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**WELLBORE THERMAL SIMULATION
FOR GEOTHERMAL WELLS**

**SURVEY OF EXISTING CAPABILITY AND
INDUSTRY NEEDS AND INTEREST**

BY

Malcolm A. Goodman

**Subcontract to Prime Contract
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
GEOTHERMAL ENERGY DIVISION
ERDA Contract No. EG 76-C-07-1603
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Houston, Tx.**

June 1977

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SCOPE OF STUDY

Four operating companies and five service companies in the petroleum and geothermal industry were contacted 1.) to determine needs for wellbore temperature predictions during operations and 2.) to evaluate interest in use of a wellbore thermal simulator (computer program) if developed by ERDA. As a basis for contacting industry, a literature survey was undertaken to assess the state-of-the-art and availability of wellbore thermal simulation capability. The literature review is summarized in the four tables of Appendix 1. Written abstracts of the individual articles is given in Appendix 2. The feedback from industry is presented in Appendix 3 in the form of completed questionnaires.

CONCLUSIONS

Based on the literature review and industry response, the following conclusions are presented:

1. The major need expressed by industry for wellbore temperature predictions in geothermal wells is for highly transient behavior during drilling and completion operations. The steady-state behavior during production is not a major concern.
2. All nine companies, that were contacted, indicated an interest and need for wellbore temperature predictions during and immediately following transient circulation. Cementing and logging problems were most frequently mentioned.
3. The producing companies were also interested in highly transient wellbore temperature predictions for monitoring geothermal gradients while drilling and for short-term production testing.
4. All of the companies that completed and returned the questionnaire (eight out of nine) indicated that their present thermal simulation capability was lacking and that they would use, if available at reasonable cost, a computer program to predict transient wellbore temperatures.
5. A computer program for predicting highly transient wellbore temperatures does not presently exist in the public domain. Existing capability is limited to long time behavior and is not accurate for early times (less than 24 hours) or short time periods (less than 7 days).

RECOMMENDATIONS:

1. A fully transient, two-dimensional thermal simulator for single phase flow during drilling, circulation, production, and injection should be developed and made available for public use. This basic program would be capable of handling most needs as presently indicated by industry and, later, could be extended to incorporate two-phase flow.

2. As part of the development program the thermal simulator should be tested and correlated with downhole and surface well temperature data. Simple field tests with thermistors strapped on the outside of casing should be considered for new wells in geothermal areas.

3. The wellbore thermal simulator should be used to perform sensitivity studies to evaluate those input properties most important for accurate temperature predictions.

I SURVEY OF LITERATURE

I-1 General Highlights

Analytical modeling of wellbore heat transfer, regardless of application, can be separated into three parts as shown in Figure 1 - the flowing fluid, the wellbore assembly (consisting of tubing, casing, and annulus materials), and the surrounding formation. Each part can be modelled separately with a coupling term and/or boundary conditions to describe the heat transfer between parts.

Figure 1 - Temperature Distribution Through Flowing Fluid, Wellbore Completion, and Formation (Willhite, 1967)

The flowing stream is characterized mainly by vertical convection associated with the flow rate. In the case of counter-current flow, such as during drilling and cementing, two vertical flow streams are handled independently. The wellbore assembly can be treated explicitly with each annulus modelled separately, or the entire completion can be handled with an overall heat transfer coefficient. The use of such a coefficient is based on the assumption of steady-state radial heat transfer. The formation part is formulated in terms of the Fourier heat conduction equations.

The literature history on wellbore thermal simulation parallels the introduction of new applications in the industry. Each time a new thermal application arises, a group of new papers with updated technology appears in the literature. This is particularly evident with the papers on steam stimulation in the 1960's and the most recent papers in the 1970's on permafrost thaw around wellbores. It was found that the articles in the literature can be divided into the following four distinct categories, depending on application:

1. drilling, cementing, and circulation
2. two phase injection or production
3. single phase injection or production
4. permafrost thaw around wellbores.

The four tables in Appendix 1 reflect this division and provide a quick overview or summary of the thermal simulation capabilities in the papers surveyed. A complete bibliography of the papers reviewed is given at the end of the report. The review of each paper is documented in the form of a written abstract. In Appendix 2 abstracts are compiled alphabetically according to author.

I-2 Specific Characteristics

The importance of the detailed characterization of the three parts - flow stream, wellbore completion, and formation - is dependent on application. For example, in geothermal production, the two-phase nature of the production stream is the most important feature of the problem and, for all practical purposes, the heat losses through the wellbore to the formation can be neglected, particularly for high rate wells. On the other-hand, for permafrost the most important aspect of the problem is thaw and heat transfer in the formation, with the exact representation of the flow stream being less of a concern. The modelling of circulating systems associated with drilling or cementing is somewhere in between. Both the flow stream and the formation are equally important in this case. This is especially significant since industry has indicated a high interest for thermal simulation of transient circulating systems (see Section II).

The salient features of existing capability for modelling the flow stream, wellbore completion, and formation are discussed below. In Section III, for the purpose of making recommendations, these features will be evaluated in terms of the industry needs.

I-2.1 Flow Stream Heat Transfer

With the exception of papers on two phase flow, the tables in Appendix 1 show a trend towards complete modelling of the transient behavior in the flowing stream. The table on circulating systems shows that, historically, the treatment

of the flowing stream moved from empirical (early 1960's), thru steady-state (late 1960's), and then to transient (1970's). Also, we note that inclusion of non-thermal sources of energy in the flow stream, such as pressure and friction effects and bit work, are prominent in the later papers.

On two-phase flow, Lessem, et al [1957] solved the fully transient equations for a flowing gas stream, but completely neglected the wellbore completion. Later papers on steam wells included the wellbore part, but treated the flow stream as constant temperature or steady-state. Presently, most attention on two-phase flow is directed at modelling the complex interaction of the two phases under steady-state assumptions. Effects such as flow patterns (bubble, slug, and annular flow shown in Figure 2), vaporization/condensation, and dissolved solids and gases are analyzed. Gould [1974] and Coury [1977] give excellent discussions on the significance of these various two-phase flow effects.

Figure 2 - Flow Regimes in Two-Phase Vertical Flow
(Coury, 1977)

In thermal simulation of drilling, the temperature and time effects due to depth and wellbore size during the drilling operation must be accounted for over and above the circulation itself. Edwardson, et al [1962], Holmes and Swift [1970], and Pui and Kljuec [1975] incorporate these additional variables in their drilling simulation models.

In Figure 3, the Pui and Kljuec model of Exxon/Imperial gives good agreement between measured and calculated temperatures for drilling.

Figure 3 - Wellbore Thermal Simulation of Drilling in an Arctic Well (Pui & Kljuec, 1975)

Static considerations, e.g. tripping, logging, and setting of cement, are not only dependent on the heat flow to or from the formation, but also on the prior circulation history. Raymond [1969] analytically examined the fully transient effects of circulation on subsequent shut-in wellbore temperature. Calculated temperature buildup during tripping is demonstrated in Figure 4.

Figure 4 - Temperature Behavior During and After Circulation in a Simulated Well (Raymond, 1969)

In recent years graphical methods, comparable to Horner plots for reservoir pressure buildup, have been used to investigate shut-in temperatures after circulation. Dowdle and Cobb [1975] have presented the theoretical basis for using a Horner temperature plot as in Figure 5 to determine static formation temperatures. Although not mathematically correct, the Horner plot can be used if circulating times are short. Figure 6 shows how measured shut-in data is plotted to form a Horner graph and extrapolated to determine initial formation temperatures. This method is strictly empirical. It is useful for approximating initial formation temperatures when shut-in temperatures are known, but cannot be used to estimate circulating temperatures or shut-in temperatures themselves.

Figure 5 - Theoretical Horner Temperature Buildup (Dowdle & Cobb, 1975)

Figure 6 - Bottom-Hole Temperature Extrapolated from Data on a Horner Plot (Dowdle & Cobb, 1975)

I-2.2 Wellbore Completion Heat Transfer

The heat transfer resistance between the flow stream and the formation is determined by the wellbore completion. During shallow drilling and before casing is set, there is no completion and, hence, this part of the simulation model

can be neglected. However, after casing has been set, this resistance to heat flow can be significant and must be incorporated in the model, even though open-hole drilling is occurring at a deeper depth. For production and injection systems, as well as during cementing, the wellbore completion resistance should be considered as an integral part of the thermal model.

In most instances the wellbore completion can be represented by an overall heat transfer coefficient. Determination of this coefficient, however, is one of the most difficult aspects of wellbore heat transmission. A detailed analysis of this problem is presented by Willhite [1967]. The overall heat transfer coefficient is a function of the thermal properties of the wellbore completion materials, which in turn can be dependent on temperature, the parameter to be determined in the first place. Moreover, the tubing film coefficient and the coefficients for natural convection and radiation in tubing-casing or casing-casing annuli are evaluated on the basis of empirical correlations. Figure 7 shows how natural convection alters the temperature distribution across an annulus, and Figure 8 demonstrates the variation in overall heat transfer coefficient with temperature for different materials outside the tubing.

Figure 7 - Natural Convection in a Casing Annulus (Willhite, 1967)

Figure 8 - Variation of Overall Heat Transfer Coefficient with Tubing Temperature (Willhite, 1967)

The use of an overall heat transfer coefficient is based on steady-state radial heat transfer. In most papers, this

coefficient is taken as a constant, even though it is temperature dependent (see Thermal Properties in Tables of Appendix 1). Some authors use the steady-state representation for the overall heat transfer coefficient, but allow the value of the coefficient to vary with temperature according to each time step in the calculation. Hence, a series of steady-state values for the coefficient is used to approximate the true transient behavior.

Other authors, as noted in the Tables of Appendix 1, handle each annulus of the wellbore completion separately and in a fully transient fashion. This is necessary if heat flow in a given annulus is to be explicitly analyzed, particularly if vertical heat transfer in an annulus is a major consideration.

I-2.3 Formation Heat Transfer

Heat transfer in the formation is governed by the Fourier law of linear heat conduction. The specific heat and thermal conductivity are the two formation thermal properties of interest. The solution to the Fourier equations for energy balance with the appropriate boundary conditions determines the transient heat flow in the regions around the wellbore.

Until recently, many authors have used a pseudo-transient approach for the formation, instead of working the fully transient problem. This pseudo-transient approach is based on an analytical time function derived from the radial Fourier equations under the assumption of either a constant flux or constant temperature at the wellbore face. The time function for heat flow is analogous to the van Everdingen-Hurst flux function for reservoir fluid flow. But, in the case of wellbore heat flow, neither the heat flux nor temperature at the wellbore face is constant, except in special cases. The constant heat flux and temperature conditions are bounds on the actual behavior, as shown in Figure 9, and the difference can become significant at early times.

Figure 9

Transient Heat Conduction in an Infinite Radial System (Ramey, 1962)

Ramey [1962] and Gould [1974] estimate that the time function will provide adequate results if times are greater than seven (7) days, indicating that the use of such a function for changing or startup conditions would not be appropriate. Using a finite element model to predict transient formation temperatures for comparison with the pseudo-transient approach, Leutwyler [1966] showed that for steam injection wells the convergence time between the two methods is on the order of 100 hours (4 days), see Figure 10.

Figure 10 - Comparison of Pseudo-Transient Predictions from Carslaw-Jaeger with Fully Transient Finite Difference Method (Leutwyler, 1966)

This again confirms the inappropriateness of the use of the time function for early time behavior. In particular, for drilling, circulating, and cementing, the time function should not be used; but, as noted in Table 1 of Appendix 1, the pseudo-transient approach has been used almost exclusively for modelling circulating systems. By comparison of field measurements with the pseudo-transient predictions of Raymond [1969], Sump and Williams [1973] have shown that predicted temperatures are off by as much as 12% with a maximum difference of 60°F.

For circulating systems, only two papers, Keller, et. al. [1973] and Pui and Kljucac [1975], handle the full transient response of the formation. Both are proprietary codes and unavailable in the public domain. These two papers are also the only ones in the literature on circulation that treat both the vertical and radial heat conduction in the formation. Others neglect the vertical heat conduction which can be important in the bottom hole region or in zones with a variable geothermal gradient. And it is precisely in these regions where temperature predictions are most desirable for

operational purposes.

With regard to production and injection, the extent of detail in modelling the formation is seen to correlate with the type of application. For high rate steam production/injection wells, heat losses to the formation are not that significant in comparison to heat produced/injected and, therefore, the one-dimensional pseudo-transient method is sufficient. This is reflected in Table 2 in Appendix 1. An exception here is for low rate wells and for production startup and testing. For permafrost thaw around wellbores, the formation temperatures are very important and, hence, most papers in Table 4 of Appendix 1 treat the formation as a fully transient, two-dimensional system. The permafrost papers represent the most up-to-date technology on wellbore thermal simulation and many of these papers could be extended to handle circulating flow streams. All of these papers, however, were published by major oil companies and the corresponding proprietary codes are for in-house use only.

II SURVEY OF INDUSTRY NEEDS AND INTEREST

II-1 Objectives and Procedure

The objective of the industry survey was three-fold:

1. To determine individual company needs for wellbore temperature predictions;
2. To determine what thermal simulation capability, if any, is presently used by industry; and
3. To determine if industry would use a transient wellbore thermal model if available in the public domain.

A representative group of service and producing companies were selected for the survey. Manufacturing companies were not included since most manufactured products are made to producing company specifications, and hence the manufacturing companies would not have need for thermal simulation. The companies contacted were the following:

Producing Companies

Union Oil Co. of Calif. (Brea, Ca.)
Phillips Petroleum Co. (Del Mar, Ca.)
Aminoil USA, Inc. (Santa Rosa, Ca.)
Republic Geothermal, Inc. (Santa Fe Springs, Ca.)

Service Companies

Schlumberger Ltd. (Houston, Tx.)
The Analysts, Inc. (Houston, Tx.)
NL Baroid Petroleum Services (Houston, Tx.)
Dowell Div. of the Dow Chemical Co. (Tulsa, Okla.)
Dresser Industries (Houston, Tx.)

The service companies represent drilling, logging, and cementing operations. The producing companies represent the four major geothermal operators in 1975 with regard to number and footage of wells drilled.

Each company was initially contacted by telephone for introductory purposes and to evaluate willingness to participate in the survey. All nine companies agreed to participate. The person contacted at each company was either an operating manager or a technical supervisor. In the case of the producing companies, the operating manager usually referred the contact to a member of the technical staff. The introductory call was then followed with a presentation of the four tables in Appendix 1 along with the questionnaire in Appendix 3. For the companies in Houston, personal visits were arranged; for those out-of-town, the contact was handled by mail (a mutually convenient time to meet with the four producing companies in California could not be arranged). Followup telephone calls were then made with each company until the completed questionnaire was returned.

As of the date of this report, eight of the nine questionnaires have been completed and returned, and are presented in Appendix 3.

II-2 Summary of Industry Feedback

All of the companies responding to the questionnaire indicated that

1. they do have need for wellbore temperature predictions;
2. their present program or method cannot handle all thermal simulation needs; and
3. they would use, if available at reasonable cost, a computer program to predict transient wellbore temperatures.

Both the producing and service companies expressed a need for transient temperature predictions during cementing and logging. In cementing, slurry pumpability and setting strength are the major concern. Dowell does possess a wellbore thermal model, but the code is not applicable to circulating environments. In logging, equipment design and well log interpretation are of interest, and both Schlumberger and The Analysts indicated that energy dissipated at the bit during drilling is important for mud logging purposes and should be incorporated in any new simulation developments. Neither Schlumberger or The Analysts have wellbore thermal simulation capability at the present time.

Although the producing companies and mud companies indicated an interest in temperature predictions for drilling fluid design, the need was not considered essential to drilling operations. Both NL Baroid and Dresser (by personal communication) stated that their present high temperature mud systems are sufficient

for most existing applications. NL Baroid did, however, indicate that thermal simulation capability would be helpful for selecting fluids for particular needs. NL Baroid does presently use a wellbore thermal model that is available in the public domain, but the program is not suitable for early time predictions.

Of the four producing companies contacted, Union expressed the least interest in the use of a new wellbore thermal simulator. Union does have an in-house proprietary program that can handle 90% of their needs, but the program lacks transient circulation capability. Aminoil, Phillips, and Republic Geothermal presently use some method of temperature predictive capability, but all indicated that their present methods were insufficient for early time predictions. Phillips and Republic Geothermal use a computer code, and Aminoil uses a graphical empirical method.

Besides cementing, logging, and drilling, other applications of interest to the producing companies are reservoir detection (monitoring temperature while drilling) and short term production testing. Long term production was not considered a major need for wellbore thermal simulation since heat losses to the surrounding rock, in this case, are only a small fraction of the total heat produced.

In production testing the standard practice is to wait many hours until stability is reached. Republic Geothermal and Aminoil both noted with high interest that early time predictions could be valuable for shortening the testing time and for estimating the time required for the heat loss to the formation to reach steady-state conditions.

III SIMULATION REQUIREMENTS TO MEET INDUSTRY NEEDS

In Section I existing wellbore thermal simulation capability was reviewed. We conclude that present models in the public domain cannot handle the highly transient behavior associated with early times and changing conditions, particularly for circulating systems. In Section II, the industry survey showed that this lack of transient capability is precisely the area where the industry needs are the greatest. Furthermore, industry indicated that their present in-house capability in this area was lacking and that they would use a program of this type if developed by ERDA.

The industry needs can be categorized according to priority as

1. single phase counter-current flow (drilling, circulating, logging, and cementing) and
2. two phase vertical flow (production testing).

This priority is convenient and practical from a program development standpoint since a single phase model is much less complex than a two-phase model. To meet industry needs, therefore, the development

of a transient wellbore thermal simulator should occur in two stages, with the single phase model being developed first and then later extended to a two-phase model.

Since the industry needs are primarily for highly transient behavior, the formation heat transfer should be modelled explicitly with time and in two dimensions, radial and vertical. All significant sources of energy should be included in the flow stream characterization. Specifically, friction heating and viscous dissipation during circulation, bit work during drilling, and heat of hydration during cementing should be incorporated as separate terms in the flow stream equations.

If a transient wellbore thermal model is developed, it should be fully tested against existing downhole and surface temperature data. For the most part, this data would be from temperature logs after circulation is stopped or from special tools placed in the drill string to measure temperatures while circulating. One source of data is the API Committee on Standardization of Oil-Well Cements. This committee set up a task group in 1971 to collect downhole circulating temperatures (see Shell and Tragesser [1972]). Another potential source of data is from thermistor cables strapped on the outside of casing in arctic wells. Both ARCO and Imperial Oil have used thermistors to record temperatures while circulating and drilling (see Pui and Kljucic [1975]). The geothermal industry should consider similar use of thermistors in new wells. Being on the outside of casing, the thermistors can determine cement temperatures during placement and setting, and afterwards can monitor formation temperatures along the entire wellbore length.

As part of the program utilization, the model should be used to thoroughly investigate the sensitivity of the various parameters and input properties. Such sensitivity studies will determine those properties that are most important for accurate thermal predictions.

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APPENDIX 1

TABLES SUMMARIZING LITERATURE ON WELLBORE THERMAL SIMULATION

- Table 1 - Drilling, Cementing, and Circulation
- Table 2 - Two Phase Injection or Production
- Table 3 - Single Phase Injection or Production
- Table 4 - Permafrost Thaw Around Wellbores

WELLBORE THERMAL SIMULATION
SUMMARY OF PAST WORK

TABLE 1 - Drilling, Cementing, and Circulation

Author Affiliation Date	Application	Flow Stream Heat Transfer		Wellbore Completion Heat Transfer	Formation Heat Transfer		Thermal Properties
		Time Dependence	Non-Thermal Sources		Time Dependence	Spatial Dependence	
1. Edwardson, et al (Shell) 1962	Circulation & Drilling	Empirical	None	Empirical	Pseudo-transient*	Radial	Constant
2. Tragesser, et al (Western) 1967	Circulation (Cementing)	Empirical	None	Overall heat transfer coef.	Pseudo-transient	Radial	Constant
3. Keller-Couch (Mobil) 1968	Circulation (Well cooling)	Steady-state	None	Overall heat transfer coef.	Pseudo-transient	Radial	Constant
4. Raymond (Exxon) 1969	Circulation (Tripping)	Transient	None	Open hole	Pseudo-transient	Radial	Constant
5. Holmes-Swift (Cities Service) 1970	Circulation & Drilling	Steady-state	None	Open hole	None	None	Constant
6. Sump-Williams (Exxon) 1973	Circulation (Cementing)	Transient	None	Open hole	Pseudo-transient	Radial	Variable
7. Keller, et al (Mobil) 1973	Circulation	Transient	Bit work Fluid friction	Transient Conduction	Transient	Radial & Vertical	Constant
8. Pui-Kljuec (Imperial) 1975	Circulation & Drilling	Transient	Mech. work Fluid Δp	Overall heat transfer coef.	Transient	Radial & Vertical	Variable
9. Sullivan (Sandia) 1976	Circulation	Transient	None	Overall heat transfer coef.	Pseudo-transient	Radial	Constant

*Based on analytical time function. Not accurate for early times.

TABLE 1 (Continued)

Author Affiliation Date	Application	Flow Stream Heat Transfer		Wellbore Completion Heat Transfer	Formation Heat Transfer		Thermal Properties
		Time Dependence	Non-Thermal Sources		Time Dependence	Spatial Dependence	
10. Dowdle-Cobb (Chevron-1975)	After circulation	Empirical	None	Empirical	Transient (Graphical Horner plot)	Radial	Constant

WELLBORE THERMAL SIMULATION
SUMMARY OF PAST WORK

TABLE 2 - Two Phase Injection or Production

Author Affiliation Date	Application	Flow Stream Heat Transfer		Wellbore Completion Heat Transfer	Formation Heat Transfer		Thermal Properties
		Time Dependence	Non-Thermal Sources		Time Dependence	Spatial Dependence	
1. Lesem, et al (Tex. Pet. Rech. Comm.) 1957	Flowing gas wells	Transient	PE	Neglected	Transient	Radial	Constant
2. Leutwyler- Bigelow (Baker)	Steam Injection	Const. temp.	None	Overall heat transfer coef.	Pseudo-transient*	Radial	Constant
3. Satter (Pan. Amer. Pet) 1965	Steam Injection	Steady-state	None	Overall heat transfer coef.	Pseudo-transient	Radial	Constant
4. Huygen-Huitt (Gulf) 1966	Steam Injection	Const. temp.	None	Overall heat transfer coef.	Transient	Radial	Constant
5. Leutwyler (Baker) 1966	Steam Injection	Const. temp	None	transient	Transient	Radial	Constant
6. Willhite (Continental Oil) 1967	Steam/hot water in- jection	Steady-state	None	Overall heat transfer coef	Pseudo-transient	Radial	Constant
7. Pacheco, et al (Bolivia Pet. Min.) 1972	Steam Injection	Steady-state	PE, KE, Friction effects, Pressure effects	Overall heat transfer coef.	Pseudo-transient	Radial	Variable
8. Gould (Intercomp) 1974	Steam/hot water Production	Steady-state	PE, KE, Friction effects, Phase slip, Pressure effects	Overall heat transfer coef (constant)	Pseudo-transient	Radial	Variable

*Based on analytical time function. Not accurate for early times.

TABLE 2 (Continued)

Author Affiliation Date	Application	Flow Stream Heat Transfer		Wellbore completion Heat Transfer	Formation Heat Transfer		Thermal Properties
		Time Dependence	Non-Thermal Sources		Time Dependence	Spatial Dependence	
9. Tansev, et al. (Standard Oil Co. of Calif.) 1975	Steam/heat water production	Steady-state	PE, KE, Friction effects, Pressure effects	Overall heat transfer coef .	Steady-state	None (Modelled as part of well- bore thru Overall heat transfer coef.)	Constant
10. Coury (Consultant) 1977	Steam production	Steady-state	PE, KE, Friction effects, Pressure effects, flow patterns, dissolved gases and solids	Neglected	None (No heat loss to formation)	None	Variable

SUMMARY OF PAST WORK

TABLE 3 - Single Phase Injection or Production

Author Affiliation Date	Application	Flow Stream heat transfer		Wellbore Completion Heat Transfer	Formation Heat Transfer		Thermal Properties
		Time Dependence	Non-Thermal Sources		Time Dependence	Spatial Dependence	
1. Boldizar (Hungary Tech. Univ.) 1958	Flowing Wells	Steady-state	None	Neglected	Pseudo-transient*	Radial	Constant
2. Moss-White (Consultants) 1959	Water injection	Steady-state	None	Neglected	Pseudo-transient	Radial	Constant
3. Ramey (Mobil) 1962	Water or gas injection	Steady-state	P.E.	Overall heat transfer coef.	Pseudo-transient	Radial	Constant
4. Squier, et al (Calif. Rsch. Corp) 1962	Water injection	Transient	None	Neglected	Transient	Radial	Constant
5. Eickmeier, et al (Consultants) 1970	Injection & Production	Transient	None	Transient	Transient	Radial	Constant
6. Smith- Steffensen (Pan Amer. Pet) 1970	Shut-in after water inject- ion	Transient	None	Transient	Transient with friction heating in injected zone	Radial & Verti- cal (considers only injection zone)	Constant

*Based on analytical time function. Not accurate for early times.

SUMMARY OF PAST WORK
TABLE 4 - Permafrost Thaw Around Wellbores

Author Affiliation Date	Application	Flow Stream Heat Transfer		Wellbore Completion Heat Transfer	Formation Heat Transfer		Thermal Properties
		Time Dependence	Non-thermal Sources		Time Dependence	Spatial Dependence	
1.Couch, et al (Mobil) 1970	Single phase production thaw	Transient	None	Overall heat transfer coef.	Transient	Radial and Vertical	Constant
2.Howell, et al (ARCO) 1973	Two phase production thaw	Steady-state	K.E., P.E. press.effects	Overall heat transfer coef. (considers pipe eccentricity)	Transient	Radial and Vertical	Variable
3.Lea-Stegall (Sun Oil) 1973	Thaw initia- tion due to production	Const. temp	None	Overall heat transfer coef.	Pseudo-transient*	Radial	Constant
4.Merriam, et al (BP) 1975	Single phase production thaw	Transient	None	Transient	Transient	Radial and Vertical	Variable
5.Lea (Sun Oil) 1975	Single phase production thaw	Const. temp	None	Transient	Transient	Radial and Vertical	Constant
6.Lin-Wheeler (Exxon) 1976	Two phase drilling and production thaw	Transient	K.E., P.E. expansion and vaporization effect, press.effects	Overall heat transfer coef.	Transient	Radial and Vertical	Variable

*Based on analytical time function. Not accurate for early times.

APPENDIX 2: ABSTRACTS OF PAPERS REVIEWED
(Listed Alphabetically by Author)

1. The Distribution of Temperature in Flowing Wells
by T. Boldizar (1958)

Earliest reference that uses pseudo-transient time function.

Uses the time function for both constant flux and constant temperature. Notes that early times are better approximated by constant temperature function. Author gives good interpretation of these functions.

Steady state flowing stream is single phase with constant properties

Correlation with field data is presented.

2. Permafrost Thawing Around Producing Oil Wells
by E. J. Couch, H. H. Keller, J. W. Watts (1970)

Model is 2-D (radial-vertical)

Complete description in formation is coupled with overall heat transfer coeff. in the wellbore.

Wellbore model is restricted to

1. production only
2. neglects P.E. and K.E. terms
3. single phase only

Model uses implicit finite differences with a range of melting temperatures. Latent heat of formation is incorporated in the enthalpy term. Finite difference equations are outlined and the method for treating the melting range is discussed explicitly.

Case studies are performed to investigate

1. insulation of varying conductivity
2. effect of latent heat

3. Production of Geothermal Brine Wells in Two-Phase Flow
by G. E. Coury (1977)

Nature of the problem is reviewed and the pressure drop equation is discussed in terms of variables associated with two-phase flow, including the liquid volume fraction, flow patterns, vaporization, and wall friction.

The chemical problem of dissolved solids and gases is discussed. Gases are liberated as pressure is reduced and this changes the physical properties and flashing point.

Only the flowing stream problem is worked. The heat effects of

the wellbore assembly and formation are neglected on the basis of a high flow rate assumption, i.e. heat losses are small at high flow rates.

The flowing stream is in steady-state.

4. Static Formation Temperature from Well Logs - An Empirical Method
by W. L. Dowdle and W. M. Cobb (1975)

Uses Horner temperature buildup plot to estimate static formation temperature. Presents theoretical justification for use of this graphical method.

Examines radial transient heat conduction equation with appropriate boundary conditions at wellbore face. Shows that for most practical situations, the temperature gradient changes slowly and if the circulating time is short the gradient can be treated as a constant. In this case, the Horner plot gives a good estimate of bottom hole static temperature.

Good agreement shown with field examples. Temperature log data are plotted against time and extrapolated backwards to determine static formation temperature.

5. Calculation of Formation Temperature Disturbances Caused by Mud Circulation
by M. J. Edwardson, Girner, Parkison, Williams and Matthews (1962)

Extension of Ramey approximation procedure to more exact formulation.

Uses radial solution for constant temperature and constant flux cases and combines through super position over several time steps to approximate actual situation.

Wellbore part is an empirical quadratic fit based on measurements & correlations for a given well, including BHT, mud-discharge temperature, and undisturbed formation temperature. (Does not work the wellbore flow problem)

Concerned mainly with the formation temperature. In addition to the given functions relating constant flux and constant wellbore temperatures to formation temperature, the variable flux and temperature approximation depends on the wellbore temperature difference at the beginning of each circulation period. This must be calculated. Method is given in the paper.

Radial heat flow only (no vertical)

Constant geothermal gradient

6. Wellbore Temperatures and Heat Losses During Production or Injection Operations

by J. R. Eickmeier, D. Ersoy, H. J. Ramey (1970)

Transient finite difference model. Does not use a time function. Developed for short time applications.

Notes that transient predictions are important for acidizing and well start-up operations.

Assumptions

1. no vertical conduction in formation
2. thermal properties are independent of temperature
3. wellbore heat transfer coef. remains constant
4. injection temperature and rate at the surface are constant
5. neglects friction, K.E., and P.E.
6. no overall heat transfer coef. Treats annuli separately.

Uses analogy of electrical resistance and capacitance to formulate formation behavior.

For long times the predictions are comparable to results of Ramey and Squier.

Predictive results presented for an Arctic well and for a cold water injection well with high flow rate.

7. Vertical Two-Phase Steam-Water Flow in Geothermal Wells

by T. L. Gould (1974)

Pressure drop - Steady state equations include slip between liquid and gas, and correlations for different flow regimes (bubble, slug, mist).

Heat transfer - Uses overall heat transfer coef. in wellbore and Ramey approach for unsteady flow in formation. The time dependency function is not accurate for times shorter than one week after a change, startup or shutdown.

Heat transfer and pressure drop equations are coupled thru a length increment.

Good pressure correlation with field data for high-rate wells where heat transfer not very important.

Thermal properties of formation and wellbore are constant in time, but variable overall heat transfer coeff.

Pressure gradient is dependent on quality (% steam) because of correlations for flow regimes. But quality depends on enthalpy which in turn depends on pressure and temperature.

Some slip is required to fit steam data in the field.

8. Calculation of Circulating Mud Temperatures
by C. S. Holmes & S. C. Swift (1970)

Assumptions

1. steady state wellbore
2. overall heat transfer coef. used across wellbore face
3. constant formation temperature equal to geothermal temperature
4. no PE or KE effects in flow stream
5. single phase flow

Very simplified analysis. No time dependence at all.

Examines varying wellbore depths and drillpipe sizes to simulate drilling.

9. Temperature Calculations for Wells Which Are Completed Through Permafrost

by E. P. Howell, M. S. Seth, T. K. Perkins (1973)

Eccentric tubing and casing, and metal-to-metal contacts considered in study.

Space dependent latent heat and different thermal properties for thawed and frozen permafrost are used.

Flow behavior is approximated by a series of steady-state conditions.

In the flowing stream, calculation of enthalpy and K.E. require wellbore pressures (from hydraulics), gas/liquid composition, and PVT behavior.

Calculation procedure for flow stream is as follows:

1. estimate pressure range from hydraulics
2. determine average gas composition in wellbore. If not available, use total oil composition and pressure range to make flash calculations
3. determine compressibility factors from gas composition
4. calculate gas and liquid densities
5. determine enthalpy change for gas by method of Maxwell
6. determine enthalpy change for liquid by means of a constant pressure addition of heat plus an adiabatic compression

In the wellbore completion, thermal conduction in metals is considered with an eccentricity factor. If annular fluid can transmit radiant energy, then radiation term is included. If fluids are ungelled and can convect, then correlation of Dropkin and Somerscales is used for concentric pipes. If eccentric pipes, then scaled models are used. Turbulence is considered by means of lab correlation.

In permafrost and surrounding earth, heat transfer is by transient conduction. Calculations are sensitive to thermal conditions which are based on density, moisture content, and lithology.

Mathematical simulation includes convection in the flow stream and conduction in the formation, with vertical and radially varying properties. Numerical solution uses successive over-relaxation and Gauss elimination techniques. Convection equations are uncoupled from conduction equations and treated as a series of successive steady-state conditions (highly transient conditions cannot be modelled with this technique). Heat flow between tubing and formation is steady state while making tubing calculations. Tubing temperature is held constant during formation calculations.

One year of production takes 10 min on IBM 360/65 and 15 years of production takes 20 min.

Field data comparison shows

1. wellbore profile temperature match ($\pm 2^{\circ}\text{F}$) during flow
2. temperature match during refreezing, $\pm 3^{\circ}\text{F}$.

10. Wellbore Heat Losses and Casing Temperatures During Steam Injection
by H. A. Huygen and J. L. Huitt (1966)

Presents graphical plots of solutions existing in the literature.

Makes gross assumptions to eliminate the dependence on depth.

1. assumes average geothermal temperature instead of a gradient
2. no temperature change (i.e. no pressure drop) of steam down the wellbore

Considers injection down tubing (conduction and radiation across tubing/casing annulus) and also down casing (casing temperature equals steam saturation temperature).

Comments that for deep wells temperature predictions are important because of

1. higher heat losses - large steam generators needed to get even a small fraction of steam to bottom hole
2. higher casing temperatures result and therefore buckling and casing stresses are more severe

Experiments performed to correlate annular heat loss. Tests showed conduction and radiation dominate behavior, and convection is negligible.

Addresses question of different types of insulation. Suggests that radiation is most important and paint is most attractive way. This is not consistent with Leutwyler observations.

11. Well Cooling by Down-Hole Circulation of Water
by H. H. Keller, E. J. Couch (1968)

Handles circulation with production at bottom hole.

Assumptions:

1. thermal properties are constant and constant geothermal gradient
2. injection and production rates are constant
3. no vaporization or condensation effects in wellbore
4. no PE or KE terms in flow-equations
5. use of overall heat transfer coef. for wellbore
6. no vertical heat flow in formation

Also assume 1) transient terms can be eliminated from flow equations since heat flow in wellbore is much greater than in the surrounding soil 2) use Ramey approximation for solution to soil equation.

Presents results in non-dimensional graph form.
Non-dimensional parameters are not clearly discussed as to physical significance.

Boundary conditions in soil are no heat flux at a large distance.

Applications to in-situ combustion where well temperatures can get up to 1500°F.

12. Temperature Distribution in Circulating Mud Columns
by H. H. Keller, E. J. Couch, P. M. Berry (1973)

Finite difference model for circulation.

Wellbore flowing streams, outer annuli, and formation are handled explicitly.

Transient behavior considered for wellbore and formation.

No overall heat transfer coefficient.

Single phase.

Constant properties and constant geothermal gradient.

Source terms in flow streams to account for friction heat, bit energy losses, and energy in rotating drill string.

Compares predictions with Holmes and Swift:

1. Steady state curves are in agreement
2. Early times show deviation, particularly at depth.
Higher temperature in drill string at early times.
3. Comparison with/without source terms shows that the source terms can be quite significant.

Presents all equations in detail for finite difference calculations.

Vertical heat transfer considered, but not clear how far below hole is considered. Vertical grid may end at bottom hole.

13. The Application of a Thermal Network Analyzer Program to Pipe Flow and Wellbore Heat Transfer

by J. F. Lea, Jr. (1975)

Very general program. Heat transfer equations are presented in terms of electrical analogy using resistances and capacitances. Transient behavior considered. Finite difference methods are used.

Wellbore material characterization and flowing stream modelling is part of the input. The program is too general to be useful for a user oriented type of simulator.

Consider examples of pipe flow, circulating mud columns, and production through permafrost. In the circulating example, steady state is assumed. In the permafrost example, constant wellbore temperature is assumed.

14. Graphical Design Procedure Points to Best Arctic Well Insulation

by J. F. Lea, R. D. Stegall (1973)

Based on Ramey time function with radiation boundary condition.

Temperature plots allow determination of depth versus time for melting to begin for different completion schemes.

Wellbore flowing stream is neglected. Oil temperature is assumed constant.

No thaw predictions, only thaw initiation at wellbore.

15. A Method of Calculating the Distribution of Temperature in Flowing Gas Wells

by L. B. Lesem, F. Greytok, F. Marotta, J. J. McKetta (1957)

Calculation of bottom hole pressure in gas wells from surface measurements requires knowledge of temperature distribution in flow string. Past methods assume constant average temperature or linear distribution with depth.

Assumptions

1. constant mass velocity
2. chemical composition of gas is constant (no pressure effects)
3. ρc is constant, geothermal gradient is constant
4. no vertical conduction
5. neglect KE and friction effects.

Uses exact equations in unsteady conditions

Assumes wellbore is part of formation and that gas temperature

equals formation temperature at wellbore face.

1. this implies overall heat transfer coefficient is infinite (i.e. neglects wellbore materials)
2. no variation of thermal properties radially to account for wellbore
3. this assumption is most critical at early times.

Solution is obtained analytically in closed form using Laplace Transforms. Full solution is presented.

Considers examples

1. dry gas
2. 2-phase flow. Uses effective heat capacity determined from correlation with time-temperature curve at surface. Best fit specific heat may take up some slack of wellbore neglect. Notes high specific heat correlation and claims due to liquid condensation.

16. Casing Temperature Studies in Steam Injection Wells
by K. Leutwyler (1966)

Assumes constant tubing temperature (does not work wellbore part).

Compares Ramey function with finite difference unsteady state solution (radial only) and shows results are nearly the same after 100 hours (4 days).

Evaluates different insulating methods. Heat loss can be reduced significantly only if some insulation barrier is used. Radiation barrier alone does not help much.

Lab experiments show that increase in pressure in nitrogen filled annulus can increase heat transfer.

17. Temperature Effects on Subsurface Equipment in Steam Injection Systems
by K. Leutwyler and H. L. Bigelow (1965)

Equipment oriented paper but does examine temperature modelling.

Steady state wellbore radiation and transient formation heat transfer with time function (radial only). Further approximates for long time (> 3 mo) by equating average casing temperature and formation temperature, since after 3 months formation temperature is nearly constant in the near wellbore region.

Model is independent of depth since

1. geothermal temperature is taken as an average temperature
2. tubing is at a uniform temperature throughout its length

Uses a graphical method of solution.

Examines elastic and plastic mechanical behavior in casing due to the predicted temperature changes.

Gives good discussion on downhole sealing methods and concepts for reducing stresses in casing and tubing.

Use of packer to isolate tubing/casing annulus and casing from injection fluid is particularly important for old wells where casing may be lower grade or corroded.

Questions most insulating techniques. But notes that emissivity reduction can be significant on reducing temperature.

Mentions casing-cement system as a prestressed concrete unit for added strength. Also mentions concepts of bitumastic coating between casing and cement to allow slippage when heated.

Casing and tubing slip or expansion joints require special seals and need centralizers to prevent frictional lockup during expansion.

Discusses seal systems for 700°F, 3000 psi

1. Casing and tubing threads - Conventional sealing compounds not good for temperature >300°F. Special compounds with non-metallic fillers have been developed for temperature up to 600°F.
2. Casing packers - Usual elastomers not good for temperatures 400°F. Inorganic sealing materials are temperature resistant but inherently non-resilient. Requires high pressures and intricate pack-off devices to maintain pressure behind seal.
3. Tubing, packers and expansion joints - Organic compounds are used but these are also non-resilient. Use spring loaded mechanisms to compensate for non-resiliency.

18. Simulation of Permafrost Thaw Behavior at Prudhoe Bay
by C. J. Lin, J. D. Wheeler (1976)

Handles transient heat flow in wellbore and formation. Uses finite difference 1-D, unsteady, convective heat transfer for flowing stream of oil, gas, water and variational method for 2-D unsteady heat conduction with change of phase in formation.

Formation and flowing stream calculations are coupled through overall heat transfer coefficient for the wellbore. Formation temperature at cement/formation interface is used as boundary condition for the wellbore. Temperature distribution for flowing stream and the overall heat transfer coefficient are calculated and used as boundary conditions for the formation calculations.

Volume averaged properties are used in the flowing stream. Enthalpy of flow stream includes expansion and vaporization effects. Density, velocity, and specific heat are calculated for mixture

assuming no slip between phases. These properties are calculated in the program as function of temperature and pressure in the flowing stream.

In the wellbore completion, ungelled oil will convect and the effective thermal conductivity is calculated from the Dittus-Boelter equation. The local heat transfer coefficient for 2-phase flow in tubing is calculated as a function of the Martinelli parameter.

Field data match includes

1. wellbore temperatures during production flow
2. wellbore temperatures during circulation (drilling) and freezeback
3. permafrost temperatures during thaw test.

19. Steady-State and Transient Wellbore Temperatures During Drilling
by W. J. McDonald (1976)

Gives results from two wellbore simulation sources:

1. Holmes & Swift (steady state)
2. Exxon Circus Program - based on Raymond

Study done to determine temperature for input to design of Geothermal bits.

Conclusions:

Need for improved technology for calculation of borehole temperatures since

1. 40°F difference between measured and calculated temperatures have not been resolved;
2. no attempts to calibrate thermal models for high bottom-hole temperatures;
3. no transient model publicly available;
4. no attempts to simulate temperatures within the bit.

Recommends:

1. development of transient model for public use
2. comparisons between computed and measured geothermal borehole temperatures
3. sensitivity studies to determine most important parameters affecting borehole temperatures
4. development of thermal model for drill bit

Reviews Raymond model

Use of two model sources shows

1. difference in 40°F between steady-state and transient bottom hole temperatures
2. effects of different variables

20. Insulated Hot Oil - Producing Wells in Permafrost
by R. Merriam, A. Wechsler, R. Boorman, B. Davies (1975)

Models production flow stream and formation like Mobil paper.

Models wellbore explicitly (no overall heat transfer coefficient)

1. Tubing-casing annulus with insulation is modeled with heat flow radially and vertically.
2. Casing-casing annuli and cement are modeled as part of the soil system and, hence, have both vertical and radial conduction. Convection in wellbore materials is handled through correlation to obtain an effective conductivity.

Flowing stream is single phase. Kinetic and potential energy terms are not included.

Specific heat of the formation accounts for latent heat and has a continuous temperature range for freezing. Thermal properties can vary with position and temperature. Density is constant. Tables of properties are given.

Finite difference equations are solved using the method of simultaneous displacements with block-relaxation.

Model predictions are compared with results from two analytical solutions and with Mobil predictions.

Case studies include

1. completions with and without insulation
2. effect of thermal conductivity and moisture content
3. effects of casing coupling
4. effects of "failure" of joints of insulation

21. How to Calculate Temperature Profiles in a Water - Injection Well
by J. T. Moss and P. D. White (1959)

This paper serves as a basis for the Ramey approach to formation heat flow. Assumes continuous source of heat at the origin in a thin plane sheet (heat flow is constant). Method is not good for early times. Vertical formation heat transfer is neglected.

Neglects wellbore resistance, implies U equals infinity.

Flow stream assumptions

1. single phase
2. steady state
3. no PE or KE effects
4. constant properties with temperature.

Method is a simple approach that can be used for hand calculations as a first approximation.

22. Wellbore Heat Losses and Pressure Drop in Steam Injection
by E. F. Pacheco, S. M. Faroug Ali (1972)

Two phase wellbore model but no slip between phases. Uses effective viscosity in proportion to mole fractions of each phase.

Steady state.

Formation treated with Ramey function (radial only).

Wellbore handled with overall heat transfer coefficient calculated using Willhite's method.

Fourth Order Runge-Kutta Method used for solving the finite difference equations.

New value of U calculated with each time step.

Source terms included in flow stream description.

Results

1. percent heat losses increase with tubing diameter.
2. steam pressure and heat loss decrease, and steam quality increases as injection rate increases.
3. U increases and steam quality decreases with pressure.

Examines effects of insulation and aluminum paint on outside of tubing.

Compares results with other models - Ramey, Satter, Leutwyler, Holst & Flock

23. Temperature Simulation While Drilling Permafrost
by N. K. Pui, N. M. Kljucic (1975)

Combines transient, 2-D formation simulator of Exxon with a wellbore circulating model.

In the wellbore and drill pipe:

1. equations are fully transient
2. one dimension vertically
3. neglects PE and KE
4. no internal source terms due to friction at the bit or otherwise
5. constant mass flow (i.e. no leakage into or from the formation)
6. incompressible drill fluid

Drill bit is assumed to penetrate formation in a stepwise fashion. Grid interval drilled when more than half of interval is penetrated.

Considers wellbore annuli with effective conductivity if convection can occur.

Finite difference solution in wellbore.

Variational method in formation.

Variable properties and geothermal gradient.

Field permafrost thermistor data matched and thaw predicted. Gas hydrate decomposition predicted.

Vertical heat transfer considered in formation.

24. Wellbore Heat Transmission
by H. J. Ramey (1962)

Considers injection down tubing or casing

Steady-state wellbore heat transfer

Unsteady formation heat transfer. Radial only with assumption of time function estimated with wellbore boundary conditions (depends on overall heat transfer coefficient and varies between constant temperature condition and constant heat flux condition).

Gives good first approximation and compares well with field data for steady wellbore behavior.

Assumptions

1. thermal properties
2. no gas expansion or phase change latent heat effects in wellbore.
3. single phase, incompressible flow

Good method for hand calculations. No iterative calculation required.

Calculation method is the following:

1. since steady state wellbore, U can be calculated and assumed constant.
2. Radiation boundary condition at casing can be evaluated for given injection time and time function read from given curves.
3. temperature at depth can then be calculated from given relationships.

25. Temperature Distribution in a Circulating Drilling Fluid
by L. R. Raymond (1969)

Considers unsteady equations in wellbore and formation.

Wellbore - neglects kinetic and P.E. terms but this is not important.

Formation - no vertical heat flow. Uses Hurst-Van Everdingen functions which are like the Ramey approximation. Not good for rapidly changing conditions (see Ramey and Gould)

Uses constant temperature properties and constant geothermal gradient. Effects overall heat transfer coefficient since dependent on properties, particularly the boundary layer coefficient in the drill pipe.

Results:

1. Bottom hole temperature never reaches steady state, even though inlet/outlet temperatures are nearly constant.
2. Maximum temperature in annulus is above bottom hole.
3. For tripping only 16 hours required for temperature to be within 10% of geothermal.
4. During circulating and tripping, formation only effected 10 feet from wellbore.

Depth not changing. Only circulation at fixed depth.

Does not apply to drilling.

26. Heat Losses During Flow of Steam Down a Wellbore
by A. Satter (1965)

Steam injection

Formation - uses Ramey function (radial)

Overall heat transfer coefficient in wellbore

For cooling of superheated steam, uses Ramey gas injection solution.

For condensation case, uses Ramey approach but assumes enthalpy change only related to quality change and latent heat, i.e. assumes no pressure change due to friction or other means and hence no temperature change.

Results show strong dependence on early times, but Ramey function is not valid for early times.

27. API is Seeking More Accurate Bottom-Hole Temperatures
by F. Shell, A. Tragesser (1972)

Report on API Task Group to gather information on bottom hole temperature for cementing.

Circulating temperature is important to thickening time and pumpability.

Static temperature is important to curing and cement strength.

Problem is to use enough retarder to overcome high temperature during circulation, but not enough to prevent setting.

Tendency to overretard cement for liner jobs. Makes accurate temperature information important at top of liner.

Gives field test results on measured temperatures:

1. Maximum temperature does occur just above bottom.
2. Plot of circulating temperature vs static temperature as function of geothermal temperature gradient gives good correlation.

Discusses temperature bombs and suppliers - Dowell, Halliburton, Western.

28. Computer Study of Factors Affecting Temperature Profiles in Water Injection Wells

by R. C. Smith and R. J. Steffensen (1970)

Only looks at region in vicinity of injection zone. Mainly concerned with temperature injection zone and in wellbore after shut in.

Model consists of 300 feet above and 100 feet below injection zone.

Considers transient behavior in formation with

1. convection due to injection
2. friction heat due to viscous dissipation.

After shut-in, fluid flow in formation and wellbore is zero.

During injection, no vertical convection in wellbore is considered.

Steady-state fluid flow prior to shut-in is assumed.

Heat generated in formation by volume expansion and/or K.E. is negligible in comparison to friction heating. Wellbore temperature rise after shut-in is influenced considerably by friction heating in the formation.

Wellbore heat transfer is modelled with an effective conductivity.

Compares predictions with two sets of field data, but uses best fit thermal properties which turn out to be extreme. Examines effects of various parameters, including conductivity, water leak-off, geometry, reservoir temperature, injection temperature.

29. Calculated Temperature Behavior of Hot-Water Injection Wells

by D. P. Squier, D. D. Smith, E.L. Dougherty (1962)

Similar to Lessem approach.

Assumptions

1. no heat transfer by radiation
2. no vertical conduction
3. flow rate constant
4. ρc is constant
5. formation conductivity constant

6. no temperature change at large distance from wellbore
7. water temperature equals formation temperature at wellbore (i.e. overall heat transfer coefficient is infinite - tantamount to neglect of wellbore).

Exact analytical solution given. Uses Laplace transform to obtain solution.

Also makes a "large" time approximation of the general equations.

Predictions show temperature at times > 19 days. Author comments that temperature changes rapidly at early times, but early time behavior is not plotted. Neglect of the wellbore completion is more significant at early times than later times.

Gives predictions compared to field data. Calculated results are high by 25%.

30. A Wellbore Thermal Model
by W. N. Sullivan (1976)

Similar to Raymond approach.

Unsteady in wellbore and single phase.

Uses constant flux time function for the formation with superposition of heat flux at each time step to solve problem. Notes that this is time consuming. Then uses average constant flux as an approximation. For given conditions, shows that this is adequate.

Treats each annulus separately in terms of radial and axial heat flow. Since radial flow treated explicitly, author doesn't use any heat transfer coefficient for radial flow. But at casing formation interface, an effective conductivity is used.

Shows large temperature difference between initial geothermal and mud temperatures at bottom hole. Also large difference for formation temperature. This is probably due to neglect of vertical heat flow in formation, which should be important at bottom hole.

Author notes good agreement with Raymond after 1 hour. But Sump and Williams have shown that after one hour discrepancy between measured and calculated wellbore temperature increases to a 12% difference or 60°F in one case.

Constant properties and constant geothermal gradient

31. Prediction of Wellbore Temperatures During Mud Circulation and Cementing Operations
by G. D. Sump and B. B. Williams (1973)

Uses Raymond model to regress on field data from six wells to obtain best fit thermal properties: heat transfer coefficient h at tubing wall, overall heat transfer coefficient U , conductivity k of formation, and density of formation.

With this correlation a good match is obtained for these six wells and also three others.

Notes that Raymond predictions (with fixed properties) gives temperatures that are 12% off measured values with a maximum difference of 60° F. Also predictions from API Recommended Practice gives values 10% off.

Both the boundary layer coefficient and the overall heat transfer coefficient are correlated as functions of viscosity which in turn is a function of temperature thru depth. But temperature is the predicted quantity and therefore the predicted behavior is forced to correlate with the measured behavior thru the property choice.

In general, the behavior should not correlate for early times because of the time function used.

Since the heat transfer coefficients and thermal diffusivity are rate quantities, then they can effect the heat transfer rate behavior and rectify early time differences. Note: values of h required to match data are more than an order of magnitude different from Sieder-Tate correlations. Also values used for conductivity cannot be verified from existing experimental data.

Conclusions from the predictions and sensitivity study:

1. Circulation rate and mud heat capacity have a moderate effect on temperature.
2. Thermal conductivity and hole size have limited effect.
3. Plastic viscosity and geothermal gradient are important factors.

Authors note importance of heat of hydration and recommend 30 minute shortening of cement pumping times in deep hot wells. Heat of hydration begins to increase greatly as consistency increases.

32. Predicting Pressure Loss and Heat Transfer in Geothermal Wellbores
by E. Tansev, R. A. Startzman and A. M. Cooper (1975)

Two-phase flow equations are presented for steady-state heat transfer in wellbore and earth.

Considers potential and kinetic energy effects and also frictional effects.

Uses overall heat transfer coefficient to model the system outside the flowing stream, including the earth. The steady-state heat transfer in the earth is modelled in terms of an effective earth conductivity times the temperature difference between the flowing stream temperature and the initial earth temperature.

Correlations for heat transfer film coefficient at the tubing wall are presented for single phase, low steam volume two phase flow, and high steam volume two phase flow.

Uses Orkiszewski's correlation for two-phase pressure drop.

Matches field data by adjusting earth conductivity within a certain range, or by adjusting U.

33. Method for Calculating Circulating Temperatures

by A. F. Tragesser, P. B. Crawford, and H. R. Crawford (1967)

Published in 1967. Not much earlier work. Reference to Farris and Edwardson. No explicit outline of equations used, but indications are empirical fit in wellbore and use of time function in formation. Overall heat transfer coefficient for wellbore.

No vertical formation heat transfer

Example predictions given.

Field test results correlated for bottom hole temperature during short circulation period < 2.5 hours (time function not adequate for this). More than 10°F difference noted between predictions and measurements. Attributes difference to significant role played by fluid properties.

Good discussion on need for temperature predictions for cementing.

Constant geothermal gradient

34. Using Improved Technology to Obtain Better Cement Jobs on Deep, Hot Liners

by A. Tragesser, P. N. Parker (1972)

Lab and field data paper on effects of temperature.

Serves to justify program developed by Tragesser in 1967 and is a followup to the thermal simulation paper.

Liners are special problem because a good seal is required at both top and bottom, unlike production casing cementing where cement performance is judged mainly opposite the producing zone.

Chemical reaction of cement is highly dependent on circulating temperature and static temperature after circulation ceases. Temperature effects compressive strength and pumpability.

Field tests show

1. Circulation temperatures are much below API bottom hole test temperatures. Implies overretardation and possible prevention of adequate strength.
2. Oil base mud gives 5-25°F cooler circulating temperature than water base.

Compatability between cement and mud displaced is dependent on temperature because of viscosity dependence.

Cement design for liner must not be based on bottom hole conditions alone. Top of liner conditions must be taken into consideration.

35. Over-All Heat Transfer Coefficients in Steam and Hot Water Injection Wells

by G. P. Willhite (1967)

Steady-state heat flow through wellbore to determine overall heat transfer coefficient U.

Considers tubing, casing, and cement, and also convection/radiation in tubing/casing annulus.

Heat flow to formation is estimated using Ramey procedure with a transient heat conduction function (radial only)

Does not consider variable tubing temperature as occurs during transient flow.

Gives step-by-step procedure for calculating casing temperatures and U for given formation and wellbore properties.

Considers evaporation in the cement and formation to create a "dry zone" that leads to higher casing temperatures because of insulating effect.

Field data match is poor during first sixty hours, but good after steady state is reached.

APPENDIX 3
COMPLETED QUESTIONNAIRES FROM INDUSTRY

Producing Companies

Aminoil USA, Inc.
Republic Geothermal, Inc.
Phillips Petroleum Company
Union Oil Co. of California

Service Companies

Schlumberger Ltd.
The Analysts, Inc.
Dowell Division of the Dow Chemical Co.
NL Baroid Petroleum Services

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by
ENERTECH Engineering and Research Co., Houston, Texas.

Company: Aminoil USA, Inc.

Address: P. O. Box 11279, Santa Rosa, CA 95406

Person Contacted (Telephone): G. A. Frye

1. Does the company have need for wellbore temperature predictions?

Geothermal: Yes

Other: _____

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc ? To predict bottom hole temperature for geophysical analysis cementing and logging operations.

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? Yes. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? Rarely now but use is anticipated in the future.

3. Does the company presently use a wellbore thermal simulator computer program? No, or other method (graphical or hand calculations)? Yes. If a computer program is used, is it available in the public domain? _____.

Is the program or method capable of handling all thermal simulation needs? No. If not, what capability is lacking? _____

Can the program or method handle early times? Empirical Can it handle both radial and vertical heat flow in the formation? Convection overrides vertical. Can it handle a variable geothermal gradient? No

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? Yes, but prefer graphical

where applicable. same
Would the application be for drilling Yes, circulation as drilling
production Yes, and/or injection? Possibly

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation? _____

Use of a pseudo-transient radial heat flow approach is common in the industry.

Because early time behavior is suspect, it is standard practice to wait many
valuable hours to reach some stability.

Thank you

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by ENERTECH Engineering and Research Co., Houston, Texas.

Company: Republic Geothermal, Inc.

Address: P. O. Box 3388, Santa Fe Springs, CA 90670

Person Contacted (Telephone): Tom Campbell

1. Does the company have need for wellbore temperature predictions?

Geothermal: Yes

Other: _____

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc)? Cementing, logging, and production predictions

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? Early times and short. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? No - early time (cementing), yes - short time (production modeling)

3. Does the company presently use a wellbore thermal simulator computer program? Yes, or other method (graphical or hand calculations)? No. If a computer program is used, is it available in the public domain? No.

Is the program or method capable of handling all thermal simulation needs? No. If not, what capability is lacking? Early and short time predictions

Can the program or method handle early times? No Can it handle both radial and vertical heat flow in the formation? No
Can it handle a variable geothermal gradient? Yes

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? Yes

Would the application be for drilling Yes, circulation Yes, production Yes, and/or injection? Yes

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation? _____

Early time simulations would be useful in determining cement constituents for cementing casing and for determining mud temperatures and circulating times prior to logging to prevent logging tool failures. Short time predictions are useful in determining the time required for the heat loss out of the well bore to the formation to reach steady-state conditions.

Thank you

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by ENERTECH Engineering and Research Co., Houston, Texas.

Company: Phillips Petroleum Company

Address: P. O. Box 72, Del Mar, CA 92014

Person Contacted (Telephone): Gary W. Crosby

1. Does the company have need for wellbore temperature predictions?

Geothermal: Yes Other: Deep oil/gas wells

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc ? Monitor temperature while drilling and logging

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? Yes. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? No

3. Does the company presently use a wellbore thermal simulator computer program? Yes, or other method (graphical or hand calculations)? Yes. If a computer program is used, is it available in the public domain? Yes.

Is the program or method capable of handling all thermal simulation needs? No. If not, what capability is lacking? More accuracy

Can the program or method handle early times? Yes Can it handle both radial and vertical heat flow in the formation? Not vertical
Can it handle a variable geothermal gradient? No

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? Yes if more accurate than existing methods
Would the application be for drilling Yes, mainly, circulation Yes, production Yes, and/or injection? Yes

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation? _____

Thank you

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by
ENERTECH Engineering and Research Co., Houston, Texas.

Company: Union Oil Co of Calif.
Address: P.O. Box 76 Brea, CA 92621
Person Contacted (Telephone): L.A. Klotz 714-524-7201

1. Does the company have need for wellbore temperature predictions?

Geothermal: Minimal Other: Minimal

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc? drilling fluids, completion

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? 24 hr. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? yes - we have computer programs to do this

3. Does the company presently use a wellbore thermal simulator computer program? yes, or other method (graphical or hand calculations)? no. If a computer program is used, is it available in the public domain? no.

Is the program or method capable of handling all thermal simulation needs? 50%. If not, what capability is lacking? transient circulation temperatures

Can the program or method handle early times? yes Can it handle both radial and vertical heat flow in the formation? no - why do that
Can it handle a variable geothermal gradient? yes

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? yes - once every 10 years

Would the application be for drilling X, circulation X, production , and/or injection?

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation?

Such a program would be handy but is not a priority need -
Refer to my letter of April 18 '77
J.A. Klotz

Thank you

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by ENERTECH Engineering and Research Co., Houston, Texas.

Company: SCHLUMBERGER LTD

Address: 2300 W. LOOP S HOUSTON 77027 TEX

Person Contacted (Telephone): J.T. DEWAN

1. Does the company have need for wellbore temperature predictions?

Geothermal: _____ Other: ☒

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc? Geo pressure prediction; well log interpretation

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? Yes. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? NO

3. Does the company presently use a wellbore thermal simulator computer program? NO, or other method (graphical or hand calculations)? NO. If a computer program is used, is it available in the public domain? N/A.

Is the program or method capable of handling all thermal simulation needs? N/A. If not, what capability is lacking? _____

Can the program or method handle early times? N/A Can it handle both radial and vertical heat flow in the formation? "
Can it handle a variable geothermal gradient? "

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? Yes

Would the application be for drilling ☒, circulation _____, production _____, and/or injection? _____

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation? _____

PROGRAM SHOULD ALLOW FOR INPUT OF MUD
TEMPERATURE JUST AHEAD OF AND JUST AFTER THE
BIT; THESE MAY BE MEASURED BY FORTHCOMING
DOWNHOLE MEASUREMENT - WITH DRILLING TOOLS.

Thank you

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by ENERTECH Engineering and Research Co., Houston, Texas.

Company: THE ANALYSTS, INC.

Address: 4120 D. DIRECTORS ROW, HOV 77092

Person Contacted (Telephone): J. A. GILL 686-5516

1. Does the company have need for wellbore temperature predictions?

Geothermal: YES Other: PERMAFROST; PRESSURE DETECTION
(LITHOLOGY DETERM BY BIT HEATING - FORM. TEMP)

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc? WELL LOGGING

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? EARLY. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? YES

3. Does the company presently use a wellbore thermal simulator computer program? NOT PRESENTLY or other method (graphical or hand calculations)? YES. If a computer program is used, is it available in the public domain? YES.

Is the program or method capable of handling all thermal simulation needs? YES. If not, what capability is lacking? NO

Can the program or method handle early times? YES Can it handle both radial and vertical heat flow in the formation? YES
Can it handle a variable geothermal gradient? YES

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? YES

Would the application be for drilling LOGGING WHILE DRILLING, circulation YES, production YES, and/or injection? YES

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation?

WE WOULD BE HAPPY TO CONTRIBUTE TO DEVELOPMENT OR TAKE A LICENSE FOR USE.

Thank you

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by ENERTECH Engineering and Research Co., Houston, Texas.

Company: Dowell Division of the Dow Chemical Co

Address: P.O. Box 21, TULSA, OKla. 74102

Person Contacted (Telephone): Rev. Aoo- 718-680-0001

1. Does the company have need for wellbore temperature predictions?

Geothermal: yes Other: oil & gas wells

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc? Circulating temperatures during stimulation tubing & packer movement

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? yes. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? NO

3. Does the company presently use a wellbore thermal simulator computer program? yes, or other method (graphical or hand calculations)? NO. If a computer program is used, is it available in the public domain? NO.

Is the program or method capable of handling all thermal simulation needs? NO. If not, what capability is lacking? Circulating environments

Can the program or method handle early times? yes Can it handle both radial and vertical heat flow in the formation? yes Can it handle a variable geothermal gradient? yes

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? not without a source program

Would the application be for drilling NO, circulation yes, production NO, and/or injection? yes

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation?

Thank you

QUESTIONNAIRE

ERDA Project "Feasibility Study of Thermal Simulation to Predict Wellbore Temperatures in Geothermal Wells" by ENERTECH Engineering and Research Co., Houston, Texas.

Company: NL Baroid Petroleum Services

Address: P. O. Box 1675, Houston, Texas 77001

Person Contacted (Telephone): Jay P. Simpson (527-1142)

1. Does the company have need for wellbore temperature predictions?

Geothermal: Yes Other: Yes

If so, what is the need, e.g. drilling fluids, completion equipment, operations, etc)? Drilling fluids, monitoring wireline services

2. Are wellbore temperature predictions needed for early times (less than 24 hrs) or short time periods (less than 7 days) e.g. startup conditions or changing conditions? Yes. Are the wellbore fluids ever in two phase flow when wellbore temperature predictions are needed? Yes

3. Does the company presently use a wellbore thermal simulator computer program? Yes, or other method (graphical or hand calculations)? Yes. If a computer program is used, is it available in the public domain? Yes.

Is the program or method capable of handling all thermal simulation needs? No. If not, what capability is lacking? _____

Can the program or method handle early times? No Can it handle both radial and vertical heat flow in the formation? No
Can it handle a variable geothermal gradient? No

4. Would the company use, if available at reasonable cost, a computer program to predict transient wellbore temperatures? Yes

Would the application be for drilling Yes, circulation Yes, production _____, and/or injection? _____

5. Are there any additional comments that would be of value concerning the company's needs and interest in wellbore thermal simulation? _____

Better wellbore temperature predictions would be helpful,

but are not essential to NL Baroid's operations.

Thank you