SANDIA REPORT

SAND86—0369 • Unlimited Release • UC—70
Printed December 1986

Mass Balance Computation in SAGUARO

Bruce L. Baker, Roger R. Eaton

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

SAND86-0369
Unlimited Release
Printed December 1986

Mass Balance Computation in SAGUARO

Bruce L. Baker
Technadyne Engineering Consultants Inc.
P. O. Box 13928, Albuquerque, New Mexico 87192

Roger R. Eaton
Fluid and Thermal Sciences Department
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

This report describes the development of the mass balance subroutines used with the finite-element code, SAGUARO, which models fluid flow in partially saturated porous media. Derivation of the basic mass storage and mass flux equations is included. The results of the SAGUARO mass-balance subroutine, MASS, are shown to compare favorably with the linked results of FEMTRAN. Implementation of the MASS option in SAGUARO is decribed. Instructions for use of the MASS option are demonstrated with three sample cases.

CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

The finite-element code, SAGUARO (Eaton, Gartling, and Larson, 1983), has been used extensively to model groundwater flow in the partially saturated porous media region near a proposed nuclear waste repository site.* In modeling these types of problems, transient water fluxes are calculated for very long time periods. The accuracy of these long-time calculations cannot be directly verified by experiments or by comparison with analytic solutions as a result of the complexity of the problems attempted. Hence, as an indicator of the accuracy of the hydrologic solution, mass-balance routines have been written and incorporated into the SAGUARO code. These routines allow the user to specify regions, not necessarily contiguous regions, over which to calculate the mass balance by listing the grid elements making up that region. The exterior boundary sides for mass-flux calculations are then automatically determined from this element list.

The mass-balance calculation includes: (1) computation of the total mass stored within the specified region at the current time, (2) the mass flux through all the specified boundary sides, (3) the change in the mass stored in the specified region during the last time step, and (4) the net mass gain in the region, which is the difference between the change in mass

---

*The Nevada Nuclear Waste Storage Investigations Project, managed by the Nevada Operations Office of the U. S. Department of Energy, is examining the feasibility of siting a repository for high-level nuclear wastes at Yucca Mountain, on and adjacent to the Nevada Test Site. This work was funded in part by the NNWSI Project. The ultimate use of this information will be to develop appropriate criteria for design of subsurface facilities and for performance assessments of the site.

stored and the mass flux through the boundaries. A zero net mass gain indicates perfect conservation of the calculated mass.

The first section of this report is a brief description of the equations and techniques used to derive the mass-balance equations. Next is the definition of the input to the program necessary to implement the MASS options. The third section shows results from three test problems selected to demonstrate the use of SAGUARO's MASS command and test the mass-balance equation implementation.

2.0 FORMULATION OF MASS BALANCE EQUATIONS

The mass-balance procedure contains two calculations for a given time step: (1) calculation of the total mass stored within the specified region, and (2) calculation of the mass flux through the region boundary during this time step.

2.1 Total Stored Mass

The region for calculation of stored mass is specified by a user-defined input list (see Subsection 2.2). The total mass stored at time t for each element in this region is calculated by

$$m_s = \int \rho_f \theta dA \tag{1}$$

where ρ_f is the liquid density and θ is the volumetric moisture content (volume of water / total unit volume). To evaluate this integral over a region dA, the moisture content is expressed in terms of the finite-element shape functions, θ^T, and calculated moisture contents at node points at specific times, $\theta(x,y,t)$. The area dA is evaluated using the Jacobian, J, and the normalized natural coordinates s and t for the element. Therefore,

$$\theta = \theta^T \theta(t) \tag{2}$$

and

$$dA = |J| ds\, dt. \tag{3}$$

SAGUARO uses the Boussinesq approximation, which states

$$\rho_f = \rho_o(1-g\beta\Delta T) \tag{4}$$

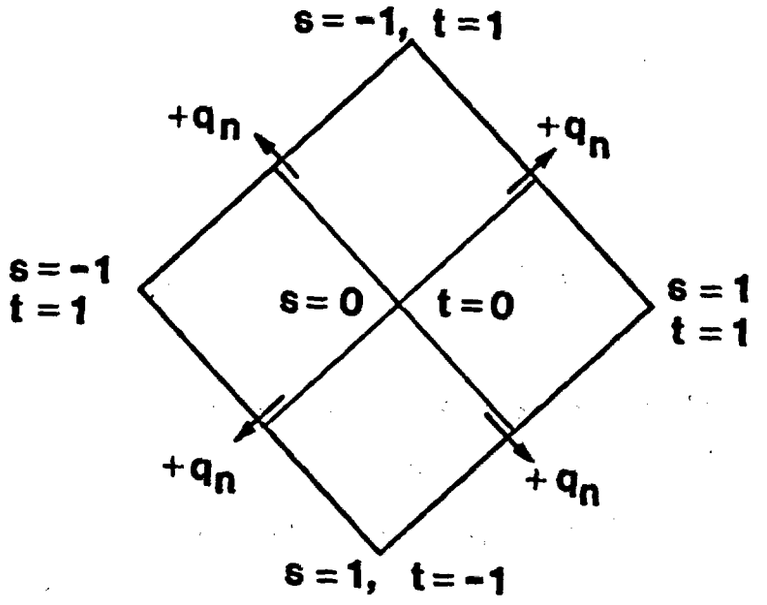
where β is the compressibility, ρ_o is the density at the initial temperature T_o, and $\Delta T = T - T_o$. For mass flux calculations, it is generally true that $g\beta\Delta T << 1$, and thus, the water density is assumed to be constant. Using this assumption, the original integral (1) becomes

$$\rho_f \int_{\Theta}^{T} |J| ds\, dt\Theta(t) \tag{5}$$

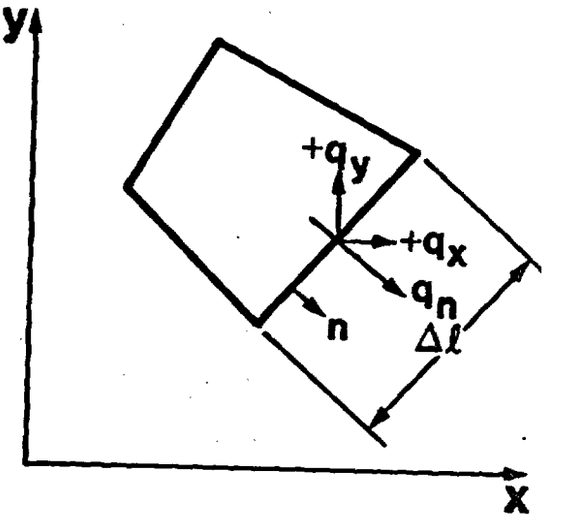
with $\Theta(t)$ being the only time-dependent term. The time-invariant portion of Equation (5) is calculated once per run, along with the geometric shape functions in the FORMKF subroutine. At each time step, the calculated moisture content $\Theta(t)$ is used to evaluate the integral in Equation (5) to solve for the total mass stored. The mass-stored value is then compared to the value at the last time step to compute the change in mass stored.

2.2 Mass Flux Across the Boundary

The exterior sides defining the boundary of the mass-balance area are derived automatically from the list of elements specified by the user. This boundary may define a contiguous region or be made of disjoint parts. Flux across the boundary of an arbitrary region is expressed in terms of the natural coordinates (s,t) for an element; see Figure 1-1a.



1a. Normal Flux in Natural Coordinates (s,t)



1b. Orthogonal Components of Total Flux (x, y)

Figure 1-1. Mass-Flux Coordinates

The normalized flux q_n is positive in a direction out of the element, whereas the orthogonal fluxes q_x and q_y are positive up and to the right (see Figure 1-1b). The mass-flux equations based on this sign convention, where n_x and n_y are the x and y components of the unit normal vector n, are derived as follows:

$$q_n = [(q_x n_x + q_y n_y)\Delta\ell]\ \Delta t = [(q_x \frac{\partial y}{\partial \ell} + q_y [\frac{-\partial x}{\partial \ell}])\Delta\ell]\ \Delta t \quad .$$

Therefore,

$$q_n = [(q_x\ (\ y_{i+1} - y_i) - q_y(\ x_{i+1} - x_i)]\ \Delta t \tag{6}$$

with x_i, y_i and x_{i+1}, y_{i+1} the cartesian coordinates of points i and i+1, respectively, and $\Delta\ell$ is the length of a side dA. If u and v are the horizontal and vertical components of the velocity, then the orthogonal fluxes are given by

$$q_x = \rho_f u_{average} = \rho_f (u_i + u_{i+1})/2 \tag{7a}$$

and

$$q_y = \rho_f v_{average} = \rho_f (v_i + v_{i+1})/2. \tag{7b}$$

The total normal mass flux across an element boundary is

$$q_n = 1/2\ \rho_f \Delta t[(u_i + u_{i+1})(y_{i+1} - y_i) - (v_i + v_{i+1})(x_{i+1} - x_i)]. \tag{8}$$

3.0 PROGRAM INPUT REQUIREMENTS

The input data required to use the mass-balance option are given below. The format of this section is identical to the one used in the SAGUARO user's manual (Eaton, Gartling, and Larson, 1983). Reference should be made to this manual to completely understand the structure of the input data.

3.1 Mass Command Card

The MASS command requests the computation, at every time step, of a mass balance over a defined region. To allow for an arbitrary region, possibly non-contiguous, the MASS command allows selection of individual grid elements. The selection of elements may be set up by using one or more of the following command cards:

MASS,delimiter type,n1,n2,...,n50.

where

delimiter type is an alphanumeric name indicating how the element arguments are to be interpreted. If delimiter type = SINGLE, each argument is an individual element number. If delimiter type = RANGE, every two arguments are interpreted as a pair, specifying an inclusive series of elements to be included in the mass balance (i.e., MASS,RANGE,5,9,14,18. specifies elements 5,6,7,8,9,14,15,16,17,18).

n1,n2,n3,...,n50 is a list of element numbers indicating which elements are to be included in the mass-balance calculation. A maximum of 50 individual elements or 25 element ranges may be specified on a single MASS command card. There is no restriction on the number of MASS commands or the mixing of MASS cards of different delimiter types in the same input deck.

The MASS command cards must be placed somewhere between the SETUP and FORMKF command cards to be processed correctly. If no MASS command cards are encountered before the FORMKF card, then mass-balance calculations are not performed.

4.0 TEST PROBLEM RESULTS

The objective of these test problems is demonstrating the use of the MASS command in SAGUARO and verifying the accuracy of its algorithm implementation. The test problems presented here include: (1) a simple three-by-three element grid with constant fluid flux in the top and out the bottom of a fully saturated region, (2) a multiple-material, one-dimensional problem in which the boundary mass flux is an imposed condition, and (3) a two-dimensional drainage problem used in benchmarking studies (Hayden, 1984). Mass-balance results (Eaton and Martinez, in preparation) that were calculated in FEMTRAN (Martinez, 1985) for hydrologic flow fields calculated with SAGUARO were used for comparison in Problem 3.

4.1 Problem 1. Three-by-Three Element Grid

This problem consisted of a fully saturated three-by-three element grid with each element side being 1 m in length (Figure 2). A fixed velocity boundary condition of 0.127 m/s was applied at the top and bottom boundaries. The vertical sides are impermeable. This should give a total mass flux of zero. The fluxes were calculated across four individual element sides. The density of water is 1,000 kg/m^3, and the time step is 0.04 s. The vertical mass flux through each horizontal element side should, therefore, be

$$q_y = \rho v A \Delta t = -5.08 \text{kg/time step.} \qquad (9)$$

The values computed with the MASS command compared to this result to better than eight significant places (the displayed accuracy). The fluxes through

the top and bottom sides of each element summed to zero. The horizontal mass flux through the vertical side of each element should also be zero because no driving force is applied. Horizontal fluxes ranging from 1. x 10^{-10} to 1. x 10^{-14} kg/time step were computed. These nonzero horizontal small fluxes resulted from machine roundoff and other numerical inaccuracies. The total residual flux through all the boundary sides over the whole region was computed to be 2.3 x 10^{-10} kg/time step.

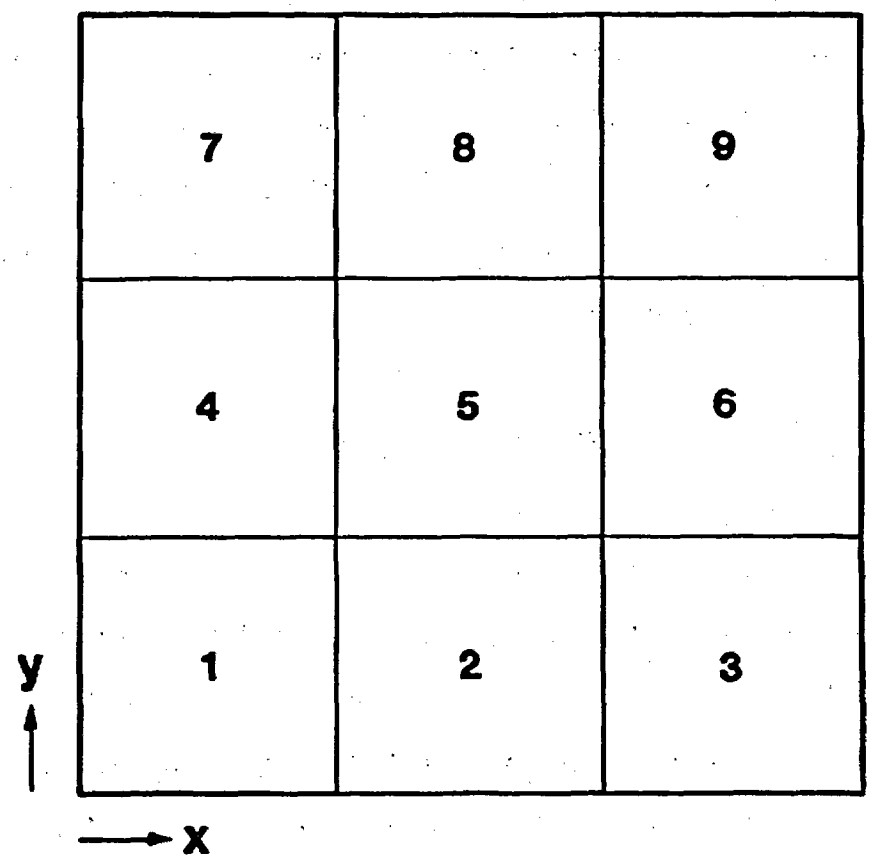


Figure 4-1. Three-by-Three Element Grid for Problem 1

4.2 Problem 2. One-dimensional Infiltration with Multiple Material Strata

This is a simplified one-dimensional model of infiltration in multi-layered tuff (Figure 4-2), using properties given by Eaton (1983). One hundred elements divided into five distinct material strata are used. A constant Darcy velocity influx of 3.17×10^{-8} m/s is applied at the top surface. All other boundaries are held impermeable (i.e., the problem is analogous to filling a bucket containing porous material). Each element is 10 m wide by 1 m deep, varying in height. The water density is 994 kg/m^3. The time step is 3.15×10^7 s (1 yr). Thus, the mass flux through the top boundary can be calculated to be

$$q = \rho v A \Delta t = 9925.6 \text{kg/time step.}$$

Computed mass-balance results for every 5 yr are shown in Table 4-1. The calculation of the mass flux at the boundary quickly converges to 9925.6 kg/time step. The difference between the change in mass stored per time step and the boundary mass flux (net gain) indicates the degree of convergence of the hydrological solution at any time step. The normalized net gain (net gain/stored mass * 100) is a percentage-error term that is small for all time steps. Under upon the prescribed boundary conditions and initial moisture distribution, the entire region fills in approximately 73 yr. The total stored mass for a completely saturated grid is solved analytically to be 2.72×10^6 kg. According to Table 4-1, the calculated stored mass value is converging to this value. At the time the region fully saturates, calculations become nonphysical because of the imposed boundary conditions (no flow at bottom, constant infiltration at top).

TABLE 4-1.
Computed Mass
Conservation Values

Time (years)	Stored Mass (kg)	Δ Mass (kg/tstep)	Flux (kg/tstep)	Net Gain (kg)	Normalized Net Gain (%)
5	2060690	10409	-10614	-206	.1
10	2111980	10199	-10260	-61	.00289
15	2162480	10079	-10071	8	.00037
20	2212740	10012	-9935	77	.00348
25	2263020	10042	-9926	116	.00513
30	2313170	10042	-9926	117	.00506
35	2363480	10068	-9926	143	.00605
40	2413860	10069	-9926	144	.00597
45	2463630	9846	-9926	-80	-.00325
50	2510880	8919	-9926	-1007	-.04011
55	2553890	9619	-9926	-307	-.01202
60	2602400	9731	-9926	-194	-.00746
65	2650770	9600	-9926	-326	-.01230
70	2698140	9250	-9926	-676	-.02505

where

Stored Mass = total mass stored within the region

Δ Mass = change in the mass stored within the region during the last time step

Flux = mass flux through all boundary sides during last time step

Net Gain = Δ mass - flux

Normalized Net Gain = net gain/stored mass

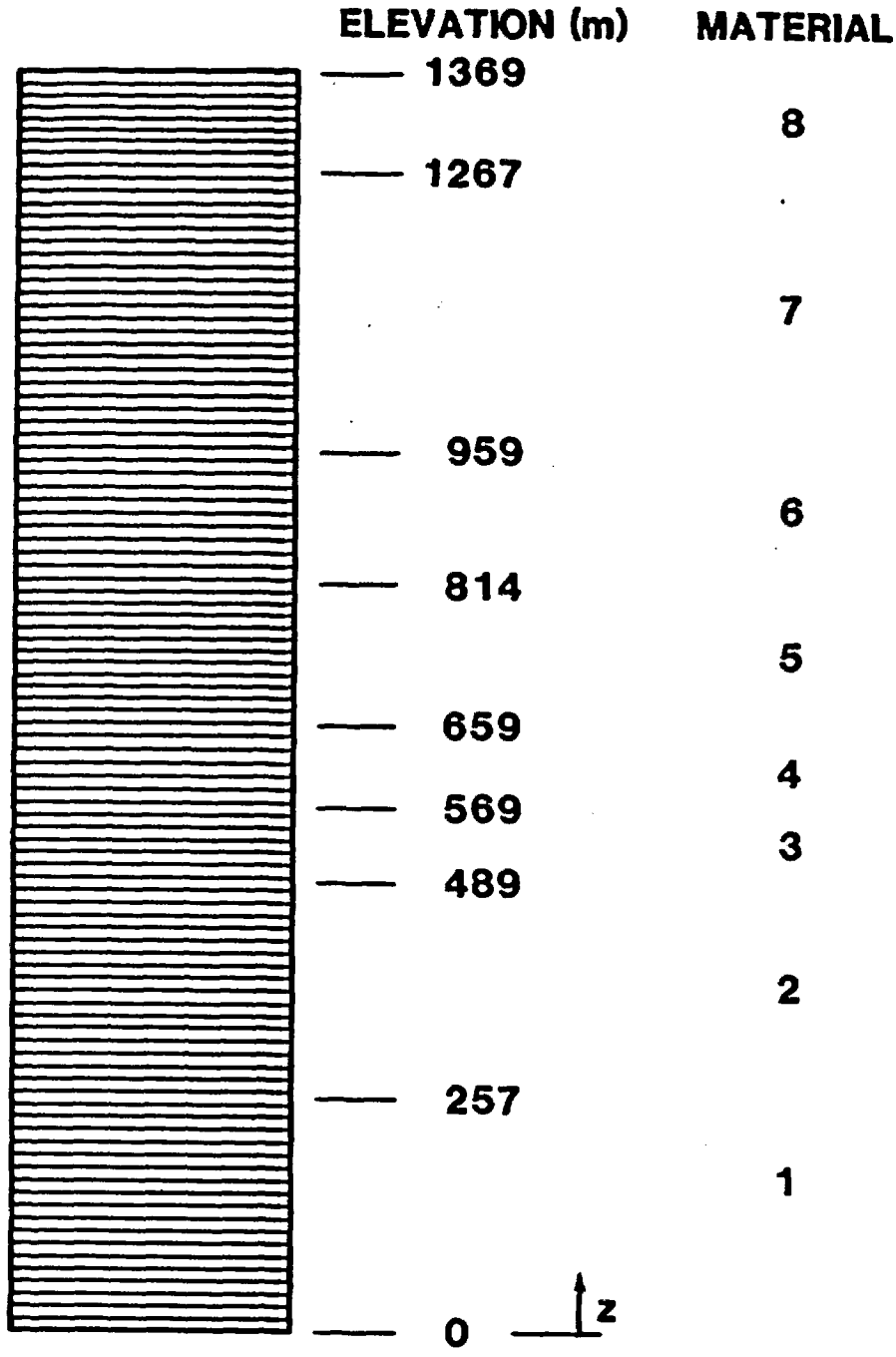


Figure 4-2. Element Grid for One-Dimensional Multi-Strata Problem

4.3 Problem 3. Two-Dimensional Drainage Problem

This drainage problem was first posed by Pickens et al, 1979, and was used extensively in the NNWSI COVE benchmarking series (Hayden, 1984; Eaton and Martinez, in preparation). A mass-balance calculation was made by linking the hydrologic solution of SAGUARO to the solute transport code FEMTRAN (Eaton, 1983) and was used as the basis of comparison. A finite-element grid of 221 elements was used for these solutions (see Figure 4-3) in which the initial stored mass is 7,500 g. Initial and boundary conditions are identified in Figure 4-4. The first 4 hr of this transient solution were compared. Mass-balance values computed by FEMTRAN are shown in Table 4-2. Some numerical error is always introduced when coupling results of SAGUARO to FEMTRAN because of limits that format constraints place on accuracy. The mass balances that SAGUARO calculated with the MASS command are shown in Table 4-3. The net gains of both sets of mass balances are compared graphically in Figure 4-5. A net mass gain of zero implies perfect mass balance. The results of SAGUARO compare favorably with the results of FEMTRAN.

TABLE 4-2

FEMTRAN Mass Balance

Time (min)	Flux (g/tstep)	Δ Mass (g/tstep)	Net Gain (g)	Normalized Net Gain (%)
2.7	-5.7	-9.6	-3.9	0.052
12.	-30.3	-31.3	-1.0	0.013
30.	-67.3	-62.6	4.7	0.063
60.	-110.3	-97.2	13.1	0.175
120.	-138.9	-123.5	15.4	0.205
180.	-111.5	-103.7	7.8	0.104
240.	-94.6	-84.0	10.6	0.141

TABLE 4-3

SAGUARO Mass Balance

Time (min)	Flux (g/tstep)	Δ Mass (g/tstep)	Net Gain (g)	Normalized Net Gain (%)
2.6	-5.9	-7.2	-1.3	-0.017
13.	-30.2	-29.9	0.3	0.004
30.	-65.9	-62.1	3.8	0.051
60.	-108.7	-100.2	8.5	0.113
120.	-137.4	-126.4	11.0	0.147
180.	-110.6	-102.7	7.9	0.105
240.	-93.0	-86.9	6.1	0.081

where

Stored Mass = total mass stored within the region

Δ Mass = change in the mass stored within the region during the last time step

Flux = mass flux through all boundary sides during last time step

Net Gain = Δ mass - flux

Normalized Net Gain = net gain/stored mass

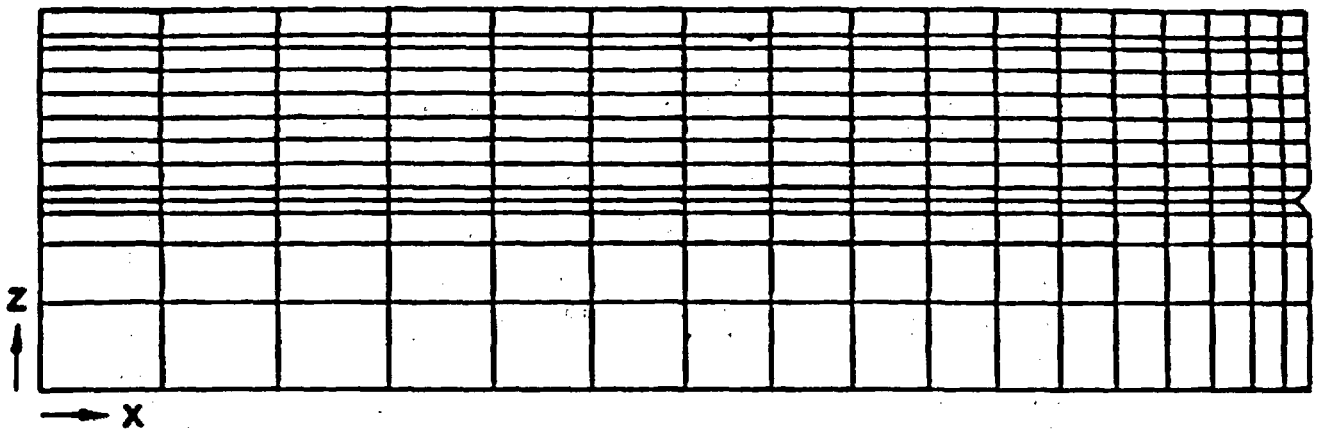


Figure 4-3. Element Grid for Tile Drainage Problem (221 Elements)

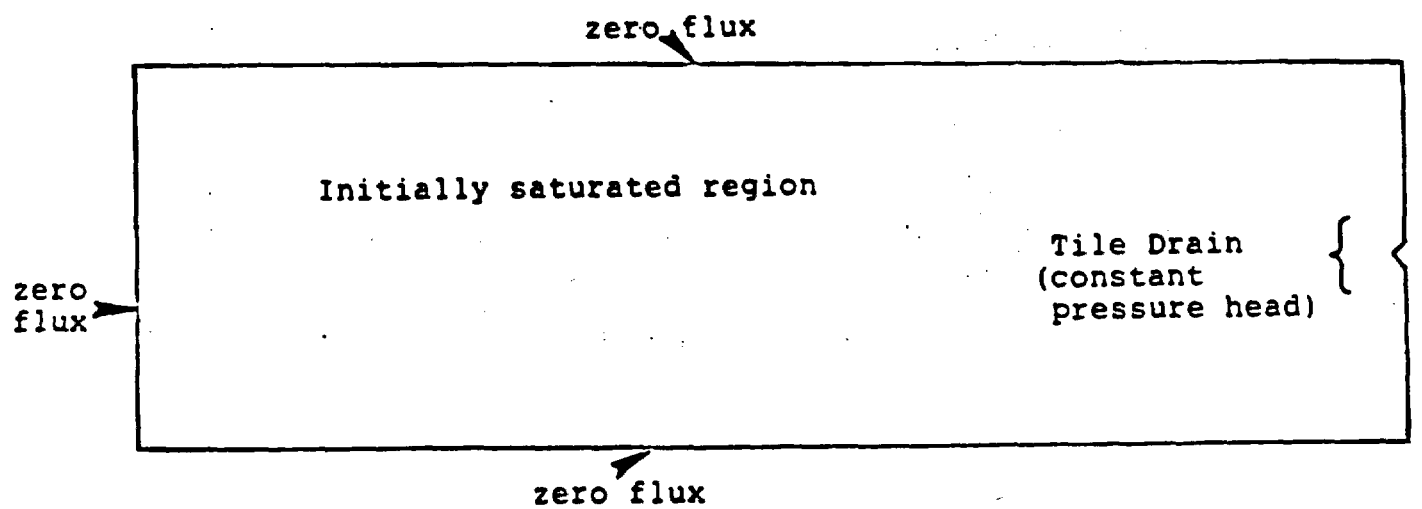


Figure 4-4. Boundary and Initial Conditions for Tile Drainage Problem.

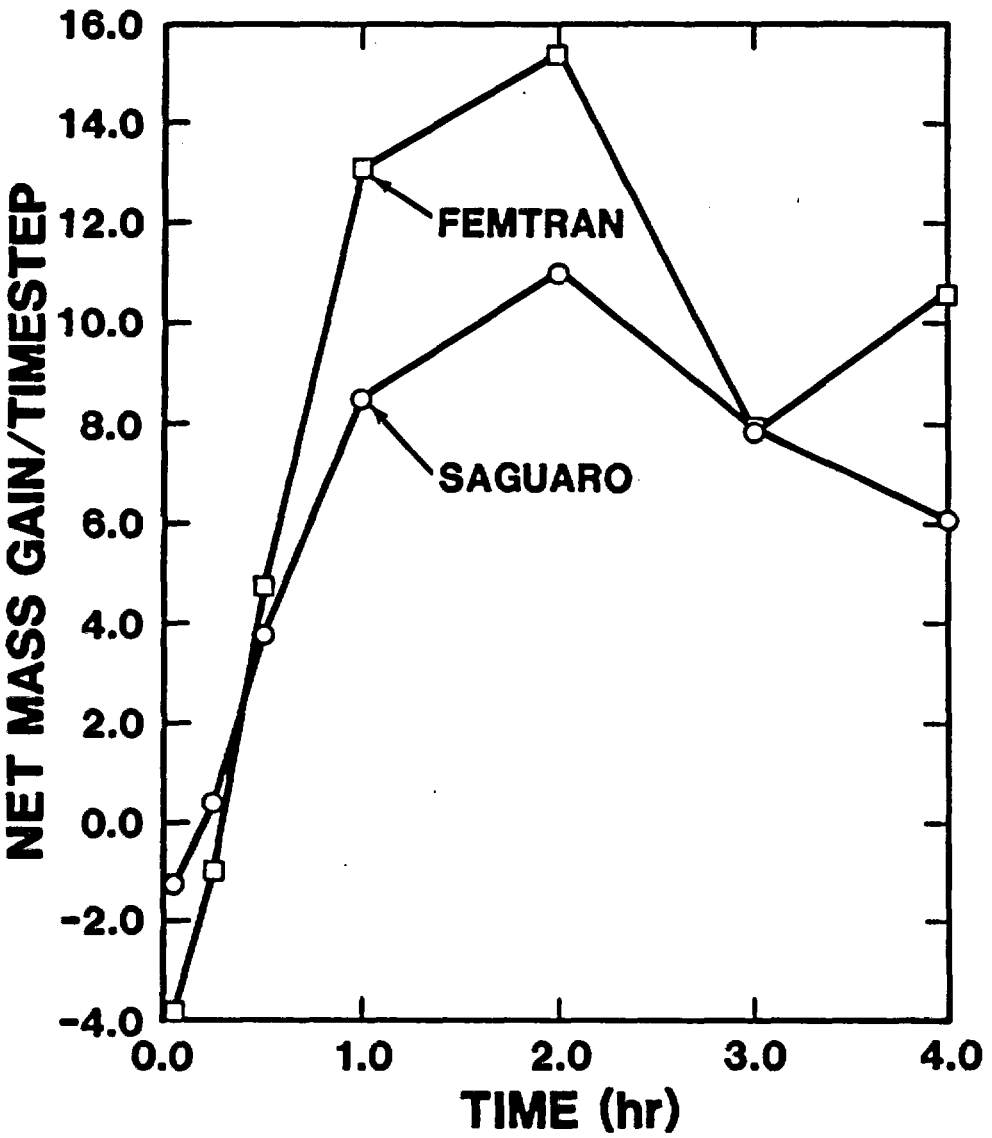


Figure 4-5. Mass Balance as a Function of Time for Problem 3

5.0 CONCLUSIONS

The mass-balance routine described in this report has been developed to assess the accuracy of results calculated by the finite-element code SAGUARO. The computer time required to execute the mass-balance calculations is minimal, and the input data requirements are straightforward.

In Problem 1, the implementation of the mass-balance calculations in a saturated two-dimensional flow field was verified with an analytical solution. The mass flux across all interior and exterior element sides and the total mass stored were correctly calculated by the mass-balance subroutine.

Problem 2 was used to verify the mass-balance calculations in SAGUARO for time-dependent problems with multiple material strata. The actual mass-balance values for the run were known a priori and compared to the mass balances calculated by the new subroutine.

Results of a more complex sample calculation, Problem 3, show that the net mass balances calculated with the new subroutine in SAGUARO are more accurate than those calculated by FEMTRAN. In general, the mass balances calculated in SAGUARO are closer to zero than the corresponding balances calculated by FEMTRAN. The results imply that the mass balances calculated with the new subroutine in SAGUARO are better than mass balances obtained by coupling SAGUARO and FEMTRAN.

6.0 REFERENCES

1. R. R. Eaton, "Capabilities of SAGUARO to Accurately Conserve Mass," Memo to Nancy Hayden, Sandia National Laboratories, Albuquerque, NM, May 24, 1983.

2. R. R. Eaton, D. K. Gartling, and D. E. Larson," SAGUARO--A Finite Element Computer Program for Partially Saturated Porous Flow Problems," SAND82-2772, Sandia National Laboratories, Albuquerque, NM, 1983.

3. R. R. Eaton and M. J. Martinez, "COVE Benchmarking Calculations Using SAGUARO and FEMTRAN," SAND85-0051, Sandia National Laboratories, Albuquerque, NM, in preparation.

4. N. K. Hayden, "Benchmarking NNWSI Flow and Transport Codes: COVE 1 Results," SAND84-0996, Sandia National Laboratories, Albuquerque, NM, 1984.

5. M. J. Martinez, "FEMTRAN--A Finite Element Computer Program for Simulating Radionuclide Transport Through Porous Media," SAND84-0747, Sandia National Laboratories, Albuquerque, NM, 1985.

6. J. F. Pickens, R. W. Gillham, and Dr. R. Cameron, "Finite Element Analysis of the Transport of Water and Solutes in Tile-Drained Soils," Journal of Hydrology, 40, pp. 243-264, 1979.

Distribution:

B. C. Rusche (RW-1)
Director
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

V. J. Cassella (RW-22)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

Ralph Stein (RW-23)
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

J. J. Fiore (RW-22)
Program Management Division
Office of Geologic Repositories
Forrestal Building
Washington, DC 20585

M. W. Frei (RW-23)
Engineering & Licensing Division
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

E. S. Burton (RW-25)
Siting Division
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

C. R. Cooley (RW-24)
Geosciences & Technology Division
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

T. P. Longo (RW-25)
Program Management Division
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

Cy Klingsberg (RW-24)
Geosciences and Technology Division
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

B. G. Gale (RW-25)
Siting Division
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

R. J. Blaney (RW-22)
Program Management Division
Office of Geologic Repositories
Forrestal Building
Washington, DC 20585

R. W. Gale (RW-40)
Office of Policy, Integration, and
Outreach
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

J. E. Shaheen (RW-44)
Outreach Programs
Office of Policy, Integration, and
Outreach
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

J. O. Neff, Manager
Salt Repository Project Office
U.S. Department of Energy
505 King Avenue
Columbus, OH 43201

D. C. Newton (RW-23)
Engineering & Licensing Division
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

O. L. Olson, Manager
Basalt Waste Isolation
Project Office
U.S. Department of Energy
Richland Operations Office
Post Office Box 550
Richland, WA 99352

D. L. Vieth, Director (4)
Waste Management Project Office
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

P. M. Bodin (12)
Office of Public Affairs
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

B. W. Church, Director
Health Physics Division
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

Chief, Repository Projects Branch
Division of Waste Mangement
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Document Control Center
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, DC 20555

S. A. Mann, Manager
Crystalline Rock Project Office
U.S. Department of Energy
9800 South Cass Avenue
Argonne, IL 60439

K. Street, Jr.
Lawrence Livermore
National Laboratory
Post Office Box 808
Mail Stop L-209
Livermore, CA 94550

L. D. Ramspott (3)
Technical Project Officer for NNWSI
Lawrence Livermore National
Laboratory
P.O. Box 808
Mail Stop L-204
Livermore, CA 94550

D. T. Oakley (4)
Technical Project Officer for NNWSI
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop F-671
Los Alamos, NM 87545

W. W. Dudley, Jr. (3)
Technical Project Officer for NNWSI
U.S. Geological Survey
Post Office Box 25046
418 Federal Center
Denver, CO 80225

NTS Section Leader
Repository Project Branch
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, DC 20555

V. M. Glanzman
U.S. Geological Survey
Post Office Box 25046
913 Federal Center
Denver, CO 80225

D. F. Miller, Director
Office of Public Affairs
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

P. T. Prestholt
NRC Site Representative
1050 East Flamingo Road
Suite 319
Las Vegas, NV 89109

M. E. Spaeth
Technical Project Officer for NNWSI
Science Applications
International, Corporation
2769 South Highland Drive
Las Vegas, NV 89109

SAIC-T&MSS Library (2)
Science Applications
International, Corporation
2950 South Highland Drive
Las Vegas, NV 89109

W. S. Twenhofel, Consultant
Science Applications
International, Corporation
820 Estes Street
Lakewood, CO 80215

A. E. Gurrola
General Manager
Energy Support Division
Holmes & Narver, Inc.
Post Office Box 14340
Las Vegas, NV 89114

J. A. Cross, Manager
Las Vegas Branch
Fenix & Scisson, Inc.
Post Office Box 15408
Las Vegas, NV 89114

W. J. Purcell (RW-20)
Associate Director
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

J. B. Wright
Technical Project Officer for NNWSI
Westinghouse Electric Corporation
Waste Technology Services Division
Nevada Operations
Post Office Box 708
Mail Stop 703
Mercury, NV 89023

ONWI Library
Battelle Columbus Laboratory
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201

W. M. Hewitt, Program Manager
Roy F. Weston, Inc.
2301 Research Blvd., 3d Floor
Rockville, MD 20850

H. D. Cunningham
General Manager
Reynolds Electrical &
Engineering Co., Inc.
Post Office Box 14400
Mail Stop 555
Las Vegas, NV 89114

T. Hay, Executive Assistant
Office of the Governor
State of Nevada
Capitol Complex
Carson City, NV 89710

R. R. Loux, Jr., Director (3)
Nevada Agency for Nuclear Projects
Nuclear Waste Project Office
State of Nevada
Capitol Complex
Carson City, NV 89710

Neal Duncan
Office of Policy, Integration, and Outreach
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

John Fordham
Desert Research Institute
Water Resources Center
Post Office Box 60220
Reno, NV 89506

Department of Comprehensive Planning
Clark County
225 Bridger Avenue, 7th Floor
Las Vegas, NV 89155

Lincoln County Commission
Lincoln County
Post Office Box 90
Pioche, NV 89043

Community Planning and Development
City of North Las Vegas
Post Office Box 4086
North Las Vegas, NV 89030

City Manager
Henderson
Henderson, NV 89015

Timothy G. Barbour
Science Applications International Corporation
1626 Cole Boulevard
Golden, CO 80401

N. A. Norman
Project Manager
Bechtel National Inc.
P.O. Box 3965
San Francisco, CA 94119

Flo Butler
Los Alamos Technical Associates
1650 Trinity Drive
Los Alamos, New Mexico 87544

C. H. Johnson, Technical Program Manager
Nevada Agency for Nuclear Projects
Nuclear Waste Project Office
State of Nevada
Capitol Complex
Carson City, NV 89710

Dr. Martin Mifflin
Desert Research Institute
Water Resources Center
Suite 1
2505 Chandler Avenue
Las Vegas, NV 89120

Planning Department
Nye County
Post Office Box 153
Tonopah, NV 89049

Economic Development Department
City of Las Vegas
400 East Stewart Avenue
Las Vegas, NV 89101

Director of Community Planning
City of Boulder City
Post Office Box 367
Boulder City, NV 89005

Commission of the European City of Communities
200 Rue de la Loi
B-1049 Brussels
BELGIUM

Technical Information Center
Roy F. Weston, Inc.
2301 Research Boulevard, 3d Floor
Rockville, MD 20850

R. Harig
Parsons Brinckerhoff Quade & Douglas, Inc.
1625 Van Ness Ave.
San Francisco, CA 94109-3678

Dr. Madan M. Singh, President
Engineers International, Inc.
98 East Naperville Road
Westmont, IL 60559-1595

E. P. Binnall
Field Systems Group Leader
Building 50B/4235
Lawrence Berkeley Laboratory
Berkeley, CA 94720

T. H. Isaacs (RW-22)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

D. H. Alexander (RW-23)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

B. J. King, Librarian (2)
Basalt Waste Isolation Project
Library
Rockwell Hanford Operations
P.O. Box 800
Richland, WA 99352

David K. Parrish
RE/SPEC Inc.
3815 Eubank, NE
Albuquerque, NM 87191

D. L. Fraser, General Manger
Reynolds Electrical & Engineering
Co., Inc.
Mail Stop 555
P.O. Box 14400
Las Vegas, NV 89114-4400

Gerald Parker (RW-25)
Office of Geologic Repositories
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

J. P. Pedalino
Technical Project Officer for NNWSI
Holmes & Narver, Inc.
Mail Stop 605
P.O. Box 14340
Las Vegas, NV 89114

Roger Hart
Itasca Consulting Group, Inc.
P.O. Box 14806
Minneapolis, MN 55414

J. P. Knight (RW-24)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

Allen Jelacic (RW-23)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Forrestal Building
Washington, DC 20585

J. R. Rollo
Deputy Assistant Director
for Engineering Geology
U.S. Geological Survey
106 National Center
12201 Sunrise Valley Drive
Reston, VA 22092

R. Lindsay Mundell
U.S. Bureau of Mines
P.O. Box 25086
Building 20
Denver Federal Center
Denver, CO 80225

Vincent Gong
Technical Project Officer for NNWSI
Reynolds Electrical & Engineering
Co., Inc.
Mail Stop 615
P.O. Box 14400
Las Vegas, NV 89114-4400

Christopher M. St. John
J.F.T. Agapito Associates, Inc.
27520 Hawthorne Blvd., Suite 137
Rolling Hills Estates, CA 90274

S. D. Murphy
Technical Project Officer for NNWSI
Fenix & Scisson, Inc.
Mail Stop 940
P.O. Box 15408
Las Vegas, NV 89114

Mike Revelli
Lawrence Livermore National Laboratory
P.O. Box 808
Mail Stop L-204
Livermore, CA 94550

Mike Toibner
Science Application International Corporation
2950 South Highland Drive
Las Vegas, NV 89109

Suresh Pahwa
Intera Environmental Consultants, Inc.
11999 Katy Freeway
Suite 610
Houston, TX 77079

Kjell Anderson
Swedish Nuclear Power Inspectorate
Box 27106
S-102 52 Stockholm
Sweden

Tim Broyd
Atkins Research and Development
Woodcote Grove, Ashley Road
Epsom, Surry KT18 5BW
United Kingdom

Eckhart Butow
Institut fur Kerntechnik der Technische
Universitat Berlin
Marchstrabe 18
D-1000 Berlin, W. Germany

Charles Cole
Battelle Pacific Northwest Laboratories
Battelle Boulevard
Richland, WA 99352

Bertil Grundfelt
KEMAKTA Consultants Co.
Luntmakargatan 94
S-113 51 Stockholm
Sweden

C. Peter Jackson
AERE
Harwell
GBR-Didcot Oxon OX11 ORA
United Kingdom

P. Hufschmied
Nationale Genossenschft fur die Lagerung Radioactiver Abfalle
NAGRA
Parkstrabe 23
CH-5402 Baden, Switzerland

Hideo Kimura
JAERI
Tokai-mura
Naka-gun
Ibaraki-ken
Japan

Thomas Nicholson
U.S. Nuclear Regulatory Commission
Earth Sciences Branch
Division of Radiation Programs and Earth Sciences
Washington, DC 20555

Haruto Nakamua
JAERI
Chief of HLW Management Research Laboratory
Division of Environmental Safety Research
Tokai-mura
Naka-gun
Ibaraki-ken
Japan

Seppo Vuori
Technical Research Centre of Finland
Nuclear Engineering Laboratory
P.O. Box 169
SF-001 81 Helsinki
Finland

Eric Anderson
Mountain West Research-Southwest, Inc.
398 South Mill Avenue, Suite 300
Tempe, AZ 85281

Dr. T. N. Narasimhan (2)
Earth Sciences Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

B. J. Travis
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Robert Brockhaus
Battelle Pacific Northwest
Laboratories
P.O. Box 999
Richland, WA 99352

Donald R. F. Harleman
Ford Professor of Engineering
Building 48
Massachusetts Institute of Technology
Cambridge, MA 02139

Emil Frind
Earth Sciences Department
University of Waterloo
Waterloo, Ontario
Canada

Claes Thegerstrom
Nuclear Energy Agency
38, Boulevard Suchet
F-75016 Paris
France

N. E. Carter
Battelle Columbus Laboratory
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201

Charles Keller
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Mike Foley
Battelle Pacific Northwest
Laboratories
Battelle Blvd.
Richland, WA 99352

T. R. Pigford
Department of Nuclear Engineering
University of California
Berkeley, CA 94720

J. F. Pickens
Geologic Testing Consultants, Ltd.
785 Carling Avenue, Fourth Floor
Ottawa, Ontario k1S 5H4
Canada

David Noy
Nicker Hill
Nottingham NG12 5GG
United Kingdom

1510 J. W. Nunziato
1511 D. K. Gartling
1511 N. E. Bixler
1511 R. R. Eaton
1511 P. Hopkins
1512 J. C. Cummings
1513 D. W. Larson
1513 J. A. Schutt
1520 D. J. McCloskey
1530 L. W. Davison
1540 W. C. Luth
6300 R. W. Lynch

6310 T. O. Hunter
6310 24/12143/1510/PDM-0/QIII
6310 72-12143-0/QIII
6311 L. W. Scully
6311 C. Mora (2)
6312 F. W. Bingham
6312 G. E. Barr
6312 M. L. Green
6312 B. S. Langkopf
6312 R. R. Peters
6312 A. C. Peterson
6312 R. W. Prindle
6312 M. S. Tierney
6312 J. G. Yeager
6313 T. E. Blejwas
6313 E. A. Klavetter
6314 J. R. Tillerson
6314 S. Bauer
6314 J. A. Fernandez
6314 A. J. Mansure
6315 S. Sinnock
6315 Y. T. Lin
6332 WMT Library (20)
6430 N. R. Ortiz
6431 B. Cranwell
3141 S. A. Landenberger (5)
3151 W. L. Garner (3)
8024 P. W. Dean
3154-1 C. H. Dalin (28)
for DOE/TIC

Org.	Bldg.	Name	Rec'd by	Org.	Bldg.	Name	Rec'd by

Sandia National Laboratories