Computer Modeling of a Three-Dimensional
Steam Injection Experiment

SUPRI TR 94

By
Sameer Joshi
Louis M. Castanier

August 1993

Work Performed Under Contract No. DE-FG22-93BC14899

Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Thomas B. Reid, Project Manager
Bartlesville Project Office
P.O. Box 1398
Bartlesville, OK 74005

Prepared by
Stanford University
Petroleum Research Institute
Stanford, CA 94305-4042

MASTER

Acknowledgements

The authors are grateful for the financial support from the Department of Petroleum Engineering of Stanford University, the SUPRI Industrial Associates and DOE through contract No. DE-FG22-93BC14899.

Abstract

The experimental results and CT scans obtained during a steam-flooding experiment with the SUPRI 3-D steam injection laboratory model are compared with the results obtained from a numerical simulator for the same experiment.

Simulation studies were carried out using the STARS (Steam and Additives Reservoir Simulator) compositional simulator. The saturation and temperature distributions obtained and heat-loss rates measured in the experimental model at different stages of steam-flooding were compared with those calculated from the numerical simulator.

There is a fairly good agreement between the experimental results and the simulator output. However, the experimental scans show a greater degree of gravity override than that obtained with the simulator for the same heat-loss rates. Symmetric sides of the experimental 5-spot show asymmetric heat-loss rates contrary to theory and simulator results.

Some utility programs have been written for extracting, processing and outputting the required grid data from the STARS simulator. These are general in nature and can be useful for other STARS users.

TABLE OF CONTENTS

Acknowledgements	iii
Abstract	v
LIST OF TABLES	ix
LIST OF FIGURES	xii
1 Introduction	1
2 Numerical Simulation of Thermal Processes	2
3 Features of STARS	3
4 Input Parameters and their Estimation	5
4.1 Input/Output Control	5
4.2 Reservoir Description	6
4.3 Component Properties	7
4.4 Rock-Fluid Data	8
4.5 Initial Conditions	8
4.6 Numerical Methods Control	10
4.7 Well and Recurrent Data	10
5 Experimental and Simulator Results	12
5.1 Saturation and Temperature Distributions	12
5.2 Heat Losses	12
5.2.1 Semi-Analytical Infinite-Overburden Model	12
5.2.2 Constant/Convective Heat-Loss Model	13
5.2.3 Comparision of Heat-Losses	13
5.3 Discussion of Figures	13
6 Conclusions	24
Appendix	24
A STARS Utility Programs	25
A.1 gridx	26
A.2 gconx	29
A.3 addx	30
A.4 gpsx	32
A.5 hlxx	34

A.6 hgpsx	39
A.7 starsout	41
Bibliography	41

LIST OF TABLES

3.1	Executable Versions of STARS Available at Stanford	4
4.1	Water Viscosity Table Used	8
4.2	Water-Oil Relative Permeability Table	9
4.3	Steam-Water Relative Permeability Table	9

LIST OF FIGURES

5.1	Experimentally Observed Saturation and Temperature Cross-Sections	15
5.2	Calculated Saturation and Temperature Cross-Sections — for the case *UHTR = -720 J/D-C.	16
5.3	Calculated versus Experimental Heat-Loss Rates — for the case *UHTR = -720 J/D-C.	17
5.4	Calculated Saturation and Temperature Cross-Sections — for the case *UHTR = -820 J/D-C.	18
5.5	Calculated versus Experimental Heat-Loss Rates — for the case *UHTR = -820 J/D-C.	19
5.6	Calculated Saturation and Temperature Cross-Sections — for the case *UHTR = -920 J/D-C.	20
5.7	Calculated versus Experimental Heat-Loss Rates — for the case *UHTR = -920 J/D-C.	21
5.8	Calculated Saturation and Temperature Cross-Sections — for the case *UHTR = -1080 J/D-C.	22
5.9	Calculated versus Experimental Heat-Loss Rates — for the case *UHTR = -1080 J/D-C.	23

1. Introduction

The aim of this research project was to computer model the experimental results obtained with the SUPRI 3-D steam injection laboratory model. A detailed description of the laboratory model may be found in Demiral et al 1991, 1992 [9, 10]. The experimental model had been designed as one quadrant of a theoretical 5-spot and was used to record temperature, pressure and heat-flux data during the course of the experiment. It was capable of being scanned in the SUPRI-A CT scanner, to allow in-situ saturation measurements. Experiments were carried out on steam-flooding alone, as well as steam-flooding with additives and nitrogen, of the water saturated model.

The STARS¹ (Steam and Additives Reservoir Simulator) compositional simulator was used to model the experimental results. This would be useful in predicting the results of further experimental runs with the apparatus. The results could also be applied to actual field studies using appropriate scaling parameters.

The goal of a model is usually to produce quantitative results on the rate of oil production as a function of operating conditions. The present work differs from this in that the aim was to match, via numerical simulation, the saturation and temperature distributions and heat loss rates observed during the steam injection experiment. The main aim of the laboratory experiment had been to visualize the saturation distributions and displacement fronts.

Since the aim of the steam injection experiment was mainly to visualize the displacement fronts by utilizing the CT scanner, no production data or other flow measurements were made at the outlet end of the experimental model. Hence, modeling the experimental results proved to be a challenging task as there was no data available to compare with the simulator material balance statistics.

¹The simulator is available from the Computer Modelling Group (CMG), Alberta, Canada.

2. Numerical Simulation of Thermal Processes

The two main types of models are numerical simulators and physical models. A mathematical description of fluid flow in a permeable medium is obtained from the following principles:

- The Law of Conservation of Mass.
- Laws describing fluid transport, like Darcy's Law and Fick's Law.
- Equations of State (EOS).

In addition, for thermal simulators the amount of heat actually accumulated in the formation for oil displacement is a necessary parameter, so energy transfer is an important mechanism involved in the process.

These energy and mass balances are used to develop the partial differential equations representing the physical processes taking place within the model. When the continuity equation is applied separately to each component of interest in the reservoir process being considered, the development is known as compositional.

There are several numerical methods in the literature to solve the system of partial differential equations characteristic of the hot fluid injection method under consideration. See [11] through [20] for the details.

The complexity of the problem depends upon:

- The number of dimensions of the problem.
- The number of components and phases being considered.
- The physical phenomena being taken into account — gravity forces, capillary pressure, mass transfer between phases, rock compressibility, homogeneity and isotropy of the medium.
- The complexity of description of physical laws — type of EOS, relations for viscosities, densities, effective permeabilities, thermal conductivities and heat capacities.

The agreement between experimental and simulator results should improve with the complexity of the description. However usually the simulator requires more information about the distribution of properties in the reservoir than is normally available, and in some cases the formulation of the physical processes is approximate or established for different operational conditions.

Thus it is useful to compare simulator results with actual experimental data so as to:

- Test the accuracy of numerical models on the basis of experimental data.
- Test the sensitivity of the results to the input parameters.

The compositional thermal simulator STARS is available on the Petroleum Engineering departmental computers. It was decided to utilize this for modeling the experimental results.

3. Features of STARS

STARS is a three-phase multi-component thermal and steam additive simulator. Grid systems can be defined to be cartesian, cylindrical or variable depth/thickness in either two or three dimensions. Some of its features are:

Dispersed Components Stabilized dispersions of one phase in another (droplets, bubbles and lamellae) can be treated as components in the carrying phase, thus providing a unified perspective in the modeling of polymers, gels, fines, emulsions and foam. The component property input capabilities include adsorption, blockage, non-linear viscosity, dispersion and non-equilibrium mass transfer. There are two different methods available for modeling foam.

Naturally Fractured Reservoirs Flow in naturally fractured reservoirs can be simulated by four different models:

- Dual Porosity (DP).
- Dual Permeability (DK).
- Multiple Interacting Continuua (MINC).
- Vertical Refinement (VR).

Adaptive Implicit Formulation In many cases only a small number of grid blocks need to be solved fully implicitly and most other blocks can be solved by the explicit method. This is achieved by the adaptive implicit option, which selects the blocks to be solved implicitly in a dynamic manner, based on specified thresholds or on matrix switching criteria. This method can result in a savings of one third to one half of the execution time.

Fully Implicit Wells The bottomhole pressure and the block variables for the blocks where the wells are completed are solved fully implicitly. If a well is completed in more than one layer, then its bottomhole pressure is solved in a fully coupled manner by accounting for all completions. There is a comprehensive well-control facility with a large number of constraints which can be specified.

Local Grid There is a facility for local grid refinement. A region of the reservoir can be specified which is to be subdivided. All inter-block connections and transmissibilities are automatically calculated.

Aquifer Models Aquifer modeling can be done either by adding boundary cells containing only water or by using a semi-analytical aquifer model.

In addition, a Graphics and Control Module can be obtained from the supplier for data extraction and data display. This is, however, not available with the Petroleum Engineering Department. So some utility programs were written for data extraction, data processing and color display through GRIDCON and GPS. The programs written are general in nature and can be easily utilized by other STARS users for extracting and processing any required grid data, by simple modifications to the control files. These programs are described in Appendix A.

The STARS version available at Stanford is version 4.0.1 installed Feb. 1991. This comes in three executable versions: starsa, starse and starsi. Their features are summarized in Table 3.1.

Executable Name	starsa	starse	starsi
Active grids	180	1290	408
Total grids	250	1200	600
Dimensions	3	3	3
Components	7	3	8
Fluids	6	3	7
Liquids	5	3	5
Dispersion	Y	N	N
# Refined Grids	12	0	0
Reactions	5	10	10
Wells	6	15	15
Layers/Well	6	10	10
Nine-Point	Y	Y	Y
Orthogal's	d	d	d
Connections	d	d	d
Storage(MB)	4.5	12	12

Table 3.1: Executable Versions of STARS Available at Stanford

4. Input Parameters and their Estimation

STARS takes the initial input data set and then creates three other files. These are an output restart file, an output Simulation Results File (SRF) and an output data file. An initial run needs only the input data file. For a restart run three input files are needed. They are:

- Input data file
- SRF (Input) file
- Restart (Input) file

There are seven different data groups which must be specified in the input data file. Keywords belonging to one group cannot appear in another group, unless specially allowed (usually in the case of recurrent data). The groups (and some keywords within a group) must follow a certain input order. The order of groups is as follows:

- Input/Output Control
- Reservoir Description
- Component Properties
- Rock-Fluid Data
- Initial Conditions
- Numerical Methods Control
- Well and Recurrent Data

Each different data group consists of different keywords appearing in a certain specified order. A keyword is preceded by a keyword indicator¹ which is an asterisk, *. The keyword should immediately follow the asterisk² without any intervening spaces. Each keyword is followed by the data items for that particular keyword, separated by spaces³. The input data file is created in this manner.

Each data group, some of its important and required keywords, and the data values calculated for them for this model, will be described in the following sections.

4.1 Input/Output Control

This section consists mainly of keywords which specify the unit systems used, the types of data to be recorded to the output print and SRF files, the frequency of recording data and the default grid printout orientation. Some of the keywords used and their data values are:

***TITLE1** A title to be used for project identification.

¹The keyword indicator is optional.

²Two asterisks in a row indicate a comment line.

³An important point to be noted, which is not mentioned in the users manual, is that the simulator differentiates between types of whitespace. Thus a tab space is not equivalent to an ordinary space and will result in an error during initial opening of the input data file if data items are delimited by tab spaces rather than ordinary spaces.

- *INUNIT** This specifies the input data units. SI units were used for this simulation except for pressure which was kept in *psi* and length which was kept in *cm*.
- *OUTUNIT** This specifies the output data units, which were kept the same as in ***INUNIT**.
- *WRST** This controls the frequency of writing restart records to the output restart file. Restart records were written at every ***TIME**⁴ keyword.
- *WPRN** This controls the frequency of writing data to the output print files. Output data was written at every ***TIME** keyword.
- *OUTPRN** This identifies which grid, well and iteration information is written to the output print file. Grid data recorded were pressure, water and gas saturations, temperature and overburden heat loss. The well and iteration data were recorded in a brief format.
- *OUTSRF** This identifies which grid, well and certain special data are written to the output Simulation Results File (SRF). Convective heat losses were also recorded in the SRF, in addition to the data recorded in the output print file.

4.2 Reservoir Description

This section deals with the specification of the gridding scheme and the petrophysical and thermal properties of the reservoir. A few of the keywords are:

- *GRID** This indicates the beginning of the input of reservoir conditions. The grid can be specified as Cartesian (***CART**) or radial-angular (***RAD**) and the number of grid blocks entered. For this simulation a Cartesian $6 \times 6 \times 6$ grid was used for the initial runs and later a $10 \times 10 \times 7$ grid was used.
- *DIP** The tilt angles in degrees of the I and J axes above the horizontal can be entered using this keyword.
- *POR** This indicates input of porosities. Grid properties like this are actually arrays of data with one array element for each grid block. There are six different methods which may be used to read in arrays of grid properties. The keywords used to indicate the array reading options are:
 - ***CON**
 - ***IJK**
 - ***IVAR**
 - ***JVAR**
 - ***KVAR**
 - ***ALL**

Once an array has been input it can immediately be modified using the keyword ***MOD**. These keywords describe to the program how to read in multi-dimensional arrays of data.

The porosity calculated for the model was 0.39.

⁴A real number specifying the length of time after the simulation date that the well will be changed. This can also be used as a convenient way of recording data periodically by entering different values of ***TIME** without any corresponding well change.

***PERMI** This indicates entry of I direction permeability. Similarly J and K direction permeabilities are entered using the keywords ***PERMJ** and ***PERMK**. The model permeability was taken as 25 Darcies, as calculated during the experiment.

***CPOR** This is used to enter the rock compressibility. For the model the value estimated was $5 \times 10^{-6} \text{psi}^{-1}$.

***ROCKCP** The rock heat capacity is entered by this keyword. This was estimated as $2.08 \times 10^6 \text{J/cm}^3 - K$.

***THCONR** This indicates the thermal conductivity of reservoir rock, which was taken to be 1152 J/cm-D-K. Similarly the water thermal conductivity is entered using ***THCONW**. This was taken as $5.35 \times 10^2 \text{J/cm-D-K}$. The way in which the thermal conductivities are to be weighted can also be specified in three different ways.

***HLOSSPROP** This defines the heat-loss directions and over/underburden thermal properties for the semi-analytical infinite-overburden heat-loss model. The thermal properties to be specified are the volumetric heat capacity of the formation adjacent to the reservoir and its thermal conductivity. These were calculated to be $1000 \text{J/cm}^3 - K$ and 2834J/cm-D-K respectively.

4.3 Component Properties

This section is used to input the fluid component properties, molecular weights and reference conditions. Keywords include:

***MODEL** This indicates the number of each type of component in the model in preparation for fluid data input. It has four arguments:

- The total number of components in the simulation
- The total number of components in the fluid phases
- The total number of components in the liquid phases
- The number of water-like or aqueous components

For this model all of the above arguments were 1 as we were only considering water displacement by steam.

***COMPNAME** This inputs a component name character string for the different components.

After this keyword is entered, then the different component properties are to be specified, like:

- K value correlations
- Molecular weights
- Critical pressures and temperatures
- Reference conditions for fluid properties and surface conditions
- Heat capacities and vaporization enthalpies
- Component liquid densities and mixing rules
- Liquid viscosities and mixing rules
- Critical reaction data for a number of reactions

Temperature (K)	Viscosity (kPa-Day)
297.0	1.078×10^{-11}
310.9	7.928×10^{-12}
338.7	4.977×10^{-12}
366.5	3.565×10^{-12}
394.3	2.662×10^{-12}
422.0	2.107×10^{-12}
449.8	1.892×10^{-12}
533.2	1.464×10^{-12}

Table 4.1: Water Viscosity Table Used

- Non-critical and optional chemical reactions and non-equilibrium mass transfer data
- Specification of the possible dependence of chemical reactions and non-equilibrium mass transfer on permeability or phase velocity
- Specification of non-equilibrium blockage by captured solid (non-fluid) components

Since the only component used was water, most of these properties could be set equal to the internal defaults. The viscosity data used is given in Table 4.1.

4.4 Rock-Fluid Data

This data group consists of the rock-fluid interaction properties like relative permeabilities and capillary pressure data. Stone's three-phase models can be used for relative permeability. There are five wettability options. Important keywords are:

***ROCKFLUID** This keyword indicates the start of entry of rock-fluid data.

***SWT** This keyword defines the water-oil relative permeability table. At least one *SWT table must be entered.

***SLT** This defines the liquid-gas relative permeability table. This table must be entered at least once and must occur after *SWT.

Capillary pressure was not considered in this model due to the high permeability/big grain size (25 Darcies and 25-30 mesh size Ottawa sand). The water-oil relative permeability table is given in Table 4.2, on the next page. The steam-water relative permeability table is given in Table 4.3.

4.5 Initial Conditions

This data group is used to specify the reservoir initial conditions. Main keywords are:

***INITIAL** This indicates the beginning of initial condition values and is a required keyword.

***VERTICAL** Specifies the vertical equilibrium option.

***PRES** Specifies the initial reservoir pressure. For the model the value was 25 psi.

***TEMP** Specifies the initial reservoir temperature. This was $293^{\circ}K$ for the model.

S_w	k_{rw}	k_{row}
0.30	0.0	1.0
0.35	0.0043	0.928
0.40	0.005672	0.857
0.45	0.01898	0.786
0.50	0.0334	0.714
0.60	0.0845	0.571
0.70	0.1815	0.428
0.80	0.3462	0.286
0.85	0.4627	0.214
0.90	0.6074	0.143
0.95	0.7849	0.071
1.0	1.0	0.0

Table 4.2: Water-Oil Relative Permeability Table

S_w	k_{rg}	k_{rw}
0.0	1.0	0.001
0.04	0.98	0.0025
0.08	0.975	0.0035
0.14	0.970	0.004
0.21	0.960	0.005
0.38	0.955	0.0055
0.5	0.93	0.1
0.6	0.921	0.12
0.7	0.90	0.18
0.8	0.86	0.29
0.9	0.78	0.53
1.0	0.0	1.0

Table 4.3: Steam-Water Relative Permeability Table

***SW** Specifies the initial water saturation in the reservoir, which was 1.0 initially in the model. Similarly the initial oil and gas saturations in the reservoir are specified by the keywords ***SO** and ***SG** respectively.

4.6 Numerical Methods Control

This data group is used to specify the options for the numerical solution techniques used by the simulator. The defaults provided should only be overridden where absolutely necessary, as inappropriate use may result in the use of much more CPU time than is required. Main keywords are:

***NUMERICAL** This specifies the beginning of all numerical methods control keywords.

***MAXSTEPS** Specifies the maximum number of timesteps for the simulation run.

***DTMAX** Identifies the maximum timestep size.

***NORM** This identifies the typical changes in the basic variables over a timestep.

***NEWTONCYC** Specifies the maximum number of Newtonian cycles.

***ITERMAX** Specifies the maximum number of iterations allowed in the Jacobian matrix solution technique.

***AIM** This indicates the adaptive implicit option.

4.7 Well and Recurrent Data

This is the last keyword group in the input data file. Some keywords from other data sections may also appear in this group. Important keywords are:

***RUN** This keyword indicates the beginning of all well and recurrent data entries.

***DATE** This indicates that a well change will occur at a specified date.

***TIME** This indicates that a well change will occur at a specified time. Its argument is a real number specifying the length of time after the simulation starting date that the well will be changed.

***WELL** This is used to identify wells. It assigns well numbers and names and optionally assigns them to a well gathering center. It also identifies vertical wells.

***PRODUCER** It indicates that the well identified by the well number is a producer. Similarly, the keyword ***INJECTOR** identifies a well as an injector.

***OPERATE** This defines the well operating constraints, and the remedial action to be taken when a constraint is violated. Constraints can be of a minimum or a maximum type and can refer to oil, gas, water or total liquid flow rates. They can also refer to bottomhole pressure constraints for a well.

***GEOMETRY** This keyword specifies the well geometric characteristics to be used by the simulator to calculate the well index internally. Its arguments are the well radius, the geometric factor for the well element, the fraction of a circle that the well models and the well skin factor.

***PERF** It specifies the location of the well completion grid blocks.

***HEATR, *TMPSET, *UHTR** These three keywords assign data for the constant and convective heat transfer models. ***HEATR** can assign a constant heat transfer rate to grid blocks. ***UHTR** is a proportional heat transfer coefficient used together with ***TMPSET**. If ***UHTR** is specified to be < 1 , then it acts as an overall convective heat transfer coefficient, where ***TMPSET** is a reference temperature. The rate of heat loss is given by,

$$ABS(UHTR) \times (T - TMPSET)$$

while $T > TMPSET$. Otherwise the rate is zero.

***STOP** This keyword causes simulation to terminate and is usually the last keyword in the input data file. It is used in conjunction with a ***DATE** or ***TIME** keyword to indicate when to stop the simulation.

5. Experimental and Simulator Results

During the experiment, four sets of CT scans were taken at six different cross-sections of the model between the injection and production ends of the five-spot quadrant. The four sets of scans were taken at the end of injection of 0.04 PV, 0.30 PV, 0.54 PV and 1.31 PV of 100 % quality steam. There were also pressure and temperature sensors embedded within the model at three different height levels so that they could cover almost the entire cross-section of the model. In addition there were heat flux sensors on five of the six outside faces of the model¹, so that the rates of heat loss from these faces could be measured at all times. The CT data was recorded directly onto magnetic tape and all the other data was recorded on disc via a H-P² data logger.

For this study the simulator output data was retrieved primarily from the output Simulation Results File (SRF). This was achieved by means of a few programs that were written specifically for this purpose. These programs were combined in the form of a single shell script file so that all the data extraction, processing and color PostScript³ output could be achieved by means of a single command. These programs are described in Appendix A. They can be easily adapted to any other grid data extraction task for this simulator by appropriate modification of the control files.

5.1 Saturation and Temperature Distributions

There is a fairly good match between the experimentally obtained saturation⁴ and temperature distributions and those calculated from the simulator.

The experimentally obtained results are compared with the simulator results in the figures at the end of this chapter. The figures are discussed in Section 5.3.

5.2 Heat Losses

As far as heat losses are concerned it should be noted that there are two different heat-loss models which can be specified in STARS. They are:

- A semi-analytical infinite-overburden model
- A constant/convective heat-loss model

These models can be used separately or in combination for a particular simulation run.

5.2.1 Semi-Analytical Infinite-Overburden Model

This is the primary heat-loss model used in STARS. It uses a semi-analytical procedure to solve the one-dimensional linear heat conduction equation, with the following assumptions:

- Conduction within the cap and base rock wipes out any sharp temperature differences. Thus, the temperature in the cap and base rock varies smoothly.
- Longitudinal heat conduction in the cap and base rock can be neglected.

¹Excluding the bottommost face which contained all the instrumentation wiring.

²H-P is a registered trademark of the Hewlett-Packard Corporation.

³PostScript is a registered trademark of Adobe Systems Incorporated, Mountain View, CA.

⁴It should be noted that the experimentally obtained saturation distributions are actually CT number distributions whereas the simulator results are calculated saturation distributions. Hence the two distributions being compared are not strictly the same.

- The most important features of the heat-loss process are good descriptions of the boundary conditions at the interface, and conservation of total energy.

These points suggest that the temperature profile into the cap or base rock can be adequately approximated by a fitting function with a few parameters. The function chosen is:

$$T(t, z) = (\phi + pz + qz^2)e^{-z/d}$$

where p and q are the fitting parameters, ϕ is the temperature at the interface between the reservoir and the cap or base rock and d is the diffusion length, where d is chosen as

$$d = \sqrt{kt}/2$$

Utilizing a finite difference scheme into the equation of heat flow along with the appropriate boundary conditions gives the parameters p and q . The heat-loss rate can also be calculated. See Vinsome and Westerveld, 1980 [21] for the full details of this model.

5.2.2 Constant/Convective Heat-Loss Model

In addition to the previous heat-loss model there is a facility for applying a constant or convective heat-loss rate to selected grid blocks. This is done by specifying a proportional convective heat transfer coefficient for the model by utilizing the keywords *HEATR, *UHTR and *TMPSET as mentioned on page 11. Since the lab model has a large component of convective heat-loss this is an important part of the modeling.

5.2.3 Comparison of Heat-Losses

As far as heat-losses are concerned it was found that it was not possible to match the heat-losses using solely the semi-analytical model. However with the addition of the convective heat-loss model there is a closer agreement. This is as expected since the original design calculations for the model were made with the assumption that the heat transfer mechanism between the outer insulator surface and air is natural convection only.

One problem faced in modeling the experimentally observed heat-losses is that theoretically the rates of heat-loss from the symmetric sides of the 5-spot should be similar if the steam front is propagating symmetrically. A typical areal temperature distribution during the experiment shows that the isotherms are almost symmetrical. However the measured rates of heat-losses from the symmetric sides of the 5-spot were always unmatched. The hypothesis put forward by the investigators (Demiral et al. 1991, 1992) to explain this phenomenon is that there are local temperature differences around the lab model, which caused the differences in heat-loss rates.

The simulator results on the other hand show an almost perfectly matching rate of heat-loss from the symmetric sides of the 5-spot, as expected. There is no facility in the simulator to model an asymmetrical local temperature distribution around the model.

The figures⁵ on the following pages compare the experimentally observed heat-losses with those obtained from the simulator.

5.3 Discussion of Figures

Figure 5.1 shows the experimentally obtained CT scans and temperature distributions during the course of the continuous steam-injection experiment. It shows experimental saturation and temperature cross-sections for CT slice Number 2 of the laboratory model⁶.

⁵All of the figures on the following pages are originally in color.

⁶For clarity of presentation in all of the following figures only this particular slice (CT slice number 2) is considered, although results are available for all six experimental slices

Figure 5.2 shows the results obtained from the simulator for one particular value of the proportional convective heat transfer coefficient $*UHTR$ ($*UHTR = -720 \text{ J/D-C}$). It can be seen that there is a fairly good match of both the saturation and temperature distributions with the experimental results shown in Figure 5.1. The next figure, Figure 5.3, shows the experimental and calculated heat-loss rates from the five heat-flux sensors for this particular value of $*UHTR$. The laboratory model is designed as one quadrant of a 5-spot. Thus there are two symmetric faces on either side of the injector and the heat-flux sensors on these sides are labeled Injector-Left (I-L) and Injector-Right (I-R), respectively. Similarly there are two symmetric faces on either side of the producer and the heat-flux sensors on these sides are labeled Producer-Left (P-L) and Producer-Right (P-R), respectively. There is one heat-flux sensor on the top of the model, which is labeled Top. It can be seen that the calculated rates of heat-loss from all five sensors are lower than the experimentally measured rates. An interesting result that can be seen from this is that the experimentally measured heat-loss rates from symmetric sides of the experimental model are asymmetric, contrary to theory. The asymmetry is greater for the sensors on the producer end. The heat-loss rates calculated from the simulator for these symmetric sides, on the other hand, are almost perfectly symmetric.

Figure 5.4 shows the simulator results at $*UHTR = -820 \text{ J/D-C}$. Both the saturation and temperature cross-sections are still similar to the experimental scans, but they show lesser gravity override. The heat-loss plots corresponding to these are shown in Figure 5.5. It can be seen that the calculated heat-loss rates have risen and are closer to the experimentally measured rates than previously. The calculated heat-loss rates are still symmetric, unlike the experimental rates.

Figure 5.6 shows the calculated saturation and temperature cross-sections obtained at $*UHTR = -920 \text{ J/D-C}$. There is lower gravity override than in the experimental case and the area swept out by the steam zone is also lower. Figure 5.7 shows the corresponding heat-loss data. The experimental and calculated rates are closer to each other, especially for the top and injector side sensors. The calculated heat-loss rates are still symmetric.

Figure 5.8 shows the calculated saturation and temperature distributions for $*UHTR = -1080 \text{ J/D-C}$. This case shows much lower gravity override than the experimental results. However the calculated heat-loss rates show a very good match to the experimental results, particularly for the top and the injector side sensors.

Thus we can see that as the convective heat transfer coefficient is increased there is a better match between the experimentally observed and the calculated heat-loss rates. However as the calculated heat-loss rates come closer to the experimental results the calculated gravity override decreases, and becomes smaller than observed in the experiments. Thus, it appears that a close simultaneous match of the displacement and the heat loss is not possible. The reason for this result is not known, and clearly needs further study.

Figure 5.1: Experimentally Observed Saturation and Temperature Cross-Sections

Figure 5.2: Calculated Saturation and Temperature Cross-Sections — for the case *UHTR = -720 J/D-C.

Figure 5.3: Calculated versus Experimental Heat-Loss Rates — for the case $*UHTR = -720 \text{ J/D-C}$.

Figure 5.4: Calculated Saturation and Temperature Cross-Sections — for the case *UHTR = -820 J/D-C.

Figure 5.5: Calculated versus Experimental Heat-Loss Rates — for the case $*U_{HTR} = -820 \text{ J/D-C}$.

Figure 5.6: Calculated Saturation and Temperature Cross-Sections — for the ca: J/D-C.

Figure 5.7: Calculated versus Experimental Heat-Loss Rates — for the case *UHTR = -920 J/D-C.

Figure 5.8: Calculated Saturation and Temperature Cross-Sections — for the case *UHTR = -1080 J/D-C.

Figure 5.9: Calculated versus Experimental Heat-Loss Rates — for the case *UHTR = -1080 J/D-C.

6. Conclusions

From the simulation studies described in the preceding pages we can conclude that:

- The major input parameters of the numerical simulator have been estimated, as was the aim of the project. However, the estimates are not as accurate as would be desirable.
- There is a fairly good match between experimentally observed data and the simulator results. However, the experimental scans show a greater degree of gravity override than the simulator results.
- Further work is needed to improve the correspondence between the experimental data and the computer model predictions.

At this stage, I would like to briefly mention the main difficulties faced during the course of this work, which were:

1. Production data during the course of the experiment had not been collected, as the main stress had been upon the use of the CT scanner as a tool to visualize saturation distributions and displacement fronts during such experiments. This, however, made it impossible to compare the simulator material balance statistics with any experimental results.
2. Another area of difficulty was that some of the input parameters like steam-water relative permeability tables are not reliably determined and hence this may lead to errors in the simulation.

In summary therefore, we feel that the major objectives of this research study have only been partially achieved. Further refinement of this technique is possible, particularly in relation to the influence of the gridding scheme. A sensitivity study on the influence of a larger number of grid blocks may alleviate the problem regarding gravity override. This study would be possible when the STARS simulator has been fully ported onto the CRAY machine¹.

¹At the date of writing the executable has still not been properly installed and debugged on the CRAY.

Appendix A. STARS Utility Programs

The simulator output data was processed using the programs GRIDCON and GPS available on Pangea. Processing of the simulator output data consisted of the following steps:

1. Extract the required grid data (e. g. steam saturation, temperature or heat-loss data) from the simulator output files.
2. Process the extracted data into a form suitable for GRIDCON and send it to GRIDCON.
3. Process the GRIDCON output data into a form suitable for GPS and send it to GPS. This step results in the final color PostScript output files which can be imported into Latex or made into color slides on the Mac.

Carrying out all the above steps manually for each trial run was extremely tedious as the simulator output files are large, and the relevant data tends to be scattered about the files. However there is no graphics module available for this simulator with the department. Thus it was decided to develop some simple utility programs which would automate the above data processing steps. These programs were all combined into a single shell script file so that execution of one single command would carry out all the required data processing steps and directly result in the color PostScript output files. The programs are as follows:

1. The program, grid.f, with executable, gridx, and input control file, datex. This is a modification of a program available for the simulator, IMEX 4.3¹. This extracts from the output SRF (Simulation Results File) the saturation and temperature grid-block values for any particular saturation or temperature slice at any particular time (both to be specified in the control file, datex).
2. The shell script file, gconx. This takes the data files generated in the previous step and runs them through GRIDCON using the appropriate GRIDCON control files² for these data files.
3. The program, add.f, with executable, addx. This takes the GRIDCON output files of the previous step and adds the information required for processing by GPS.
4. The shell script file, gpsx. This takes the output files from addx and runs them through GPS along with the appropriate GPS control files³ to produce the final saturation and temperature slices required in color PostScript format.
5. The shell script file, hlsx. This extracts the heat-loss data from the SRF for the two specified heat-loss models for each heat-loss sensor using the program, mapm.f (with executable mapmx and some control files). It then adds the heat-loss rates from both models for each sensor to get the composite heat-loss rate, converts it to the required units and writes this data along with the measured heat-loss data, at different pore volumes (PV's) injected, to an output file.
6. The shell script file, hgpsx. The output file from the previous step is used as an input to GPS, along with the GPS control files to produce graphs of heat-loss rates at different PV's of steam injected.

¹I am grateful to Santosh Verma for help in modifying the programs imexgrid.f and imexmap.f for use in my STARS application.

²The GRIDCON control files should reside in the user's directory.

³The GPS control files should reside in the user's directory.

All these above programs are combined into a single master shell script file starsout. Thus by giving the single command, starsout, all the above programs are accessed and after a short while all the required color PostScript output files are created without any further input from the user. This is extremely convenient when several trial runs are to be made on the simulator. Once the initial control files are made for a particular problem then no further effort is required for processing the output data no matter how many trial runs are made. The control files are also easily modified for any other problem (e. g. if the number of grid blocks is increased or decreased).

These programs are described below along with the program listings. They are general in nature and can easily be modified by other STARS users for their particular problem.

A.1 gridx

This program requires an input control file which has the grid block numbers from which data is to be extracted and their x and y positions corresponding to the slice to be extracted. This control file is to be given as an input to the command, gridx, as follows:

pangea > gridx < datex

The program, grid.f, is listed below:

```

PROGRAM grid.f

C      This program extracts the required grid data from an SRF file.
C      The data to be extracted should be specified in the control file
C      datex.
C
C      This program is modified from a similar program for IMEX v. 4.3
C      ---Sameer Joshi---June 1993----

PARAMETER(NP=100,NBLOCK=5000)
CHARACTER*40 LINE,SRFNAM*15,GRDNAM*15,OUTNAM*15,LINE2*40,
$      ANS*1
INTEGER IX(NP),IY(NP),IZ(NP),IVAL(NP)
REAL*8 POSX(NP),POSY(NP),VAL(NBLOCK),DUM(NP)

WRITE(6,*)'GIVE THE SRF FILE NAME'
READ(5,1000)SRFNAM
WRITE(6,*)'GIVE THE FILE NAME WITH GRID NUMBERS'
READ(5,1000)GRDNAM
OPEN(UNIT=1,FILE=SRFNAM)
OPEN(UNIT=2,FILE=GRDNAM)

READ(2,*)NVAL
READ(2,*)(IX(I),IY(I),IZ(I),POSX(I),POSY(I),I=1,NVAL)

DO I=1,7
      READ(1,1100)LINE
ENDDO
READ(1,*)NX,NY,NZ

```

```

      NT=NX*NY*NZ

      DO I=1,NVAL
        IVAL(I)=NX*NY*(IZ(I)-1)+NX*(IY(I)-1)+IX(I)
      ENDDO

100  READ(1,1100,END=2000)LINE
      IF(LINE(1:5).EQ.'$GRID')GO TO 200
      GO TO 100
200  READ(1,*)TIME,NTYPE
      WRITE(6,*)'$GRID FOUND AT TIME ',TIME
      DO I=1,NTYPE
        READ(1,1100)LINE
        READ(1,1100)LINE2
        READ(1,*)(VAL(J),J=1,NT)
        WRITE(6,1200)LINE
        READ(5,1300)ANS
        IF(ANS.EQ.'y'.OR.ANS.EQ.'Y')THEN
          WRITE(6,*)'GIVE THE OUTPUT FILE NAME'
          READ(5,1000)OUTNAM
          OPEN(UNIT=3,FILE=OUTNAM)
          DO J=1,NVAL
            K=IVAL(J)
            DUM(J)=VAL(K)
            WRITE(3,1400)POSX(J),POSY(J),VAL(K)
          ENDDO
          CLOSE(3)
        END IF
      ENDDO
      GO TO 100

1000 FORMAT(A15)
1100 FORMAT(A40)
1200 FORMAT('DO YOU WANT TO TABULATE (Y/N)? ',A40)
1300 FORMAT(A1)
1400 FORMAT(F10.4,2X,F10.4,2X,F10.4)
2000 WRITE(6,*)'END OF SRF FILE REACHED'
      STOP
      END

```

A sample input control file (datex) with responses for the above program is listed below:

```

srf.out
gridfile
n
n
n
n
n
n
n

```

```

n
n
y
grd.04si
y
grd.04ti
n
n
n
n
y
grd.3si
y
grd.3ti
n
n
n
n
y
grd.54si
y
grd.54ti
n
n
n
n
y
grd.31si
y
grd.31ti
n
n

```

The above control file is for the case when the SRF file has four different \$GRID values in it. Similar files can be specified for any particular output SRF file.

The data file with grid numbers for this case (gridfile) is as follows:

```

36
1 2 1 1.6665 1.5
2 2 1 4.9995 1.5
3 2 1 8.3325 1.5
4 2 1 11.6655 1.5
5 2 1 14.9985 1.5
6 2 1 18.3315 1.5
1 2 2 1.6665 3.75
2 2 2 4.9995 3.75
3 2 2 8.3325 3.75
4 2 2 11.6655 3.75
5 2 2 14.9985 3.75
6 2 2 18.3315 3.75

```

1	2	3	1.6665	5.0
2	2	3	4.9995	5.0
3	2	3	8.3325	5.0
4	2	3	11.6655	5.0
5	2	3	14.9985	5.0
6	2	3	18.3315	5.0
1	2	4	1.6665	6.0
2	2	4	4.9995	6.0
3	2	4	8.3325	6.0
4	2	4	11.6655	6.0
5	2	4	14.9985	6.0
6	2	4	18.3315	6.0
1	2	5	1.6665	6.75
2	2	5	4.9995	6.75
3	2	5	8.3325	6.75
4	2	5	11.6655	6.75
5	2	5	14.9985	6.75
6	2	5	18.3315	6.75
1	2	6	1.6665	7.25
2	2	6	4.9995	7.25
3	2	6	8.3325	7.25
4	2	6	11.6655	7.25
5	2	6	14.9985	7.25
6	2	6	18.3315	7.25

A.2 gconx

This program takes the output files from the previous step⁴ and runs them through GRIDCON. As is normal for GRIDCON, a parameter file is to be specified for each of these files⁵. The file, gconx, for this particular case is listed below:

```
#!/bin/csh -f
gridcon par=grd.04s
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
pspen grd.04cons>cons04.ps
gridcon par=grd.3s
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
pspen grd.3cons>cons3.ps
gridcon par=grd.54s
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
```

⁴In this particular case we had six output files — grd.04si, grd.3si, grd.54si, grd.31si, grd.04ti, grd.3ti, grd.54ti and grd.31ti. These were the saturation and temperature data files at cumulative steam injection values of 0.04 PV, 0.3 PV, 0.54 PV and 1.31 PV.

⁵Refer to the GRIDCON manual for details of these parameter files

```

pspen grd.54cons>cons54.ps
gridcon par=grd.31s
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
pspen grd.31cons>cons31.ps
gridcon par=grd.04t
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
pspen grd.04cont>cont04.ps
gridcon par=grd.3t
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
pspen grd.3cont>cont3.ps
gridcon par=grd.54t
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
pspen grd.54cont>cont54.ps
gridcon par=grd.31t
rm ERRORFILE
rm GRIDLOG
rm PLOTLOG
pspen grd.31cont>cont31.ps

```

At the end of this step we have six output GRIDCON files for the six input files. These output files have been gridded on a 49×49 grid, from the input 6×6 grid. This step also produces contour plots of the input data on the same output grid detail. A sample GRIDCON control file (grd.04s) for one of the input files (grs.04si) is listed below:

```

in=grd.04si
out=grd.04cons
grid=1
nx=49
ny=49
zgrdmin=0.1
zpltmin=0.1
gridout=grd.04so
xmin=0
xmax=20
ymin=0
ymax=7.5

```

A.3 addx

The GRIDCON output files of the previous section are now in almost the correct form required for input to GPS. However they require the addition of one line on top of each file specifying

the grid size of the gridded data (49×49 in this case). This is done by running the files through the program add.f (executable addx) as given below:

```
PROGRAM add.f

C      This program opens the output files from GRIDCON, adds one
C      single line at their top and writes them to another file, so
C      that the files are in the proper input format for GPS.
C      --Sameer Joshi--June 1993--

REAL A(2500)
OPEN (1,FILE='grd.04so')
OPEN (2,FILE='grd.04sof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
OPEN (1,FILE='grd.04to')
OPEN (2,FILE='grd.04tof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
OPEN (1,FILE='grd.3so')
OPEN (2,FILE='grd.3sof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
OPEN (1,FILE='grd.3to')
OPEN (2,FILE='grd.3tof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
OPEN (1,FILE='grd.54so')
OPEN (2,FILE='grd.54sof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
OPEN (1,FILE='grd.54to')
OPEN (2,FILE='grd.54tof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
```

```

WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
OPEN (1,FILE='grd.31so')
OPEN (2,FILE='grd.31sof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
OPEN (1,FILE='grd.31to')
OPEN (2,FILE='grd.31tof')
WRITE (2,*) '49 49 1'
READ (1,*) (A(I),I=1,2401)
WRITE (2,100) (A(I),I=1,2401)
CLOSE(1)
CLOSE(2)
100 FORMAT (E17.9)
STOP
END

```

A.4 gpsx

The output files are now in the proper input format for GPS. The shell script file `gpsx` runs them through GPS and produces the final saturation and temperature slices in color PostScript format. This requires a control file for each saturation and temperature slice processed.

The shell file, `gpsx`, is listed below:

```

#!/bin/csh -f
gps gps.04s sat04.ps
gps gps.04t tem04.ps
gps gps.3s sat3.ps
gps gps.3t tem3.ps
gps gps.54s sat54.ps
gps gps.54t tem54.ps
gps gps.31s sat31.ps
gps gps.31t tem31.ps
gps smulti.gps smulti.ps

```

The GPS control file (`gps.04s`) for one of the output files (`sat04.ps`) is shown below:

```

%***** COLORMAP *****
%
% This is an example GPS command file which creates a colormap plot using
% the default colorscale.
%
size 5 3
title "SATURATION SLICE 2 (0.04 PV)"
labelx " x, cm "
labely " y, cm "

```

```

xmin 0 xmax 20
ymin 0 ymax 7.5
wmin 0.0 wmax 1.0
labelw "Saturation"
&/gondwana/scr2/joshi/run1/cs_cgyrmb.gps
readw grd.04sof          % Read file w.dat having format w.

colormap                  % Write colormap at default placement point.

ato 1.02 0 colorscale 0.15 % Place colorscale relative to colormap.
                        % Specify dx of scale to be 0.15.
                        % The scale's dy defaults to the
                        % same as dy as the colormap.

atg 20 20                 % Set placement point using graph coordinates.

```

The GPS control file (smulti.gps) for another output file (smulti.ps) is shown below:

```

%***** MULTI *****
%
% This is a GPS command file which demonstrates the use of scenes and file
% inserting to place several previously defined plots on a single page.
%
landscape
stringsize 20 20
at 5.5 8 string "Composite plot (-820 loss rate)", cb

%**** scene coordinates and scaling factor
scenesize 2.5 4.166666667 % Distance between scenes
sceneorigin 0.25 0.25 % Scene origin
scenyscale 0.350 % Amount to shrink what's in a scene
scenecolumns 4 % Move from scene to scene first by
               % columns. 4 columns per row.

beginscene
  reset
  &gps.04t
endscene

beginscene
  reset
  &gps.3t
endscene

beginscene
  reset
  &gps.54t
endscene

```



```

beginscene
  reset
  &gps.31t
endscene

```

```

beginscene
  reset
  &gps.04s
endscene

```

```

beginscene
  reset
  &gps.3s
endscene

```

```

beginscene
  reset
  &gps.54s
endscene

```

```

beginscene
  reset
  &gps.31s
endscene

```

A.5 hlsx

Now the saturation and temperature data has been extracted and processed. The heat-loss data must now be extracted and processed. This is done by the shell file, hlsx, given below:

```

#!/bin/csh -f
~/scr2/run1/mapmx<planei1
~/scr2/run1/mapmx<planei6
~/scr2/run1/mapmx<planej1
~/scr2/run1/mapmx<planej6
~/scr2/run1/mapmx<planek6
cat hlc*i1>hlc11
rm hlc??i1
cat hlc*i6>hlc16
rm hlc??i6
cat hlc*j1>hlcj1
rm hlc??j1
cat hlc*j6>hlcj6
rm hlc??j6
cat hlc*k6>hlck6
rm hlc??k6
cat hlo*i1>hloi1
rm hlo??i1

```

```

cat hlo*i6>hloi6
rm hlo??i6
cat hlo*j1>hloj1
rm hlo??j1
cat hlo*j6>hloj6
rm hlo??j6
cat hlo*k6>hlok6
rm hlo??k6
hcomp
rm hlc*
rm hlo*

```

This utilizes the program mapm.f (executable mapmx) to extract the required grid data from the SRF. This is similar to the program, grid.f. It also requires an input control file for automatic processing. The program, mapm.f, is shown below:

PROGRAM mapm.f

```

C      This program extracts heat-loss data from the SRF for the
C      specified grid blocks. The input parameters should be specified
C      in a control file for automatic execution.
C      This program is modified from a similar program for IMEX v. 4.3
C      ---Sameer Joshi--June 1993---

```

```

PARAMETER(NP=2000,NBLOCK=5000)
CHARACTER*40 LINE,SRFNAM*15,GRDNAM*15,OUTNAM*15,LINE2*40,
$      ANS*1
INTEGER IX(NP),IY(NP),IZ(NP),IVAL(NP)
REAL*8 POS(NP),VAL(NBLOCK),DUM(NP)

```

```

WRITE(6,*)'GIVE THE SRF FILE NAME'
READ(5,1000)SRFNAM
WRITE(6,*)'GIVE I1:I2 J1:J2 AND K1:K2'
READ(5,*)I1,I2,J1,J2,K1,K2
OPEN(UNIT=1,FILE=SRFNAM)

```

```

DO I=1,7
  READ(1,1100)LINE
ENDDO
READ(1,*)NX,NY,NZ
NT=NX*NY*NZ
II=1
DO K=K1,K2
  DO 75 J=J1,J2
    DO 75 I=I1,I2
      IVAL(II)=NX*NY*(K-1)+NX*(J-1)+I
      II=II+1
    ENDDO
  ENDDO

```

```

        II=II-1
        WRITE(6,*)'II :',II
100      READ(1,1100,END=2000)LINE
        IF(LINE(1:5).EQ.'$GRID')GO TO 200
        GO TO 100
200      READ(1,*)TIME,NTYPE
        WRITE(6,*)'$GRID FOUND AT TIME ',TIME
        DO I=1,NTYPE
            READ(1,1100)LINE
            READ(1,1100)LINE2
            READ(1,*)(VAL(J),J=1,NT)
            WRITE(6,1200)LINE
            READ(5,1300)ANS
            IF(ANS.EQ.'Y'.OR.ANS.EQ.'Y')THEN
                WRITE(6,*)'GIVE THE OUTPUT FILE NAME'
                READ(5,1000)OUTNAM
                OPEN(UNIT=3,FILE=OUTNAM)
                DO J=1,II
                    K=IVAL(J)
                    DUM(J)=VAL(K)
                    WRITE(3,1400)VAL(K)
                ENDDO
                CLOSE(3)
            END IF
        ENDDO
        GO TO 100

1000     FORMAT(A15)
1100     FORMAT(A40)
1200     FORMAT('DO YOU WANT TO TABULATE (Y/N)? ',A40)
1300     FORMAT(A1)
1400     FORMAT(F15.5)
2000     WRITE(6,*)'END OF SRF FILE REACHED'
        STOP
        END

```

A sample input control file (planeil) for this is shown below:

```

srf.out
1 1 3 4 2 2
n
n
n
n
n
n
n
n
n
n

```

```

y
hlo1.i1
y
hlc1.i1
n
n
n
n
y
hlo2.i1
y
hlc2.i1
n
n
n
n
y
hlo3.i1
y
hlc3.i1
n
n
n
n
y
hlo4.i1
y
hlc4.i1

```

The output files resulting from this process are the heat-loss data for the two different heat-loss models. These two heat-loss rates are added for each sensor to get the composite heat-loss rate, converted to the required units and written to file along with the experimentally measured heat-loss data at different pore volumes (PV) injected. This is accomplished by means of the program, hcomp.f (executable hcompx), which is given below:

```

PROGRAM hcomp.f

```

```

C      This program takes the output heat-loss data from the SRF file,
C      adds the heat-loss rates from both heat-loss models, converts
C      them to required units and writes them to an output file,
C      together with the experimentally measured heat-loss rates at
C      different pore volumes (PV's) injected.
C      ---Sameer Joshi---June 1993---

```

```

      REAL A(20), B(20)
      OPEN (1,FILE='hlc11')
      OPEN (2,FILE='hlo11')
      OPEN (3,FILE='hli11')
      DO I=1,8
        READ (1,*) A(I)

```

```

      READ (2,*) B(I)
ENDDO
WRITE (3,*) '5'
WRITE (3,*) '0 0 0'
WRITE (3,*) '0.04 35',((-A(1)-A(2))/2.+(-B(1)-B(2))/2.)*1.0566
WRITE (3,*) '0.30 92',((-A(3)-A(4))/2.+(-B(3)-B(4))/2.)*1.0566
WRITE (3,*) '0.54 105',((-A(5)-A(6))/2.+(-B(5)-B(6))/2.)*1.0566
WRITE (3,*) '1.31 100',((-A(7)-A(8))/2.+(-B(7)-B(8))/2.)*1.0566
CLOSE (1)
CLOSE (2)
CLOSE (3)
OPEN (1,FILE='hlci6')
OPEN (2,FILE='hloi6')
OPEN (3,FILE='hli6')
DO I=1,8
  READ (1,*) A(I)
  READ (2,*) B(I)
ENDDO
WRITE (3,*) '5'
WRITE (3,*) '0 0 0'
WRITE (3,*) '0.04 10',((-A(1)-A(2))/2.+(-B(1)-B(2))/2.)*1.0566
WRITE (3,*) '0.30 75',((-A(3)-A(4))/2.+(-B(3)-B(4))/2.)*1.0566
WRITE (3,*) '0.54 125',((-A(5)-A(6))/2.+(-B(5)-B(6))/2.)*1.0566
WRITE (3,*) '1.31 110',((-A(7)-A(8))/2.+(-B(7)-B(8))/2.)*1.0566
CLOSE (1)
CLOSE (2)
CLOSE (3)
OPEN (1,FILE='hlcj1')
OPEN (2,FILE='hloj1')
OPEN (3,FILE='hlj1')
DO I=1,8
  READ (1,*) A(I)
  READ (2,*) B(I)
ENDDO
WRITE (3,*) '5'
WRITE (3,*) '0 0 0'
WRITE (3,*) '0.04 25',((-A(1)-A(2))/2.+(-B(1)-B(2))/2.)*1.0566
WRITE (3,*) '0.30 82',((-A(3)-A(4))/2.+(-B(3)-B(4))/2.)*1.0566
WRITE (3,*) '0.54 90',((-A(5)-A(6))/2.+(-B(5)-B(6))/2.)*1.0566
WRITE (3,*) '1.31 85',((-A(7)-A(8))/2.+(-B(7)-B(8))/2.)*1.0566
CLOSE (1)
CLOSE (2)
CLOSE (3)
OPEN (1,FILE='hlcj6')
OPEN (2,FILE='hloj6')
OPEN (3,FILE='hlj6')
DO I=1,8
  READ (1,*) A(I)
  READ (2,*) B(I)

```

```

ENDDO
WRITE (3,*) '5'
WRITE (3,*) '0 0 0'
WRITE (3,*) '0.04 5',((-A(1)-A(2))/2.+(-B(1)-B(2))/2.)*1.0566
WRITE (3,*) '0.30 40',((-A(3)-A(4))/2.+(-B(3)-B(4))/2.)*1.0566
WRITE (3,*) '0.54 70',((-A(5)-A(6))/2.+(-B(5)-B(6))/2.)*1.0566
WRITE (3,*) '1.31 70',((-A(7)-A(8))/2.+(-B(7)-B(8))/2.)*1.0566
CLOSE (1)
CLOSE (2)
CLOSE (3)
OPEN (1,FILE='hlck6')
OPEN (2,FILE='hlok6')
OPEN (3,FILE='hlk6')
DO I=1,16
    READ (1,*) A(I)
    READ (2,*) B(I)
ENDDO
WRITE (3,*) '5'
WRITE (3,*) '0 0 0'
WRITE (3,*) '0.04 5',((-A(1)-A(2)-A(3)-A(4))/4.
$      +(-B(1)-B(2)-B(3)-B(4))/4.)*1.0566
WRITE (3,*) '0.30 90',((-A(5)-A(6)-A(7)-A(8))/4.
$      +(-B(5)-B(6)-B(7)-B(8))/4.)*1.0566
WRITE (3,*) '0.54 105',((-A(9)-A(10)-A(11)-A(12))/4.
$      +(-B(9)-B(10)-B(11)-B(12))/4.)*1.0566
WRITE (3,*) '1.31 80',((-A(13)-A(14)-A(15)-A(16))/4.
$      +(-B(13)-B(14)-B(15)-B(16))/4.)*1.0566
CLOSE (1)
CLOSE (2)
CLOSE (3)
STOP
END

```

A.6 hgpsx

The output heat-loss data file from the previous step is used as an input to GPS together with a GPS control file to get plots of heat-loss rates versus different PV's of steam injected. The shell file, hgpsx, is as follows:

```

#!/bin/csh -f
gps hli1.gps hli1.ps
gps hli6.gps hli6.ps
gps hlj1.gps hlj1.ps
gps hlj6.gps hlj6.ps
gps hlk6.gps hlk6.ps
gps hmulti.gps hmulti.ps

```

One of the GPS control files (hli1.gps) is shown below:

```

line 1 2

```

```

symbol 0 6
ymax 130
ymin 0
xmax 1.5
xmin 0

title "Heat Loss Rates I-L "
labelx "PV Injected"
labely "Heat Loss Btu/hr-sq-ft"

readxy hli1 1 2
readxy hli1 1 3
at 1 1 xy
name 1 "actual"
name 2 "calc"
ato 0.74 0.15 legend

```

Another of the control files (hmulti.gps) is shown below:

```

%***** MULTI *****
%
% This is a GPS command file which demonstrates the use of scenes and file
% inserting to place several previously defined plots on a single page.
%
stringsize 30 30
at 4.5 10.5 string "Sensor Heat Loss Rates (-820 rate)", cb

%*** scene coordinates and scaling factor
scenysize 4 3 % Distance between scenes
sceneorigin 1 1 % Scene origin
scenyscale 0.425 % Amount to shrink what's in a scene
scenecolumns 2 % Move from scene to scene first by
% columns. 2 columns per row.

beginscene
reset
&hlj6.gps
endscene

beginscene
reset
&hli6.gps
endscene

beginscene
reset
&hli1.gps
endscene

beginscene

```

```
reset
&hlj1.gps
endscene
```

```
beginscene 0.5 2
reset
&hlk6.gps
endscene
```

A.7 starsout

All the utility programs described earlier are put into one single shell file, called starsout, so that by giving just one command the entire data extraction and processing job is done. The file, starsout, is listed below:

```
#!/bin/csh -f
gridx<datex
gconx
addx
gpsx
hlx
hgpsx
```

These above programs can be modified for extraction and processing of other simulator output data by modifying the control files as needed.

REFERENCES

- [1] J. Burger, P. Sourieau and M. Combarneau. *Thermal Methods of Oil Recovery*. Éditions Technip, Paris, 1985.
- [2] R. B. Bird, W. E. Stewart and E. N. Lightfoot. *Transport Phenomena*. John Wiley and Sons Inc. , New York City (1960).
- [3] Roger M Butler. *Thermal Recovery of Oil and Bitumen*. Prentice Hall, Englewood Cliffs, N. J. , (1991).
- [4] H. S. Carslaw and J. C. Jaeger. *Conduction of Heat in Solids*. Oxford U. Press, London (1950).
- [5] R. E. Collins. *Flow of Fluids Through Porous Materials*. Reinhold Publishing Corp. , New York City (1961); reprinted by Petroleum Publishing Co. , Tulsa, OK (1976).
- [6] M. Jakob. *Heat Transfer*. John Wiley and Sons Inc. , New York City (1949).
- [7] M. Prats. *Thermal Recovery*. SPE Monograph Vol. 7, Soc. Pet. Eng. (1982), Dallas.
- [8] M. W. Zemanski. *Heat and Thermodynamics*. Mc Graw-Hill, New York (1943).
- [9] B. M. R. Demiral, L. M. Castanier and W. E. Brigham. *CT Imaging of Steam and Steam/Foam Laboratory Experiments*. SPE 22644, 66th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Dallas, TX (Oct. 1991).
- [10] B. M. R. Demiral, P. A. Pettit, L. M. Castanier and W. E. Brigham. *A Three-Dimensional Laboratory Steam Injection Model Allowing In Situ Saturation Measurements*. SUPRI TR 83, Petroleum Engineering, Stanford University, Stanford, California (June 1992).
- [11] A. G. Spillete and R. L. Nielsen. *Two-Dimensional Method for Predicting Hot Waterflood Recovery Behaviour*. JPT, Vol. 20, p. 627-638 (1968).
- [12] N. D. Shutler. *Numerical Three-Phase Model of the Linear Steamflood Process*. SPEJ, Vol. 9, p. 232-246 (1969).
- [13] N. D. Shutler. *Numerical Three-Phase Model of the Two-dimensional Steamflood Process*. SPEJ, Vol. 10, p. 405-417 (1970).
- [14] P. K. W. Vinsome. *A Numerical Description of Hot-Water and Steam Drives by the Finite-Difference Method*. Annual Fall Meeting of SPE, SPE Paper Number 5248 (Oct. 1974).
- [15] J. Ferrer and S. M. Farouq Ali. *A Three-Phase, Two-Dimensional compositional Thermal Simulator for Steam Injection Processes*. JCPT, Vol. 16, No. 1, p. 78-90 (Jan. - March 1977).
- [16] H. G. Weinstein, J. A. Wheeler and E. G. Woods. *Numerical Model for Thermal Processes*. SPEJ, Vol. 17, p. 65-78 (1977).

- [17] A. Abdalla and K. H. Coats. *A Three-Phase, Experimental and Numerical Simulation Study of the Steam Flood Process*. Annual Fall meeting of SPE, SPE Paper number 3600, (Oct. 1971).
- [18] K. H. Coats, W. D. Georges, C. Chu and B. E. Marcum. *Three-Dimensional Simulation of Steamflooding*. SPEJ Vol. 14, p. 573-592 (1974).
- [19] K. H. Coats. *A Highly Implicit Steamflood Model*. SPEJ, Vol. 18, p. 369-383 (1978).
- [20] P. Lemonnier. *Three-Dimensional Numerical Simulation of Steam Injection*. 1981 Europ. Symp. on EOR, Proc. , Elsevier Sequoia, Lausanne, p. 374-394 (1981).
- [21] P. K. W. Vinsome and J. D. Westerveld. *A Simple Method for Predicting Cap and Base Rock Heat Losses in Thermal Reservoir Simulators*. JCPT, Vol. 19, No. 3 (July-Sept. 1980).

END

**DATE
FILMED**

10 / 22 / 93