   0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                I
  95   + 3.126E08  9.765E07                                                            +
       I                                                                                I
  96   I   1   -1   -1   -1    1   -1  000    0 0000    0   00    1  111   00R2-13     I
       I                                                                                I
  97   I   0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                I
  98   I 4.507E08  1.381E08                                                            I
       I                                                                                I
  99   I  -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     I
       I                                                                                I
 100   +   0    0    0    0    0    0    0    0    0                        R2-1       +
       I                                                                                I
       +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.2-1 Continued.

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```
                 1         2         3         4         5         6         7         8
        12345678901234567890123456789012345678901234567890123456789012345678901234567890
        +---------+---------+---------+---------+---------+---------+---------+---------+
        |                                                                                 |
101     |  6.459E08  1.952E08                                                             |
        |                                                                                 |
102     |   -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     |
        |                                                                                 |
103     |    0    0    0    0    0    0    0    0    0                        R2-1       |
        |                                                                                 |
104     |  9.220E08  2.761E08                                                             |
        |                                                                                 |
105     |   -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     |
        |                                                                                 |
106     |    0    0    0    0    0    0    0    0    0                        R2-1       |
        |                                                                                 |
107     |  1.312E09  3.904E08                                                             |
        |                                                                                 |
108     |   -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     |
        |                                                                                 |
109     |    0    0    0    0    0    0    0    0    0                        R2-1       |
        |                                                                                 |
110     |  1.864E09  5.520E08                                                             |
        |                                                                                 |
111     |   -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     |
        |                                                                                 |
112     |    0    0    0    0    0    0    0    0    0                        R2-1       |
        |                                                                                 |
113     |  2.645E09  7.805E08                                                             |
        |                                                                                 |
114     |   -1   -1   -1   -1   -1   -1  000    0 0000    0   00   -1  111   00R2-13     |
        |                                                                                 |
115     |    0    0    0    0    0    0    0    0    0                        R2-1       |
        |                                                                                 |
116     |  7.829E09  8.640E08                                                             |
        |+++++                +++++                           +++++                       |
117     |    1   -1   -1   -1    1   -1  000    0 0000    0   00    1  111   00R2-13     |
        |+++++                +++++                           +++++                       |
118     |    0    0    0    1    0    0    0    0    0                        R2-1-STOP  |
        |                                                                                 |
        +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.2-1 Continued.

Here the various component terms, except for C_l and Δz_l, which are given above, are prescribed in Cards R1-6 (ρ), R0-1 ($\tau = \ln(2)/\lambda$), R1-20 (ϕ), R1-17 (Δx_l), R1-18 (Δy_l) and R2-6 (q).

Fourthly, and lastly, to implement the concept of a "well-stirred" reservoir, the dispersivity

$$\alpha_{L1} = 4 \times 10^{8} \text{ m} \quad , \quad \text{R1-2.5-2} \qquad (2.2\text{-}2d)$$

is selected for Block 1 only. This value, without question, is sufficiently large that the transmissibility (Theory and Implementation, Section 6.1.3) connecting Blocks 1 and 2 reduces to a boundary-like transmissibility for Block 2. In the data input, this value is given to Rock-Type 2. Rock-Type 2 is then ascribed in R1A-1 to Block 1 only. Rock-Type 1, with $\alpha_L = 0.5$ m, refers to the transporting region of the fracture, Blocks 2 - 21.

Results. Figures 2.2-2 and 2.2-3 show the results from the finite-difference SWIFT plotted alongside those of Huyakorn's finite-element code FTRANS. Both within the fracture and within the matrix, the two show reasonable agreement. The dissimilarity between Figure 2.2-2 and Figure 2.1-5, however, is somewhat striking. Obviously, transport within the fracture is significantly more retarded by the spherical-matrix characterization than by the prismatic-matrix characterization. In spite of reduction of approximately three in the matrix diffusivity, the spherical characterization still yields a retardation which is greater, by a factor of three or more, than that for the prismatic characterization.

Discussion of the Code Output. The results shown are dependent, at lea in part, upon the convective velocity and upon the constant-concentration condition discussed earlier. To check these two, the reader is referred to the microfiche listing. Insofar as the fluid velocity is concerned, note in the table "Homogeneous Reservoir" the value of porosity for the composite global system ($\phi = 4.167 \times 10^{-5}$). Note also, in the first recurrent series output, the first table, which is entitled "INDQ IWELL ...". The purpose the computations referred to here is simply to establish a steady-state flow with boundary wells. Well rates are given and the printing of the Darcy

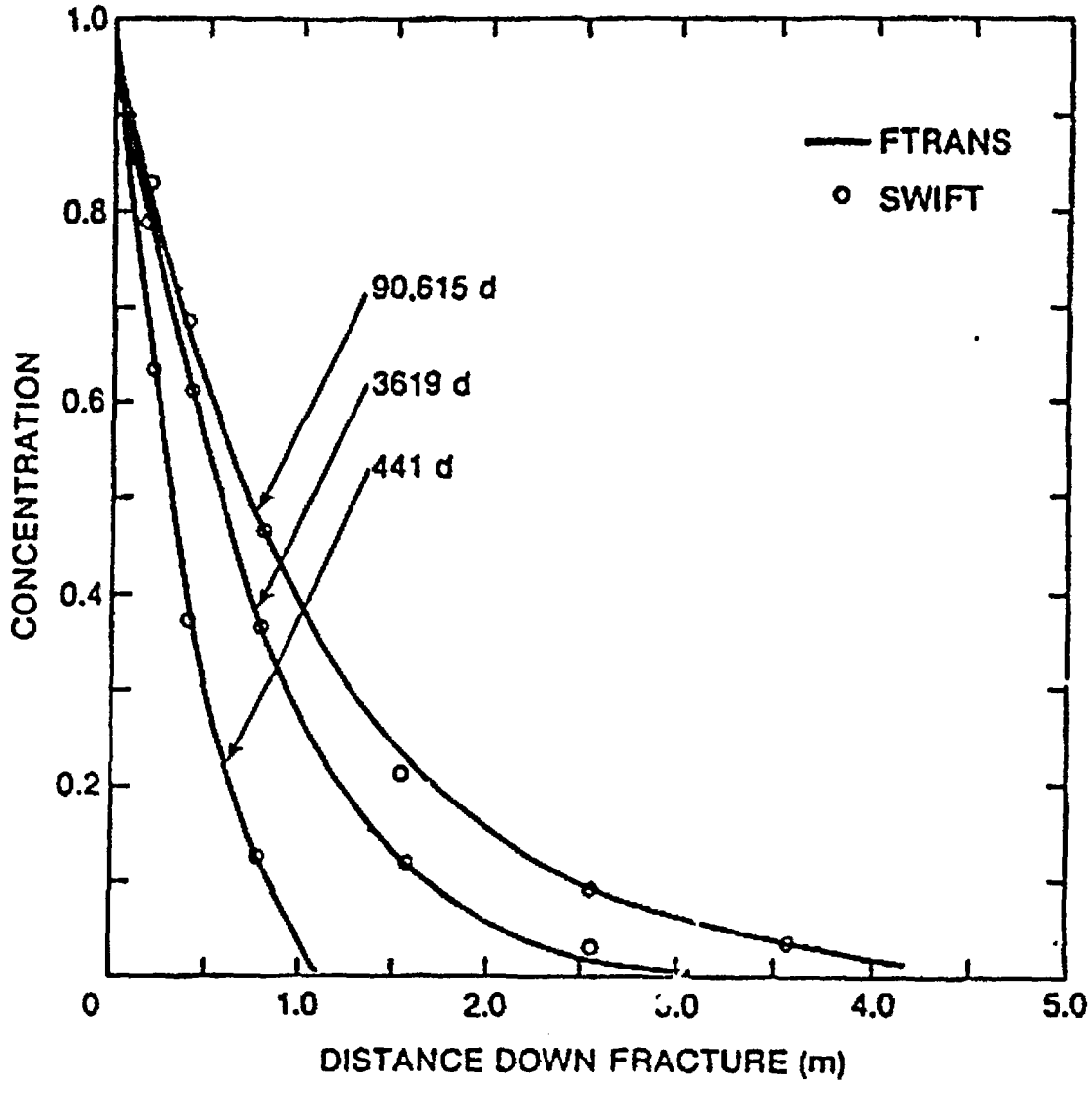

Figure 2.2-2. Radionuclide Concentrations Within the Fracture for a Spherical Characterization of the Rock Matrix.

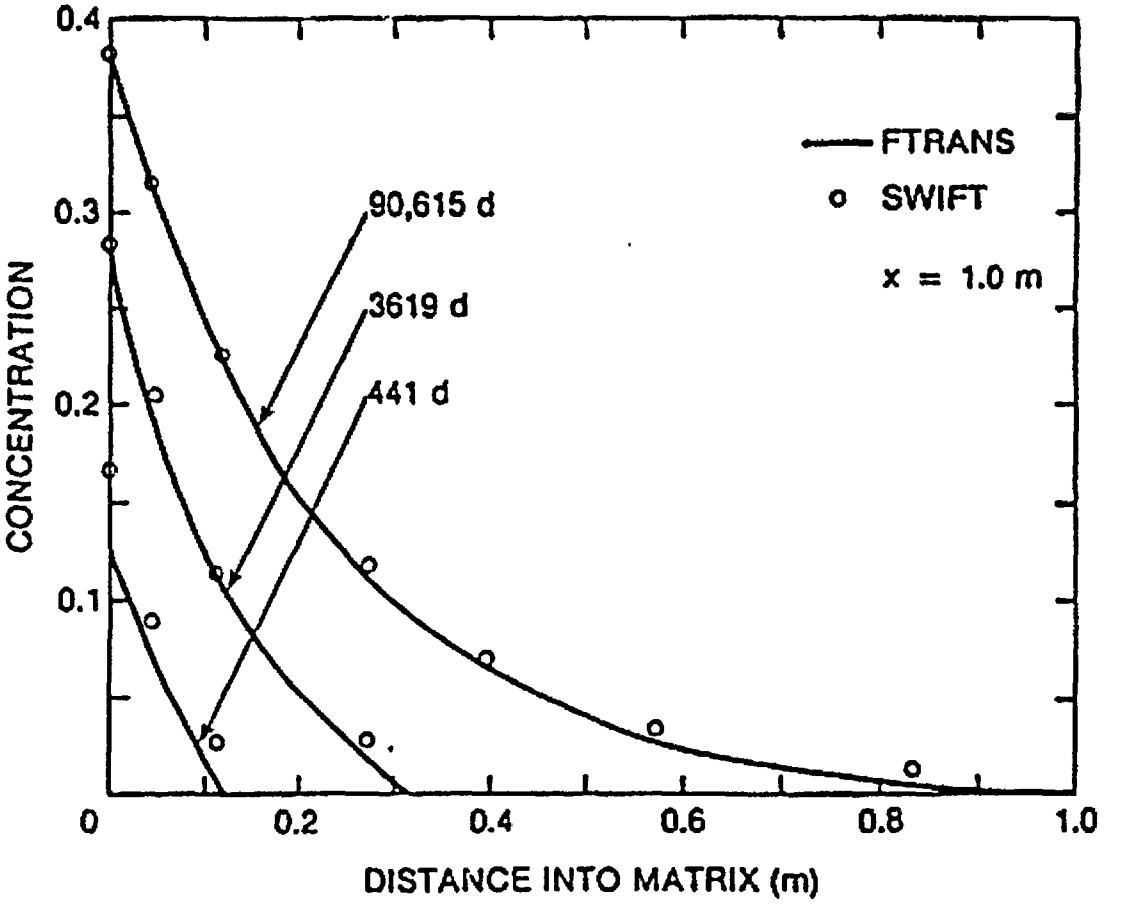

Figure 2.2-3. Radionuclide Concentrations Within the Rock Matrix for a Spherical Characterization of the Rock Matrix.

velocity is prescribed by the control parameter IIPRT = 13. The table "X-Direction Darcy Velocity" then provides the desired check on the convective velocities. As shown in the table, it is constant throughout the entire length of the system, and it has the magnitude

$$v = u/\phi = (4.8208 \times 10^{-12}/4.167 \times 10^{-5})\ m/s = 0.01\ m/d \qquad (2.2\text{-}3)$$

which is consistent with the problem specifications (Table 2.1-1).

To verify the constant-concentration boundary condition, it is sufficient to examine the radionuclide concentration tables labelled "Component-1 Concentration." As the reader will note, there are several such tables, which are displayed at selected time intervals out to the maximum time, t = 90,615 d. In each case, the C = 1.000 condition is maintained to at least 4 significant figures.

2.2.4 Exercises

Level 1. Using the Input-Data Guide, Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1 From the description of the problem, Equation (2.2-3) and Table 2.1-1 what physical parameters are required for the blanks labelled "1" through "4" in the input-data set (Figure 2.2-1)? Check the answers by referring to the echo of the input data printed at the beginning of the output.

Exercise 2 Interpret the output-control parameters identified in the last R2-13 Card of Figure 2.2-1.

Level 2. The reader who wants to develop a deeper understanding of the code should also consider the following exercise:

Exercise 3 If the retardation of the rock matrix were increased from $K' = 1$ to $K' = 3$, would the penetration of the radionuclide front in the fracture be increased or decreased? To answer this question, the problem may be run anew with the value of the distribution coefficient on Card R1D-4 changed to $k_d = 7.41 \times 10^{-6}$ kg/m^3.

2.3 PROBLEM 3. TRANSPORT OF A RADIONUCLIDE CHAIN IN A FRACTURED POROUS MEDIA [INTRACOIN, 1983]

2.3.1 Objective

- To illustrate the coupled effects of fracture/matrix transport and chain decay.

2.3.2 Description of the Problem

Problem Statement. Radionuclides, it is assumed, are buried in a fractured medium. As indicated in the schematic drawing of Figure 2.3-1, the system consists of parallel horizontal fractures with apertures 2d and spacings 2a. It is infinite in its lateral extent but confined to a vertical thickness $b = \Delta z$ by impermeable beds. The radionuclides leach from their storage (leach duration, T_2) and contaminate the entire unit. They are then transported laterally by a one-dimensional flow field. Convection and dispersion occur within the fractures while diffusion and sorption occur within the rock matrix. The geometry presented for the diffusion process may be characterized by one-dimensional prismatic units.

Transport Equations. Mathematically, transport within the fractures for radionuclide r is governed by the equation

$$\frac{\partial}{\partial x}(\rho C_r u) + \frac{\partial}{\partial x}\left(\rho D \frac{\partial C_r}{\partial x}\right) - \Gamma_r \tag{2.3-1}$$

$$+ k_{r,r-1}\lambda_{r-1}K_{r-1}\phi\rho C_{r-1} - \lambda_r K_r \phi\rho C_r = \frac{\partial}{\partial t}(K_r\phi\rho C_r)$$

and transport within the rock matrix is governed by the equation

$$\frac{\partial}{\partial s}\left(\rho' D'_m \frac{\partial C'_r}{\partial s}\right) + \Gamma_r \tag{2.3-2}$$

$$+ k_{r,r-1}\lambda_{r-1}K'_{r-1}\phi'\rho' C'_{r-1} - \lambda_r K'_r \phi'\rho' C'_r = \frac{\partial}{\partial t}(K'_r\phi'\rho' C'_r)$$

Coupling then arises from the flux at the fracture/matrix interface:

$$\Gamma_r = A_V \rho' D'_m \frac{\partial C'_r}{\partial s}(s=0) \tag{2.3-3}$$

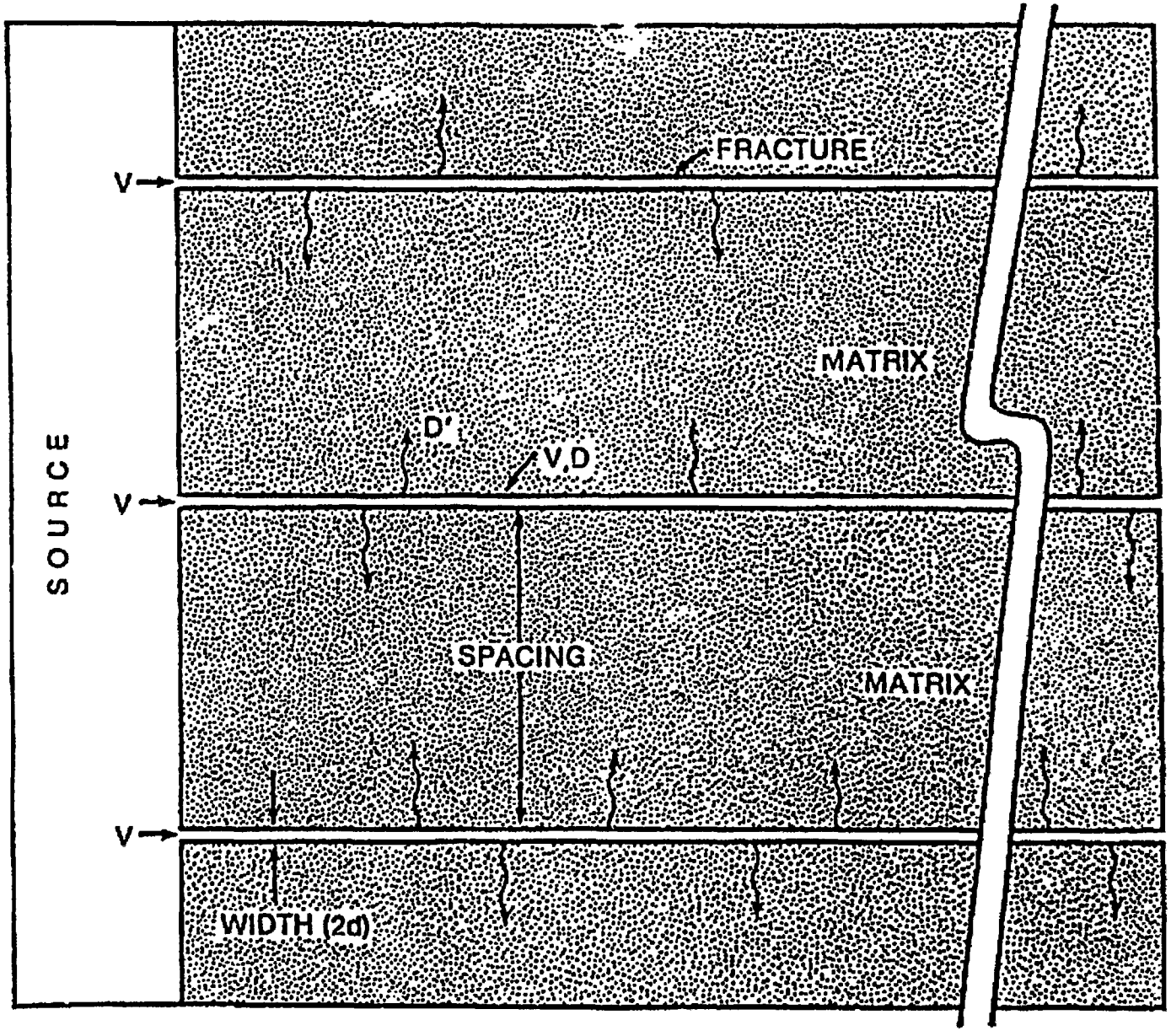

Figure 2.3-1. Problem 3. Schematic Characterization of Transport Within the Fracture and Diffusion Within the Matrix.

Initial/Boundary Conditions. Within the rock matrix the concentration is initially zero:

$$C'_r(x,s,t=0) = 0 \quad , \quad 0 < s < a \quad , \quad x > 0 \qquad (2.3\text{-}4a)$$

a no-flux condition holds at the symmetry boundary:

$$\frac{\partial C'_r}{\partial s}(x,s=a,t) = 0 \quad , \quad t > 0 \qquad (2.3\text{-}4b)$$

and fracture and matrix concentrations are identical at the fracture/matrix interface:

$$C'_r(x,s=0,t) = C_r(x,t) \quad , \quad t > 0 \qquad (2.3\text{-}4c)$$

Within the fractures the initial concentration is also zero:

$$C_r(x,t=0) = 0 \quad , \quad x > 0 \qquad (2.3\text{-}5)$$

and the infinite boundary is held at this initial concentration.

Source Specification. At x = 0, however, the boundary condition for the fractures must take into account decay/production processes within the inventory and the leaching of the inventory. To do this, the time-dependent source concentrations $\tilde{C}_r$ are defined by the Bateman equations:

$$\frac{d\tilde{C}_r}{dt} = k_{r,r-1}\lambda_{r-1}\tilde{C}_{r-1} - \lambda_r\tilde{C}_r \qquad (2.3\text{-}6a)$$

with initial conditions

$$\tilde{C}_r(t=0) = I_r/UT \qquad (2.3\text{-}6b)$$

The B_2 boundary condition chosen here is then expressed in terms of these source concentrations:

$$uC_r - D_r\frac{\partial C_r}{\partial x} = u\tilde{C}_r \quad , \quad x = 0 \qquad (2.3\text{-}7)$$

Input Specifications. The geometry, the leaching process and the transport process are characterized by the parameter values given in Table 2.3-1. Radionuclide-dependent processes are then characterized by those given in Table 2.3-2.

2.3.3 Numerical Simulation

Discussion of Code Input. Within the input-data listing of Figure 2.3-2, two items are selected for emphasis in this section. They are the fracture velocity v and the boundary specification B_2. In contrast to Problems 1 and 2, the velocity here is established by means of a pressure boundary condition:

$$v = [K/\rho(g/g_c)\phi](p_o - p_1)/L = 500 \text{ m/yr} \qquad (2.3\text{-}8)$$

In this equation the porosity of the global system

$$\phi = d/(a+d) = 1.99996 \times 10^{-5} \quad , \quad \text{R1-20} \qquad (2.3\text{-}9a)$$

is fixed by the input specifications (Table 2.3-1). The system length

$$L = 2{,}500 \text{ m} \quad , \quad \text{R1-17} \qquad (2.3\text{-}9b)$$

(the sum of all increments in Card R1-17) is taken to be large compared to the observation length (500 m) in order to simulate a theoretically semi-infinite system. Of course, the gravitational constant ($g = 9.81 \text{ m/s}^2$) is fixed internally by the code.

Aside from these, all other parameters in Equation (2.3-8) are arbitrarily specified to yield the desired interstitial velocity:

$$\rho = 1000 \text{ kg/m}^3 \quad , \quad \text{R1-3} \qquad (2.3\text{-}10a)$$

$$K = 1.99996 \times 10^{-5} \text{ m/s} \quad , \quad \text{R1-20} \qquad (2.3\text{-}10b)$$

$$p_o = 388.44495 \text{ Pa} \quad , \quad \text{R1-28-2} \qquad (2.3\text{-}10c)$$

and

$$p_1 = 0 \quad , \quad \text{R1-28-2} \qquad (2.3\text{-}10d)$$

Table 2.3-1. Problem 3. Input Specifications.

Parameter	Symbol	Value
Observation Length	L_1	500 m
Aquifer Thickness	b	5.0 m
Fracture Aperture	2d	1.0×10^{-4} m
Fracture Spacing	2a	5.0 m
Fracture Porosity	ϕ	2.0×10^{-5}
Fracture Velocity	v	500 m/y
Fracture Dispersity	α_L	50 m
Matrix Porosity	ϕ'	5.0×10^{-3}
Rock Density	ρ_R	2700 kg/m^3
Matrix Diffusivity	D'_m	1.0×10^{-12} m^2/s
Leach Duration	t_2	10^5 y

Table 2.3-2. Nuclide Inventory (I_2) and Matrix[1] Retardation (R_3).

Number	Isotope	Inventory (Ci)	Inventory (kg)	Half-Life[2] τ(y)	Retardation K_v	Distribution Coefficient[3] k_d (m^3/kg)	Specific Activity A_m (Ci/kg)
1	^{245}Cm	0.7	4.074×10^{-3}	8.500×10^{3}	570	0.211	171.8
2	^{237}Np	1.0	1.418	2.140×10^{6}	80	2.96×10^{-2}	0.7055
3	^{233}U	0.004	4.147×10^{-4}	1.592×10^{6}	30	1.11×10^{-2}	9.646

1 No sorption occurs within the fracture.

2 The corresponding decay constant is given by $\lambda = \ln(2)/\tau$.

3 The two sorption parameters are related via $K_v = \rho_R k_d$.

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```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
|                                                                                |
|PROBLEM NO. 3.   INTRACOIN LEVEL 1, CASE 5, I2,R3,B2,P2,T2,E1,L1        M-1-1  |
|                                                                                |
|12/83,  ONE-D TRANSPORT IN FRACTURED MEDIA WITH CHAIN DECAY              M-1-2  |
|                                                                                |
|    4    0    0    0    0    0    0    1    1                           M-2    |
|                  *****                                                         |
|  126    1    1    1*(1)*    1    1   -1    0    2    0    1    1     OM-3-1   |
|                  *****                                                         |
+    1    2    1    1                                                      M-3-2  +
|                            **********                                          |
|245CM 245          1    0    0*   (2)  *                                RO-1-1 |
|                            **********                                          |
|237NP 237          2    1    0*   (3)  *                                RO-1-1 |
|                            **********                                          |
|    1       1.0                                                          RO-1-2 |
|                            **********                                          |
|233 U 233          3    1    0*   (4)  *                                RO-1-1 |
|                            **********                                          |
+    2       1.0                                                          RO-1-2 +
|**********                                                                      |
|*   (5)  *       0.0       0.0     ******************************       RO-2-1 |
|**********                         * "***" REFERENCED IN TEXT     *             |
|*   (6)  *       1.0       1.0     * "***" REFERENCED IN EXERCISE *     RO-2-2 |
|**********                         ******************************               |
|    0                                                                   ROD-1  |
|                                                                                |
|   25                                                                   ROD-2  |
|                                                                                |
+    1  126    1    1    1    1    1    0                                ROD-3  +
|                                                                                |
|                                                                       ROD-3-BLN |
|                                                                                |
|       0.0       0.0       0.0    4186.0       1.0                      R1-1   |
|                                                                                |
|       0.0       0.0       0.0       0.0      50.0       0.0    1.0E-20R1-2   |
|                                  *******************                           |
|    2700.0       0.0      20.0*   (7)  **   (8)  *                      R1-3   |
|                                  *******************                           |
+    2    2    2    2                                                      R1-6  +
|                                                                                |
|      20.0     0.001      20.0     0.001                                  R1-7 |
|                                                                                |
|      0.20     0.001      0.80     0.001                                  R1-8 |
|                                                                                |
|     100.0     0.001     200.0     0.001                                  R1-9 |
|                                                                                |
|     100.0     0.001     200.0     0.001                                  R1-10 |
|                                                                                |
+       0.0      20.0                                                      R1-11  +
|                                                                                |
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.3-2. Listing of SWIFT II Input Data.

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```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
26      100.0      20.0                                                   R1-11
27    0    0                                                              R1-12
28      20.0       0.0       0.0       0.0                                R1-16
29       1.0       2.0       3.0    98*5.0       9.0      10.0      20.0
30      30.0      40.0      50.0      60.0      80.0  16*100.0     105.0
31       1.0
32    5.0001
                                   **********
33 1.99996E-51.99996E-51.99996E-51.99396E-5 0.0       0.0       0.0       R1-20
                                   **********
34                                                                        R1-26-BLN
35    4    0                                                              R1-27
36    1    1    1    1    1    1                                          R1-28-1
           **********
37       1.0 388.44495      20.0       0.0                                R1-28-2
           **********
38  126  126    1    1    1    1                                          R1-28-1
           **********
39       2.0       0.0      20.0       0.0                                R1-28-2
           **********
40                                                                        R1-28-BLN
41                                                                        R1-33-BLN
42       0.0                                                              R1D-1
43  1.00F-12       0.0  5.00E-03       0.0       0.0       0.0       1.0R1D-2-1
44    1    1       2.5   1.00E-3       0.0                                R1D-2-2
45                                                                        R1D-3-BLN
46  *   (9)  **  (10)  **  (11)  *                                        R1D-4
47                                                                        R1D-5-BLN
48    0    0    0                                                        I-1
49       0.0                                                              R1A-2
50    0                                                                   R1A-3
```

Figure 2.3-2 Continued.

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```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
I                   **********                                                    I
51 I      0.0       0.0  0.199996        0.0                            R1A-4    I
I                   **********                                                    I
52 I      1.0       1.0       1.0                                       R1A-5    I
I                                                                                I
53 I   1    1    1    1    1    1                                       R1A-6    I
I                                                                                I
54 I      0.0                                                            R1A-7    I
I          **********                                                            I
55 +CM 245 +  (12)  +                                                    R1A-8    +
I          **********                                                            I
56 INP 237 +  (13)  +                                                    R1A-8    I
I          **********                                                            I
57 I U 233 +  (14)  +                                                    R1A-8    I
I          **********                                                            I
58 I     10.0      10.0      10.0                                        R1A-9    I
I                                                                                I
59 I  102   1    1                                                       N-1      I
I                                                                                I
60 +                                                                     N-1-BLN  +
I                                                                                I
61 I   0    0    1    0    0    0    0    0    0    0                   R2-1     I
I                                                                                I
62 I  -1       0.5                                                       R2-2     I
I                                                                                I
63 I      1.0       1.0                                                          I
I                                                                                I
64 I   1   -1    1   -1   -1    1  111    0 0000    0   11   -1  211   11R2-13   I
I                                                                                I
65 +   0    0    0    0    2    0    0    0    0    0                   R2-1     +
I**********                                                                      I
66 I* (15) +       0.0                                                    R2-10.5  I
I**********                                                                      I
67 I6.3072 E11 15.768E09                                                         I
I                                                                                I
68 I   1   -1   -1   -1    1   -1  211    1 0000    0   00    1  211   00R2-13   I
I                                                                                I
69 I   0    0    0    0    0    0    0    0    0    0                   R2-1     I
I                                                                                I
70 +25.2288E11 15.768E09                                                         +
I                                                                                I
71 I   1   -1   -1   -1    1   -1  211    1 0000    0   00    1  211   00R2-13   I
I                                                                                I
72 I   0    0    0    0    0    0    0    0    0                   R2-1         I
I                                                                                I
73 I4.7304 E12 3.1536E10                                                         I
I                                                                                I
74 I   1   -1   -1   -1    1   -1  211    1 0000    0   00    1  211   00R2-13   I
I                                                                                I
75 +   0    0    0    0    0    0    0    0    0                   R2-1         +
I                                                                                I
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.3-2 Continued.

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```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
!                                                                                !
76 !5.67648E12 3.1536E10                                                         !
!                                                                                !
77 !    1   -1   -1   -1    1   -1  211    1 0000    0   00    1  211   00RZ-13  !
!                                                                                !
78 !    0    0    0    1    0    0    0    0    0                       RZ-1-END !
!                                                                                !
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 2.3-2 Continued.

In order to approximate the B_2 boundary condition, Grid Block 1 is specified as the source in Card R1A-6. This block, of course, is of finite width with

$$\Delta x_1 = 5 \text{ m} \quad , \quad \text{R1-17} \qquad . \qquad (2.3\text{-}11a)$$

However, this increment is only one percent of the observation length and therefore should be an acceptable approximation to the theoretical boundary condition of Equation (2.3-7), which is prescribed for an infinitesimal increment.

Further, the source rate is specified within SWIFT by the equation

$$R_{wr} = - m_r(t)\rho_w/t_a \qquad (2.3\text{-}11b)$$

(Section 3.4 of <u>Theory and Implementation</u>) where

R_{wr} = source rate of radionuclide r [kg/m^3(bulk)/s],
m_r = waste density of radionuclide r [kg/m^3(waste)],
ρ_w = volumetric density of wastes [m^3(waste)/m^3(bulk)], and
t_a = T_2 = leach duration [s]

Quantities t_a, $m_r(t=0)$ and ρ_w must be specified in the input. Prescribing the leach duration is straightforward. However, the other two require some explanation. Here it is assumed arbitrarily that the waste inventory occupies one m^3 of volume so that

$$\rho_w = 1/\Delta x_1 \Delta y \Delta z = 0.199996 \quad , \quad \text{R1A-4} \qquad (2.3\text{-}12)$$

where Δx_1 = 1 m, Δy = 1 m and Δz = 5.0001 m are specified in Cards R1-17, R1-18 and R1-19, respectively. Thus, the initial densities $m_r(t=0)$ have the same numerical values as the nuclide inventories I_r given in Table 2.3-2, and the code internally solves for the Bateman decay (Equation 2.3-6a).

Results. Results are presented in the tabular form prescribed by the INTRACOIN project, and they exhibit reasonable agreement with other codes used in that study. Breakthrough curves at the observation point L_1 = 500 m are given, in abbreviated form, in Table 2.3-3 and, in expanded form, in Table 2.3-4.

Discussion of Code Output. The concentrations given in these tables (in Ci/m^3) may be obtained from the computed concentrations (in kg/kg) via the fluid density (1000 kg/m^3) and the specific activities of Table 2.3-2. For example, consider the concentration for ^{233}U at 180,000 y. The point of breakthrough is located in Block 102, which may be verified by examining, in the microfiche output listing, the echo of the block sizes (see also Figure 2.3-3). The reader will also note in the echo of Card N-1 that Block 102 is designated as a nuclide monitor block. This facility allows one to store (on Tape 9) computed concentrations at this particular location. Here such concentrations were stored so that they might be post-processed and Tables 2.3-3 and 2.3-4 written automatically in the INTRACOIN format. The concentration computed for ^{233}U at 180,000 y is printed in next-to-the last table of the output listing, the one entitled "Component-3 Concentration." The value printed there as a mass fraction may be then converted to the desired units:

$$C(Ci/m^3) = \rho A_m C(kg/kg) = 1.95\times10^{-5}\ Ci/m^3 \qquad (2.3\text{-}13)$$

using Tables 2.3-1 and 2.3-2.

To provide a check on the calculation of concentrations such as these, four material-balance summaries are printed at selected time steps. Two of them, the one for unleached components and the one for leached, but undissolved, components pertain to the source block. The other two tables, one for dissolved and sorbed material in the fracture and one for such material residing in the rock matrix, pertain to the system as a whole. Each monitors the conservation of mass within a particular phase or subsystem and then summarizes the information with balance quotients. Ideally these quotients should equal unity. The various categories used in these tables are defined in Table 2.3-5.

Table 2.3-3. Breakthrough Parameters.

	NUCLIDE	C-MAX (CI/CU.M)	T-MAX (YEAR)	T+(50%) (YEAR)	T-(50%) (YEAR)
1	CM 245	1.6952E-11	49001.	28802.	79362.
2	NP 237	1.6665E-06	158000.	77616.	464564.
3	U 233	1.9524E-06	180001.	82459.	688312.

Table 2.3-4. Breakthrough Profile.

TIME (YEARS)	CONCENTRATION (CI/CU.M)		
	CM 245	NP 237	U 233
3.50E+03	5.1824E-17	6.6839E-11	5.2623E-11
7.50E+03	1.4297E-14	1.8597E-09	1.1426E-09
1.15E+04	1.9872E-13	8.6984E-09	5.2641E-09
1.55E+04	9.1310E-13	2.2451E-08	1.4021E-08
1.95E+04	2.4360E-12	4.3552E-08	2.8395E-08
2.35E+04	4.7405E-12	7.1697E-08	4.8697E-08
2.75E+04	7.5312E-12	1.0627E-07	7.5724E-08
3.15E+04	1.0400E-11	1.4654E-07	1.0886E-07
3.55E+04	1.2972E-11	1.9177E-07	1.4819E-07
3.95E+04	1.4981E-11	2.4129E-07	1.9347E-07
4.35E+04	1.6295E-11	2.9448E-07	2.4444E-07
4.75E+04	1.6898E-11	3.5077E-07	3.0079E-07
5.15E+04	1.6855E-11	4.0967E-07	3.6221E-07
5.55E+04	1.6280E-11	4.7077E-07	4.2841E-07
5.95E+04	1.5306E-11	5.3367E-07	4.9906E-07
6.35E+04	1.4064E-11	5.9806E-07	5.7386E-07
6.75E+04	1.2670E-11	6.6364E-07	6.5251E-07
7.15E+04	1.1221E-11	7.3016E-07	7.3475E-07
7.55E+04	9.7906E-12	7.9739E-07	8.2028E-07
7.95E+04	8.4309E-12	8.6519E-07	9.0888E-07
8.70E+04	6.1792E-12	9.9323E-07	1.0824E-06
9.50E+04	4.2769E-12	1.1302E-06	1.2767E-06
1.03E+05	2.8703E-12	1.2668E-06	1.4780E-06
1.11E+05	1.8777E-12	1.3952E-06	1.6422E-06
1.19E+05	1.2019E-12	1.4974E-06	1.7481E-06
1.27E+05	7.5414E-13	1.5705E-06	1.8183E-06
1.35E+05	4.6455E-13	1.6192E-06	1.8665E-06
1.43E+05	2.8133E-13	1.6485E-06	1.9000E-06
1.51E+05	1.6778E-13	1.6631E-06	1.9231E-06
1.59E+05	9.8694E-14	1.6664E-06	1.9383E-06
1.67E+05	5.7358E-14	1.6611E-06	1.9475E-06
1.75E+05	3.2981E-14	1.6494E-06	1.9518E-06
1.86E+05	1.5172E-14	1.6256E-06	1.9514E-06
2.04E+05	4.1178E-15	1.5743E-06	1.9388E-06
2.36E+05	3.7330E-16	1.4660E-06	1.8923E-06
2.68E+05	3.1725E-17	1.3541E-06	1.8281E-06
3.00E+05	2.5832E-18	1.2473E-06	1.7551E-06
3.32E+05	2.0417E-19	1.1491E-06	1.6785E-06
3.64E+05	1.5793E-20	1.0599E-06	1.6013E-06
3.96E+05	1.2023E-21	9.7947E-07	1.5255E-06

Table 2.3-4 Continued.

TIME (YEARS)	CONCENTRATION (CI/CU.M)		
	CM 245	NP 237	U 233
4.28E+05	9.0552E-23	9.0709E-07	1.4520E-06
4.60E+05	6.8074E-24	8.4191E-07	1.3816E-06
4.92E+05	5.5825E-25	7.8321E-07	1.3144E-06
5.24E+05	8.5281E-26	7.3009E-07	1.2509E-06
5.56E+05	5.0058E-26	6.8206E-07	1.1907E-06
5.88E+05	3.4527E-26	6.3843E-07	1.1339E-06
6.20E+05	3.5234E-26	5.9872E-07	1.0803E-06
6.52E+05	8.2965E-26	5.6247E-07	1.0299E-06
6.84E+05	6.8849E-26	5.2931E-07	9.8243E-07
7.16E+05	5.1387E-26	4.9889E-07	9.3768E-07
7.48E+05	3.9422E-26	4.7092E-07	8.9559E-07
7.80E+05	1.3475E-25	4.4516E-07	8.5596E-07

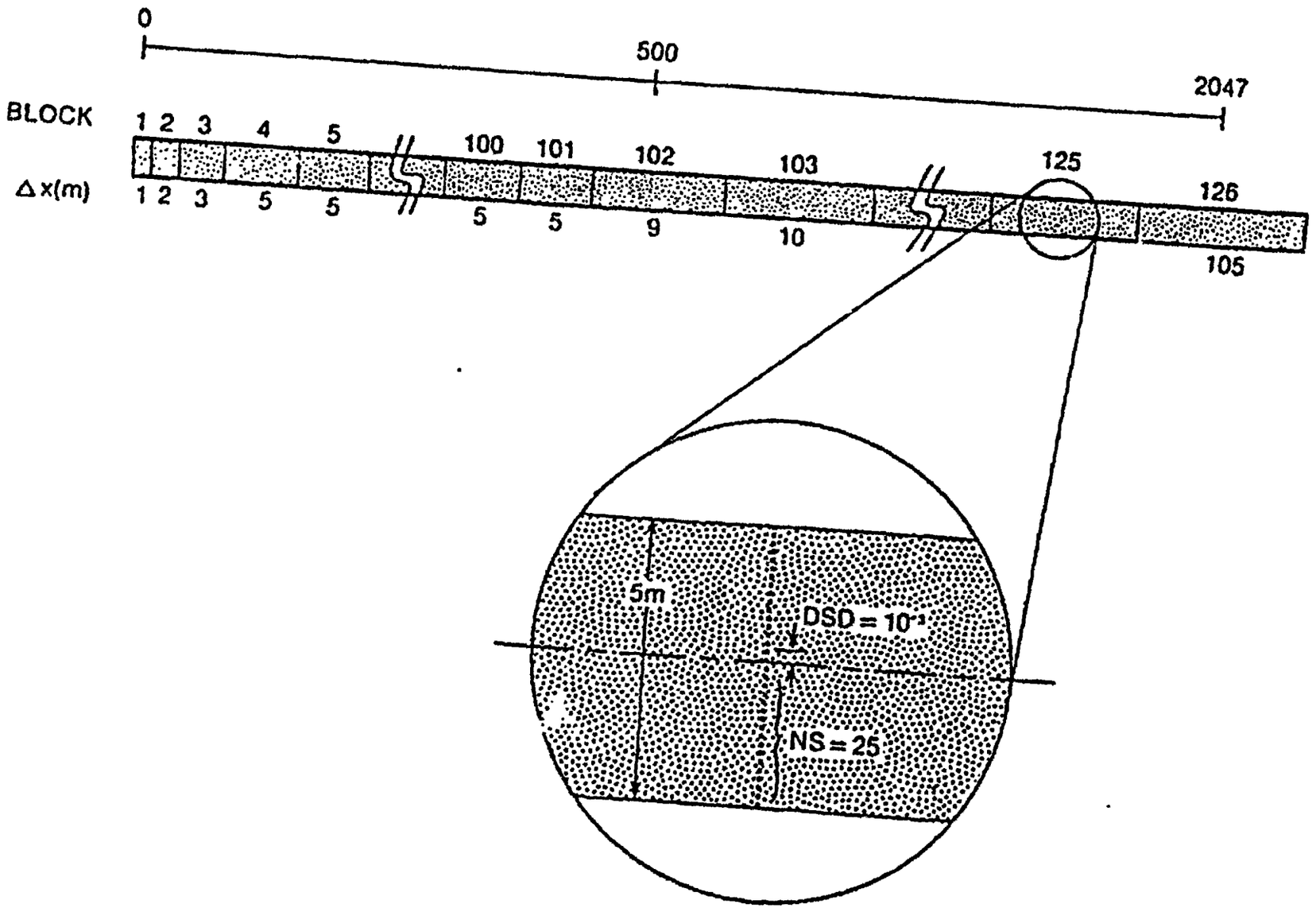


Figure 2.3-3. Gridding of the Fracture/Matrix System.

Table 2.3-5. Material-Balance Summaries[1].

	Unleached[2]	Leached but Undissolved[2,3]	(Fracture) Dissolved and Sorbed	Matrix Dissolved and Sorbed
In Place	Mass unleached from radioactive-waste storage	Mass leached from storage but, as yet, undissolved	Total mass in transport within fracture	Total mass in transport within matrix
Sources	---	Gain from unleached phase	Gain from leached-but-undissolved phase and from specified sources	Gain of mass transported from fracture to matrix subsystem
Sinks	Loss to leached-but-undissolved phase	Loss to (fracture) dissolved and sorbed phase	Loss to withdrawal wells	Loss of mass transported from matrix to fracture subsystem
Generation	Mass generated by radioactive decay of parent(s) within the inventory	Mass generated by radioactive decay of parents(s) within the phase	Mass generated by radioactive decay of parent(s) within the fracture	Mass generated by radioactive decay of parents(s) within matrix
Decay	Loss through radioactive decay of initial inventory	Loss through radioactive decay of within the phase	Loss through radioactive decay within the fracture	Loss through radioactive decay within matrix
E-Flux	---	---	Loss at boundary-discharge locations	---

1 All entries are masses accumulated over time.

2 Refer to source block only.

3 Undissolved due to solubility limitation.

2.3.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1 Fill in the blanks labelled "1" through "15" in Figure 2.3-1, making reference as necessary to Tables 2.3-1 and 2.3-2. The data called for here are either source- or radionuclide-dependent information and may be verified by reference to the output listing.

Level 2. The reader who wants to develop a deeper understanding of the code should also consider the following exercises:

Exercise 2 What effect does the rock matrix have on the transport? Contrast the computed breakthrough-time parameters (Table 2.3-3) with those for the case of convective transport in the fracture with no matrix effects.

Exercise 3 Table 2.3-3 indicates that the peak for ^{237}Np occurs before that for ^{233}U. Why? Since the latter is in secular equilibrium with the former, one would expect the peaks to occur at approximatley the same time providing that the retardations were equal. Here, however, ^{237}Np has the larger retardation (Table 2.3-2). Thus, should not ^{237}Np peak later than does ^{233}U?

3 FLUID FLOW THROUGH DUAL-POROSITY MEDIA

3.1 PROBLEM 4. ANALYSIS OF WELL-TEST DATA FOR A DOLOMITE FORMATION [PAHWA AND BAXLEY, 1980]

3.1.1 Objective

- To illustrate the effects of stress-relief fracturing upon a slug-injection test.

3.1.2 Description of the Problem

Background. A number of slug and recovery tests were conducted by Sandia National Laboratories and by the U.S. Geological Survey [Mercer and Orr, 1979; Dennehy and Davis, 1981] during the site-characterization work for the Waste-Isolation Pilot Plant (WIPP) [Powers et al, 1978]. Two formations of particular interest were the Culebra and Magenta dolmite members of the Rustler unit, both of which are significant water-bearing rocks lying above the Salado salt layer. These tests were analyzed by Dennehy and Davis using an analytical model and, since many of the tests exhibited an anomalously high flow rate at small values of time, they were analyzed also by Pahwa and Baxley [1980] using a dual porosity implementation of their numerical code.

In the SWIFT Self-Teaching Curriculum, Problem 11 [Finley and Reeves, 1981], the H2A test (Figure 3.1-1) of the Magenta member was chosen, and the conceptual model of Pahwa and Baxley was used. This model assumes that, in addition to the primary porosity, which may itself represent connected fractures extending throughout the dolomite, there are secondary-porosity fractures which extend radially outward an average distance of 2000 ft (Figure 3.1-2a). It is then these fractures which affect the small-time response of the flow rate. As in the work of Pahwa and Baxley, heterogeneity was used in Problem 11 to characterize the secondary porosity.

Problem Statement. Here, a different conceptual model is invoked. It is assumed that the secondary porosity is provided by stress-relief fracturing which extends to a radial distance of about one foot surrounding the wellbore (see Figure 3.1-2b). The generalized dual-porosity approach of the SWIFT II Model is then used to simulate the measured data.

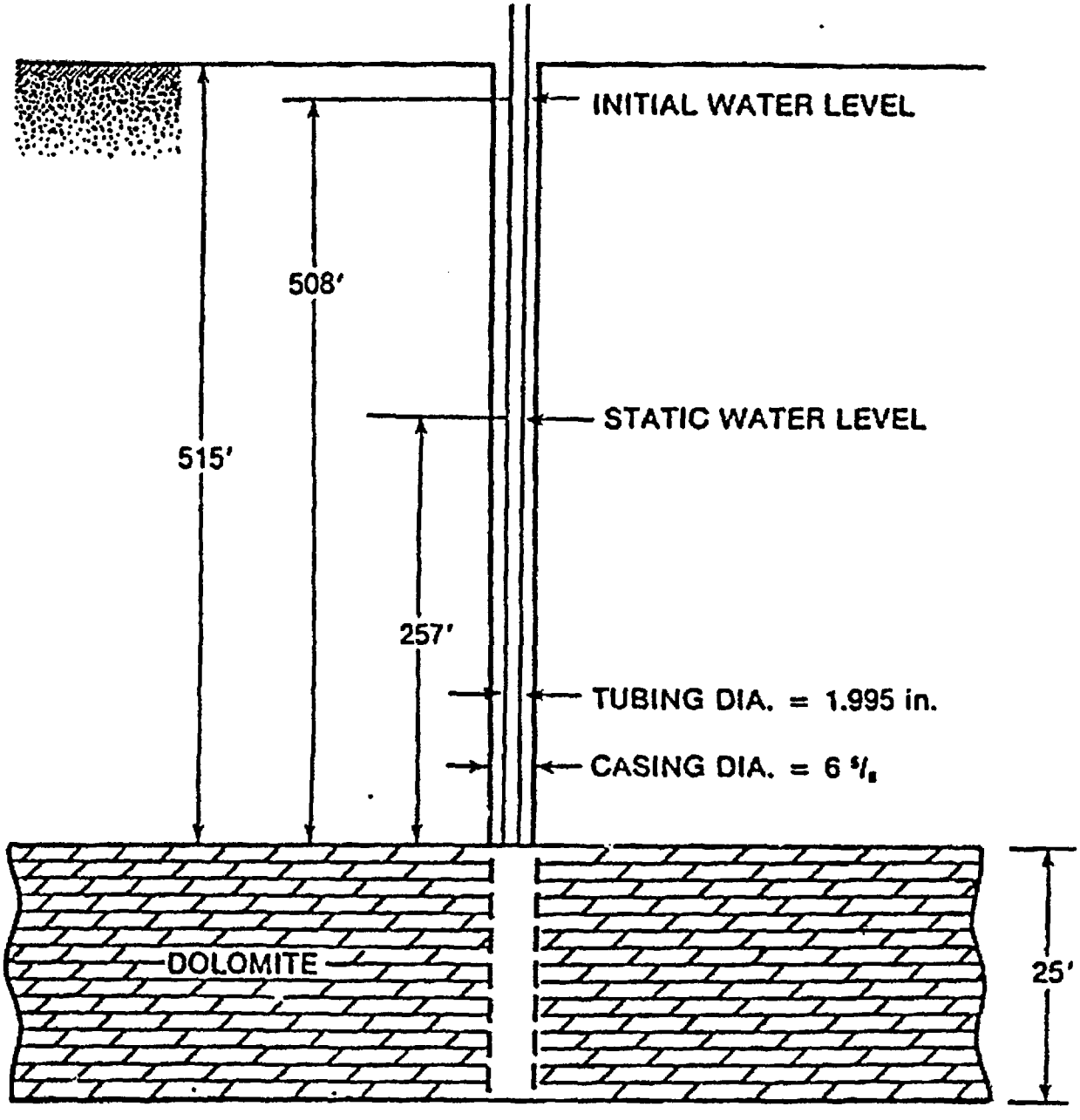


Figure 3.1-1. Problem 4. Schematic Diagram of Well-Test H2A Within the Magenta Dolomite Formation.

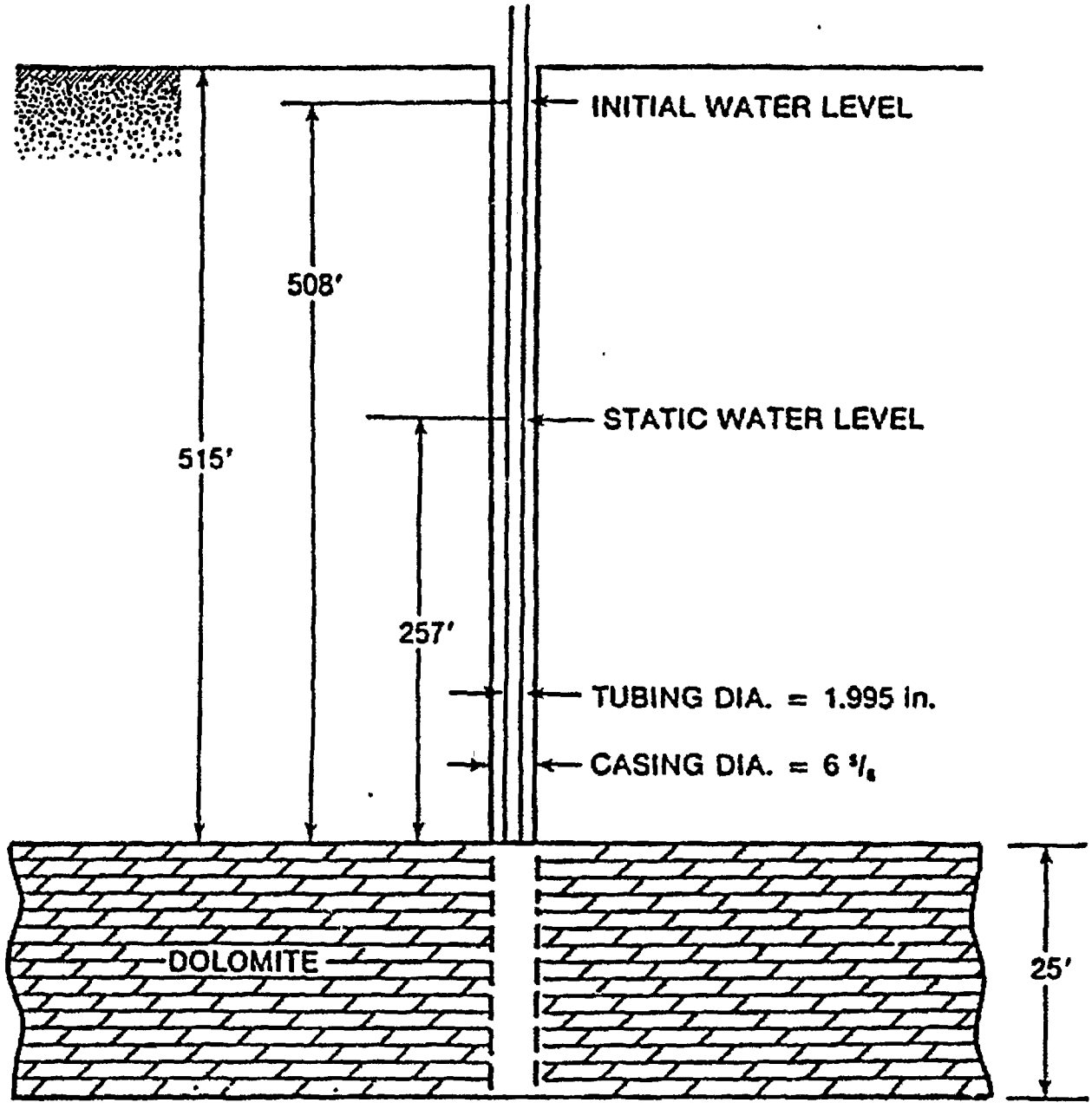
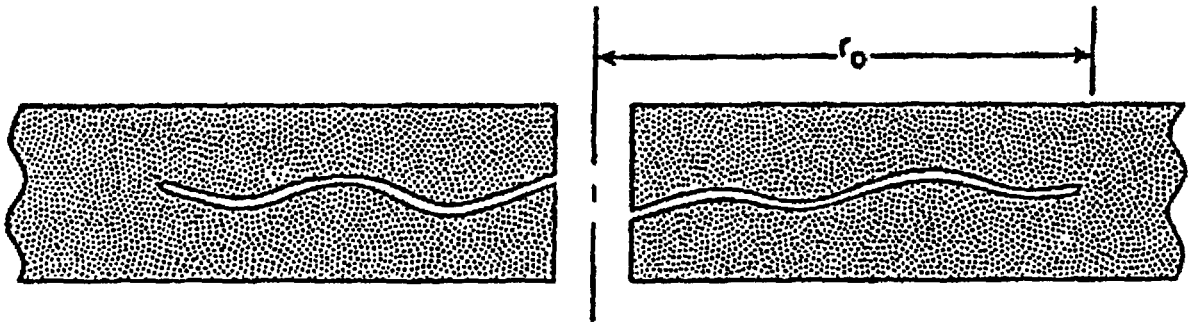
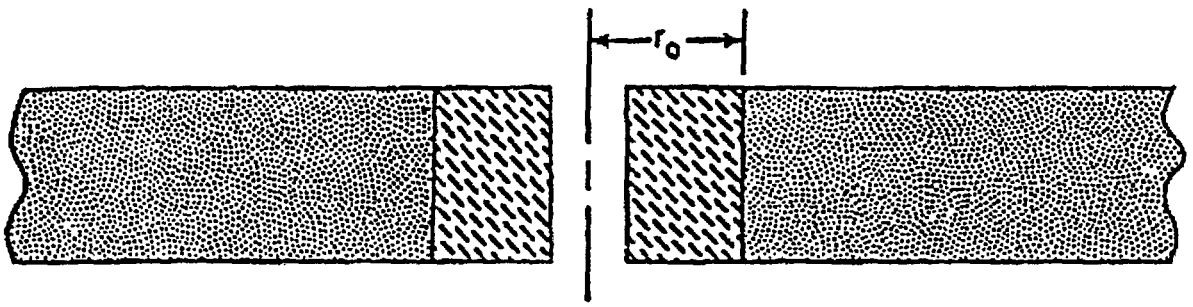


Figure 3.1-1. Problem 4. Schematic Diagram of Well-Test H2A Within the Magenta Dolomite Formation.



(a) Partially Penetrating Fracture(s).



(b) Stress-Relief Fractures

Figure 3.1-2. Conceptual Models for the Secondary Fracture Porosity.

Flow Equations. Mathematically, within the primary porosity, the flow is characterized by the equation

$$T \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \bar{s}}{\partial r}\right) - b\Gamma_W = S \frac{\partial \bar{s}}{\partial t} \quad , \quad r_w < r < \infty \qquad . \qquad (3.1\text{-}1)$$

and, within the secondary porosity, by the equation

$$K' \frac{\partial^2 \bar{s}'}{\partial s^2} + \Gamma_W = S'_s \frac{\partial \bar{s}'}{\partial t} \quad , \quad 0 < s < a \quad , \quad r_w < r < r_o \qquad (3.1\text{-}2)$$

where a is the average length of the connected secondary fracturing and r_o denotes the maximum extent of the stress-relief fracturing surrounding the wellbore (radius, r_w). The coupling between primary and secondary porosity is provided by the relation

$$\Gamma_W = - A_V K' \frac{\partial \bar{s}'}{\partial s} (s=0) \qquad (3.1\text{-}3)$$

Initial/Boundary Conditions. Within the secondary porosity, the initial drawdown is zero:

$$\bar{s}'(r,s,t=0) = 0 \quad , \quad 0 < s < a \quad , \quad r_w < r < r_o \qquad (3.1.4a)$$

the drawdowns are set equal at the interfaces:

$$\bar{s}'(r,s=0,t) = \bar{s}(r,t) \quad , \quad r_w < r < r_o \qquad (3.1\text{-}4b)$$

and a symmetry condition is prescribed within the interior:

$$\frac{\partial \bar{s}'}{\partial s} (r,s=a,t) = 0 \quad , \quad r_w < r < r_o \qquad (3.1\text{-}4c)$$

Within the primary porosity, the initial drawdown is also taken as zero

$$\bar{s}(r,t=0) = 0 \quad , \quad r_w < r \qquad (3.1\text{-}5)$$

and the water-level above the bottom-hole condition is escribed at the wellbore radius r_w:

$$\bar{s}(r_w,t) = s_o(t) \tag{3.1-5b}$$

Input/Output Specifications. Rather than the drawdown formulation, the SWIFT Model uses a pressure formulation. Thus, in the equations above, drawdown is replaced by pressure as the dependent variable:

$$s = p_o - p \tag{3.1-6}$$

where p_o is the initial pressure. Also the storativity and transmissivities are replaced by the equivalent expressions:

$$S = \rho(g/g_c)\phi(c_w+c_R)b \tag{3.1-7a}$$

$$T = Kb \tag{3.1-7b}$$

and

$$S_s' = \rho(g/g_c)\phi'(c_w+c_R') \tag{3.1-7c}$$

Input data appropriate for both formulations are then given in Table 3.1-1. For the primary porosity, the values given there are the same as those used by Pahwa and Baxley. For the secondary porosity, however, which is assumed herein to arise from stress-relief fracturing, the values given are entirely different from those of Pahwa and Baxely and were developed especially for this problem by an optimization procedure. The remainder of the input data, i.e., the time-dependent height of the water level within the wellbore, is provided by Table 3.1-2. Actually, the analytical work of Dennehy and Davis and the numerical work of Pahwa and Baxley treated the wellbore storage implicitly so that the height of the water level, in addition to the injected flow rates, was calculated. We, too, have a special-purpose update which permits such a computation. However, in order to use the publically available code on this, an illustrative example, the measured water levels are prescribed as input data, and only the injected flow rates are calculated.

Table 3.1-1. Problem 4. Input Specifications.

Parameter	Symbol	Value
Density of Water	ρ	62.4 lb/ft^3
Aquifer Thickness	b	25.0 ft
Compressibility of Water	c_w	3.0×10^{-6} psi^{-1}
Primary-Porosity Media:		
Porosity	ϕ	0.10
Compressibility of Rock	c_R	4.0×10^{-6} psi^{-1}
Hydraulic Conductivity	K	2.0×10^{-4} ft/d
Storativity	S	7.58×10^{-6}
Transmissivity	T	0.005 ft^2/d
Secondary-Porosity Media:		
Porosity	ϕ'	0.10
Compressibility of Rock	c'_R	4.0×10^{-5} psi^{-1}
Hydraulic Conductivity	K'	2[illegible].0 ft/d
Length	a	25.0 ft
Specific Storativity	S'_s	1.86×10^{-6} ft^{-1}

Table 3.1-2. Observed Decline in Water-Level Height and Bottom-Hole Pressure.

Time Interval (days)	Water Level Height (ft)	Bottom-Hole Pressure (psi)
10^{-4} - 10^{-2}	505	219
10^{-2} - 10^{-1}	496	215
0.1 - 0.2	485	210
0.2 - 0.5	468	203
0.5 - 0.8	450	195
0.8 - 1.0	434	188
1.0 - 1.5	415	180
1.5 - 2.0	392	170
2.0 - 2.5	374	162
2.5 - 3.0	360	156

3.1.3 Numerical Simulation

Discussion of the Code Input. In contrast to the problems presented in the previous chapter, this problem, like several that follow, employs a radial coordinate system. The inner boundary condition derives from the presence of a well of radius $r_w = 0.276$ ft (Card R1-22, Figure 3.1-3). This well communicates with the aquifer through a wellskin, which, in general, represents a disturbed zone of modified hydraulic properties. For the SWIFT Model it is assumed that the wellskin has no storage and that its hydraulic-conduction property is characterized by a well index (Theory and Implementation, Section 4.1):

$$WI_o = 2\pi K_s \Delta z / \ln(r_1/r_w) \qquad (3.1\text{-}8)$$

where quantities $r_1 = 1.0$ ft, the position of the first node within the mesh, and $\Delta z = 25$ ft appear in Cards R1-22 and R1-23.

Here, the disturbed zone, a region assumed to have stress-relief fractures, is also represented by a one-dimensional unit attached to the first grid block (Card ROD-3). This unit does have some storage and a relatively large hydraulic conductivity. In a sense, then, in this case the well index (Card R2-7-2) has been superceded by the one-dimensional unit.

The outer boundary is chosen consistently with the maximum simulation time:

$$\tilde{r}_e = (Tt_{max}/S)^{1/2} \approx 100 \text{ ft} \qquad (3.1\text{-}9a)$$

with r_e (Card R1-22) being greater than the characteristic length $\tilde{r}_e$:

$$r_e = 2000 \text{ ft} \qquad (3.1\text{-}9b)$$

At this boundary, the numerical solution is matched onto an analytic continuation for an (assumed) infinite external aquifer using the method of Carter and Tracy [1960]. The data appropriate for this method appear on Card R1-27 through R1-33. They should be examined carefully since, in the application of SWIFT, they are used frequently (Theory and Implementation, Section 4.1).

DRAFT

```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
PROBLEM NO. 4, SWIFT II EXAMPLE, ENGLISH UNITS, 12/83,                          M-1-1
INTERPRETATION OF WELL TEST DATA FOR A DOLOMITE FORMATION, NEW MEXICO M-1-2
                                   *****
  1    0    0    0    0    0    0    0    0                                    M-2
*****          *****                *****
 50    1    1    3    0    1    1    2    0    1    0    0    0               OM-3-1
     *****     *****
  0    1    1    1                                                             M-3-2
     *****
  0                          ******************************
                             * "***" REFERENCED IN TEXT    *                   ROD-1
                             * "***" REFERENCED IN EXERCISE *
  8                          ******************************                    ROD-2
**********
  1    1    1    1    1    1    1    0                                         ROD-3
**********
                                                                              ROD-3-BLN
********************
**   (1)  **   (2)  *       0.0       1.0       1.0                           R1-1
********************
       1.0       1.0       1.0       1.0       1.0       0.0      .0001R1-2
      120.      100.       70.      62.4      62.4                            R1-3
  0    1    0    2                                                             R1-6
      70.       1.0       70.       1.0                                        R1-7
     100.       1.0                                                            R1-9
      0.0      70.0                                                            R1-11
    1000.0     70.0                                                            R1-11
  0    0                                                                       R1-12
     70.0     111.5     514.6     514.6                                        R1-16
*****************************
    0.276      1.00     2000.     514.6                                        R1-22
*****************************************
      25.*   (3)  **   (4)  **   (5)  *                                        R1-23
          ****************************
                                                                              R1-26-BLN
*****
  3                                                                           R1-27
***************
  1    0    1                                                                 R1-29
*****************************************
    0.005      2.5     2000.      360.                                         R1-31
```

Figure 3.1-3. Listing of the SWIFT II Input Data.

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```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678904234567890123456789012345678901234567890
24                                                                      R1-33-BLN
27 (6)                                                                  R10-1
28      .0003       0.0    (7)    (8)          0.0       0.0       0.0R10-2-1
29     1    1      25.0       2.0       0.0                           R10-2-2
30                                                                      R10-3-BLN
31                                                                      R10-5-BLN
32     0    0    0                                                     I-1
33        0.0                                                          R1A-2
34     2    1    1    0    0    0    0    1    0                       R2-1
35     1       0.5                                                     R2-2
36     1                                                               R2-4
37     1    -9999.                                                     R2-6
38                                                                      R2-6-BLN
39     1    1    1    1    1   -3                                      R2-7-1
40        .10     220.0      70.0       0.0                            R2-7-2
41                                                                      R2-7-BLN
42     1    1    1                                                     R2-11
43     0.0001    0.0001
44     1    1    1    1                                                R2-13
45     0    1    0    0    0    0    0    0                            R2-1
46     1    1    1    1    1   -3                                      R2-7-1
47        .10     219.0      70.0       0.0                            R2-7-2
48                                                                      R2-7-BLN
49       0.01       0.0       0.0       0.0       3.0       0.0       0.5    0.0001
50    -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011    0R2-13
```

Figure 3.1-3 Continued.

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```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
51   0    1    0    0    0    0    0    0                                R2-1
52   1    1    1    1    1   -3                                         R2-7-1
          **********
53        .10     215.0      70.0       0.0                             R2-7-2
          ***********
54                                                                      R2-7-BLN
     *********
55        0.10       0.0       0.0       0.0       3.0       0.0       0.5    0.0001
     ***************                 *****                   *****
56   1    1    1    1    1    1  011    0 0000    0    0    1  011     0R2-13
          *****                    *****                   *****
57   0    1    0    0    0    0    0    0                                R2-1
58   1    1    1    1    1   -3                                         R2-7-1
59        .10     209.5      70.0       0.0                             R2-7-2
60                                                                      R2-7-BLN
61        0.20       0.0       0.0       0.0       3.0       0.0       0.5    0.0001
62  -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011     0R2-13
63   0    1    0    0    0    0    0    0                                R2-1
64   1    1    1    1    1   -3                                         R2-7-1
65        .10     203.9      70.0       0.0                             R2-7-2
66                                                                      R2-7-BLN
67        0.50       0.0       0.0       0.0       3.0       0.0       0.5    0.0001
68  -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011     0R2-13
69   0    1    0    0    0    0    0    0                                R2-1
70   1    1    1    1    1   -3                                         R2-7-1
71        .10     196.0      70.0       0.0                             R2-7-2
72                                                                      R2-7-BLN
73        0.80       0.0       0.0       0.0       3.0       0.0       0.5    0.0001
74  -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011     0R2-13
75   0    1    0    0    0    0    0    0                                R2-1
```

Figure 3.1-3 Continued.

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```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
I                                                                                I
76 I    1    1    1    1    1   -3                                   RZ-7-1     I
I                                                                                I
77 I       .10     190.0      70.0       0.0                          RZ-7-2     I
I                                                                                I
78 I                                                                   RZ-7-BLN   I
I*********                                                                       I
79 I      1.00       0.0       0.0       0.0       3.0       0.0       0.5    0.0001I
I**************                                                                  I
80 +    1    1    1    1    1    1  011    0 0000    0    0    1  011    0RZ-13   +
I          *****                                                                 I
81 I    0    1    0    0    0    0    0    0                              RZ-1   I
I                                                                                I
82 I    1    1    1    1    1   -3                                   RZ-7-1     I
I                                                                                I
83 I       .10     184.0      70.0       0.0                          RZ-7-2     I
I                                                                                I
84 I                                                                   RZ-7-BLN   I
I                                                                                I
85 +      1.25       0.0       0.0       0.0       3.0       0.0       0.5    0.0001+
I                                                                                I
86 I   -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011    0RZ-13   I
I                                                                                I
87 I    0    1    0    0    0    0    0    0                              RZ-1   I
I                                                                                I
88 I    1    1    1    1    1   -3                                   RZ-7-1     I
I                                                                                I
89 I       .10     179.5      70.0       0.0                          RZ-7-2     I
I                                                                                I
90 +                                                                   RZ-7-BLN   +
I                                                                                I
91 I      1.50       0.0       0.0       0.0       3.0       0.0       0.5    0.0001I
I                                                                                I
92 I   -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011    0RZ-13   I
I                                                                                I
93 I    0    1    0    0    0    0    0    0                              RZ-1   I
I                                                                                I
94 I    1    1    1    1    1   -3                                   RZ-7-1     I
I                                                                                I
95 +       .10     175.0      70.0       0.0                          RZ-7-2     +
I                                                                                I
96 I                                                                   RZ-7-BLN   I
I                                                                                I
97 I      1.75       0.0       0.0       0.0       3.0       0.0       0.5    0.0001I
I                                                                                I
98 I   -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011    0RZ-13   I
I                                                                                I
99 I    0    1    0    0    0    0    0    0                              RZ-1   I
I                                                                                I
100 +   1    1    1    1    1   -3                                   RZ-7-1     +
I                                                                                I
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 3.1-3 Continued.

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```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
       +---------+---------+---------+---------+---------+---------+---------+---------+
       I                                                                                 I
 101   I      .10     171.0      70.0       0.0                                R2-7-2   I
       I                                                                                 I
 102   I                                                                        R2-7-BLN  I
       I                                                                                 I
 103   I     2.00       0.0       0.0       0.0       3.0       0.0       0.5    0.0001I
       I                                                                                 I
 104   I  -1   -1   -1   -1   -1   -1  0.1    0 0000    0    0    1  011    0R2-13     I
       I                                                                                 I
 105   +   0    1    0    0    0    0    0    0                                R2-1     +
       I                                                                                 I
 106   I   1    1    1    1    1   -3                                         R2-7-1    I
       I                                                                                 I
 107   I      .10     167.0      70.0       0.0                                R2-7-2   I
       I                                                                                 I
 108   I                                                                        R2-7-BLN  I
       I                                                                                 I
 109   I     2.25       0.0       0.0       0.0       3.0       0.0       0.5    0.0001I
       I                                                                                 I
 110   +  -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011    0R2-13     +
       I                                                                                 I
 111   I   0    1    0    0    0    0    0    0                                R2-1     I
       I                                                                                 I
 112   I   1    1    1    1    1   -3                                         R2-7-1    I
       I                                                                                 I
 113   I      .10     164.0      70.0       0.0                                R2-7-2   I
       I                                                                                 I
 114   I                                                                        R2-7-BLN  I
       I                                                                                 I
 115   +     2.50       0.0       0.0       0.0       3.0       0.0       0.5    0.0001+
       I                                                                                 I
 116   I  -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011    0R2-13     I
       I                                                                                 I
 117   I   0    1    0    0    0    0    0    0                                R2-1     I
       I                                                                                 I
 118   I   1    1    1    1    1   -3                                         R2-7-1    I
       I                                                                                 I
 119   I      .10     161.0      70.0       0.0                                R2-7-2   I
       I                                                                                 I
 120   +                                                                        R2-7-BLN  +
       I                                                                                 I
 121   I     2.75       0.0       0.0       0.0       3.0       0.0       0.5    0.0001I
       I                                                                                 I
 122   I  -1   -1   -1   -1   -1   -1  011    0 0000    0    0    1  011    0R2-13     I
       I                                                                                 I
 123   I   0    1    0    0    0    0    0    0                                R2-1     I
       I                                                                                 I
 124   I   1    1    1    1    1   -3                                         R2-7-1    I
       I                                                                                 I
 125   +      .10     158.0      70.0       0.0                                R2-7-2   +
       I                                                                                 I
       +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 3.1-3 Continued.

DRAFT

```
          1         2         3         4         5         6         7         8
 12345678901234567890123456789012345678901234567890123456789012345678901234567890
 +---------+---------+---------+---------+---------+---------+---------+---------+
 I                                                                                I
126 I                                                                   R2-7-BLN  I
   *********                                                                     I
127 I      3.00       0.0       0.0       0.0       3.0       0.0       0.5    0.0001I
    I***************                                                              I
128 I    1    1    1    1    1    1  011    0 0000    0    0    1  011    OR2-13   I
    I         *****                                                               I
129 I    0    0    0    1    0    0    0    0    0                       R2-1-STOP I
    I                                                                             I
    +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 3.1-3 Continued.

Results. Figure 3.1-4 shows the simulated flow rates, which agree reasonably well with the measured results. As indicated earlier, however, the simulated values for times less than about 10^{-2} d were fitted to the measured values by an optimization procedure for the one-dimensional unit. In so doing, two relations were found to be useful. They were a time constant,

$$\tilde{\tau} = a^2 S_s'/K' \qquad (3.1\text{-}10a)$$

and a flow-rate dependence,

$$\Delta\tilde{q} \sim K'/a \qquad (3.1\text{-}10b)$$

both of which were inferred from approximate analytic expressions. They show that the only two values, $\tau = 10^{-2}$ d and $\Delta q = 15$ ft^3/d, which may be inferred from the experimental data are functions of the three hydraulic parameters, a, S_s', and K'. Thus, the inferred parameter set (Table 3.1-1) is, unavoidably, nonunique.

Discussion of the Code Output. Two tables included in the input echo (see microfiche) may be of interest to the reader since this is the first use of radial coordinates in this document. One, entitled "Radial Grid Block Data," exhibits nodal points and grid-block boundaries. In this case these radii have been internally generated (RI ≠ 0 in Card RI-22) assuming an equal ratio:

$$A = r_{i+1}/r_i \qquad (3.1\text{-}11a)$$

for neighboring nodal points. That ratio is

$$A^{n-1/2} = r_e/r_1 \quad \text{or} \quad A = 1.16597 \qquad (3.1\text{-}11b)$$

where n = NX = 50 (Card M-3-1), r_e = RE = 2000 ft (Card RI-22) and r_1 = RI = 1.0 ft (Card RI-22). That all neighboring radii have this same constant rati may be verified by the reader.

The other table is exhibited under the title "Data for Carter-Tracy Wate Influx Calculations". It shows the so-called terminal-rate-influence functic P_I [Van Everdingen and Hurst, 1949] as a function of time. Implicit in this

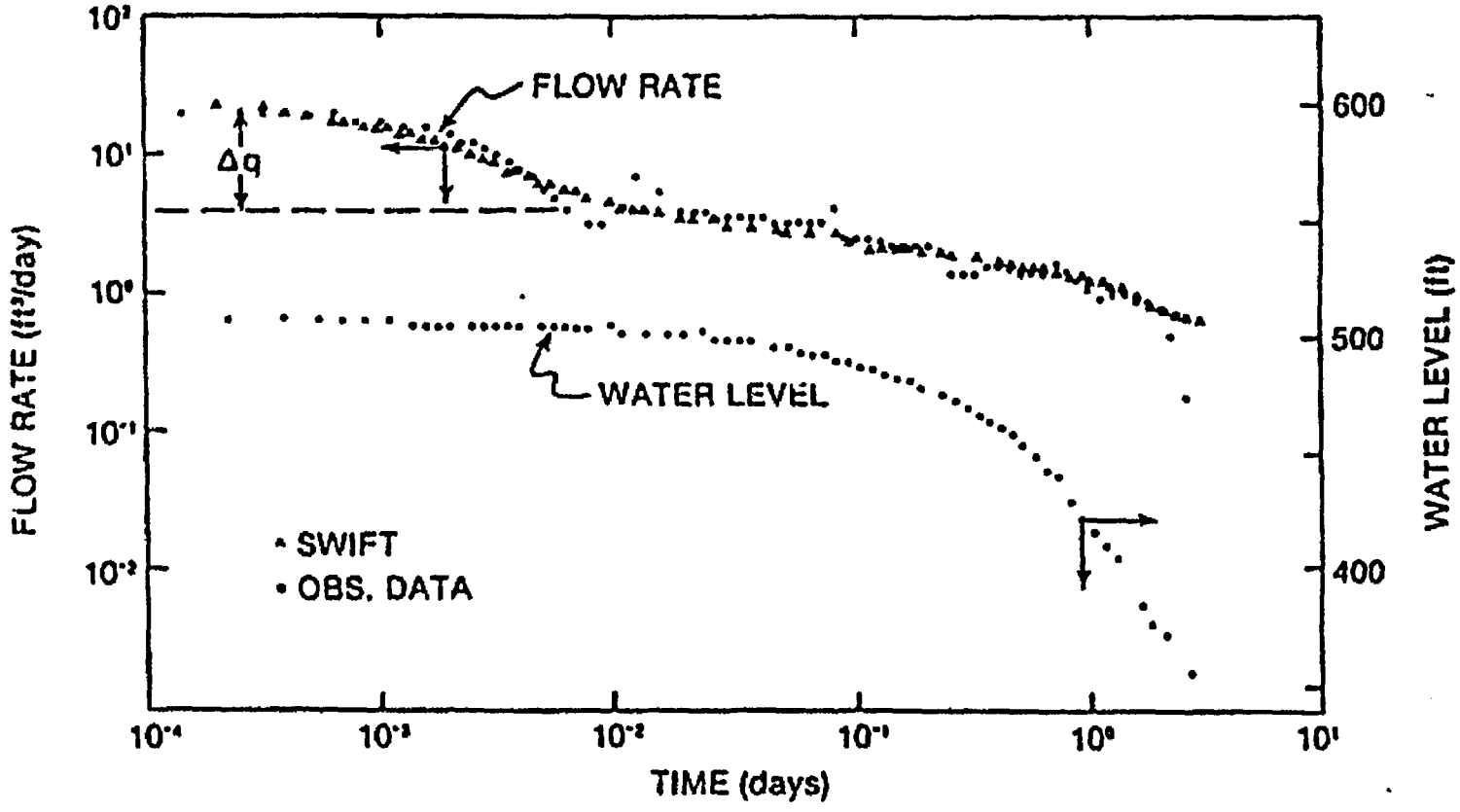

Figure 3.1-4. Flow Rate and Drawdown of the H2A Slug Test Within the Magenta Dolomite Formation.

function is the assumption that the interior aquifer under detailed numerical study for $r < r_e$ (RAQ) may be analytically continued to infinity by an aquifer having the prescribed Kb (KH) and ϕb (PHIH) parameters. The influence function denotes, in dimensionless form, the pressure drop at the boundary $r = r_e$ between the two regions which results from a unit flow across this boundary. Carter and Tracy [1960] used this function to achieve an efficient, though approximate, relation

$$e_W = a_W + b_W \delta p \qquad (3.1\text{-}12)$$

It expresses the boundary flux e_W in terms of the pressure-change δp at $r = r_e$ which occurs during a given time step. Quantities a_W (P_I) and b_W (P_I), according to this technique, are themselves functions fo the terminal rate-influcent function and, of course, are implicit functions of time. Other relations for P_I may be used to correspond to, say, a finite external aquifer. The function presented in the output table, however, which corresponds to an infinite aquifer, is the only one which is available internally within SWIFT. The Theory and Implementation Document (Section 5.2) provides additional information on this boundary condition.

Perhaps the most crucial tables of all, however, are those entitled "Well Operation Summary," which are printed at selected time steps and which provide the desired results. For example, from the first such table,

$$Q(t=10^{-4}d) = 1.48 \times 10^3 \text{ lb/d} = 23.7 \text{ ft}^3/\text{d} \qquad (3.1\text{-}13a)$$

and from the second

$$Q(t=10^{-1}d) = 165 \text{ lb/d} = 2.64 \text{ ft}^3/\text{d} \qquad (3.1\text{-}3b)$$

both of which are consistent with the computed results of Figure 3.1-4. The detailed results shown in this figure were actually obtained by post-processing a plot file (Table 12) on which the well-summary data was written automatically for each time step.

3.1.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1 From Tables 3.1-1 and 3.1-2, what data are required for the blanks labelled "1" through "8" in Figure 3.1-3? The data called for here are the hydraulic properties of the global and local units and may be verified by reference to the output listing.

Exercise 2 Explain the meaning of the control parameters identified on Cards M-2, M-3-1 and M-3-2.

Exercise 3 Explain the meaning of the well-control parameters identified on on Cards R2-6 and R2-7-1 and the physical parameter identified on the second Card R2-7-2.

Exercise 4 Examine the printer-control parameters identified on several R2-13 Cards. Then check the output to see that they produce the specified output tables at the times indicated on the corresponding R2-12 Cards.

Exercise 5 How would you obtain the well-summary table for intermediate time values between 10^{-4} d and 10^{-1} d?

Level 2. The reader who wants to develop a deeper understanding of the code should also consider the following exercise:

Exercise 6 Check the validity of Equations (3.1-10) for this application. For example, increase the value of K' and run the simulation out to about 10^{-1} d. Are the flow rates increased and the duration of the dual-porosity effect decreased in accordance with these equations?

3.2 PROBLEM 5. ANALYSIS OF WELL-TEST DATA FOR THE MUSQUODOBOIT AREA, NOVA SCOTIA [PINDER AND BREDEHOEFT, 1968]

3.2.1 Objective

- To show the feasibility of characterizing the delayed-yield effect in pumping-test data from the Musquodoboit River Basin with a dual-porosity model and to illustrate the manner in which such a simulation is carried out.

3.2.2 Description of the Problem

Background. The setting for this problem is the Musquodoboit River Basin in Nova Scotia (Figure 3.2-1), and the aquifer of interest is the zone of glacio-fluvial deposits shown in Figures 3.2-2 and 3.2-3. As a part of a water-supply feasibility study for the city of Musquodoboit Harbor, a pumping test was performed. The configuration of the pumping well and the three observation wells is shown in Figure 3.2-4, and the measured data are presented in Figure 3.2-5.

Pinder and others [Pinder and Bredehoeft, 1968, and Pinder and Frind, 1972], in their numerical studies, used these data for calibration of a site model, with which they predicted drawdowns over a 20-year time period (Figure 3.2-6). These investigations characterized the site by the two-dimensional geometry and the transmissivities shown in Figure 3.2-5. A delayed yield, which they observed in the measured data, was characterized by a temporally varying storativity:

$$S = \begin{cases} 0.003 & , \ t = 0 \\ (3\times10^{-4})(10-t) + (6\times10^{-3})t & , \ 0 < t < 10 \text{ min} \\ 0.06 & , \ t > 10 \text{ min} \end{cases} \qquad (3.2\text{-}1)$$

Problem Statement. That this delayed yield may also be characterized a flow in a doubly porous media is the focus of this problem. Here it is assumed that the observed drawdowns derive from the distribution of fine san

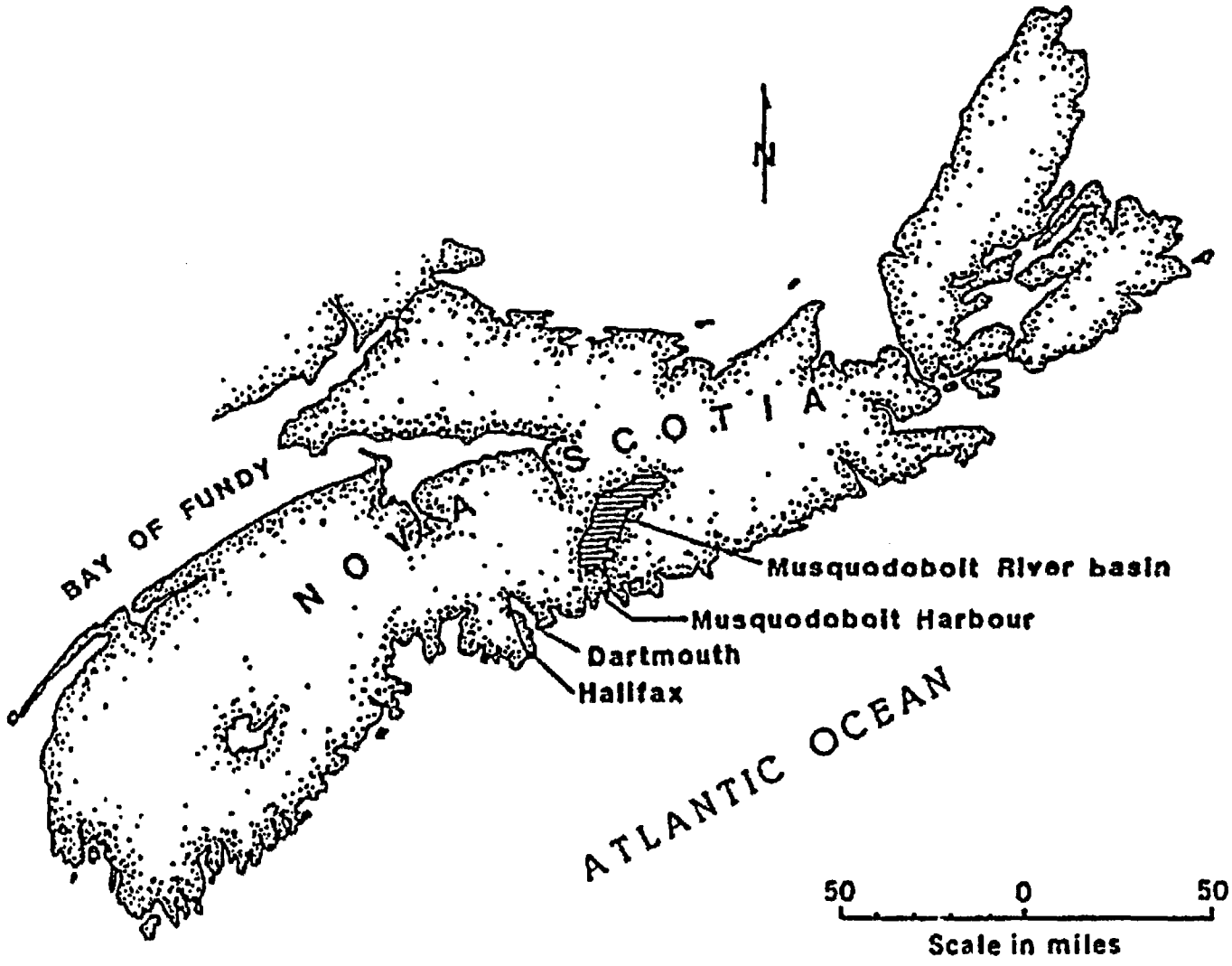

Figure 3.2-1. Problem 5. Location Map of the Musquodoboit River Basin (From Pinder and Bredehoeft [1968]).

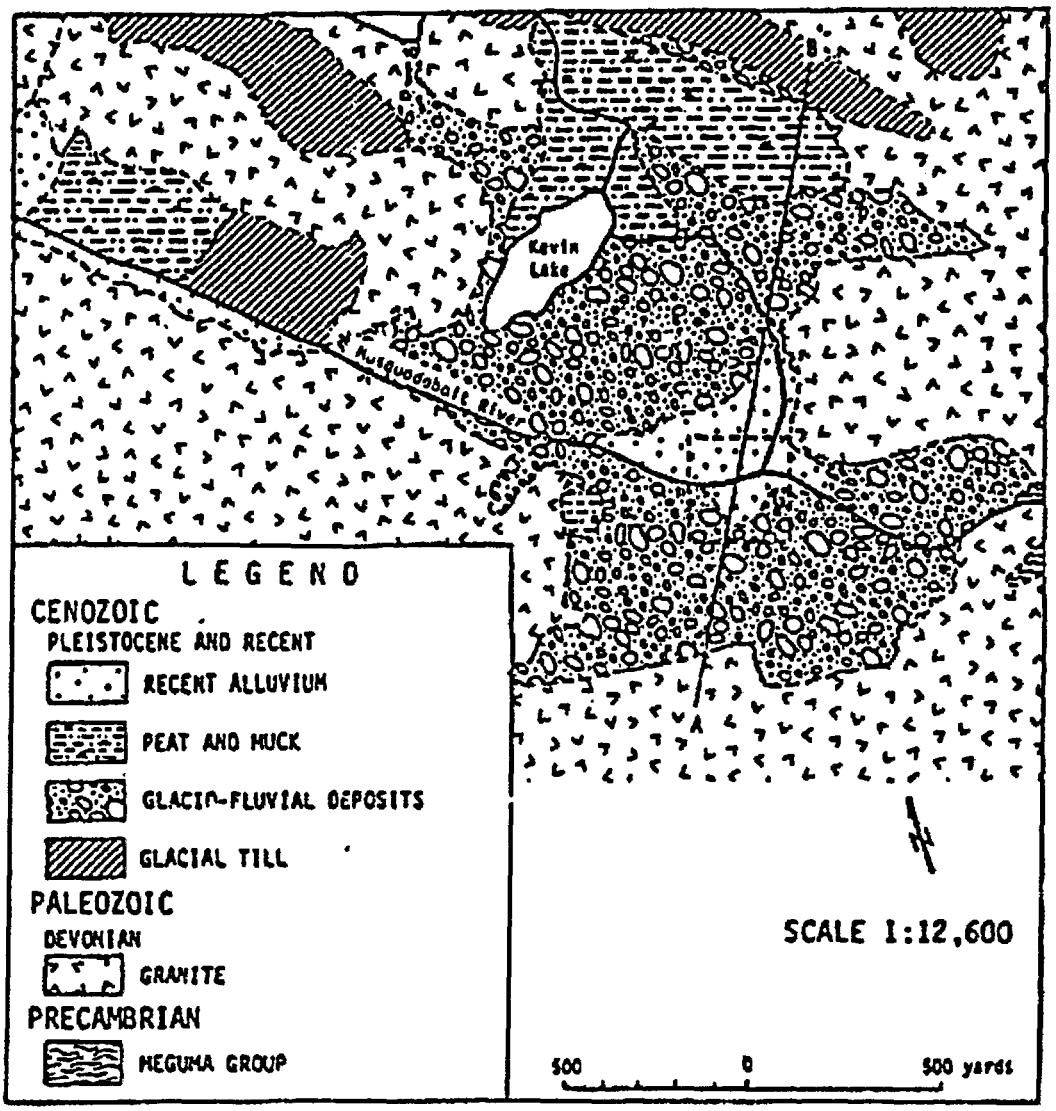

Figure 3.2-2. Geologic Map of Musquodoboit Harbour Area, Nova Scotia (Corrected From Pinder and Bredehoeft, 1968).

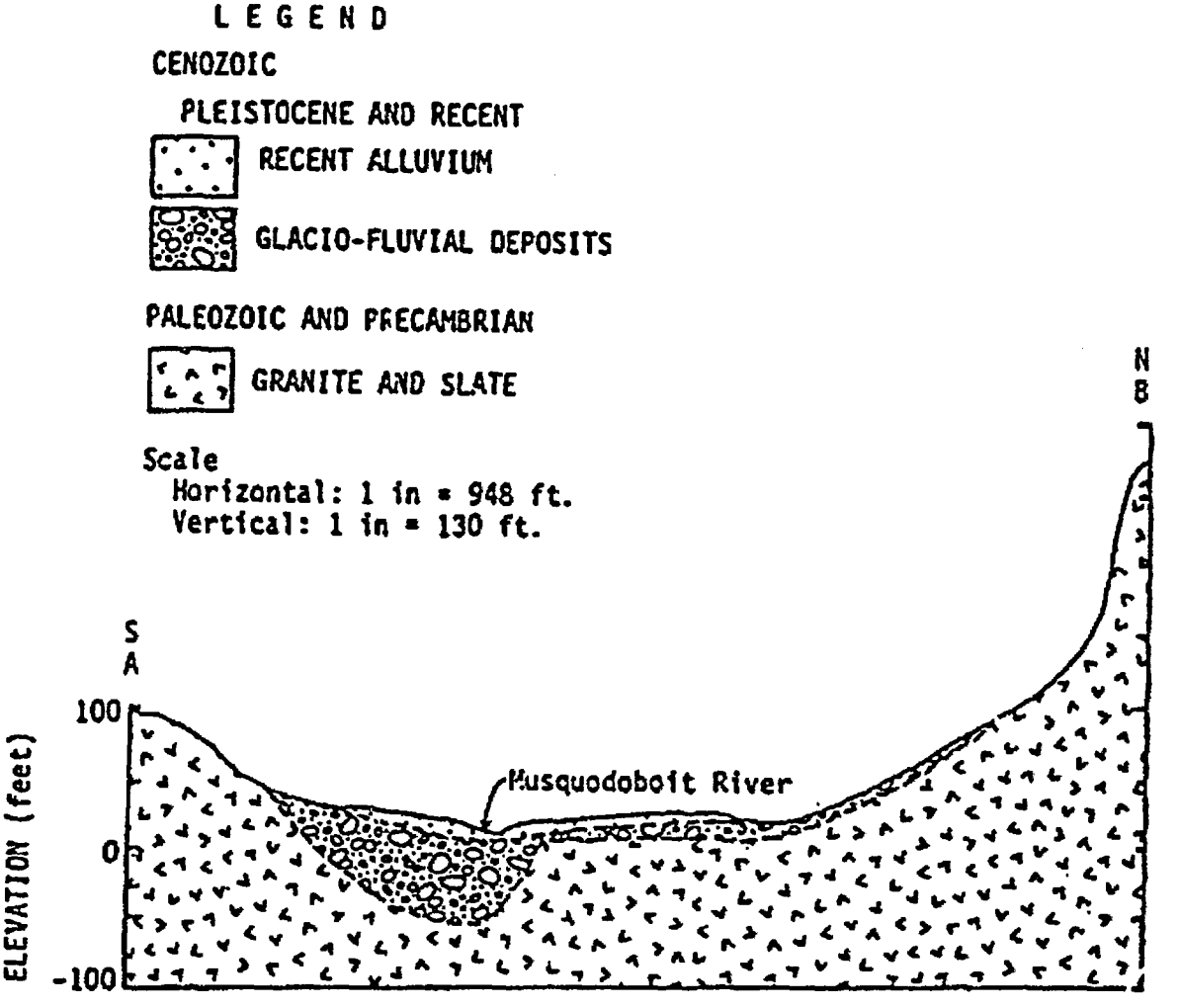

Figure 3.2-3. Geologic Cross Section, Musquodoboit Harbour Area, Nova Scotia

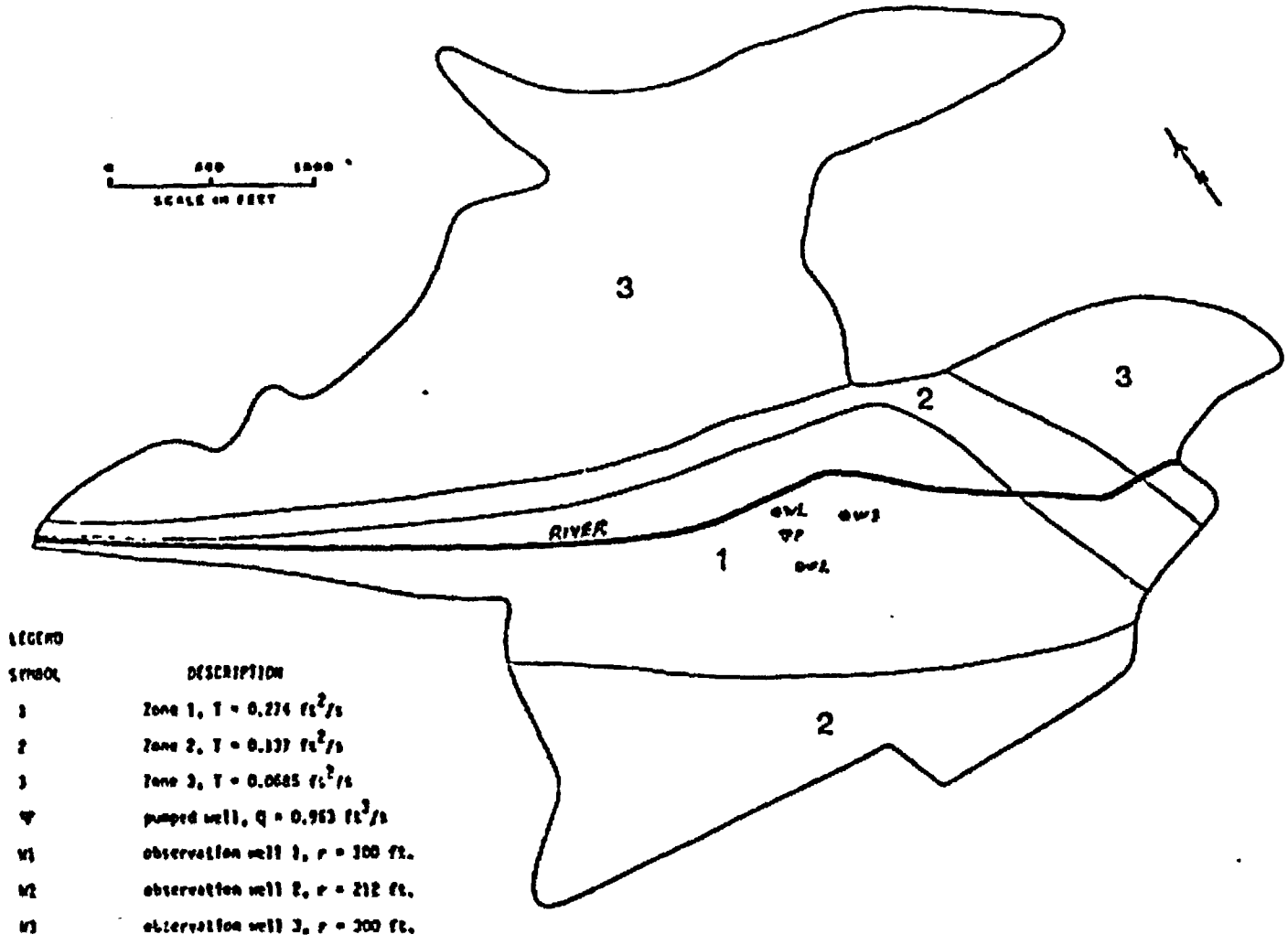

Figure 3.2-4. Location of Observation Wells and Characterization of Hydraulic Properties.

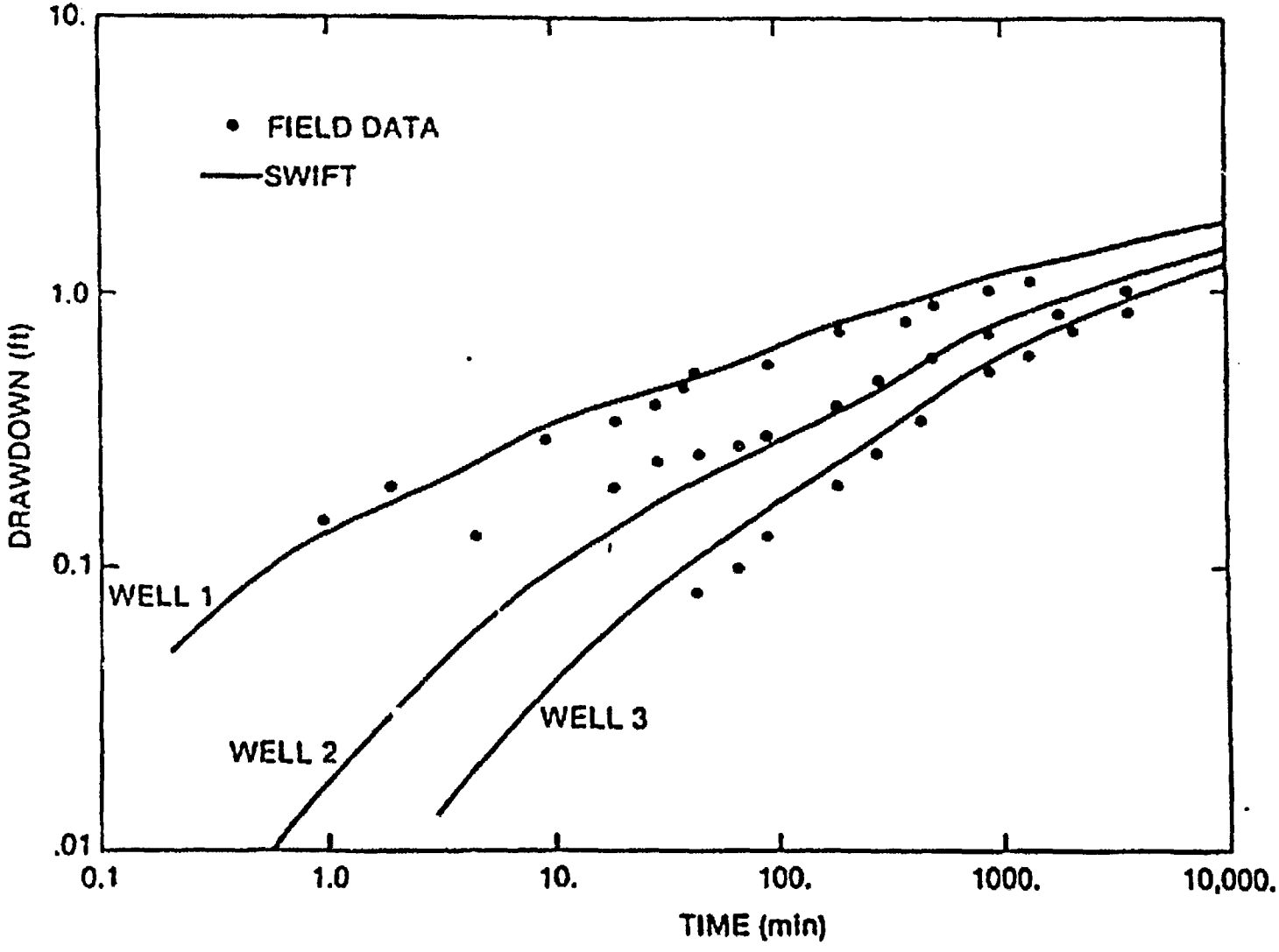

Figure 3.2-5. Observed and Simulated Drawdowns for Wells 1, 2 and 3 Using a Homogeneous Dual-Porosity Model.

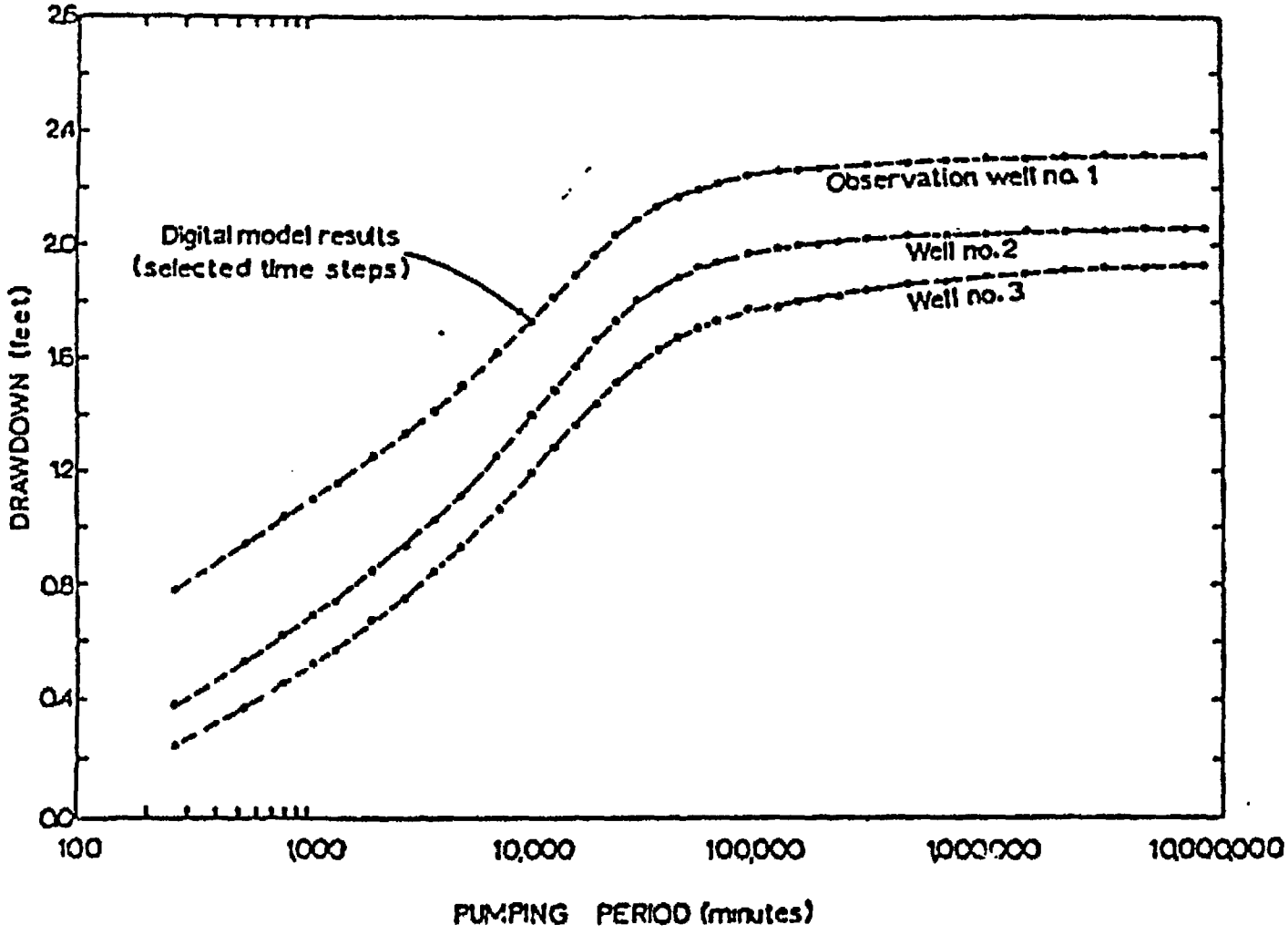

Figure 3.2-6. Time-Drawdown Curves Obtained From the Simulation of Pinder and Bredehoeft [1968].

and of coarse sands and gravels (denoted hereafter as gravels), that the value 0.06, determined by Pinder, represent the storativity of and the fine sands and that the measured transmissivities represent the connected gravel lenses within the aquifer. The delayed yield, then, rather than coming from the time-dependent storativity of Equation (3.2-1) is controlled by the conductivity of the fine sands and, to a limited extent, the storativity of the gravels.

In order to demonstrate the delayed yield effects as simply as possible, it is assumed that the drawdown cone is confined to Zone 1 (Figure 3.2-4) and, correspondingly, that the time period of interest is restricted to times less than 10,000 min, the time scale of the pumping test. For these limited space and time regimes, an axisymmetric site model may be used.

Flow Equations. The equations depicting coupled flow in the coarse- and fine-grained regimes are identical to those for coupled flow in the two fractured regimes, which were employed in the previous problem (Equations 3.1-1 through 3.1-3). Here, however, the dual-porosity zone is present throughout the system rather than confined to the immediate vicinity of the wellbore.

Input/Output Specifications. Data selected for this demonstration are summarized in Table 3.2-1. As indicated in the discussion above, all of these parameters are taken from the work of Pinder, with two exceptions. The hydraulic conductivity of the fine sands and the storativity of the gravels were obtained by calibration against the drawdown curve for Well Number 1 (Figure 3.2-5) for times $t < 10{,}000$ min. Comparison of measured and calculated drawdowns is the desired result.

3.2.3 Numerical Simulation

Discussion of the Code Input. Although the two porosities here refer to two different porous-media components, rather than the two different fractured-media components of the last problem, the code inputs (Figures 3.1-3 and 3.2-7) are quite similar in some respects. Both problems use radial coordinates with a Carter-Tracy aquifer-influence function (Cards R1-27 through R1-33) affixed to the outer boundary. There are differences, however. The well produces in this case (positive value of Q, Card R2-5) with a rate control (IINDW1 = 1 in Card R2-7-1) rather than a pressure control.

Table 3.2-1. Problem 5. Input Specifications.

Parameter	Symbol	Value
Gravels		
Transmissivity	T	0.274 ft^2/s
Storativity	S	1.95×10^{-5}
Fine Sands		
Conductivity	K'	4.63×10^{-7} ft/s
Storativity	S'_s	0.012 ft^{-1}
Thickness	a	2.5 ft
Location of Observation Wells		
Well 1	r_1	100 ft
Well 2	r_2	212 ft
Well 3	r_3	300 ft

DRA

```
                1         2         3         4         5         6         7         8
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
     +---------+---------+---------+---------+---------+---------+---------+---------+
     I                                                                                 I
  1  IPROBLEM NO. 5, SWIFT II EXAMPLE, ENGLISH UNITS, 12/83,                   M-1-1  I
     I                                                                                 I
  2  IINTERPRETATION OF WELL TEST DATA IN MUSQUODOBOIT AREA, NOVA SCOTIA        M-1-2  I
     I                                                                                 I
  3  I    1    0    0    0    0    0    0    0    0                            M-2    I
     I                                                                                 I
  4  I   40    1    1    3    0    1    1    1    0    2    0    1    0       OM-3-1  I
     I                                                                                 I
  5  I    0    1    1    1                                                      M-3-2  I
     I                                                                                 I
  6  I    0                                                                      ROD-1  I
     I                                                                                 I
  7  I   25                                                                      ROD-2  I
     I     *****                          *****                                        I
  8  I    1   40    1    1    1    1    1    0                                  ROD-3  I
     I     *****                          *****                                        I
  9  I                                                                      ROD-3-BLN  I
     I*******************                                                              I
 10  I*   (1)  **   (2)  *       0.0       1.0       1.0                        R1-1   I
     I*******************                                                              I
 11  I       0.0       0.0       0.0       0.0       0.0       0.0       0.0R1-2       I
     I                                                                                 I
 12  I     140.0       1.0      68.0      62.4      62.4                        R1-3   I
     I                                                                                 I
 13  I    0    1    1    2                                                      R1-6   I
     I                                                                                 I
 14  I      68.0       1.0      68.0       1.0                                  R1-7   I
     I                                                                                 I
 15  I      80.0       1.0                                                      R1-9   I
     I                                                                                 I
 16  I      80.0       1.0          ******************************              R1-10  I
     I                               * "***" REFERENCED IN TEXT    *                   I
 17  I       0.0      68.0          * "***" REFERENCED IN EXERCISE *              R1-11  I
     I                               ******************************                    I
 18  I       1.0      68.0                                                      R1-11  I
     I                                                                                 I
 19  I    0    0                                                                 R1-12  I
     I                                                                                 I
 20  I      68.0       0.0       0.0       0.0                                  R1-16  I
     I          **********                                                             I
 21  I     0.375       0.0    1200.0       0.0                                  R1-22  I
     I*************************************                                             I
 22  I*   (3)  **   (4)  **   (5)  **   (6)  *       0.0                        R1-23  I
     I*************************************                                             I
 23  I     0.457     0.680     1.012     1.506     2.241     3.334     4.959R1-25       I
     I                                                                                 I
 24  I     7.378    10.977    16.330    24.295    36.145    53.773    76.887R1-25       I
     I                                                                                 I
 25  I     100.0     122.4     144.8     167.2     189.6     212.0     229.6R1-25       I
     I                                                                                 I
     +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 3.2-7. Listing for the SWIFT II Input Data.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
      +---------+---------+---------+---------+---------+---------+---------+---------+
      I                                                                                 I
   26 I     247.2     264.8     282.4     300.0   324.046   348.092   381.512R1-25     I
      I                                                                                 I
   27 I   416.140   458.285   502.284   550.508   603.361   661.289   724.778R1-25     I
      I                                                                                 I
   28 I   794.363   870.628   954.216  1045.829  1146.237                    R1-25      I
      I                                                                                 I
   29 I                                                                    R1-26-BLN    I
      I**********                                                                       I
   30 *    3    0                                                          R1-27       *
      I**************                                                                   I
   31 I    1    0    0                                                     R1-29       I
      I*************************************                                            I
   32 I   2.367E4      15.0    1200.0     360.0                             R1-31       I
      I*************************************                                            I
   33 I                                                                    R1-33-BLN    I
      I**********                                                                       I
   34 I*   (7)  *                                                          R10-1       I
      I**********          *******************                                          I
   35 *       0.0       0.0*   (8)  **   (9)  *       0.0       0.0       0.0R10-2-1   *
      I           ******************************                                        I
   36 I    1    1*  (10)  *   1.00E-4       0.0                            R10-2-2     I
      I           **********                                                            I
   37 I                                                                    R10-3-BLN    I
      I                                                                                 I
   38 I                                                                    R10-5-BLN    I
      I                                                                                 I
   39 I    0    0    0                                                     I-1         I
      I                                                                                 I
   40 *       0.0                                                          R1A-2       *
      I                                                                                 I
   41 I    1    1    1    2    0    0    0    0    0                       R2-1        I
      I                                                                                 I
   42 I    1       0.5                                                     R2-2        I
      I                                                                                 I
   43 I    4                                                               R2-4        I
      I                                 **********                                      I
   44 I       0.0       0.0       0.0   8.32E04                            R2-5        I
      I                             ***************                                     I
   45 *    1   15    1    1    1    1                                      R2-7-1      *
      I                             *****                                               I
   46 I    1000.0       1.0      68.0       0.0                            R2-7-2      I
      I                                                                                 I
   47 I    2   20    1    1    1    1                                      R2-7-1      I
      I                                                                                 I
   48 I    1000.0       1.0      68.0       0.0                            R2-7-2      I
      I                                                                                 I
   49 I    3   25    1    1    1    1                                      R2-7-1      I
      I                                                                                 I
   50 *    1000.0       1.0      68.0       0.0                            R2-7-2      *
      I                                                                                 I
      +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 3.2-7 Continued.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
       +---------+---------+---------+---------+---------+---------+---------+---------+
       I                                                                                 I
 51    I    4    1    1    1    1    1                                   R2-7-1        I
       I                                                                                 I
 52    I    1000.0       1.0      66.0       0.0                         R2-7-2        I
       I                                                                                 I
 53    I                                                                   R2-7-BLN      I
       I                                                                                 I
 54    I 6.9444E-4 1.3889E-4                                                             I
       I                                                                                 I
 55    +    1    1    1    1    1    1  111    0 0000    0   00   -1  111   00R2-13     +
       I                                                                                 I
 56    I    0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                 I
 57    I 6.9444E-3 1.3889E-3                                                             I
       I                                                                                 I
 58    I    1    1    1    1    1    1  111    0 0000    0   00   -1  011   00R2-13     I
       I                                                                                 I
 59    I    0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                 I
 60    + 6.9444E-2       0.0       .95       .25       .20        9. 6.9444E-2      .001+
       I                                                                                 I
 61    I    1    1    1    1    1    1  111    0 0000    0   00   -1  111   00R2-13     I
       I                                                                                 I
 62    I    0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                 I
 63    I 6.9444E-1       0.0       .95       .25       .20        9. 6.9444E-2      .001I
       I                                                                                 I
 64    I    1    1    1    1    1    1  111    0 0000    0   00   -1  011   00R2-13     I
       I                                                                                 I
 65    +    0    0    0    0    0    0    0    0    0                        R2-1       +
       I                                                                                 I
 66    I 6.9444          0.0       .95       .25       .20        9. 6.9444         .001I
       I                                                                                 I
 67    I    1    1    1    1    1    1  111    0 0000    0   00   -1  111   00R2-13     I
       I                                                                                 I
 68    I    0    0    0    0    0    0    0    0    0                        R2-1       I
       I                                                                                 I
 69    I 6.9444E 1       0.0       .95       .25       .20        9. 6.9444E 1      .001I
       I                                                                                 I
 70    +    1    1    1    1    1    1  111    0 0000    0   00   -1  111   00R2-13     +
       I                                                                                 I
 71    I    0    0    0    1    0    0    0    0    0                        R2-1-STOP  I
       I                                                                                 I
       +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 3.2-7 Continued.

Further, the nodal radii are specified here in Cards R1-25 (control parameter R1 = 0.0 in Card R1-22) instead of being internally generated. Finally, local one-dimensional units are here imbedded in each global grid block, as indicated by the parameters IIB = 40 and IFD = 0 in Card ROD-3.

Results. Figure 3.2-8 shows the end result of the calibration of simulated to field data. For this purpose the two curves labelled "lower bound" and "upper bound" were quite helpful. Both are single-porosity Theis solutions which assume that the gravels provide all of the transmissivity of the aquifer. The lower bound uses the combined storativity of the fine sands and the gravels, whereas the upper bound uses only the storativity of the gravels. Thus, the system resonse initially coincides with that of the upper bound but bridges over to the lower bound at a rate controlled by the magnitude of the conductivity assumed for the fine sands. Figure 3.2-5 shows calculated and observed drawdowns for Wells 2 and 3, as well as for Well 1. It would appear that in the vicinity of Well 2, the gravels are a bit more dominant than for Well 1, whereas, in the vicinity of Well 3, the fine sands are somewhat more dominant. Both Figure 3.2-5 and Figure 3.2-8 demonstrate the feasibility of using dual porosity to characterize the delayed-yield phenomenon.

Discussion of the Code Output. The latter also indicates that drawdowns (pressures) within the fine-sands come to equilibrium with those in the gravels after about 100 min of pumping. After that the fine- and coarse-grained materials behave as a single-porosity media. This effect may be seen in the output tables (see microfiche) which, in this case, are inappropriately labelled as "Pressure Within the Rock Matrix." Take, for example, the fine-sand surrounding Well 1 (Block 5). At t = 1 min (6.9×10^{-4}d) the pressure drop across the block is 1.0 psi; at t = 10 min (6.9×10^{-3}d) the pressure drop is 0.1 psi; and at t = 100 min (6.9×10^{-4}d) this drop becomes negligible at 0.01 psi. Because of the choice of an initial pressure $p_o = 0$, the pressures may be converted to drawdown using the relation

$$s = -p/0.433 \text{ psi/ft} \qquad (3.2\text{-}2)$$

in order to spot-check the results shown in Figures 3.2-5 or 3.2-8.

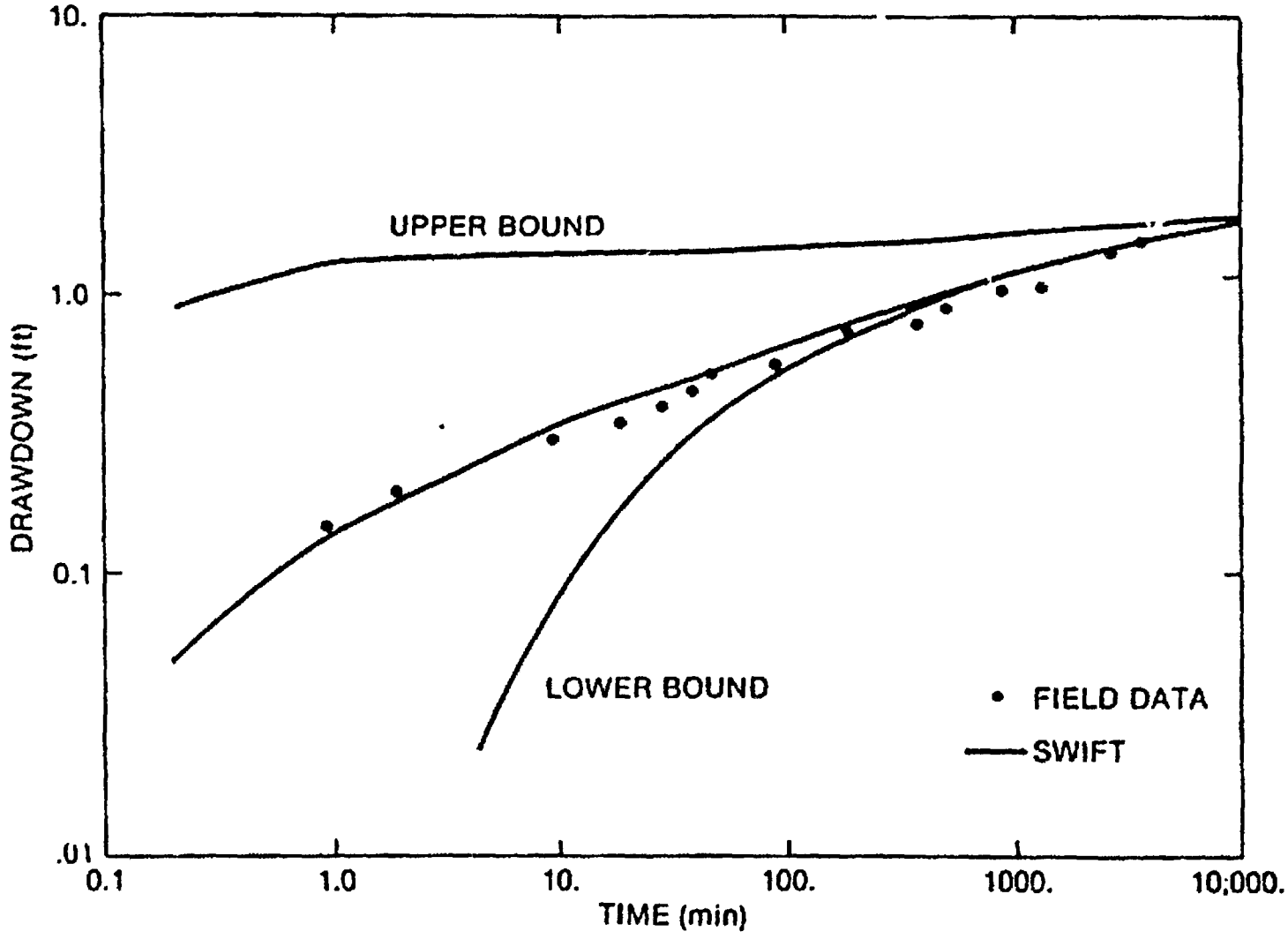

Figure 3.2-8. Simulation of the Observed Drawdowns for Well 1 Using a Homogeneous Dual-Porosity Model. The upper bound is a single-porosity simulation using the gravel storativity only. The lower bound is a single-porosity simulation using the storativity of both gravel and sand.

3.2.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1 From Table 3.2-1, what data are required for the blanks labelled "1" through "10" in Figure 3.2-7? The data called for here are the hydraulic properties of the gravel and fine sand. They may be verified by reference to the output listing.

Exercise 2 In what blocks are the observation wells located? (Hint: examine the R2-5 and R2-7 Cards). These wells correspond to Wells 1, 2 and 3 and their function is simply that of convenience. The appropriate grid-block pressures are placed within the "Well Operation Summary" so that they may be easily tabulated and plotted. The reader is referred to the output listing, where he may examine several of these summaries.

Level 2. The reader who wants to develop a deeper understanding of the code should also consider the following exercise:

Exercise 3 Figure 3.2-8 shows the behavior of the drawdown to lie intermediate between the two single-porosity curves labelled "upper bound" and "lower bound". If one increases the conductivity of the fine sand, will it move the simulated drawdown in the direction of the upper bound? Check your prediction by rerunning the problem.

4 FLOW AND TRANSPORT THROUGH AN AQUIFER WITH CONFINING LAYERS

4.1 PROBLEM 6. DRAWDOWN FROM A FULLY PENETRATING WELL IN A LEAKY AQUIFER [HANTUSH, 1960]

4.1.1 Objective

- To illustrate the use of the one-dimensional local units to simulate the effects of a leaking aquitard.

4.1.2 Description of the Problem

Problem Statement. A well fully penetrates an infinite aquifer and is pumped at a constant rate. The aquifer is bounded from below by an impermeable bed and from above by a confining bed or aquitard. The latter influences the aquifer to a moderate degree since it is weakly conductive and contains some fluid storage. A schematic drawing is shown as Figure 4.1-1.

Flow Equations. There are two flow equations here, one for the aquifer and one for the aquitard. The former is given by

$$T \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \bar{s}}{\partial r}\right) - b\Gamma_W = S \frac{\partial \bar{s}}{\partial t} \qquad (4.1\text{-}1)$$

and the latter, which assumes perpendicular flow in the aquitard, by

$$K' \frac{\partial^2 \bar{s}'}{\partial z^2} + \Gamma_W = S'_s \frac{\partial \bar{s}'}{\partial t}. \qquad (4.1\text{-}2)$$

Coupling arises through the flow at the interface between aquifer and aquitard:

$$\Gamma = A_V K' \frac{\partial \bar{s}'}{\partial z} (z=0) \qquad (4.1\text{-}3)$$

where $A_V = 1/b$ is the interface area per unit of aquifer volume.

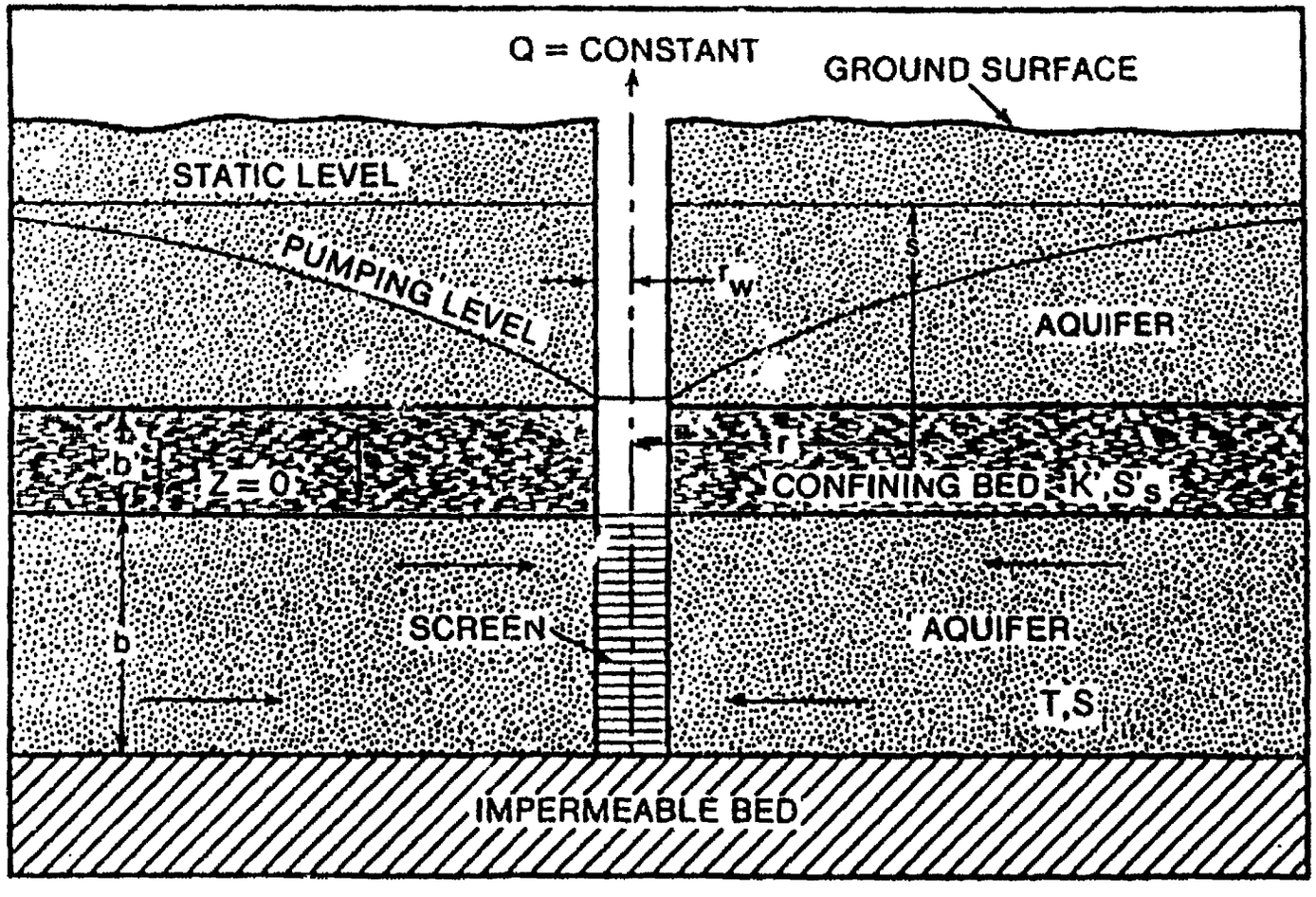

Figure 4.1-1. Problem 6. Schematic Diagram of a Fully Penetrating Constant-Discharge Well in a Leaky Aquifer.

Initial/Boundary Conditions. For the aquifer the initial drawdown is zero:

$$\bar{s}(r,t=0) = 0 \quad , \quad r > 0 \qquad (4.1\text{-}4a)$$

and the discharge at the origin is:

$$\lim_{r \to 0} \left(r \frac{\partial \bar{s}}{\partial r} \right) = \frac{Q}{2\pi T} \quad , \quad t > 0 \qquad (4.1\text{-}4b)$$

For the aquitard the initial drawdown is also zero:

$$\bar{s}'(r,z,t=0) = 0 \quad , \quad r > 0 \quad , \quad -b' < z < 0 \qquad (4.1\text{-}5a)$$

and the interface condition is:

$$\bar{s}'(r,z=0,t) = \bar{s}(r,t) \quad , \quad r > 0 \quad , \quad t > 0 \qquad (4.1\text{-}5b)$$

where z is measured positive downward from the aquifer-aquitard interface. At the upper boundary of the aquitard, there is assumed to be leakage from an overlying aquifer so that

$$\bar{s}'(r,z=-b',t) = 0 \quad , \quad r > 0 \quad , \quad t > 0 \qquad (4.1\text{-}5c)$$

Input/Output Specifications. Table 4.1-1 provides the input data, which is taken directly from the revised Benchmark Problem 3.2 [Ward, 1984b]. SWIFT, of course, uses a pressure-based formulation rather than the drawdown-based formulation assumed by the benchmark-problem specification, with the transformation between the two given by Equations (3.1-6) and (3.1-7). Table 4.1-1 gives the values appropriate for both formulations. In addition, these data are supplemented by a reasonable value of the well radius. The output specification, also taken from Benchmark Problem 3.2, calls for the drawdown-versus-time profile at a radius of 117.4 m from the withdrawal well for a time period extending out to $t = 10^6$ s.

Table 4.1-1. Problem 6. Input Specifications.

Parameter	Symbol	Value
Aquifer Transmissivity	T	$0.05\ m^2/sec$
Aquifer Hydraulic Conductivity	K	$5.00 \times 10^{-3}\ m/sec$
Aquifer Thickness	b	$10\ m$
Porosity	ϕ	0.10203
Water Density	ρ	$1000\ kg/m^3$
Water Compressibility	c_w	0
Rock Compressibility	c_R	$5.00 \times 10^{-7}\ Pa^{-1}$
Aquifer Storativity	S	0.005
Aquitard Specific Storativity	S'_s	$0.0016\ m^{-1}$
Well Radius	r_w	$0.1143\ m$
Aquitard Hydraulic Conductivity	K'	$10^{-5}\ m/sec$
Aquitard Thickness	b'	$50\ m$
Aquitard Porosity	ϕ'	0.3265
Well Pumping Rate	Q	$6.283\ m^3/sec$

4.1.3 Numerical Simulation

Discussion of Code Input. Up to this point, one-dimensional local unit conceptually have been placed interior to the global grid blocks in order to simulate dual-porosity effects. Further, the units were assumed to provide storage only with a no-flow condition assigned to one of its sides. Here, t role of these units is expanded in that they are placed external to the glob aquifer block in order to simulate an aquitard. In addition, they are given zero drawdown (Equation 4.1-5c) at the external end in order to simulate leakage from an overlying aquifer. Figure 4.1-2 typifies the numerical gridding by showing both the global aquifer blocks and the one-dimensional units of the aquitard, which are themselves subdivided into grid blocks.

Figure 4.1-3 contains the necessary code input for the local units. Tl control parameter

$$IFD = -3 \quad , \quad ROD-3 \qquad (4.1\text{-}6a)$$

effects the external placement of local units for all 50 grid blocks. Cont parameter

$$KBC = 1 \quad , \quad RID-3-1 \qquad (4.1\text{-}6b)$$

then activates the external constant-pressure boundary condition, which is specified as

$$PBD = 0.0 \quad , \quad RID-3-2 \qquad (4.1\text{-}6c)$$

Figure 4.1-3 also gives the outer radius of the simulated region:

$$r_e = RE = 2647 \text{ m} \quad , \quad R1-22$$

The selection of this radius, just as for the two previous problems was a matter of judgement. However, the appropriate characteristic radius

$$\tilde{r}_e = (Tb'/K')^{1/2} = 500 \text{ m} \qquad (4.1\text{-}7)$$

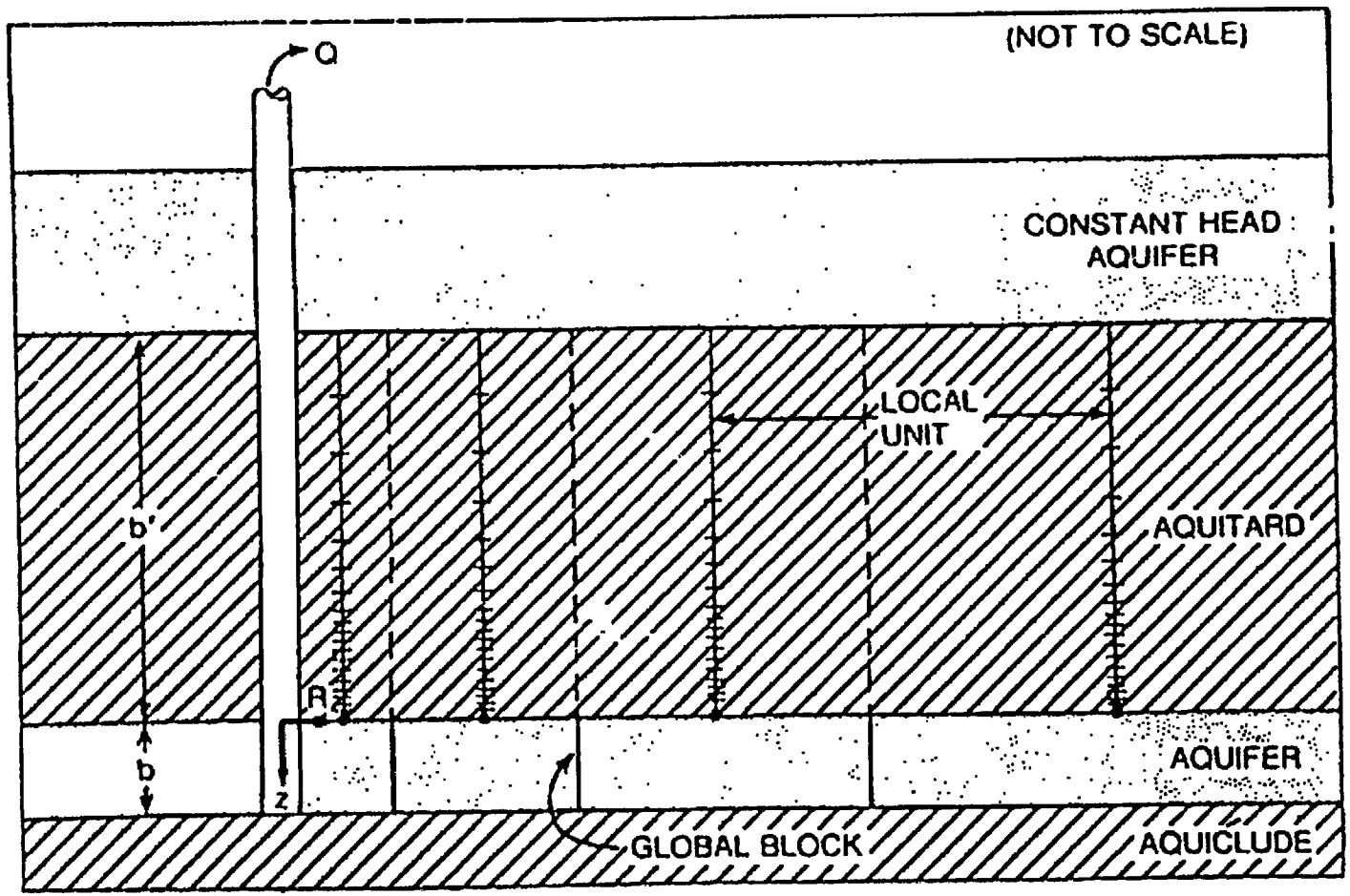

Figure 4.1-2. Numerical Characterization of the Leaky-Aquifer System.

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
1 PROBLEM NO. 6. SWIFT II EXAMPLE. SI UNITS. 12/83.                          M-1-1
2 FULLY PENETRATING WELL IN A LEAKY AQUIFER                                  M-1-2
                     *****
3    1    0    0    0    1    0    0    1    0                               M-2
                     *****
4   50    1    1    3    0    1    1    2    0    1    0    1    0           04-3-1
5    0    1    1    1          ******************************                M-3-2
                                * "****" REFERENCED IN TEXT    *
6    0                          * "****" REFERENCED IN EXERCISE *             ROD-1
                                ******************************
7   20                                                                       ROD-2
                                     *****
8    1   50    1    1    1    1    1   -3                                    ROD-3
                                     *****
9                                                                            ROD-3-BLN
           **********
10       0.0*   (1)  *       0.0       1.0       1.0                         R1-1
           **********
11       1.0       1.0       1.0       1.0       1.0       1.0       1.0R1-2
12    2000.0     5.0E5      20.0    1000.0    1000.0                         R1-3
13    2    2    2    2                                                       R1-6
14      20.0     0.001      20.0     0.001                                   R1-7
15      0.20     0.001      0.80     0.001                                   R1-8
16     100.0     0.001     .00.0     0.001                                   R1-9
17     100.0     0.001     200.0     0.001                                   R1-10
18       0.0      20.0                                                       R1-11
19     100.0      20.0      .                                               R1-11
20    0    0                                                                 R1-12
21      20.0     5.0E5       0.0       0.0                                   R1-16
                     **********
22    0.1143 0.1263842 2646.7663       0.0                                   R1-22
23 *  (2)  **   (3)  **   (4)  **   (5)  *       0.0                          R1-23
24                                                                           R1-26-BLN
25    3    0                                                                 R1-27
```

Figure 4.1-3. Listing of SWIFT II Input Data.

DRAFT

```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890123456789 0
+---------+---------+---------+---------+---------+---------+---------+---------+
I                                                                                 I
26 I    1    0    0                                                   R1-29      I
I                                                                                 I
27 I    5.0E-2  1.026304 2646.7663     360.0                            R1-31      I
I                                                                                 I
28 I                                                                    R1-33-BLN  I
I*********                                                                        I
29 I*   (6)  *                                                          R1D-1      I
I*********          ******************                                            I
30 *       0.0       0.0*   (7)  **   (8)  *       0.0       0.0       0.0R1D-2-1 *
I          ****************************                                           I
31 I    1    1*   (9)  *      0.50       0.0                             R1D-2-2    I
I     ***************                                                             I
32 I    1    1    0    0    0                                             R1D-3-1    I
I*********                                                                        I
33 I       0.0       0.0       0.0                                        R1D-3-2    I
I*********                                                                        I
34 I                                                                    R1D-3-BLN  I
I                                                                                 I
35 *                                                                    R1D-5-BLN  *
I                                                                                 I
36 I    0    0    0                                                   I-1        I
I                                                                                 I
37 I       0.0                                                          R14-1      I
I                                                                                 I
38 I    1    1    0    0    0    0    0    0    0    0                 R2-1       I
I                                                                                 I
39 I    4                                                               R2-4       I
I*********                                                                        I
40 **  (10)  *       0.0       0.0                                      R2-5       *
I*********                                                                        I
41 I    1    1    1    1    1    1                                      R2-7-1     I
I                                                                                 I
42 I     3.125       0.0      20.0       0.0                             R2-7-2     I
I                                                                                 I
43 I    2   35    1    1    1    1                                      R2-7-1     I
I                                                                                 I
44 I    1.0E10       0.0      20.0       0.0                             R2-7-2     I
I                                                                                 I
45 *    3   35    1    1    1    1                                      R2-7-1     *
I                                                                                 I
46 I    1.0E10       0.0      20.0       0.0                             R2-7-2     I
I                                                                                 I
47 I    4   35    1    1    1    1                                      R2-7-1     I
I                                                                                 I
48 I    1.0E10       0.0      20.0       0.0                             R2-7-2     I
I                                                                                 I
49 I                                                                    R2-7-BLN   I
I                                                                                 I
50 *       1.0       1.0                                                           *
I                                                                                 I
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 4.1-3 Continued.

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
51   1    1    1    1   -1    1  011    0 0000    0   00   -1  111   00R2-13
52   0    0    0    0    0    0    0    0    0    0                   R2-1
53     1.0E3       0.0       0.0       0.0     1.0E4       0.0     1.0E3    0.05E3
54   1    1    1    1   -1    1  011    0 0000    0   00   -1  011   00R2-13
55   0    0    0    0    0    0    0    0    0    0                   R2-1
56     1.0E4       0.0       0.0       0.0     1.0E4       0.0     1.0E4     0.1E4
57   1    1    1    1   -1    1  011    0 0000    0   00   -1  011   00R2-13
58   0    0    0    0    0    0    0    0    0    0                   R2-1
59     1.0E5       0.0       0.0       0.0     1.0E4       0.0     1.0E5     0.1E5
60   1    1    1    1   -1    1  011    0 0000    0   00   -1  011   00R2-13
61   0    0    0    0    0    0    0    0    0    0                   R2-1
62     1.0E6       0.0       0.0       0.0     1.0E4       0.0     1.0E6     0.2E6
63   1    1    1    1   -1    1  011    0 0000    0   00   -1  011   00R2-13
64   0    0    0    1    0    0    0    0    0    0                   R2-1-END
65   2     OBSERVATION WELL (R = 117.4 M)    SMALL TIME                P-2
66       0.0     2.0E4     4.0E2     3.0E5     5.0E5       0.0       0.0P-3-1
67       0.0       0.0       0.0       0.0                             P-3-2
68   0.40E3   4.835E5                                                  P-4
69   1.00E3   4.532E5                                                  P-4
70   2.00E3   4.230E5                                                  P-4
71   4.00E3   3.899E5                                                  P-4
72   10.0E3   3.447E5                                                  P-4
73   20.0E3   3.104E5                                                  P-4
74    -100.                                                            P-4-END
75   3     OBSERVATION WELL (R = 117.4 M)   SMALL AND LARGE TIME       P-2
```

Figure 4.1-3 Continued.

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
76       0.0     4.0E5     8.0E3     1.6E5     3.2E5       0.0       0.0P-3-1
77       0.0       0.0       0.0       0.0                           P-3-2
78    2.00E4   3.104E5                                              P-4
79    4.00E4   2.763E5                                              P-4
80    9.00E4   2.331E5                                              P-4
81    10.0E4   2.314E5                                              P-4
82    15.0E4   2.096E5                                              P-4
83    20.0E4   1.975E5                                              P-4
84    30.0E4   1.918E5                                              P-4
85    40.0E4   1.637E5                                              P-4
86     -100.                                                        P-4-END
87    4     OBSERVATION WELL (R = 117.4 MI     LARGE TIME           P-2
88       0.0     1.0E6     2.0E4     1.7E5     2.2E5       0.0       0.0P-3-1
89       0.0       0.0       0.0       0.0                           P-3-2
90    1.50E5   2.096E5                                              P-4
91    3.00E5   1.918E5                                              P-4
92    5.00E5   1.873E5                                              P-4
93    9.00E5   1.863E5                                              P-4
94     -100.                                                        P-4-END
95                                                                  P-END
```

Figure 4.1-3 Continued.

did provide some guidance. This quantity, which is derived from dimensional analysis, properly accounts for the fact that the extent of the drawdown cone is controlled by leakage from the neighboring aquifer. It, therefore, differs from the characteristic radius used for the two previous problems (Equation 3.1-9a).

Results. The numerical results are displayed graphically in Figure 4.1-4. As shown, there are two analytic solutions, both of which are taken from Hantush [1960]. One is for small values of time ($t < (b')^2 S_s'/10K' = 4\times10^4$s), and the other is for large values of time ($t > 2(b')^2 S_s'/K' = 8\times10^5$s). The comparison between numerical and analytical results is apparently quite reasonable.

Discussion of Code Output. This output illustrates the generation of SWIFT printer plots*, a facility which provides a quick, inexpensive way to display computed results. Since the code only plots data pertaining to wells, observation wells are defined in Cards R2-4 through R2-7. Further, since only one plot per well is possible, three such wells are completed in Block 35 at the specified radius r = 117.4 m. The resulting plots then display the time periods

$$0 < t < 2\times10^4 s \quad 0 < t < 4\times10^5 s \text{ and } 0 < t < 10^6 s \qquad (4.1\text{-}8)$$

with different scales of resolution, which permits a detailed comparison with the Hantush analytic solutions.

Plotting is activated by a positive value of the plotting key NPLP = 1, (Card M-2), whose value appears in the initial table of the output listing (see microfiche). Note, in the three plots, which appear at the end of the execution, that, due to the expanded scales of the ordinate, the difference between simulated (X) and analytic (O) is readily apparent. Exercise 4 deals with this relatively small (less than 0.4 percent at 10^6s) discrepancy.

---

* The term "plot" should not be confused with the term "map". Maps consist of two-dimensional contours of pressure, isopleths of concentration and isotherms of temperature. In contrast to plots, the mapping facility is, in no way, coupled to the presence of wells.

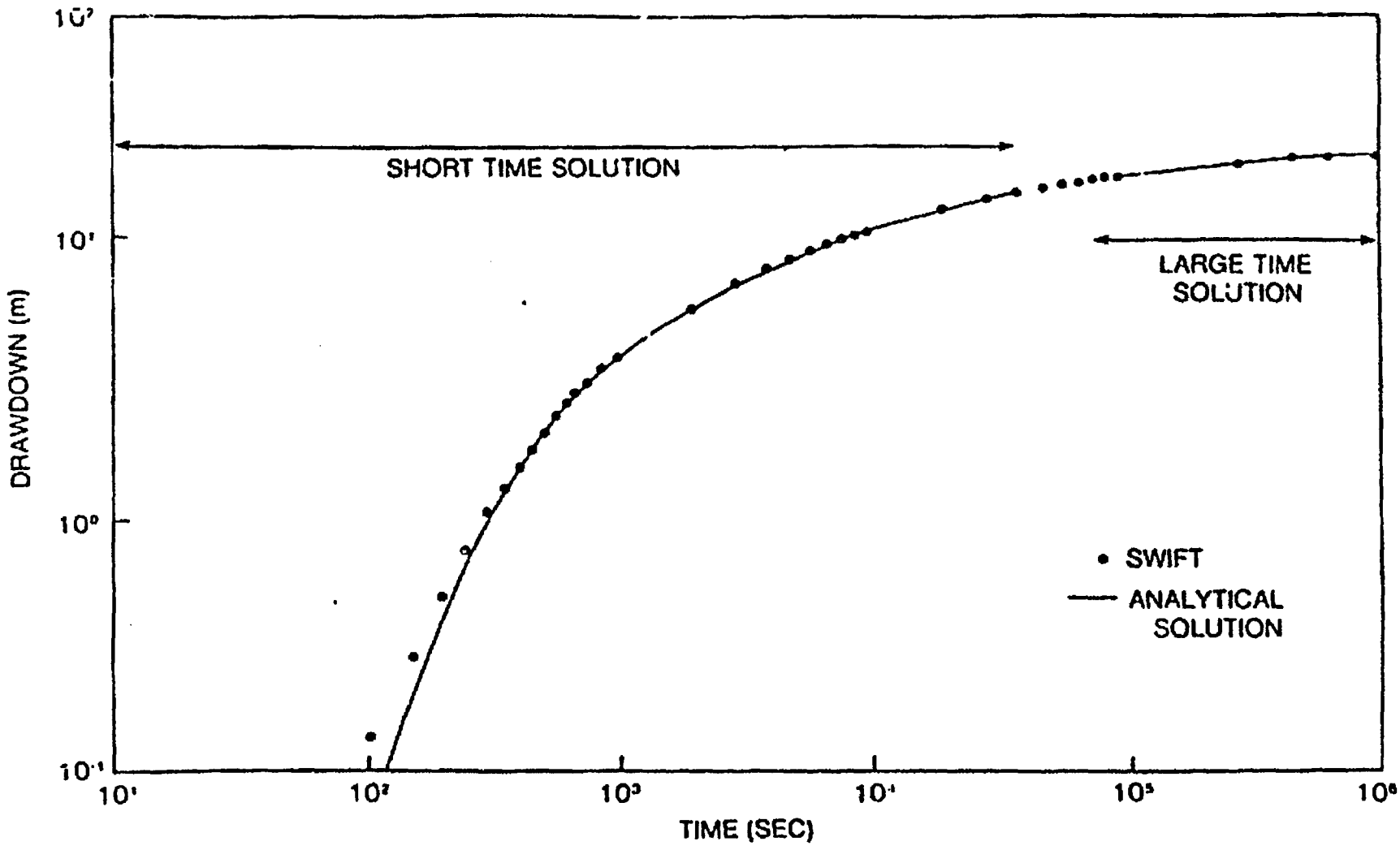

Figure 4.1-4. Graphical Comparison of the Numerical Results from SWIFT and the Analytical Solutions of Hantush for a Radial Distance of 117.4 m.

4.1.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises.

Exercise 1 From Table 4.1-1, what data are required for the blanks labelled "1" through "10" in Figure 4.1-3?

Exercise 2 Consider Card ROD-3. How would one simulate two confining beds of the same thickness? How would one include differing thicknesses?

Exercise 3 Refer in the microfiche to the table of pressures within the aquitard for radius $r = 117.4$ m, Block 35, and time $t = 10^4$ s. Convert to drawdown via $s = (p-p_o)/\rho(g/g_c)$ and plot. The initial pressure, as given by PINIT in the table entitled "Initial Conditions" is $p_o = 5\times10^5$ Pa*. Nodal positions are given in the table "Specific Matrix Discretization Parameters" located in the input echo. Has the aquitard reached steady state? Repeat the plot for time $t = 10^6$ s. Has the aquitard now reached steady state?

Level 2. The reader who wants to develop a deeper understanding of the code should consider the following exercise.

Exercise 4 In the aquitard the local mesh was generated using single-mesh generation (KGRD = 1, R1D-2), but was that the best option available? In the local mesh, Node 20 is attached to aquifer

---

* Since SWIFT plotting routines do not permit negative pressures, the initial pressure p_o, which here is arbitrary, was set sufficiently high in Card R1-16 (see also Card R1-3) that no negative pressures would be encountered.

grid and at Node 1 a constant pressure boundary was prescribed. From the output table "Specific Matrix Discretization Parameters" (see microfiche), near the aquifer the grid increment is 0.5 m (input parameter DSD, Card RID-2) whereas between Nodes 1 and 2 the increment is 7.33 m. The grid seems quite lopsided in that so many nodes are situated closest to the aquifer. The reader should try to improve upon this grid either by using double-mesh generation or by specifying the individual increments directly. One would not expect any difference in the short-term response. The long-term response, however, may be affected, but to what degree?

4.2 PROBLEM 7. HEAT TRANSPORT DURING FLUID INJECTION [AVDONIN, 1964]

4.2.1 Objective

- To illustrate the convective heat transport which results from injection into an aquifer with heat losses to the confining beds.

4.2.2 Description of the Problem

Problem Statement. An incompressible fluid of temperature, T_I, is injected into a confined aquifer of temperature, T_o, through a fully penetrating well (Figure 4.2-1). Both thermal convection and thermal conduction occur within the aquifer, and thermal conduction is operative within the confining layers, denoted herein as the over/underburden.

Transport Equations. For the aquifer, the transport equation is

$$-v\rho c_p \frac{\partial T}{\partial r} + K_m \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right) - \Gamma_H = \rho_m c_{pm} \frac{\partial T}{\partial t} \qquad (4.2\text{-}1)$$

and, for the over/underburden, the transport equation is

$$K_m' \frac{\partial^2 T'}{\partial z^2} + \Gamma_H = \rho_m' c_{pm}' \frac{\partial T'}{\partial t} \qquad (4.2\text{-}2)$$

Here the over/underburden coupling term is given by

$$\Gamma_H = -(2/b)K_m' \frac{\partial T}{\partial z} \qquad (4.2\text{-}3)$$

and the fluid velocity by

$$v = Q/2\pi rb\rho\phi \qquad (4.2\text{-}4)$$

Initial/Boundary Conditions. The conditions imposed on the solutions of these transport equations are, for the aquifer,

$$T(r,t=0) = T_o \quad , \quad r > 0 \qquad (4.2\text{-}5a)$$

$$T(r=0,t) = T_I \quad , \quad t > 0 \qquad (4.2\text{-}5b)$$

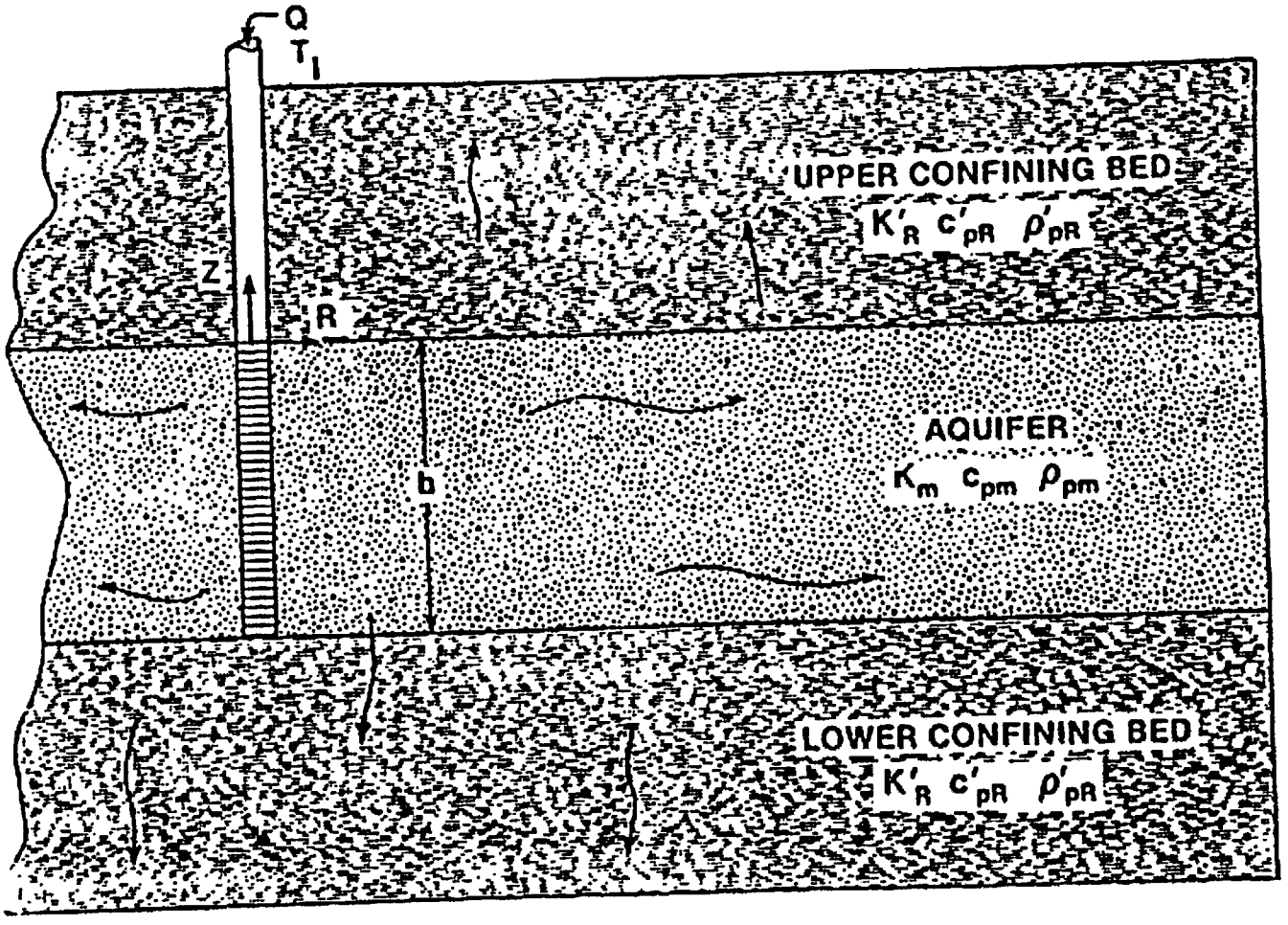

Figure 4.2-1. Problem 7. Radial Heat Transport Within an Aquifer with Losses to the Over/Underburden.

and, for the over/underburden,

$$T'(x,z,t=0) = T_o \quad , \quad z > 0 \tag{4.2-6a}$$

$$T'(x,z=\pm\infty,t) = T_o \quad , \quad t > 0 \tag{4.2-6b}$$

$$T'(x,z=0,t) = T(x) \quad , \quad t > 0 \tag{4.2-6c}$$

and

$$T'(x,z=-b,t) = T(x) \quad , \quad t > 0 \tag{4.2-6d}$$

where z is measured positive downward from the lower aquifer boundary.

Input/Output Specifications. Table 4.2-1 displays input specifications taken directly from the Benchmarking Problem 5.1 [Ross et al, 1982]. It also contains supplementary data necessary for SWIFT input. Aside from the well radius, for which a reasonable value is chosen, the composite heat capacity i partitioned as follows:

$$\rho_m c_{pm} = \rho c_p + (1-\phi)\rho_R c_{pR}/\phi \tag{4.2-7}$$

Given the composite values (subscript, m) in the benchmark specifications, tl values for the rock density and the rock heat capacities were chosen to be consistent with this relation. The output specifications, also taken from Benchmark Problem 5.1, calls for the thermal breakthrough at a radius of 37. m from the injection well for a time period extending out to $t = 10^9$ s.

4.2.3 Numerical Simulation

Discussion of Code Input. Similar considerations arise both within the aquifer and within the over/underburden. For computer efficiency, it is desirable to minimize the outer extent of the simulated system but, yet, at the same time, to adequately minic the infinite physical system. In additi and for the same reason, it is desirable to use as coarse a mesh as possibl in the spatial and temporal regimes and still to adequately characterize th thermal behavior at a radius r = 37.5 m from the injection well. Within th aquifer the controlling mechanism is the flow since it provides the convect for the heat transport. Setting up the proper fluid velocity is no problem

Table 4.2-1. Problem 7. Input Specifications.

Parameter	Symbol	Value
Injection Rate	Q	10 kg/s
Injection Temperature	T_I	160 °C
Initial Temperature	T_o	170 °C
Over/Underburden		
Thermal Conductivity	K'_m	20 W/(m °C)
Density	ρ'_m	2500 kg/m^3
Heat Capacity, Composite	c'_{pm}	1000 J/(kg °C)
Porosity	ϕ'	0.2
Aquifer		
Thermal Conductivity	K_m	20 W/(m °C)
Density	ρ_m	2500 kg/m^3
Heat Capacity, Composite	c_{pm}	1000 J/(kg °C)
Thickness	b	100 m
Porosity	ϕ	0.2
Heat Capacity, Water	c_p	4185 J/(kg °C)
Heat Capacity, Rock	c_R	2.079×10^6 J/(m^3 °C)
Well Radius	r_w	0.766 m

since, according to Equation (4.2-4), the flow is at steady state. This is done by imposing a constant pressure at the external radius in Card R1-28-2 of Figure 4.2-2 (see boxed value).

This external radius, of course, must be sufficiently large to contain the movement of the thermal front which results from this flow field. Here the retarded velocity is

$$\bar{v} = vpc_p/\rho_m c_{pm} = \bar{v}_o/r \qquad (4.2\text{-}8a)$$

where, from Equations (4.2-4) and Table 4.2-1,

$$\bar{v}_o = Qc_p/2\pi b\phi\rho_m c_{pm} = 1.332 \times 10^{-4}\ m^2/s \qquad (4.2\text{-}8b)$$

and the convective movement of the thermal front in $t = 10^9$ s is

$$\tilde{r} = (\bar{v}_o t)^{1/2} = 370\ m \qquad (4.2\text{-}9a)$$

To allow for a conductive smearing of this front and to include a slight safety factor, the external radius is chosen to be

$$r_e = 1000\ m \quad , \quad R1\text{-}22 \qquad (4.2\text{-}9b)$$

Gridding criteria are unknown in this case, and consequently it is necessary to use a trial-and-error procedure for the spatial, and temporal, regimes.

Within the over/underburden the only transport mechanism of significance is thermal conduction. The characteristic length corresponding to the time $t = 10^9$ s is

$$\tilde{a} = (K'_m t/\rho'_m c'_{pm})^{1/2} = 90\ m \qquad (4.2\text{-}10a)$$

and the value

$$a = 300\ m \quad , \quad R1D\text{-}2\text{-}2 \qquad (4.2\text{-}10b)$$

is adopted for the simulated thickness of the over/underburden. Here the spatial gridding is chosen to adequately resolve the expected behavior within

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          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
PROBLEM NO. 7, SWIFT II EXAMPLE, SI UNITS, 12/83.                          M-1-1
TAVOONIN RADIAL HEAT TRANSPORT WITH LOSS TO CONFINING BEDS                 M-1-2
  -2    0    0    0    0    1    0    1    0                              M-2
  30    1    1    3    0    1    1    0    0    1    0    0    0          OM-3-1
   0    1    1    1                                                       M-3-2
   0                                                                      ROD-1
  15                                                                      ROD-2
   1   30    1    1    1    1    1(1)                                     ROD-3
                                                                          ROD-3-BLN
 3.20E-15       0.0       0.0   (2)  ++   (3)                             R1-1
 (4)  ++   (5)  ++   (6)        1.0       0.0       0.0  1.00E-50R1-2
   2875.0  5.00E 06     160.0   (7)  ++   (8)                             R1-3
   0    1    1    2                                                       R1-6
     160.0     0.001     160.0     0.001                                  R1-7
     170.0     0.001                                                      R1-9
     170.0     0.001                                                      R1-10
          0.0   (9)                                                       R1-11
  100000.0  (10)                                                          R1-11
   0    0                                                                 R1-12
      170.       0.0       0.0       0.0                                  R1-16
  .090223   .7655922     1000.       0.0                                  R1-22
    100.0     9.8E-6    9.8E-6      0.20                                  R1-23
                                                                          R1-26-BLN
   4    0                                                                 R1-27
  30   30    1    1    1    1    0                                        R1-28-1
```

Figure 4.2-2. Listing of SWIFT II Input Data.

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```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
I          **********
26 I       2.0       0.0      170.0       0.0       0.0       0.0          R1-28-2 I
I          **********
27 I                                                                      R1-28-BLN I
I
28 I                                                                      R1-33-BLN I
I**********
29 I       0.0                                                            R10-1 I
I**********                                          ********************
30 *       0.0       0.0       0.20    9.8E-6       0.0*  (11)  **  (12)  *R10-2-1 *
I          **********                                ********************
31 I    1    1     300.0      10.0       0.0                              R10-2-2 I
I          **********
32 I                                                                      R10-3-BLN I
I
33 I                                                                      R10-5-BLN I
I
34 I    0    0    0                                                       I-1 I
I
35 *       0.0                                                            R1A-2 *
I
36 I    1    1    1    0    0    0    0    0    0                        R2-1 I
I*****
37 I    1       0.5                                                       R2-2 I
I*****
38 I    2                                                                 R2-4 I
I
39 I    -0.010       0.0                                                  R2-5 I
I
40 *    1    1    1    1    1    1                                        R2-7-1 *
I         ...         **********
41 I       1.0       0.0*  (13)  *       0.0                              R2-7-2 I
I                     **********
42 I    2   17    1    1    1    1                                        R2-7-1 I
I
43 I       1.0       0.0       0.0       0.0                              R2-7-2 I
I
44 I                                                                      R2-7-BLN I
I          **********
45 *    1.00E4    1.00E4                                                  *
I          **********
46 I    1    1    1    1    1    1  000    0 0000    0   00   -1  001   00R2-13 I
I
47 I    0    0    0    0    0    0    0    0    0                        R2-1 I
I                                                     **********          **********I
48 I    1.00E5       0.0       0.0       0.0       0.0       1.0    0.50E5    0.10E5I
I                                                     **********          **********I
49 I    1    1    1    1    1    1  000    0 0000    0   00   -1  111   00R2-13 I
I
50 *    0    0    0    0    0    0    0    0    0                        R2-1 *
I
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 4.2-2 Continued.

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```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
51   1.00E6       0.0       0.0       0.0       0.0       1.0    0.50E6    0.10E6
52   1    1    1    1    1    1  000    0 0000    0   00   -1  101   00RZ-13
53   0    0    0    0    0    0    0    0    0                          RZ-1
54   1.00E7       0.0       0.0       0.0       0.0       1.0    0.50E7    0.10E7
55   1    1    1    1    1    1  000    0 0000    0   00   -1  111   00RZ-13
56   0    0    0    0    0    0    0    0    0                          RZ-1
57   1.00E8       0.0       0.0       0.0       0.0       1.0    0.50E8    0.10E8
58   1    1    1    1    1    1  000    0 0000    0   00   -1  101   00RZ-13
59   0    0    0    0    0    0    0    0    0                          RZ-1
                                                     *********           **********
60   1.00E9       0.0       0.0       0.0       0.0       1.0    0.50E9    0.20E8
                                                     ****.****           **********
61   1    1    1    1    1    1  000    0 0000    0   00   -1  101   00RZ-13
62   0    0    0    1    0    0    0    0    0                          RZ-1-END
63   2     OBSERVATION WELL (R=37.5 METER)                                P-2
64       0.0  1.00E 09  2.00E 07       0.0       0.0       0.0       0.0P-3-1
65     160.0     170.0       0.0       0.0                                P-3-2
66  1.10E 07                        169.70                                P-4
67  1.59E 07                        169.03                                P-4
68  2.34E 07                        167.81                                P-4
69  3.409E 07                       166.35                                P-4
70  5.051E 07                       164.87                                P-4
71  7.48E 07                        163.64                                P-4
72  9.26E 07                        163.09                                P-4
73  1.138E 08                       162.65                                P-4
74  1.403E 08                       162.27                                P-4
75  1.75E 08                        161.94                                P-4
```

Figure 4.2-2 Continued.

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76	2.197E 08	161.65	P-4
77	2.579E 08	161.42	P-4
78	3.50E 08	161.22	P-4
79	4.50E 08	161.05	P-4
80	5.50E 08	160.93	P-4
81	6.50E 08	160.84	P-4
82	7.50E 08	160.78	P-4
83	8.50E 08	160.73	P-4
84	9.50E 08	160.68	P-4
85	1.03E 09	160.66	P-4
86	-100.0		P-4-END
87	0		P-STOP

Figure 4.2-2 Continued.

the over/underburden. This behavior, based on comparable solutions for a one-dimensional system, should look much like a complementary error function which is centered at the aquifer interface and which becomes more and more diffuse as time increases.

Results. Figure 4.2-3 displays the numerical solution alongside the analytical solution of Avdonin [1964]. Comparison with the case of heat transport only within the aquifer indicates that the effect of conduction within the over/underburden is relatively small. Consequently, the slight discrepancy between numerical and analytical results most likely would be attributed to the presence of some numerical dispersion, which arises in the simulation of convection within the aquifer. Exercises 5 and 6 focus on this point.

Discussion of Code Output. The microfiche provides a comprehensive listing of the code output. It includes the following: (1) an echo of the input data, (2) preliminary setup computations for the radial grid within the aquifer and the linear grid within the over/underburden, (3) time-step and well summaries, (4) a steady-state pressure distribution and (5) time-dependent temperature distributions within both aquifer and over/underburden. The reader should carefully examine this output, noting particularly those data which are pertinent to this, a heat-transport problem.

4.2.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1 From Table 4.2-1, what physical parameters are required for the blanks labelled "1" through "13" in Figure 4.2-2? Check the answers by referring to the echo of the input data printed at the beginning of the output.

Exercise 2 Explain the function of the control parameters enclosed in boxes in Cards M-2, M-3-2 and R2-2.

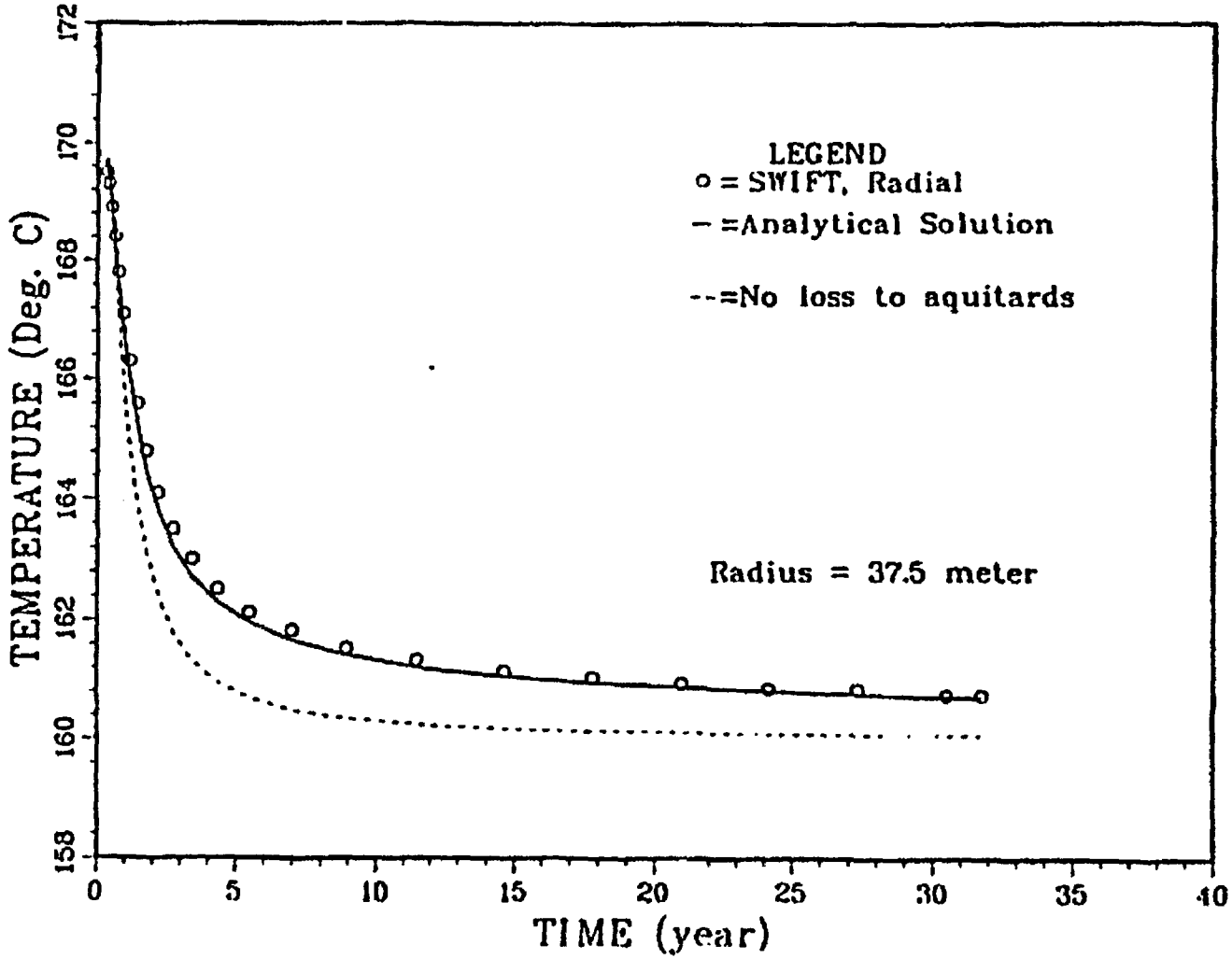

Figure 4.2-3. Temperature Breakthrough Within the Aquifer at 37.5 m from the Injection Well.

Exercise 3 How are steady-state velocities achieved as required by the analytical solution? The solution option NCALL = -2 (Card M-2) results in a coupled transient pressure and temperature solution. However, a steady-state pressure solution is achieved by assigning a very small value of water compressibility. Could a zero value have been entered? Before the reader attempts this, he should remember that a non-zero accumulation is required by the transient solution option. Would it be more accurate to first solve a steady-state isothermal velocity field (NCALL = 4) and then switch to a coupled transient simulation (NCALL = -2, Card R2-11.5)? If the value of water compressibility is small enough there should be no significant difference.

Exercise 4 Interpret the plotting data shown on Cards P-2 through P-4 (Figure 4.2-2). Also note the value of the plotting control in Card M-2.

Level 2. The reader who wants to develop a deeper understanding of the code should consider the following exercise:

Exercise 5 The source of the deviation of the numerical curve from the analytical curve in Figure 4.2-3 is the issue here. As shown in the R2-12 Cards of Figure 4.2-2, after an initial time step of $\Delta t = 10^4$ s, automatic time stepping is used, based on a temperature increment of $\Delta T = 1.0$ °C and a relatively large minimum time step. Could the coarse time step selected by the code be the source of the observed discrepancy? The reader is encouraged to reduce both of these controls, rerun the problem out to, say, $t = 2 \times 10^8$ s and then examine the effect of these changes.

Exercise 6 Also, the temperature distribution within the over/underburden may not be resolved adequately at the time $t = 2x10^8$ s, where the discrepancy first begins to appear. From the output tables labelled "Temperature Within the Rock Matrix", examine this distribution at $r = 37.5$ m (Block 17) to see if there is a need for additional resolution at this partiular time. Rerun the problem if necessary.

5 FLOW WITH A FREE-WATER SURFACE

5.1 PROBLEM 8. THE DUPUIT-FORCHHEIMER STEADY-STATE PROBLEM [BEAR, 1972]

5.1.1 Objective

- To demonstrate the simulation of steady-state flow in a phreatic aquifer.

5.1.2 Description of the Problem

Problem Statement. The following idealized problem is considered here: A phreatic aquifer of length L (Figure 5.1-1) with fixed free-water elevations

$$h(x=0) = h_a \tag{5.1-1a}$$

and

$$h(x=L) = h_L \tag{5.1-1b}$$

at its boundaries is subjected to surface recharge at a rate q. The problem is to determine the elevation h(x) of the free-water surface at positions interior to the boundaries subject to the data given in Table 5.1-1.

Analytical Solution. To solve this problem analytically, the Dupuit assumption is invoked [Bear, 1972]. This amounts to a neglect of vertical flow:

$$u_z = -K_z \partial H/\partial z = 0 \tag{5.1-2a}$$

and yields a strictly one-dimensional solution in the x coordinate. Here H is the total head, $H = h - z$. Further, it is assumed that for the horizontal flow, the transmissivity is controlled by the saturated thickness:

$$T = K_x h \tag{5.1-2b}$$

so that the total discharge through a vertical surface per unit of width in the y direction (Figure 5.1-1), is given by

$$u_x = -T \frac{\partial h}{\partial x} \tag{5.1-3}$$

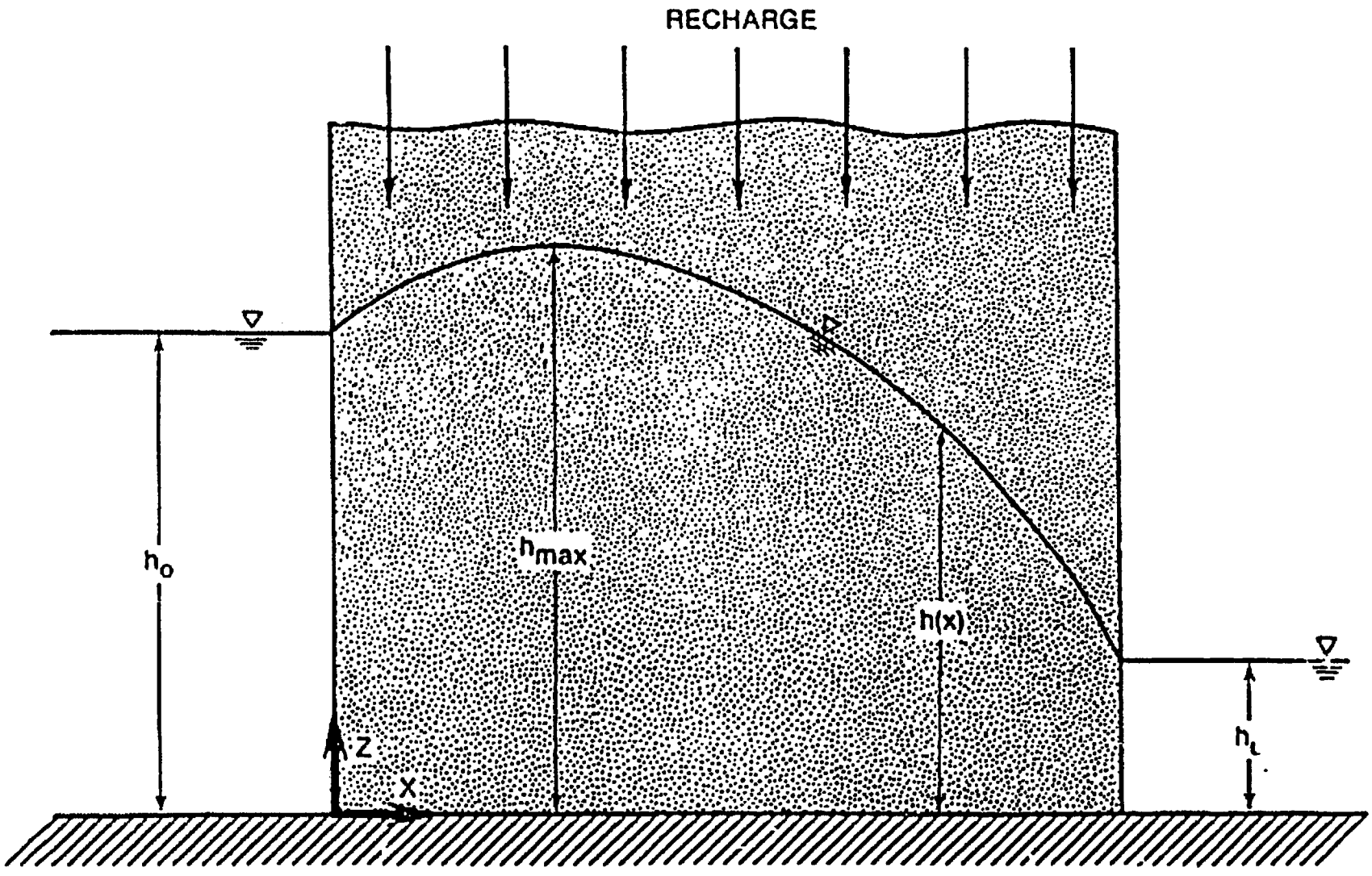

Figure 5.1-1. Problem 8. Schematic Diagram for the Dupuit-Forchheimer Problem.

Table 5.1-1. Problem 8. Input Specifications.

Parameter	Symbol	Value
Surface Recharge	q	7.505×10^{-5} m/s
Lateral Conductivity	K_x	0.03 m/s
Vertical Conductivity	K_z	0.003 m/s
Height of Free-Water Surface at x = 0	h_o	0.75 m
Height of Free-Water Surface at x = L	h_L	0.25 m
Length of System	L	20 m

The equation of continuity [Bear, 1972] then becomes, for steady state,

$$\frac{\partial}{\partial x}\left(K_x h \frac{\partial h}{\partial x}\right) + q = 0 \qquad (5.1\text{-}4)$$

which is the Forchheimer equation. For the boundary conditions prescribed in Equation (5.1-1), the analytical solution of Equation (5.1-4) is the Dupuit-Forchheimer parabola:

$$h^2 - h_o^2 = (h_L^2 - h_o^2)x/L + (q/K_x)(L-x)x \qquad (5.1\text{-}5)$$

Flow rates at the two boundaries are obtained from Equations (5.1-2b) and (5.1-3)

$$\begin{pmatrix} u_o \\ u_L \end{pmatrix} = (K_x/2L)(h_o^2 - h_L^2) + \begin{pmatrix} (-) \\ (+) \end{pmatrix}(qL/2) \qquad (5.1\text{-}6)$$

Here, the first term (on the right-hand side) represents the flow caused strictly by the difference in heads on the two ends of the system. This rate, of course is the same on both ends of the system. The second term arises from the surface recharge. It shows that half of this recharge exits through the boundary $x = 0$ and the other half through the boundary $x = L$.

5.1.3 Numerical Solution

To solve this problem numerically with SWIFT, a two-dimensional vertical cross section is gridded as listed in Cards R2-17 through R2-19 (Figure 5.1-2). Hydrostatic conditions

$$\tilde{p} = p - \rho(g/g_c)h = \text{constant} \qquad (5.1\text{-}7)$$

are then prescribed for both side boundaries (Cards R1-27 and R1-28). Here the vertical discretization is necessary for two reasons: Firstly, it provides geometrical resolution for the free-water surface. Secondly, the vertical discretization is required since the SWIFT formulation does permit vertical flow. Thus, there is some difference at this point between the one-

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          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
 1 PROBLEM NO. 8. SWIFT II EXAMPLE, SI UNITS, 12/83.                        M-1-1
 2 OUPUIT-FORCHHEIMER STEADY-STATE FREEWATER SURFACE WITH RECHARGE          M-1-2
   *****         *****
 3     4    0    0    1    0    0    0    1    0                           M-2
   *****      **********
 4    20    1   20    1    0    1    0    2    0   20   20    0    0      OM-3-1
   *****      **********
 5     0    0    0    0                                                    M-3-2
 6        0.0       0.0       0.0       1.0       1.0                     R1-1
 7        0.0       0.0       0.0       0.0       1.0       1.0   1.0E-10R1-2
 8     2130.0   1.00E07      20.0    1000.0    1000.0                     R1-3
 9     0    2    2    2                                                    R1-6
10       20.0  1.00E-03      20.0  1.00E-03                               R1-7
11       40.0  1.00E-03      80.0  1.00E-03                               R1-9
12       40.0  1.00E-03      80.0  1.00E-03                               R1-10
13        0.0      20.0                                                    R1-11
                                   ******************************
14     1000.0      20.0            * "****" REFERENCED IN TEXT     *       R1-11
                                   * "****" REFERENCED IN EXERCISE *
15     0    0                      ******************************          R1-12
16       20.0       0.0       0.0       0.0                               R1-16
   **********
17     20*1.0
   **********
18        1.0
   **********
19   20*0.050
   ****************************
20 **   (1)  **   (2)  **   (3)  *      0.50       0.0       0.0       0.0R1-20
   ****************************
21                                                                       R1-26-BLN
22     4    1                                                            R1-27
23     1    1    1    1    6    6                                        R1-28
24        1.   0.00001                                                   R1-28
25     1    1    1    1    7    7                                        R1-28
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 5.1-2. Listing of SWIFT II Input Data.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
      +---------+---------+---------+---------+---------+---------+---------+---------+
      |*******************                                                              |
   26 |        1.      488.                                                   R1-28     |
      |*******************                                                              |
   27 |    1    1    1    1    8    8                                          R1-28     |
      |                                                                                 |
   28 |        1.      976.                                                   R1-28     |
      |                                                                                 |
   29 |    1    1    1    1    9    9                                          R1-28     |
      |                                                                                 |
   30 +        1.     1464.                                                   R1-28     +
      |                                                                                 |
   31 |    1    1    1    1   10   10                                          R1-28     |
      |                                                                                 |
   32 |        1.     1952.                                                   R1-28     |
      |                                                                                 |
   33 |    1    1    1    1   11   11                                          R1-28     |
      |                                                                                 |
   34 |        1.     2440.                                                   R1-28     |
      |                                                                                 |
   35 +    1    1    1    1   12   12                                          R1-28     +
      |                                                                                 |
   36 |        1.     2928.                                                   R1-28     |
      |                                                                                 |
   37 |    1    1    1    1   13   13                                          R1-28     |
      |                                                                                 |
   38 |        1.     3416.                                                   R1-28     |
      |                                                                                 |
   39 |    1    1    1    1   14   14                                          R1-28     |
      |                                                                                 |
   40 +        1.     3904.                                                   R1-28     +
      |                                                                                 |
   41 |    1    1    1    1   15   15                                          R1-28     |
      |                                                                                 |
   42 |        1.     4392.                                                   R1-28     |
      |                                                                                 |
   43 |    1    1    1    1   16   16                                          R1-28     |
      |                                                                                 |
   44 |        1.     4880.                                                   R1-28     |
      |                                                                                 |
   45 +    1    1    1    1   17   17                                          R1-28     +
      |                                                                                 |
   46 |        1.     5368.                                                   R1-28     |
      |                                                                                 |
   47 |    1    1    1    1   18   18                                          R1-28     |
      |                                                                                 |
   48 |        1.     5856.                                                   R1-28     |
      |                                                                                 |
   49 |    1    1    1    1   19   19                                          R1-28     |
      |                                                                                 |
   50 +        1.     6344.                                                   R1-28     +
      |                                                                                 |
      +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 5.1-2 Continued.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
      +---------+---------+---------+---------+---------+---------+---------+---------+
      |                                                                                 |
 51   |    1    1    1    1   20   20                                   R1-26         |
      |          *********                                                              |
 52   |        1.     6832.                                              R1-26         |
      |          *********                                                              |
 53   |   20   20    1    1   16   16                                   R1-26         |
      |                                                                                 |
 54   |        2.   0.00001                                              R1-26         |
      |                                                                                 |
 55   +   20   20    1    1   17   17                                   R1-26         +
      |                                                                                 |
 56   |        2.      488.                                              R1-26         |
      |                                                                                 |
 57   |   20   20    1    1   18   18                                   R1-26         |
      |                                                                                 |
 58   |        2.      976.                                              R1-26         |
      |                                                                                 |
 59   |   20   20    1    1   19   19                                   R1-26         |
      |                                                                                 |
 60   +        2.     1464.                                              R1-26         +
      |                                                                                 |
 61   |   20   20    1    1   20   20                                   R1-26         |
      |*******************                                                              |
 62   |        2.     1952.                                              R1-26         |
      |*******************                                                              |
 63   |                                                                  R1-26-BLN     |
      |                                                                                 |
 64   |                                                                  R1-33-BLN     |
      |                                                                                 |
 65   +    0    0    0                                                   I-1           +
      |                                                                                 |
 66   |       0.0                                                        R1A-2         |
      |                                                  *****                          |
 67   |    0    0    0    0    0    0    0    1    0    1                R2-1          |
      |     *****          *********                   *****                            |
 68   |    1   20    1    1+   (4)  +                                    R2-2.5        |
      |     *****          *********                                                    |
 69   |                                                                  R2-2.5-BLN    |
      |     *****                                                                       |
 70   +    1   20    0                                                   R2-11         +
      |     *****                                                                       |
 71   |       0.0       0.0                                                             |
      |                         *****                       *****                       |
 72   |    1    1    1    1    1    1  011    0 0000    0    1                R2-13         |
      |                         *****                       **.**                       |
 73   |    0    0    0    1    0    0    0    0    0                      R2-1-STOP     |
      |                                                                                 |
      +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 5.1-2 Continued.

dimensional analytical treatment and the two-dimensional numerical treatment. In general, the effects of the vertical flow may be minimized by making the vertical conductivity, a free parameter in this case, sufficiently large. For this problem, however, such was not necessary, and it was sufficient simply to set $K_z = K_x$.

Insofar as the horizontal transmissivity is concerned, however, the numerical treatment is very close to the analytical treatment. For a completely saturated grid block, the full thickness Δz is used for the transmissivity. However, for a partially saturated grid block, only the saturated thickness Δh is used:

$$T_x = K_x \Delta h \tag{5.1-8}$$

Results. Figure 5.1-3 shows the numerical solution plotted alongside the analytical solution, and Figure 5.1-4 shows the same numerical solution plotted in relation to the grid blocks. An evaluation of the flow yields

$$u_L \text{ (SWIFT)} = 1.10 \times 10^{-3} \text{ m}^3/\text{s/m} \tag{5.1-9a}$$

and

$$u_L \text{ (analytic)} = 1.13 \times 10^{-3} \text{ m}^3/\text{s/m} \tag{5.1-9b}$$

a difference of about three percent.

Discussion of the Code Output. The SWIFT results are taken basically from the tables which appear near the end of the output listing (see microfiche). Water-table elevations come from the table of grid-block saturations, and the flow rate u_L comes from the table of aquifer-influx rates. The former table is printed through control IIPRT, and the latter through control I06, both of which appear on Card R2-13. To interpret these tables, however, requires some additional data from the output. For example, by examining the former table, we note that, among the unsaturated blocks,

$$\bar{S}\ (I=6, K=5) = 0.8943 \tag{5.1-10a}$$

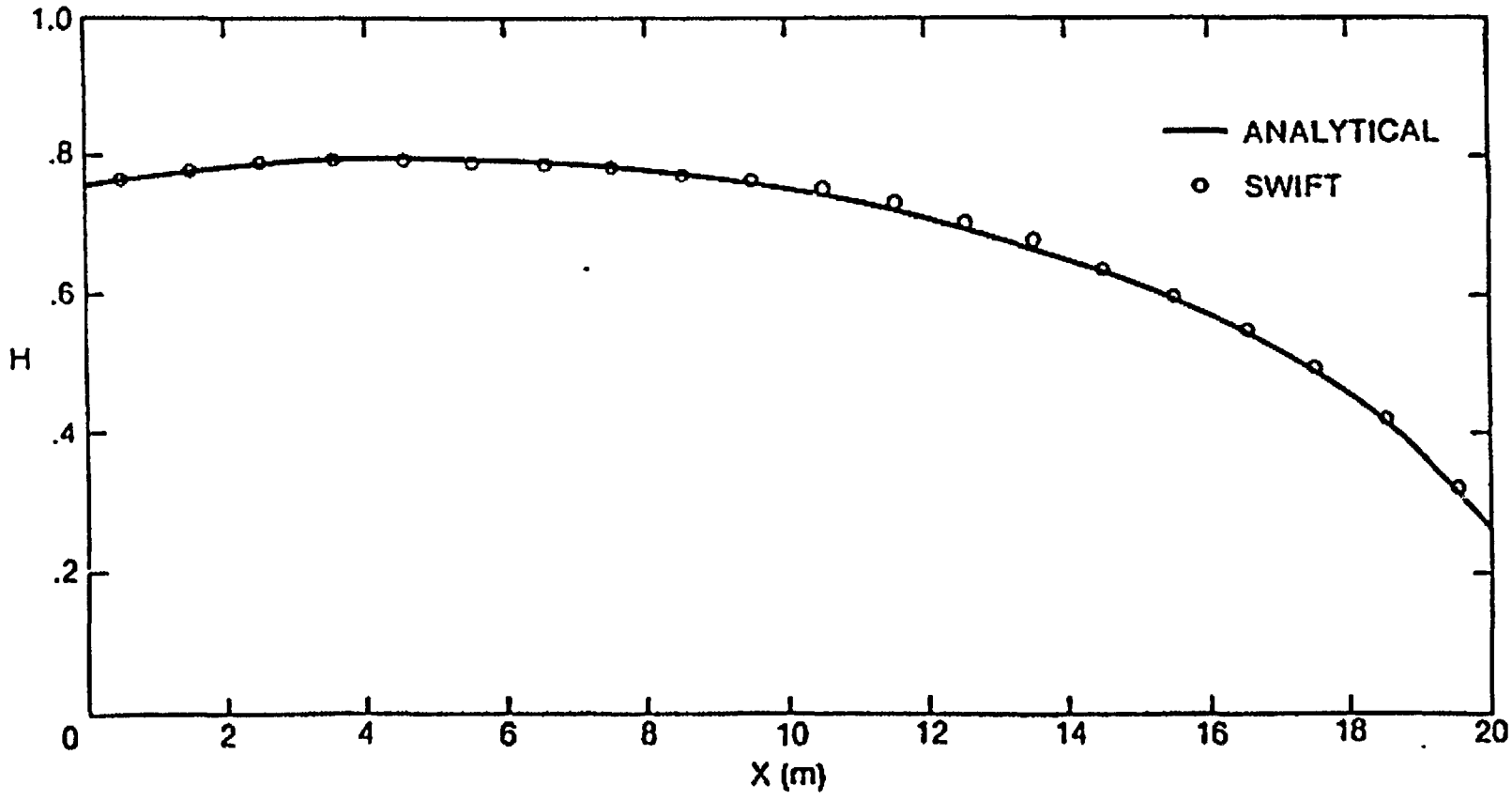

Figure 5.1-3. Steady-State Free-Water Surface for the Dupuit-Forchheimer Problem.

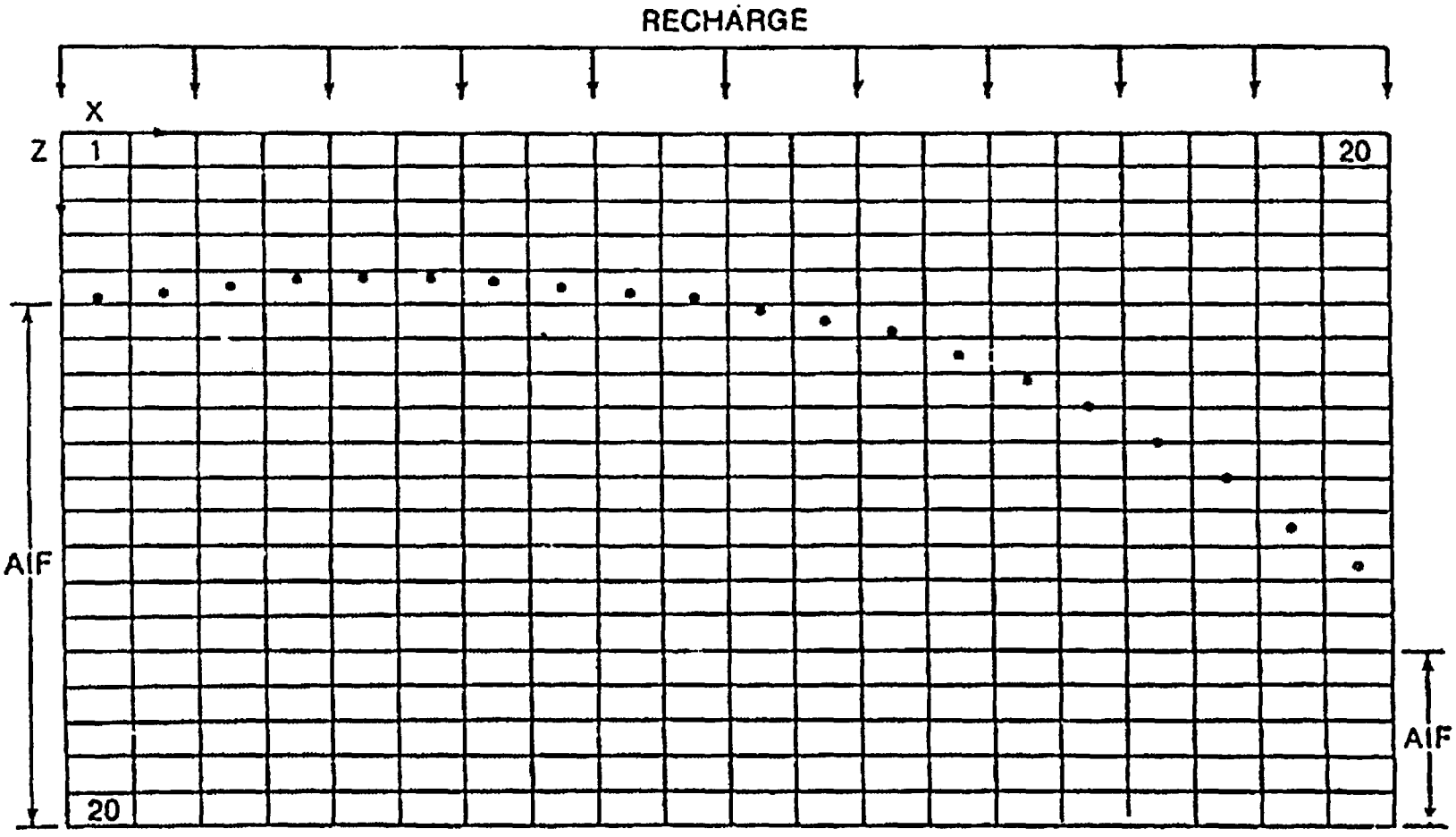

Figure 5.1-4. Geometrical Characterization of the Gridding, Boundary Conditions (Labelled "AIF") and the Recharge. The numerical solution is also shown in relation to the gridding.

is the maximum saturation. Grid-block tables, located near the front of the output, are then used to convert the grid-block saturation to the elevation

$$h\ (x_6 = 5.5\ \text{m}) = 0.795\ \text{m} \qquad (5.1\text{-}10b)$$

To interpret the aquifer-influx rates requires the use of another table of the input echo, namely the one for aquifer-influence block numbers. This table shows that for the boundary x = 0, the aquifer-influx blocks are labelled "1" through "15", whereas, for the boundary x = L, the boundary of interest here, they are labelled "16" through "20". Consequently, to obtain the flow quoted above in Equation (5.1-9), we form the sum

$$u_L = \sum_{N=16}^{20} u_{LN} = 1.10\ \text{kg/s/m} = 1.10 \times 10^{-3}\ \text{m}^3/\text{s/m} \qquad (5.1\text{-}11)$$

5.1.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1 From Table 5.1-1, what data are required for the blanks labelled "1" through "4" in Figure 5.1-2, the input data set? Check the answers by referring to the echo of the input data printed in the output.

Exercise 2 Interpret the boxed control parameters of Cards M-2, M-3-1, R2-1, R2-2.5 and R2-11.

Exercise 3 Interpret the control parameters VAB and then analytically verify the boundary pressures P1, as indicated in the R1-28 Cards. Use Equation (5.1-7). Also verify that these data were read correctly by the code by examining the tables entitled "Constant Pressure, Temperature, Concentrations Block Types" and "Constant Boundary Pressures".

Level 2. The reader who wants to develop a deeper understanding of the code should consider the following exercises:

Exercise 4 In the problem specifications the flow is essentially horizontal. To what extent can the simulation be modified before the Dupuit assumptions are in error? The problem as specified has a maximum free-water surface slope of approximately 1/10. Bear [1979, p.78] indicates that the error is small as long as $m^2 << 1$ where m is the slope of the free-water surface. The reader should challenge the code by increasing the slope and examining the error. This could be accomplished by increasing the recharge rate, decreasing the horizontal domain, and/or increasing vertical domain. An increase in the vertical conductivity may be required for some of these tests.

Exercise 5 Can the free-water surface option be used in cylindrical coordinates? Certainly, in fact, Bear [1972, p. 381] presents the analytical solution with which to compare. The reader is encouraged to switch to a cylindrical grid (HTG = 3, M-3) and execute this problem. We suggest a no-flow condition at the perimeter of the aquifer and a pumping well at the origin, completed in multiple layers, and subject to a specified bottom-hole pressure of zero.

Exercise 6 Can the free-water surface option be used for stratified aquifers? Yes. The reader is encouraged to design such a simulation in a Cartesian geometry (HTG = 2 in Card M-3) for comparison with the discharge formulas of Bear [1972, p. 370 ff]. The reader should introduce heterogeneity by adding layering in the R1-21 Cards.

5.2 PROBLEM 9. THE BOUSSINESQ TRANSIENT-STATE PROBLEM [BEAR, 1972]

5.2.1 Objective

- To demonstrate the simulation of transient-state flow in a phreatic aquifer.

5.2.2 Description of the Problem

Problem Statement. The following idealized problem is considered here: A phreatic aquifer (Figure 5.2-1), semi-infinite in length, is initially saturated to its full thickness so that

$$h(x,t=0) = h_o \quad , \quad x > 0 \qquad (5.2\text{-}1a)$$

Immediately thereafter, however, water is discharged at a sufficient rate to reduce the saturated thickness at one end to half its original amount, i.e.,

$$h(x=0,t) = h_o/2 \quad , \quad t > 0 \qquad (5.2\text{-}1b)$$

There is no recharge through the upper surface. The problem is to determine the elevation of the free-water surface h(x,t) as a function of position and time for the parameters given in Table 5.2-1.

Analytical Solution. Here, just as in Section 5.1, the Dupuit assumption (Equation 5.1-2a) is invoked, and the horizontal transmissivity is taken to be proportional to the saturated thickness h. The equation of continuity [Bear, 1972] may then be written:

$$\frac{\partial}{\partial x}\left(K_x h \frac{\partial h}{\partial x}\right) = \phi \frac{\partial h}{\partial t} \qquad (5.2\text{-}2)$$

This is the Boussinesq equation. Polubarinova-Kochina [Bear, 1972, p. 384] has obtained a general solution for this nonlinear equation, which is presented graphically in Figure 5.2-2.

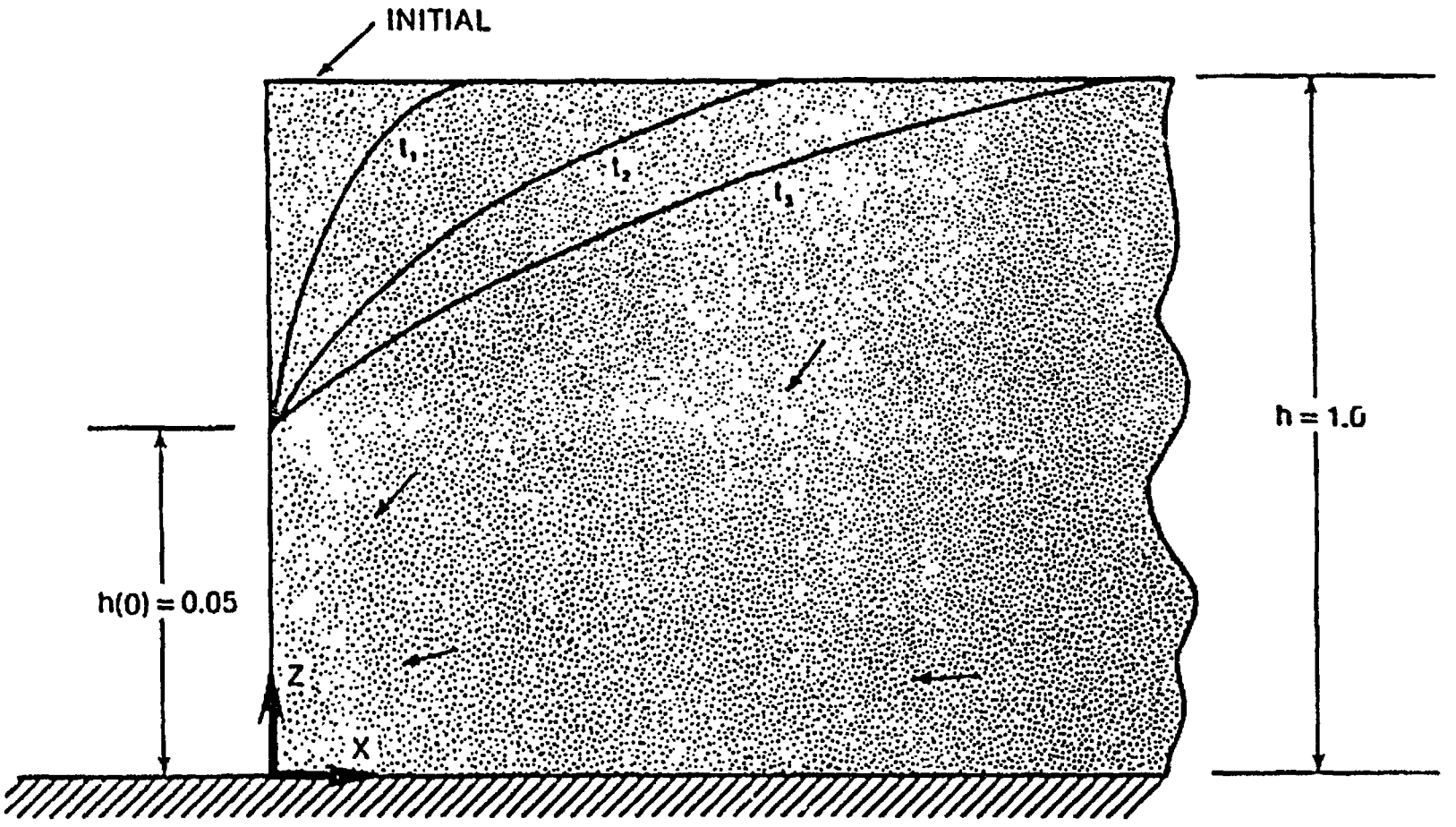

Figure 5.2-1. Problem 9. Schematic Diagram of the Boussinesq Problem.

Table 5.2-1. Problem 9. Input Specifications.

Parameter	Symbol	Value
Lateral Conductivity	K_x	0.01 m/s
Vertical Conductivity*	K_z	100.0 m/s
Porosity	ϕ	0.50
Initial Height of Free-Water Surface	h_o	1.0 m
Height of Free-Water Surface at x = 0	$h_o/2$	0.50 m

* Adjusted to a suitably large value to approximate the Dupuit Assumption.

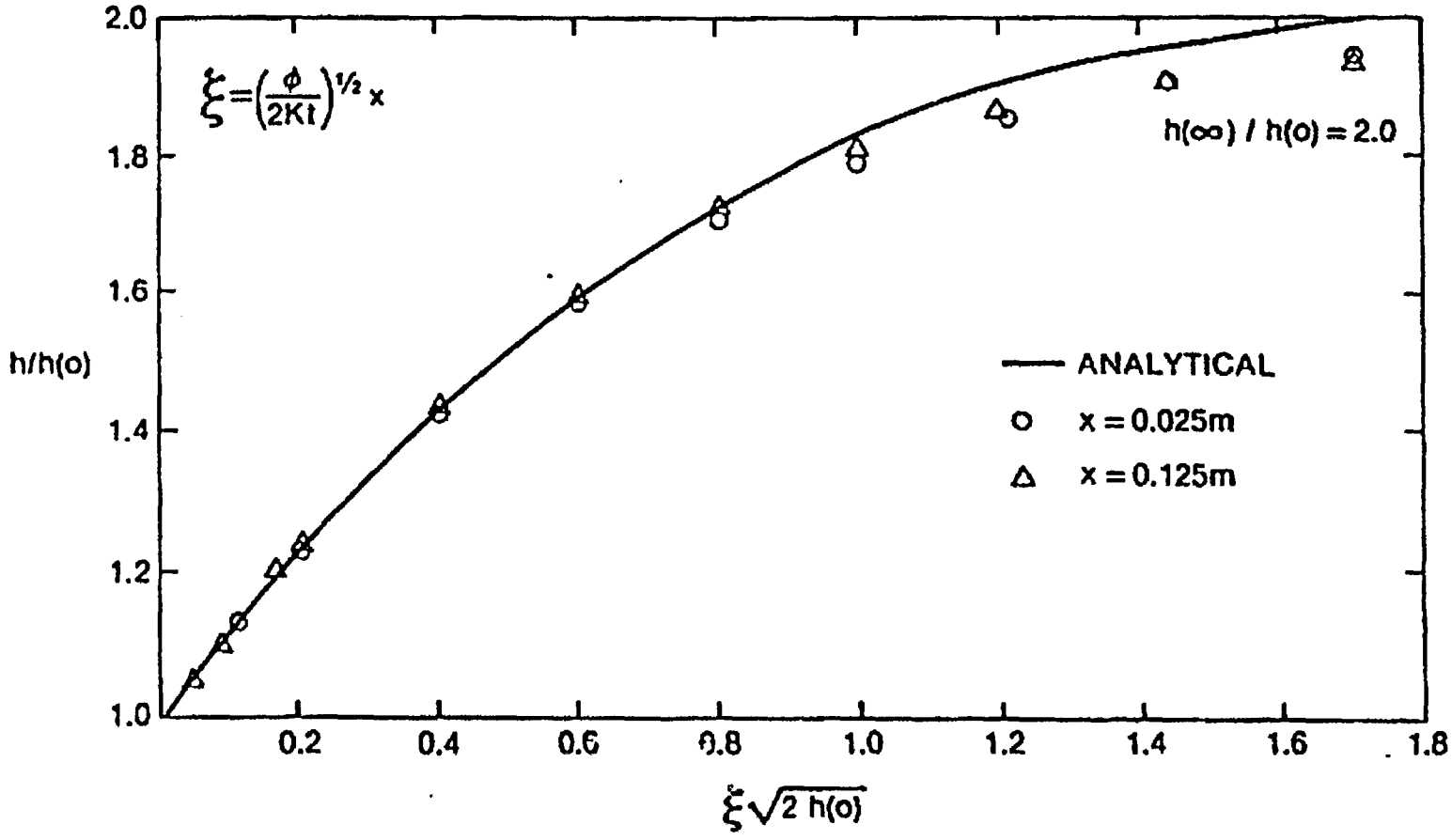

Figure 5.2-2. Transient-State Free-Water Surface for the Boussinesq Problem.

5.2.3 Numerical Solution

Discussion of Code Input. For the conduction mechanism (left-hand side of Equation (5.2-2)), the discussion here follows that of the previous problem, which may be summarized by the following three statements: Firstly, a two-dimensional grid (Figure 5.2-3 and Card M-3-1) is required for the numerical simulation as opposed to the simple one-dimensional analytical simulation. Secondly, the Dupuit assumption is not used by the numerical formalism but may be approximated by choosing a relatively large vertical conductivity K_z (Card R1-20). Thirdly, the assumption that the transmissivity is proportional to the saturated thickness is used in the numerical model just as in the analytical model.

For the accumulation mechanism, the analytical and numerical treatments are quite close. For the latter, the grid-block saturation is unity for each saturated grid block, but, for the partially-saturated block, it is

$$\bar{S} = \Delta h/\Delta z \qquad (5.2\text{-}3a)$$

where Δh measures the saturated thickness. By defining saturation in this manner, it can be shown that the general expression of accumulation, as given in the Theory and Implementation reduces, under appropriate conditions, to the right-hand side of Equation (5.2-3a):

$$\frac{\partial}{\partial t}(\phi\rho S) \rightarrow \phi\frac{\partial h}{\partial t} \qquad (5.2\text{-}3b)$$

Results. Figure 5.2-2 shows the numerical solution plotted alongside the analytical solution. For the most part, the agreement is quite reasonable. However, for the smaller values of time the numerical free-water surface does tend to drop somewhat more rapidly then does the analytical solution. Most likely, this deficiency could be corrected by a more refined spatial mesh and/or a larger value of the vertical conductivity.

Discussion of Code Output. As indicated in the discussion for the last problem, the height of the free-water surface is not a direct output of the code, but must be calculated from the output. Consequently, it is of interest

DRAFT

```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1 PROBLEM NO. 9, SWIFT II EXAMPLE, SI UNITS, 12/83,                          M-1-1
 2 BOUSSINESQ'S EQN. - TRANSIENT FREE-WATER DESATURATION FROM INIT. SAT.      M-1-2
 3    1    0    0    1    0    0    0    1    0                              M-2
 4   20    1   20    1    0    1    0    2    0   10    0    0    0          OM-3-1
 5    0    0    0                                                            M-3-2
 6  4.00E-10       0.0       0.0       1.0       1.0                         R1-1
 7       0.0       0.0       0.0       0.0       1.0       1.0  1.00E-10R1-2
 8    2130.0  1.00E 07      20.0    1000.0    100[illegible]                 R1-3
 9    0    2    2    2                                                        R1-6
10      20.0  1.00E-03      20.0  1.00E-03                                   R1-7
11      40.0  1.00E-03      80.0  1.00E-03                                   R1-9
12      40.0  1.00E-03      80.0  1.00E-03                                   R1-10
13       0.0      20.0          ..............................              R1-11
                                 . "***" REFERENCED IN TEXT     .
14    1000.0      20.0          . "***" REFERENCED IN EXERCISE .              R1-11
                                 ............. ................
15    0    0                                                                  R1-12
        ..   ******************
16      20.0*   (1)  **   (2)  *       0.0                                   R1-16
>*****************************************************
17    5*0.01    5*0.05    5*0.10    2*0.50     2*1.0       2.0
*****************************************************
18       1.0
**********
19  20*0.050
**********          ******************
20 **   (3)  *       1.0     100.0*   (4)  *       0.0       0.0       0.0R1-20
**********          ******************
21                                                                        R1-26-BLN
22    4    1                                                              R1-27
23    1    1    1    1   11   11                                          R1-28-1
24       1.   0.00001                                                      R1-28-2
25    1    1    1    1   12   12                                          R1-28-1
```

Figure 5.2-3. Listing of SWIFT II Input Data.

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
PROBLEM NO. 9. SWIFT II EXAMPLE. SI UNITS, 12/83.                          M-1-1
BOUSSINESQ'S EQN. - TRANSIENT FREE-WATER DESATURATION FROM INIT. SAT. M-1-2
   1    0    0    1    0    0    0    1    0                             M-2
  20    1   20    1    0    1    0    2    0   10    0    0    0         OK-3-1
   0    0    0                                                           M-3-2
 4.00E-10       0.0       0.0       1.0       1.0                        R1-1
      0.0       0.0       0.0       0.0       1.0       1.00E-10R1-2
   2130.0  1.00E 07      20.0    1000.0    1000.0                        R1-3
   0    2    2    2                                                      R1-6
     20.0  1.00E-03      20.0  1.00E-03                                  R1-7
     40.0  1.00E-03      80.0  1.00E-03                                  R1-9
     40.0  1.00E-03      80.0  1.00E-03                                  R1-10
      0.0      20.0          ******************************              R1-11
                             * "***" REFERENCED IN TEXT     *
   1000.0      20.0          * "***" REFERENCED IN EXERCISE *            R1-11
                             ******************************
   0    0                                                                 R1-12
          ******************
     20.0*   (1)  **   (2)  *       0.0                                  R1-16
*****************************************************
   5*0.01    5*0.05    5*0.10    2*0.50    2*1.0       2.0
*****************************************************
      1.0
*********
  20*0.050
*********          ******************
**   (3)  *       1.0     100.0*   (4)  *       0.0       0.0       0.0R1-20
*********          ******************
                                                                        R1-26-BLN
   4    1                                                               R1-27
   1    1    1    1   11   11                                           R1-28-1
      1.   0.00001                                                      R1-28-2
   1    1    1    1   12   12                                           R1-28-1
```

Figure 5.2-3. Listing of SWIFT II Input Data.

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
I*******************                                                            I
26 I        1.      488.                                                  R1-28-2  I
I*******************                                                            I
27 I    1    1    1    1   13   13                                        R1-28-1  I
I                                                                                  I
28 I        1.      976.                                                  R1-28-2  I
I                                                                                  I
29 I    1    1    1    1   14   14                                        R1-28-1  I
I                                                                                  I
30 +        1.     1464.                                                  R1-28-2  +
I                                                                                  I
31 I    1    1    1    1   15   15                                        R1-28-1  I
I                                                                                  I
32 I        1.     1952.                                                  R1-28-2  I
I                                                                                  I
33 I    1    1    1    1   16   16                                        R1-28-1  I
I                                                                                  I
34 I        1.     2440.                                                  R1-28-2  I
I                                                                                  I
35 +    1    1    1    1   17   17                                        R1-28-1  +
I                                                                                  I
36 I        1.     2928.                                                  R1-28-2  I
I                                                                                  I
37 I    1    1    1    1   18   18                                        R1-28-1  I
I                                                                                  I
38 I        1.     3416.                                                  R1-28-2  I
I                                                                                  I
39 I    1    1    1    1   19   19                                        R1-28-1  I
I                                                                                  I
40 +        1.     3904.                                                  R1-28-2  +
I                                                                                  I
41 I    1    1    1    1   20   20                                        R1-28-1  I
I                                                                                  I
42 I        1.     4392.                                                  R1-28-2  I
I                                                                                  I
43 I                                                                      R1-28-BLN I
I                                                                                  I
44 I                                                                      R1-33-BLN I
I                                                                                  I
45 +    0    0    0                                                       I-1      +
I                                                                                  I
46 I       0.0                                                            R1A-2    I
I                                                                                  I
47 I    0    0    0    0    0    0    0    0    0    0                   R2-1     I
I                                                                                  I
48 I 1.00E-07  1.00E-07                                                            I
I                                                                                  I
49 I    0    1    0    1    1    0  111    0 0000    0    0               R2-13    I
I                                                                                  I
50 +    0    0    0    0    0    0    0    0    0    0    0               R2-1     +
I                                                                                  I
+---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 5.2-3 Continued.

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
51  6.25E-04 6.249E-04
52     1    1    1    1    1    1  111    0 0000    0   11              R2-13
53     0    0    0    0    0    0    0    0    0    0                   R2-1
54 9.76563E-43.51563E-4
55     1    1    1    1    1    1  111    0 0000    0    0              R2-13
56     0    0    0    0    0    0    0    0    0    0                   R2-1
57 1.76311E-37.86547E-4
58     1    1    1    1    1    1  111    0 0000    0    0              R2-13
59     0    0    0    0    0    0    0    0    0    0                   R2-1
60 3.90625E-3       0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04
61     1    1    1    1    1    1  111    0 0000    0    0              R2-13
62     0    0    0    0    0    0    0    0    0    0                   R2-1
63 1.5625E-02       0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04
64     1    1    0    1    1    1  111    0 0000    0   11              R2-13
65     0    0    0    0    0    0    0    0    0                        R2-1
66 0.0244141        0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04
67     1    1    1    1    1    1  111    0 0000    0    0              R2-13
68     0    0    0    0    0    0    0    0    0    0                   R2-1
69 0.0434028        0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04
70     1    1    1    1    1    1  111    0 0000    0    0              R2-13
71     0    0    0    0    0    0    0    0    0    0                   R2-1
72 0.0976563        0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04
73     1    1    1    1    1    1  111    0 0000    0    0              R2-13
74     0    0    0    0    0    0    0    0    0    0                   R2-1
75 0.390625         0.0       0.0       0.0    1000.0       0.0       0.0  6.25E-04
```

Figure 5.2-3 Continued.

DRAFT

```
                1         2         3         4         5         6         7         8
       12345678901234567890123456789012345678901234567890123456789012345678901234567890
     +----------+----------+----------+----------+----------+----------+----------+
     I                                                                              I
  76 I   1    1    0    1    1    1  111    0 0000    0   11              R2-13     I
     I                                                                              I
  77 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  78 I  0.61035       0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
  79 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
  80 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  81 I  1.08507       0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
  82 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
  83 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  84 I  1.285625      0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
  85 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
  86 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  87 I  1.97754       0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
  88 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
  89 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  90 I  2.44141       0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
  91 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
  92 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  93 I  3.515625      0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
  94 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
  95 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  96 I  7.910165      0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
  97 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
  98 I   0    0    0    0    0    0    0    0    0    0                   R2-1      I
     I                                                                              I
  99 I  4.76563       0.0       0.0       0.0    1000.0       0.0       6.0  6.25E-04I
     I                                                                              I
 100 I   1    1    1    1    1    1  111    0 0000    0    0              R2-13     I
     I                                                                              I
     +----------+----------+----------+----------+----------+----------+----------+
```

Figure 5.2-3 Continued.

DRAFT

```
          1         2         3         4         5         6         7         8
 12345678901234567890123456789012345678901234567890123456789012345678901234567890
     +---------+---------+---------+---------+---------+---------+---------+---------+
     I                                                                                 I
101  I    0    0    0    0    0    0    0    0    0    0                   R2-1       I
     I                                                                                 I
102  I   31.6406       0.0       0.0       0.0    1000.0       0.0       25.0  6.25E-04I
     I                                                                                 I
103  I    1    1    1    1    1    1  111    0 0000    0   11                R2-13      I
     I                                                                                 I
104  I    0    0    0    1    0    0    0    0    0                         R2-1-STOP  I
     I                                                                                 I
     +---------+---------+---------+---------+---------+---------+---------+---------+
```

Figure 5.2-3 Continued.

to go through the appropriate procedure once again. This time, however, rather than using the grid-block saturations, as was done for Problem 8, we shall use the grid-block pressures directly.

Turn in the output to the input echo, and from the output table entitled "X-Direction Di tance to Grid-Block Center" (see microfiche), note that the distance

$$x = 0.025 \text{ m} \tag{5.2-4a}$$

falls at the center of the Blocks I = 3. This is one of the distances used for Figure 5.2-2. Advancing to the pressure-at-elevation table for time

$$t = 9.77 \times 10^{-2} \text{ s} \tag{5.2-4b}$$

for which

$$\xi = (\phi/2K_x t)^{1/2} x = 0.4 \tag{5.2-4c}$$

we cbserve that

$$p(3,6) = -287.6 \text{ Pa} \tag{5.2-5a}$$

Thus the unsaturated block thickness is

$$\Delta h(3,6) = 0.0293 \text{ m} \tag{5.2-5b}$$

Since the block thicknesses are $\Delta z = 0.05$ m throughout, we easily compute

$$h(x,t) = (15)(0.05) - 0.0293 = 0.721 \tag{5.2-6a}$$

in agreement with Figure 5.2-4. Converting to a dimensionless scale with maximum elevation $h_o = 2$ m, we obtain

$$h/h_o(\xi = 0.4) = 1.44 \tag{5.2-6b}$$

in agreement with Figure 5.2-2.

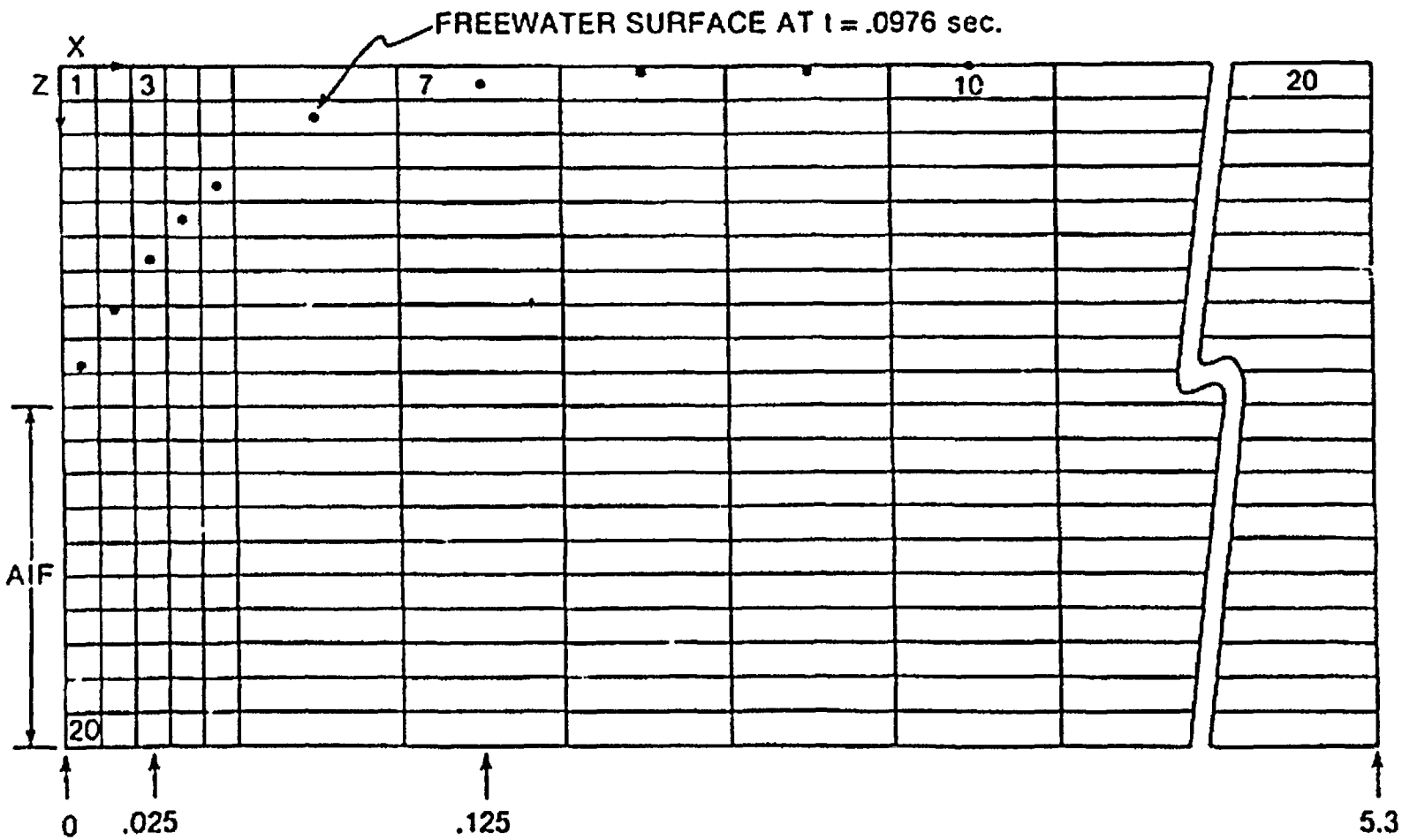

Figure 5.2-4. Geometrical Characterization of the Gridding and Boundary Conditions (Labelled "AIF") in Relation to the Numerical Solution.

5.2.4 Exercises

Level 1. Using the Input-Data Guide, the Theory and Implementation and the microfiche listing of the output, as required, complete the following exercises:

Exercise 1 From the description of the problem and Table 5.2-1, what data are required for the blanks labelled "1" through "4" in Figure 5.2-3, the input data set. Check the answers by referring to the echo of the input data in the output.

Exercise 2 Explain the reason for the relatively large value of K_z (Card R1-20) and verify the boxed numbers in Card R1-28. Hydrostati equilibrium (Equation 5.1-7) is assumed here just as for Probl 8.

Exercise 3 What is the total flow rate passing through the boundary block

Level 2. The reader who wants to develop a deeper understanding of the code should also consider the following exercise:

Exercise 4 Convert the Problem 9 data set (Figure 5.2-3) to cylindrical coordinates using a multiply-completed well with a bottom-hole pressure of zero to establish the boundary condition. Rerun t problem and plot the results using the same variables (h/h_o and ($\xi = (\phi/2Kt)^{1/2} r$) and scaling as in Figure 5.2-2. Should the radial results lie above or below the Cartesian results? Why?

NOTATION*

ROMAN SYMBOLS

a	thickness of prism or radius of sphere for the local subsystem
a_W	explicit portion of e_W, the boundary flow rate of the simulated aquifer
A	radial grid block-ratio
A_V	global/local interface area specific to global volume
A_m	specific activity
b	aquifer thickness
b'	aquitard thickness
b_W	implicit portion of e_W, the boundary flow rate of the simulated aquifer
c_{pR}	specific heat of the rock
c_R	compressibility of the pores
c_w	compressibility of the fluid
C	concentration of radioactive (trace) components

---

* The terms "global" and "local" are used in this section. Typically the global model is used to represent the fractures or the aquifer. It is regionally connected and may be three-dimensional. Usually the local submodel is used to represent either the porous rock matrix or the confining beds. It is one-dimensional only.

d fracture half-thickness

D dispersion/diffusion

D_m molecular diffusion in porous medium

D^* molecular diffusion in water

e_W boundary flow rate into the simulated aquifer arising from the aquifer which surrounds it

g acceleration of gravity

g_c units conversion factor equal to g for the English system and equal to unity for the SI system

h head

H total head

I radionuclide inventory

k_d radionuclide distribution coefficient

K_v dimensionless distribution coefficient, $K_v = \rho_R k_d$

K retardation factor or hydraulic conductivity

L length

m density of radioactive waste, i.e., mass of radionuclide per volume of waste

n_s number of nodes within a local unit

p pressure where subscripts 0 and 1 refer to boundary locations

P_I terminal-rate influence function, used for model external aquifer

q mass source rate or fluid recharge rate

q_w radionuclide source due to waste leaching

Q rate of fluid withdrawal from well

r radial coordinate

r_e external radius of aqifer model

r_o extent of stress-relief fracturing

r_w radius of wellbore

r_1 radius of skin or radius to center of first grid block

R_w source term for release of nuclides from the waste matrix

s one-dimensional coordinate for the local units. In formal equations $s = 0$ represents local/global interface. In code, however, $s = 0$ represents the external boundary of the local subsystem.

$\bar{s}$ drawdown

S storativity

S_s specific storativity

$\bar{S}$ saturation

t time

t_a total leach time

t_D dimensionless time

T temperature, transmissivity or leach duration time

u Darcy flux

U mass flow rate through radionuclide inventory

v interstitial velocity

WI well index

x,y,z Cartesian coordinates

GREEK SYMBOLS

α_L longitudinal dispersivity

Γ global-to-local radionuclide transfer rate

Γ_H global-to-local heat transfer rate

Γ_W global-to-local flow rate

δp incremental change in pressure over a time step Δt

Δh head increment

Δs spatial increment in s for the ' . ' subsystem

Δt time increment

Δx_i spatial increment in x_i where $x_1 = x$, $x_2 = y$ and $x_3 = z$

λ decay constant

ξ dimensionless Boltzmann variable

ρ fluid density

ρ_R formation density

ρ_w volumetric waste density, i.e., volume of waste per bulk volume

τ radionuclide half-life

$\bar{\tau}$ tortuosity

ϕ porosity

SUBSCRIPTS

m fluid-plus-rock composite material

r radioactive component. Subscript is suppressed whenever no confusion should arise. If given as an integer, r is the component number in a chain of species.

w radionuclide source (repository)

x,y,z directional indicator

SUPERSCRIPTS

' denotes local subsystem

~ indicates characteristic length

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APPENDIX

CONVERSION OF INPUT DATA FROM SWIFT TO SWIFT II

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
|                                                                          M-1    |
1|                                                                          M-1    |
2|                                                                          M-2    |
3|              IFREE NPLP NPLT NPLCIUNIT LRID                              |
|              +----+                    +----+                              |
4|                                                NRCHMNETHONTIMEKHCATM-3-1      |
|                                                +----+++++++++++++++-----+     |
5|NREPSKSLVD NRTDKOUTD                                                      M-3-2  |
|     +----+----+----+                                                      |
6|                                                                          RO-1-1 |
|                                                                          |
7|                              *** INDICATES THAT THESE VARIABLES          RO-1-2 |
|                                  ARE SITUATED IN REVISED FORMAT          |
8|                                  FIELDS.                                 RO-2-1 |
|                                                                          |
9|       DIS                                                                RO-2-2 |
|+---------+                                                               |
10|ICNVD                                                                     ROD-1  |
|+----+                                                                    |
11|  NSD                                                                     ROD-2  |
|+----+                                                                    |
12|  I1A  I1B  J1A  J1B  K1A  K1B   IR  IFD                                  ROD-3  |
|+----+----+----+----+----+----+----+----+                                  |
13| IMPT                                                                     M-6    |
|+----+                                                                    |
14|  MAP                                                                     M-7    |
|+----+                                                                    |
15|                                                                          R1-1   |
|                     *-* INDICATES A NEW VARIABLE FOR SWIFT.II            |
16|                                                                          R1-2   |
|                                                                          |
17|                                                                          R1-2.5 |
|                                                                          |
18|                                                                          R1-3   |
|                                                                          |
19|                                                                          R1-4   |
|                                                                          |
20|                                                                          R1-5   |
|                                                                          |
21|                                                                          R1-6   |
|                                                                          |
22|                                                                          R1-7   |
|                                                                          |
23|                                                                          R1-8   |
|                                                                          |
24|                                                                          R1-9   |
|                                                                          |
25|                                                                          R1-10  |
| (NOTE: DUE TO SPACE LIMITATIONS CERTAIN VARIABLE NAMES HAVE BEEN TRUNCATED)      |
+---------+---------+---------+---------+---------+---------+---------+---------+
```

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
26 :                                                                          R1-11     :
27 :                                                                          R1-12     :
28 :                                                                          R1-13     :
29 :                                                                          R1-14     :
30 :                                                                          R1-15     :
31 :                                                                          R1-16     :
32 :                                                                          R1-17     :
33 :                                                                          R1-18     :
34 :                                                                          R1-19     :
35 :                                                                          R1-20     :
36 :                                                                          R1-21-1   :
37 :                                                                          R1-21-2   :
38 :                                                                          R1-22     :
39 :                                                                          R1-23     :
40 :                                                                          R1-25     :
41 :                                                                          R1-26-1   :
42 :                                                   FPMI      MADD     THADDR1-26-2  :
43 :      FTUX      FTUY      FTUZ                                          R1-26-3   :
44 :                                                                          R1-27     :
45 :                                                                          R1-28-1   :
46 :                                                                          R1-28-2   :
47 :                                                                          R1-29     :
48 :                                                                          R1-30-1   :
49 :                                                                          R1-30-2   :
50 :                                                                          R1-31     :
```

DRAFT

```
          1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
51 |                                                                   R1-32     |
52 |                                                                   R1-33-1   |
53 |                                                                   R1-33-2   |
54 |       CRD                                                         R1D-1     |
   |+--------+                                                                   |
55 +     DMEFD     DMFDT      PHID      AKSD      ALPD      UKTD     CPRKDR1D-2-1 +
   |+--------+--------+--------+--------+--------+--------+--------+            |
56 |  KGD KGRD       SAD       DSD      DSDD                          R1D-2-2   |
   |+---+---+--------+--------+--------+                                         |
57 |        DS                                                         R1D-2-3   |
   |+--------+                                                                   |
58 |   IR  KBC  KPB KTPB KSWB                                          R1D-3-1   |
   |+---+---+---+---+---+                                                        |
59 |       PBD      TPBD      SWBD                                     R1D-3-2   |
   |+--------+--------+--------+                                                 |
60 +      DISD                                                         R1D-4     +
   |+--------+                                                                   |
61 |                                                                   I-1       |
62 |                                                                   I-2       |
63 |                                                                   I-3       |
64 |                                                                   I-4       |
65 +                                                                   R1A-1     +
66 |                                                                   R1A-2     |
67 |                                                                   R1A-3     |
68 |                                                                   R1A-4     |
69 |                                  CONVH                            R1A-5     |
   |                              +--------+                                     |
70 +                                                                   R1A-6     +
71 |                                                                   R1A-7     |
72 |                                                                   R1A-8     |
73 |     ARHLD                                                         R1A-8.5   |
   |+--------+                                                                   |
74 |                                                                   R1A-9     |
75 + IDSC JDSC KDSC                                                    N-1       +
   |+---+---+---+                                                                |
   +---------+---------+---------+---------+---------+---------+---------+---------+
```

DRAFT

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
+---------+---------+---------+---------+---------+---------+---------+---------+
|                                                                                |
76 |                                          IRCH                    R2-1      |
|                                          +----+                                |
77 |                                                                  R2-2      |
|                                                                                |
78 |   I1   I2   J1   J2      RCHG                                    R2-2.5    |
|+---+---+---+---+---------+                                                     |
79 |                                                                  R2-3      |
|                                                                                |
80 +                                                                  R2-4      +
|                                                                                |
81 |                                                                  R2-5      |
|                                                                                |
82 |                                                                  R2-6      |
|                                                                                |
83 |                                                                  R2-7-L    |
|                                                                                |
84 |                                                                  R2-7-2    |
|                                                                                |
85 +                                                                  R2-7-3    +
|                                                                                |
86 |                                                                  R2-7-4    |
|                                                                                |
87 |                                                                  R2-8      |
|                                                                                |
88 |                                                                  R2-9      |
|                                                                                |
89 |                                                                  R2-10     |
|                                                                                |
90 +                                                                  R2-10.5   +
|                                                                                |
91 |              IXYZPIXYZTIXYZCIXYZN IBUD      TRUD                 R2-11     |
|              +---+---+---+---+---+---+---+---+                                |
92 |                                                                  R2-11.5   |
|                                                                                |
93 |                                                                  R2-12     |
|                                                                                |
94 |                                                        IDSD IDBDIIPRTR2-13 |
|                                                        +---+---+---+---+       |
95 +NDKXYNDRXZ                                                       R2-14     +
|+---+---+---+                                                                  |
96 |      XYXL       XYYL       XZXL       XZZL                      R2-14.5   |
|+---------+---------+---------+---------+                                     |
97 |                                                                  R2-15     |
|                                                                                |
98 |                                                                  P-2       |
|                                                                                |
99 |                                                                  P-3       |
|                                                                                |
100 +                                                                 P-4       +
|     (NOTE: REVISED FORMAT FOR "IIPRT", R2-13: I.E. CHANGE "1" TO "11"1        |
+---------+---------+---------+---------+---------+---------+---------+---------+
```

DRAFT

MINIMAL CHANGES REQUIRED TO CONVERT A DATA SET FROM SWIFT I 4.61 TO SWIFT II 12.83

CARD	CHANGES
M-2	ADD IFREE = 0 AND SHIFT VARIABLES NPLC-IUNIT TO THE RIGHT ADD LSID=0
M-3	SPLIT ONTO TWO CARDS, DROP NAAR, ADD NRCHMX=0, KHEAT=0, KSLVD=0, NRTD=0, KOUTD=0
R1-26-2	ADD FPMI=0., SHIFT HADD AND THADD RIGHT
R1-26-3	ADD A BLANK (FTUX=0, FTUY=0, FTUZ=0)
R1A-5	ADD CONVH=0.
R2-1	ADD IRCH (USE DEFAULT=0)
R2-11	ADD IXYZP, IXYZT, IXYZC, IXYZC, IBUD, TBUD (ALL SET = 0)
R2-13	ADD IOSO, IOBO, IIPRTO (ALL SET = 0)
R2-14	REVISED VARIABLES FOR ENHANCED MAPPING AS NECESSARY
R2-14.5	REVISED VARIABLES FOR ENHANCED MAPPING AS NECESSARY

PROPOSED TAB TITLES

INTRODUCTION

TRANSPORT WITH DUAL POROSITY

PROB. 1: One Nuclide, Frac./Prism. Matrix

PROB. 2: One Nuclide, Frac./Spher. Matrix

PROB. 3: Nuclide Chain, Frac./Prism. Matrix

FLOW WITH DUAL POROSITY

PROB. 4: Well-Test in Dolomite

PROB. 5: Well-Test in Glacial Aquifer

FLOW AND TRANS. WITH AQUIFER/CONFINING BEDS

PROB. 6: Flow thru Aquitards

PROB. 7: Heat Trans. from Confining Beds

FLOW WITH FREE-
WATER SURFACE

PROB. 8: Steady State

PROB. 9: Transient State

NOTATION

REFERENCES

CONVERSION FROM
SWIFT TO SWIFT II