NIGHTS: A SINGLE-PHASE GEOTHERMAL RESERVOIR SIMULATOR

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ABSTRACT

Many geothermal reservoirs contain no *in-situ* steam (liquid brine only). Numerical models of systems of this type may be developed economically by taking advantage of the single-phase character of the reservoir using the NIGHTS simulator. NIGHTS invokes the Boussinesq approximation: the fluid density is regarded as independent of pressure, and depends only on temperature and brine composition. NIGHTS treats thermohaline convection problems (free and forced), and incorporates a nonequilibrium thermal model for fractured systems. The simulator is routinely used for modeling the natural state of liquid-dominated hydrothermal reservoirs and also for calculating reservoir response to fluid production/injection operations for cases in which the reservoir remains single-phase despite production-induced pressure decline.

1. BACKGROUND

NIGHTS (Nonequilibrium Incompressible Geothermal Heat Transfer Simulator) is the latest in a series of computational reservoir simulator? intended primarily for long-term unsteady three-dimensional calculations of the behavior of liquid-dominated reservoirs. Determination of the "natural" state (that is. the state of the reservoir prior to human intervention) is often the most computationally-intensive part of a numerical reservoir modeling study. since it usually involves carrying out calculations representing time periods of the order of 10^5 years. The subsequent parts of a typical reservoir modeling study (history matching of existing production records/forecasts of future performance) generally require much less computer time (time-periods of interest are generally less than 10^2 years).

Calculation of the "natural-state" is a crucial part of geothermal reservoir modeling, for at least two reasons. First. it is clearly essential that the "natural-state" (initial conditions for the "exploitation" phase of the calculation) itself constitutes a steady (or nearly steady) solution of the governing equations subject to the applied boundary conditions. Alleged "natural states" which exhibit rapid spontaneous temporal changes in underground conditions in the absence of fluid production linjection operations are clearly unacceptable. Furthermore, the requirement that the "natural state" comprise a reasonably steady solution of the governing equations (subject to the same set of boundary conditions to be prescribed for the subsequent "exploitation" modeling) provides invaluable constraints upon the modeling proccss itself, which is usually vastly underconstrained using field measurements alone. A steady natural-state model which yields distributions of underground pressures. temperatures etc. which are in good agreement with pre-production measurements lends credibility to the distributions of the various free parameters in the model (usually permeabilities and boundary conditions).

Obtaining such an internally self-consistent mathematical description of the "natural state" which is also in good agreement with field data is, of course, a major technical challenge. Such models must he developed by trial-and-error. A numerical calculation is carried out representingan extremely long period of time, until nearly-steady conditions prevail underground. Then, the computed distributions of pressure, temperature. surface discharger, etc. are compared with field data. Usually. discrepancies are found; adjustments are made in the free parameters in the model, and the calculation is repeated with modified input data. Typically 20 to 60 such "natural state" calculations are required to provide a good match.

Since each such calculation represents ~10^5 years of real time, the computer time required to carry out the calculations is usually the primary obstacle to timely completion of the model. If these calculations are carried out using a general purpose multiphase geothermal reservoir simulator, several days of computer time are often required fur each "natural-state" calculation using modern scirntificdesktopworkstations.

2. MATHEMATICAL APPROACH

For single-phase (liquid) systems, it is possible to improve this melancholy situation by using simplified mathematical models for the reservoir. Omitnng source/sink terms associated with production and injection wells for clarity, the fluid mass conservation principle may be expressed by:

$$\frac{\partial}{\partial t}\left(\phi\rho F_j\right)+\nabla\bullet\left(\vec{M}F_j-L\left|\vec{M}\right|\nabla F_j\right)=0 \tag{1}$$

Momentum conservation is provided by Darcy's law:

$$\boldsymbol{M}=k(\rho\vec{g}-\nabla P)/\nu \tag{2}$$

and the Conservation of fluid energy is given by:

$$\frac{\partial}{\partial t}(\phi\rho cT)+\dot{e}_r+V\bullet\left(\vec{M}cT-L\left|\vec{M}\right|c\nabla T\right)=V\bullet(K\nabla T) \tag{3}$$

In these expressions.

$\vec{g}$ = acceleration of gravity (a constant vector) (4)

c = brine heat capacity (a constant). (5)

$\phi(x,y,z,t)$ = rock porosity, (6)

$k(x,y,z)$ = rock permeahility, (7)

$L(x,y,z)$ = hydraulic dispersion coefficient, (8)

$K(x,y,z,t)$ = thermal conductivity of brine/rock composite. (9)

$\rho(x,y,z,t)$ = brine density. (10)

$M(x,y,z,t)$ = brine mass flux vector. (11)

$\nu(x,y,z,t)$ = brine kinematic viscosity. (12)

$\dot{e}_r(x,y,z,t)$ = rate of change of rock energy per unit total volume. (13)

$P(x,y,z,t)$ = fluid pressure (14)

$T(x,y,z,t)$ = fluid temperature, and (15)

$F_j(x,y,z,t)$ = mass fraction of species j in brine. (16)

The "j" subscript refers to different chemical components present in the brine. We adopt the convention that "$j = 0$ refers to H_2O; other values of "j" denote other dissolved materials, such as NaCI. KCI, silica, etc. Also note that:

$$\sum_{j=0}^{N} F_j = 1 \tag{17}$$

The rate at which the energy of the rock increases (**equal** to the rate of local energy **loss** from the fluid) due to differences in temperature between rock and fluid ($\dot{e}_r$) remains to be determined. One approach is to **assume** that the **rock** and the Huid **are** always in local thermodynamic equilibrium (the "porous medium" approximation): in this case, $\dot{e}_r$ in Eqn. 2 may he replaced by:

$$\dot{e}_r = \frac{\partial}{\partial t}\left[(1-\phi)\rho_r c_r T\right]$$

where

$$\rho_r(x,y,z) = \text{mass density of pore-free rock, and} \tag{19}$$

$$c_r(x,y,z) = \text{heat capacity of rock material.} \tag{20}$$

For "fractured" rocks (in which a significant time is required for the ruck bodies to reach conductive thermal equilibrium with the brine in the fractures). $\dot{e}_r$ must he computed separately (see below).

To simplify the above system of equation?. we first treat both the fluid and the rock as incompressible. This means that (1) ϕ depends on position only, and (2) the fluid density depcnds only on temperature and brine composition:

$$\rho = \bar{\rho} + \delta\rho\left(T, F_j\right)$$

where $\bar{\rho}$ is a suitable constant. In the NIGHTS code. $\delta\rho$ is expressed by a polynomial which is quadratic in temperature and linear in each of the various **mass** fractions. The coefficients in this polynomial (and the **value** of $\bar{\rho}$) are supplied as input to the simulator by the **user.** Similarly. the kinematic viscosity and thermal conductivity of the brine are expressed by algebraic fits (with user-supplied coefficients) in temperature and composition:

$$\nu = \nu(T, F_j) \tag{22}$$

$$K_f = K_f(T, F_j) \tag{23}$$

The fluid (K_f) and **rock** ($K_r(x,y,z)$) thermal conductivities are combined to form the effective conductivity (K) using Budiansky's (1970) rule:

$$\frac{\phi}{2K + K_f} + \frac{1-\phi}{2K + K_r} = \frac{1}{3K} \tag{24}$$

Next. we apply the Boussinesq approximation: **we** assume that p may adequately be represented by $\bar{\rho}$ in the **mass** and energy balance relations (Eqns. 1 and 3). Note. however, that we retain the $\delta\rho$ correction in Darcy's law (Eqn. 2). Then, if we **sum** Eqn. 1 over all species (j), we obtain an expression for total brine mass conservation:

$$\nabla \cdot \vec{M} = 0 \tag{25}$$

which may also be written (using Eqn. 2):

$$\nabla \cdot \left(k(\nabla P/\nu)\right) = \nabla \cdot \left(k(\bar{\rho} + \delta\rho)\vec{g}/\nu\right) \tag{26}$$

Eqn. 26 amounts to a Poisson equation for the pressure distribution: note that **no** time-derivatives appear. Using the incompressibility assumption together with the Boussinesq approximation therefore transforms the problem of establishing the pressure distribution from an initial-value problem to a boundary-value problem. At any instant v i time. if the distributions of density, permeability and kinematic viscosity are **known.** the pressure distribution may be found using Eqn. 26 irrespective of the prior **pressure** history

3. NUMERICAL TECHNIQUE

NIGHTS uses a three-dimensional Cartesian grid consisting of rectangular grid blocks to **solve** the above system of equations. Consider that the state of the system (temperaturcs. mass fractions! is known at time $t = t^n$ (which could be the prescribed inital state or some later time). The state of the system a short time later ($t^{n+1} = t^n + \Delta t$) is obtained by the following procedure:

Step 1: Use a spatially-discretized version of **Eqn.** 26 to **find** thr pressure distribution P at $t = t^n$. This is the most time-consuming step: in NIGHTS, a Gauss-Seidel iteration procedure with an aver-relaxation factor which is automatically and continuously optimized **is** employed.

Step 2: Compute the **mass flux** distribution ($\vec{M}$) at $t = t^n$ using Eqn. 2 and the pressure distribution found in Step 1

Step 3: Compute the new temperatures and composition\ at $t = t^{n+1}$ using a forward difference as follows:

$$\frac{\phi\bar{\rho}}{\Delta t}\left(F_j^{n+1} - F_j^n\right) = -\nabla \cdot \left(\vec{M}^n F_j^n - L\left|\vec{M}^n\right|\nabla F_j^n\right)$$

$$\frac{\phi\bar{\rho}c}{\Delta t}\left(T^{n+1} - T^n\right) + \dot{e}_r^{n+1} = \nabla \cdot \left(K^n \nabla T^n\right) - c\nabla \cdot \left(\vec{M}^n T^n - L\left|\vec{M}^n\right|\nabla T^n\right) \tag{28}$$

The convection terms in Eqns. 27 and 28 are treated using **a** second-order technique to minimize "numerical dispersion" errors. Since the update of the **mass** fractions and temperatures (Eqns. 27. 28) is explicit in character (so that no simultaneous equations arc involved), little computer time is required for this step. The penalty, ofcourse. is that the explicit forward step imposes a Courant time-step size limitation — the **value** selected for **Al** must be small enough that no element of fluid passes entirely through a single grid block within the time-step. In natural flows in geothermal systems. however. flow rates arc generally **low** so that, ordinarily, the Courant condition does not pose an unacceptable limitation.

Two approaches are available in NIGHTS for treating heat exchange between the rock and the fluid. These methods ("porous" and "fractured") may be freely intermixed within **a** single problem (some grid blocks may be treated **as** "porous" while others are "fractured'). In the "porous" case, **as** noted above, the heat exchange rate $\dot{e}_r$ is provided hy Eqn. 18. In the "fractured' **case,** we consider that each grid block may he regarded **as** containing a system of numerous fractures which serve to subdivide the **rock material** into numerous "rock bodies" separated by fractures. All of the fluid is located in, and flows through. the fractures. We furthermore consider that, within the grid block, all the "rock bodies" are the same size and have the same thermal propelties (thermal conductivity. heat capacity, and density). For simplicity. we then idealize such a "typical" rock body to be spherical in shape. as indicated in Figure 1

Thus. the problem of evaluating the heat transfer between the fluid in the fractures and the rock within the rock body may be treated as one-dimensional unsteady heat conduction in **a** spherical rock body surrounded by the fluid within the fracture, subject to maintaining the boundary temperature equal to the local instantaneous fluid temperature. NIGHTS discretizes each such "typical rock body" into concentric spherical shells, **each** of the same volume. **As** shown in Figure 1 (which exhibits such an assembly composed of 16 shells within the rock body). this tends to maximize the spatial resolution near the rock/fluid interface. Implicit time-discretization is used in the solution of the subgrid spherical heat conduction problem. Advantage is taken in NIGHTS of the linearity of the heat conduction problem—experiments have shown that the computer time requirements increase only slightly if the

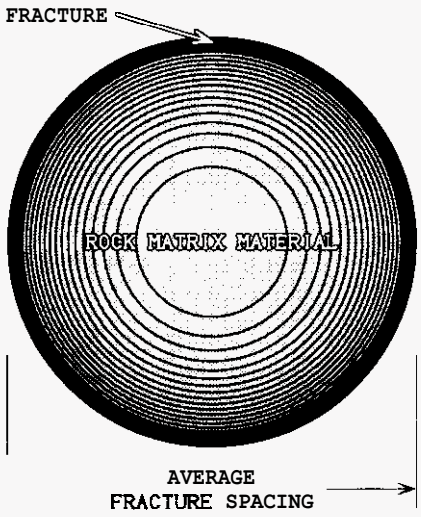

Figure 1. Assembly of 16 concentric spherical "shell?" to represent a sub-grid rock body surrounded hy liquid-filled fractures.

"fractured' formulation is used (as compared to the "porous" formulation)

Consider for the moment the simplified problem of a single spherical rock body surrounded by fluid, with the fluid and the rock initially at the same temperature (T_0). At $t = 0$, the fluid temperature is abruptly changed to a different value (T_1) and maintained at that value thereafter. Semi-analytical solutions to this problem are available (see, for example, Carslaw and Jaeger, 1959).as shownin Figure 2. Here.the "dimensionless average rock temperature" is defined as $(\bar{T}(t) - T_0 / (T_1 - T_0))$; $\bar{T}(t)$ is the average temperature within the rock body. The "characteristic relaxation time" t^* is given by:

$$t^* = \rho_r c_r \left(\frac{\lambda}{2}\right)^2 \Big/ \left(K_r (1-\phi)^{2/3}\right) \qquad (29)$$

where λ is the **"average fracture** separation". It is noteworthy that virtually all the energy is transferred by $t = t^*$; in fact. half of the heat transfer is complete by only $t = 0.03\,t^*$. Figure 3 shows the results of a series of numerical experiments to solve this same problem using the discretized approach employed in NIGHTS. with **various** numbers of subgrid concentric "shells" representing the rock body. Thew result? indicate that the discretized solution should be adequate so long as the number of shells is greater than five or so. Typically, we use 10–20 shells in NIGHTS calculations.

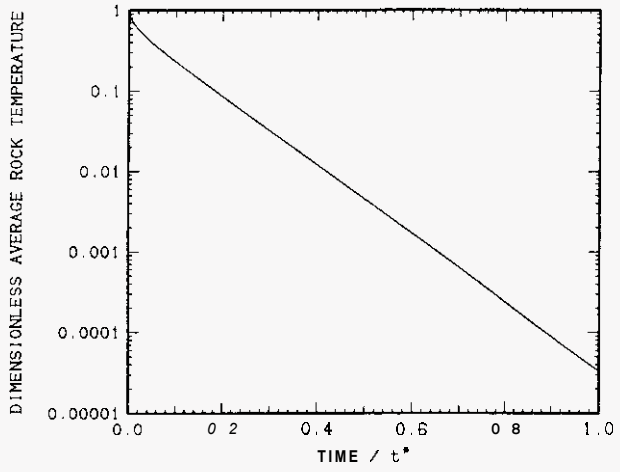

Figure 2. Change in average rock-body temperature subject to a fixed boundary **(fluid)** temperature change.

4. NATURAL-STATE SIMULATIONS

As noted above. calculations of the "natural state" of geothermal reservoirs **involve** very long time-scales ($>> t^*$), so that for such calculations the "fracture" model **is** nor necessary Figure 4 illustrates a

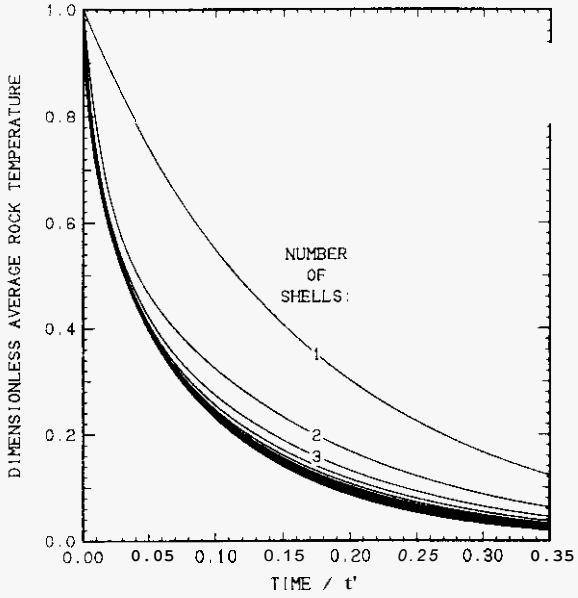

Figure 3. Effect of rock body resolution on calculated response to fluid temperature change,

succession of frames in a typical "natural-stair" calculation carried out using NIGHTS. Each frame **represents** the same vertical cross-section through the three-dimensional computational grid—the temperature distribution stabilizes after ~150,000 years. The shaded area in Figure 4 represents saline magmatic waters emanating from a prescribed fixed-**rate** hot fluid source centered along the bottom of the grid. Elsewhere. the bottom surface is impermeable, as are the lateral vertical boundaries: the top surface (corresponding to the eanh surface) is of the "fixed **pressure"** type. which permits upflow of fluid near the center at the ground surface and downward recharge of fresh meteoric water (unshaded).

The total volume of the grid in the calculation depicted in Figurc 4 is about 60 cubic kilometers; the width of thc cross-section is 4 kilometers. The computational grid used 4.096 grid block? (16 x I6 x 16), and a time-step size of four years was employed (a total of 62,500 **steps** far the 250,000 year history). This calculation was carried out on a moderate-**size** desktop scientific workstation (Silicon Graphics Iris/Indigo 4000); less than **twelve** hours were required. It is estimated that calculating the same problem using a general-purpose compressible multiphase reservoir simulator (such as STAR: Pntchett. 1995) would *take* at least ten times as long. Since NIGHTS could complete each natural-state calculation overnight, it was possible Io make one run per day - the final natural-state model for this field was therefore completed in just a few **weeks.**

Even though NIGHTS is restricted to single-phase liquid flow **(no** steam), it can sometimes bc **uscd** to help obtain an approximately steady solution fortwo-phase systems as long as the two-phase region represents a sufficiently small fraction of the grid volume Pritchett and Garg (1995) describe such a calculation forthe Oguni field in southern Japan. The NIGHTS code was first **used** to obtain a steady solution neglecting the two-phase region (coincidentally. also of 250,000 years duration). At the end of this calculation. a total of 16 shallow grid blocks (our of 3,456 total blocks) were characterized by temperatures in excess of boiling point for the local grid block pressure. Next, the pressure in each of these grid blocks was raised just sufficiently tu return it roan all-liquid state, and the calculation was transferred tu the multiphase STAR Simulator (NIGHTS **contains** special nutput features to facilitate such transitions). Immediately. of course. the I6 excess-pressure blocks decompressed. creating a small two-phase zonc. Only 6,000 years of additional computed history were required to re-stabilize the solution owing to the relatively small size of the two-phase zone.

5. HISTORY-MATCHING AND PERFORMANCE PREDICTIONS

Although NIGHTS was developed principally to facilitate calculations of the natural **state.** it has also occasionally proved useful in history matching studies and in performance forecasts tor fields in which

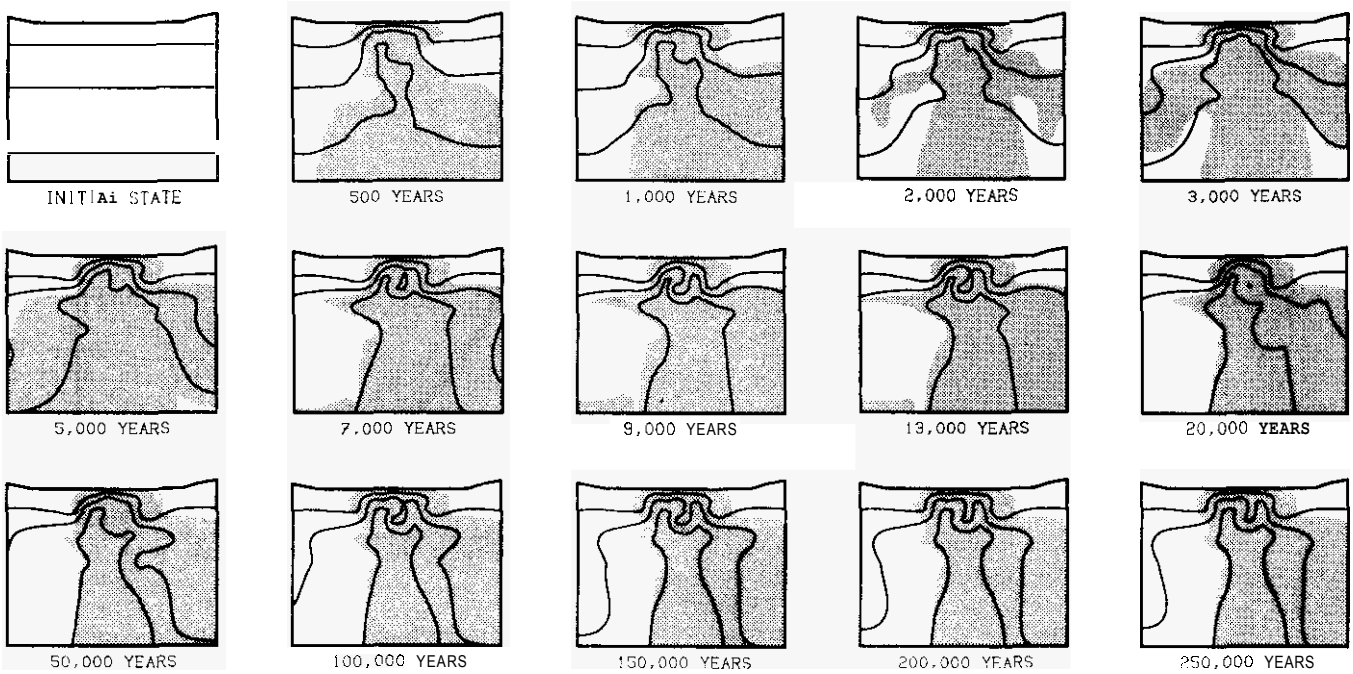

Figure 4. A typical natural-state simulation. Contours: temperature (50°C, 150°C, 250°C). Shaded area: saline magmatic waters from deep fluid source. Unshaded area, fresh meteoric waters (surface recharge). Duration: 250,000 years.

temperatures are low enough that production-induced pressure drop does not induce large-scale boiling in the reservoir. Local source and sink terms (to represent the effects of individual production and injection wells) are imposed, and changes in underground pressures and temperatures are computed.

Figure 5 illustrates the results of such a history-matching study. The field had operated for about eight years and, as shown, at early times the temperatures in the produced fluids declined rapidly. Simultaneously, the chloride content of the produced fluid increased. At early times, the production wells and injection wells were located too close together. This is manifested by the rapid early increases in chloride content, as concentrated reinjected brine began to enter the production wells. After 2–3 years, the field operator shut down several wells and drilled additional injection wells farther from the primary production area. As Figure 5 shows, this resulted in a recovery of the fluid chloride content and a reduction in the rate at which temperatures were declining.

It was necessary to use the "fracture" model in this case to simultaneously match the temperature and chloride histories. Several similar calculations were carried out, varying the "average fracture separation" (λ) in the principal production aquifer. Changing the fracture separation has negligible effects on the computed chloride history, but the early rate of temperature decline is very sensitive to fracture separation. The results shown in figure 5 were obtained using an average fracture separation of 80 meters.

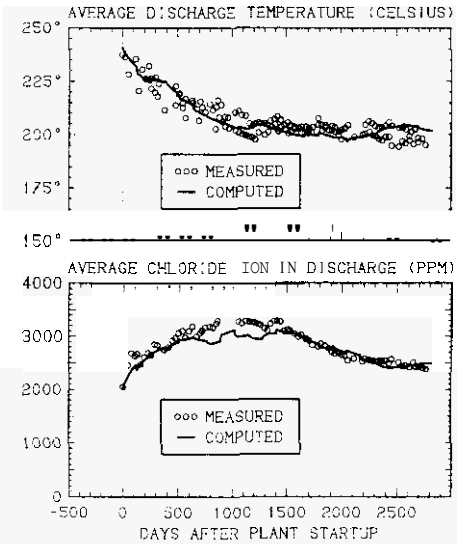

Figure 5. History-match study results for a moderate-temperature geothermal field.

6. SUMMARY

The SIGHTS simulator can significantly facilitate the development of natural-state models of liquid-dominated geothermal reservoirs by substantially reducing computer-time requirements as compared to conventional multiphase simulators. SIGHTS has been in routine use for geothermal reservoir engineering studies since 1984, and has been applied to several different geothermal fields. Postprocessors are available to prepare "snapshot" plots (contour and vector plots of the state of the system at specific instants of time) and "history" plots (variations with time of user-specified scalar quantities). The simulator is written in ANSI-standard Fortran-77 to enhance portability, and has been installed on a variety of different machines around the world ranging in capacity from "486" PC's to Cray supercomputers.

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