# Study of Electrical Heating Application for Heavy Oil Recovery

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**Abstract.** One of the promising options for heavy oil recovery purposes consists of using Joule effect at electrical current propagation for in-situ heat generation. The principal conducting medium in this case is reservoir connate water which typically has high enough initial electric conductivity. Any study of electrical heating method (EH) relates to heat and mass transfer problem combined with electrical potential field variation across reservoir. 2D fully integrated COMSOL model of EH has been developed and used for the research applications.

As the real reservoir hydrocarbons are complex liquids, a multi-component flow model is frequently required to evaluate a particular oil recovery process. The tentative coupling between COMSOL and commercial reservoir simulator STARS has been done and some results are presented.

**Keywords:** electric conductivity, potential, Joule effect, heat transfer, fluid viscosity.

## 1. Introduction

New or improved methods for the exploitation of non-conventional hydrocarbon resources become more and more a real challenge for energy producing companies. Among the most popular in the oil industrial applications is the technique of reservoir heating for diminishing the initial oil viscosity which is usually high in case of non-conventional hydrocarbon. However, in practice the widely used methods of thermal agent injection (hot water or steam) can't be applied without initial preheating period which enables to reduce initial oil viscosity to acceptable level and to start subsequently the conventional thermal recovery.

One of the known methods of in-situ heat generation is the electrical heating. The EH method has been developing for about thirty years and was already tested at large scale. From the physical viewpoint the method is based on the Joule effect, the original (connate) reservoir water playing a role of conductor. The electrical current is supplied via the electrodes settled directly in the reservoir and the heat is generated over the reservoir volume according to the current density and hence the fluid saturation and temperature fields which affect the bulk electrical conductivity [1-2]. So an understanding of physical mechanisms of this oil recovery method requires to study the heat and mass transfer under the EH conditions. The first objective of our work is to develop COMSOL based 2D fully integrated model for the EH method which can be used for the research applications.

As the real reservoir hydrocarbons are complex liquids, a multi-component flow model (which is still not available in COMSOL) is required in some cases to evaluate more precisely a particular oil recovery process. To do this for EH method applications, it seems reasonable to couple a dedicated oil reservoir simulator capable to carry out the multi-component flow computations, with electrical current model based on COMSOL. The tentative coupling between COMSOL and commercial reservoir simulator STARS by CMG has been done and is presented below followed by discussion on the results of computations.

## 2. COMSOL Fully Integrated Model

Recently the use of COMSOL *Multiphysics* flexibility has allowed us to develop a model of thermal three phase immiscible flow through porous media [3]. This model has been improved to gain in numerical performance and is used now for coupling with electrical heating term determined from the electrical potential equations. Thus the system of fluid component mass, total thermal energy and electrical charge conservation equations underlies the model. To account for the voltage distribution created by the multi-phase power delivery system, the complex potential is used which results in two similar but separate equations for real and imaginary potential parts. The temperature and water saturation dependent bulk electrical conductivity is considered, the saturation dependency being given according to Archie law.

The resulting system of non-linear strongly coupled equations for transient thermal flow and two quasi-stationary equations for electrical complex potential is modeled using PDE application mode with temperature, pressure and saturation dependent coefficients and source terms. Below are the details of the problem mathematical formulation.

## 2.1 Thermal flow equations

The thermal flow model equations include the fluid component mass and total thermal energy conservation equations [3]. The mass conservation equations are written for the water (index "*w*") and for the oil which is assumed to be uniform non-volatile hydrocarbon liquid (index "*h*"). The equations are as follows

$$\partial_t(\varepsilon\rho_w S_w)+\nabla\cdot(\rho_w u_w)=0 \qquad (1)$$

$$\partial_t(\varepsilon\rho_h S_h)+\nabla\cdot(\rho_h u_h)=0 \qquad (2)$$

where phase flows, $u_p$ , $p=w,h$, are described by generalized Darcy' law

$$u_p=-K\eta_p\cdot(\nabla P_p+\rho g e_z) \qquad (3)$$

Here $\varepsilon$ is porosity, $\rho$ and $\eta$ phase density and relative mobility, $S$ phase saturation. As the temperature will not be uniform in the reservoir, the total thermal energy conservation equation which includes solid (index "*s*") and fluid phases (index "*f*") contributions under assumption of local thermal equilibrium (one-temperature approach), complements the model

$$\partial_t(E_s+E_f)+\nabla\cdot(U_f-\lambda\nabla T)=J \qquad (4)$$

where $E$ is volumetric internal energy, $U_f$ total volumetric flow of thermal energy, $\lambda$ reservoir (bulk) thermal conductivity coefficient, $T$ temperature. The total flow $U_f$ comprises fluid phase flows, $U_p=\rho_p h_p u_p$ , where $h$ is specific enthalpy.

Finally, pore volume conservation constraints phase saturations in usual manner

$$S_w+S_h=1 \qquad (5)$$

## 2.2 Electric potential equations

In the case of complex electric potential , the electric charge conservation law may be expressed as a system of two stationary equations for real and imaginary potential parts:

$$\nabla\cdot(\sigma\nabla\varphi)=0$$

$$\nabla\cdot(\sigma\nabla\psi)=0 \qquad (6)$$

where

$$\upsilon=\varphi+i\psi$$

is electric potential and σ is bulk electric conductivity. The Joule heat release power is defined from the solution of the above equation as

$$J=\sigma|\nabla\upsilon|^2 \qquad (7)$$

The medium electric conductivity is temperature and water saturation dependent variable (see next subsection for details) and will vary according to their variations. This means that the heating power $J$ is solution dependent and there is a strong coupling between electrical and thermal flow phenomena. In particular, this non-linear coupling leads to temperature rise acceleration during heating (see **Results and Discussion** section).

## 2.3 Constitutive equations

### *Flow material functions and the component physical properties*

The system of equations (1-7) has to be completed with a set of constitutive relations which gives a local phase flows description depending on local pressure, temperature and phase saturations. For relative phase permeabilities the relationships based on *van Genuchten-Mualem* model [4] have been used for water (wetting phase) and oil (non-wetting phase).

Conventional data for the physical properties of liquid water which are available elsewhere have been used to relate such parameters as viscosity, density and enthalpy on pressure and temperature variations. Typical for heavy oil relation for temperature dependent viscosity has been chosen for our purposes:

$$\mu_h = \mu_0 \exp\left(b / T_{,K}\right) \quad (8)$$

Here $\mu_0$ and $b$ are parameters, temperature $T_{,K}$ should be taken in absolute units.

*Archie's law*

The bulk (medium) electrical conductivity depends drastically on water content because typically the reservoir solid and oil phase conductivities are negligibly small. Archie's law specifies the relation between medium and pure water electric conductivity, the porosity and the water saturation being the main variables of the law. The modified formulation of Archie's law which takes into account the temperature dependency (factor $f(T)$) is used in current work :

$$\sigma = \sigma_w \varepsilon^m S_w^n f(T) \quad (9)$$

Here $\sigma_w$ is water conductivity, $m$ and $n$ are (constant) parameters and the temperature dependency can be approximately presented by linear function which increases the conductivity by a factor of 3-4 for a temperature increase of 100°C (cf. [2]).

### 2.4 Boundary conditions

Since few different problems are concerned in current work then the particular boundary conditions will be specified together with a problem description in due place. However the common feature of all problems under consideration is the implementation of point sources for both electrical field and thermal flow equations. Mathematically the formulation of the point source for potential equations and for the flow equations is equivalent so the discussion below is equally applicable in both cases.

The relation between the applied potential and the resulting current includes the electrode radius and will evidently lead to different current for the same applied potential but different electrode radius. Implementation of point source weak formulation offered by COMSOL implies that this relation will depend on grid discretization parameter and also the order of element used in simulations. So care should be taken for the *weak term* formulations which describe potential given on the electrodes and the production wells.

### 2.5 COMSOL Application Modes

The thermal three phase flow model has been built using PDE Application mode. Generally speaking, the electrical potential equations can be modeled using both PDE or AC Application modes, the only difference being more friendly interface in the latter case. Our experience didn't show any major difference between these modes.

## 3. Tentative Coupling Model

The main idea of the coupling is to compute separately the thermal multi-component flow and the EH power field using STARS and COMSOL, respectively. Remind that the variation of the electrical conductivity with temperature and water saturation (equation (9)) couples the electrical potential equations with the thermal flow equations for the reservoir.

The code of COMSOL to STARS coupling is done via COMSOL Script facility. In particular, a COMSOL script file is written which launches first both simulators and governs the data exchange between them. Once the geometry, the solid and fluid phase properties are defined using STARS input data file, the code performs a loop of sequential computations providing the EH power field (resulting from COMSOL) as a source term for the temperature field computation (resulting from STARS). Simultaneously STARS updates the saturation fields so that the bulk medium electrical conductivity can be defined just before COMSOL makes next computation.

*Coupling algorithm*

At the iteration $n$, the electrical conductivity $\sigma^n$ is known. Then

- using COMSOL, solve the equations (6) to get the new potential and so the new heating power (7);
- using STARS, solve the transport problem with the heating power as a source term. Get the new distributions of the temperature and the water saturation;
- update the value of the electric conductivity $\sigma^{n+1}$ of the medium according to (9) and go to the iteration ($n$+1).

The coupling procedure has already been tested and is applied now for laboratory and field conditions.

## 4. Results and Discussion

### 4.1 Comparison to analytical solutions

*Dimensionless heat transfer equation*

For the sake of simplicity the initial problem has been reduced to heat transfer with single phase stationary flow under conditions of the EH in a uniform medium. It can be shown that the dimensionless problem for 1D radial case is described by following equation

$$\theta_\tau + \frac{\Pi}{\rho}\nabla\theta - \Delta\theta = \frac{\Gamma^2}{\rho^2} \qquad (10)$$

which applies for dimensionless radial distance $\rho_0 \le \rho \le 1$. Here the dimensionless variables are introduced as follows: $\theta$ is temperature, $\tau$ time, $\Gamma$ electrical current and $\Pi$ thermal Peclet number. Analytical solutions have been developed for the conduction and convection/conduction heat transfer in uniform medium using stationary boundary conditions for applied potential and no conduction heat flow at the boundaries $\rho = \rho_0, 1$.

*Radial heating with conduction*

Stationary heating with heat conduction only ($\Pi$=0) in 1D radial case gives rise first to the transient then the pseudo steady-state regime of temperature field evolution. Analytical solution for the latter regime, $\theta_s(\rho)$, shown in Figure 1 (dashed line) is in good agreement with COMSOL solution of the equation (10) for dimensionless time $\tau > 0.25$ when the stationary temperature profile sets to grow linearly in time as it follows from pseudo steady-state solution. Analytical stationary temperature profile is shown also at zero time to demonstrate the difference between transient and pseudo steady-state period.

*Radial heating with conduction and convection*

Imposed stationary flow from the electrode (left to right) improves the heating results as it can be seen from Figure 2. Even at relatively low Peclet number ($\Pi$=0.6) the flow contribution leads to considerable difference in temperature field (cf. temperature profile at similar times in Figure 1). The pseudo steady state regime can be observed at nearly similar time, the corresponding numerical and analytical temperature profiles being in good agreement. The analytical stationary profile at $\tau$=0 illustrates again (cf. Figure 1) two different regime of temperature field variation.

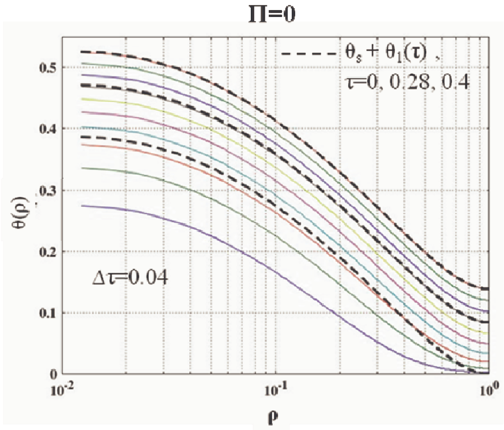

**Figure 1**. Dimensionless temperature profiles of COMSOL transient solution (solid lines) at zero Peclet number and analytical pseudo steady-state profiles (dashed black line) at $\rho_0$=0.0125.

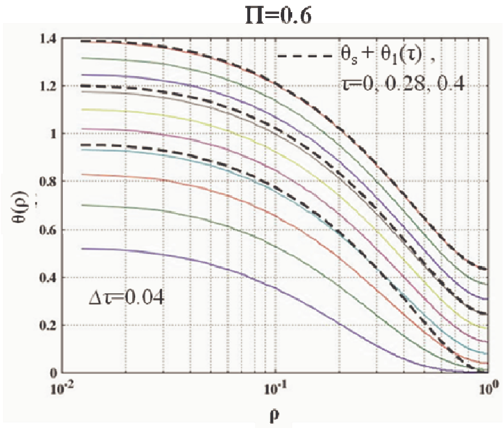

**Figure 2**. Dimensionless temperature profiles of COMSOL convection/conduction transient solution (solid lines) number and corresponding analytical pseudo steady-state profiles (dashed black line) at $\rho_0$=0.0125.

*Primary production by EH: stationary solution*

Countercurrent single phase flow example ($\Pi$=-26.6) has been taken to compare analytical solution with COMSOL and STARS computational results. During coupling the results of power computations in COMSOL are written in separate file which is read directly by STARS. Similar procedure has been used for the comparison: stationary power field has been generated and then read from STARS. The dimensionless stationary solution of equation (10) is shown in Figure 3 together with COMSOL and STARS results. In COMSOL model the r.h.s. term in equation (10) has been computed from equation (6). Unlikely the STARS computations have been done for dimensional variables and temperature dependent fluid properties which don't affect the temperature field.

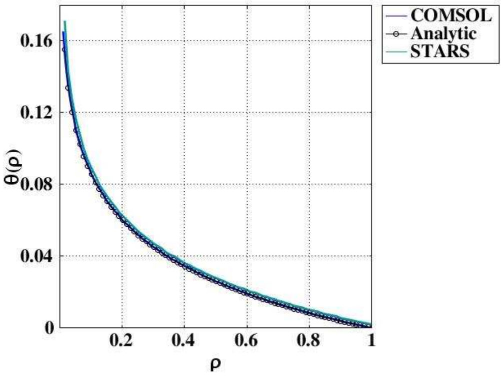

**Figure 3**. Dimensionless stationary temperature profiles for countercurrent convection/conduction problem (equation(10)).

## 4.2 COMSOL simulations of preheating in 2D multi-electrode pattern

Upon verification which has been done via comparison to developed 1D analytical solutions and to available results of laboratory experiments, both fully integrated and coupling models were used to model some particular examples of the EH application. The main purpose of our short study was the estimation of EH parameters at different process conditions.

Typical areal element of EH application in real field conditions reported in [2] has been chosen for modeling (see Figure 4). The study comprises the following cases:

(1) Closed region, uniform electrical properties;

(2) Closed region, temperature dependent properties;

(3) Imposed pressure drop between the electrodes and the wells, temperature dependent properties.

Unless otherwise specified, the reference parameters in all cases are: bulk electrical conductivity, $\sigma_0$=0.004 S/m, applied electrode potential, $V= (\varphi^2+\psi^2)^{1/2}$= 200 volts, medium thermal conductivity, $\lambda$=2.6 W/m/°C, bulk heat capacity, $C_0$=2.6 MJ/m$^3$/°C. No-flow and electrical/thermal insulation conditions on lateral sides, top and bottom of the element, constant complex (i.e. three phase) potential (and pressure/temperature conditions on the electrodes and wells – for the case (3)) have been given. The temperature dependency of the bulk electrical conductivity (equation (9)) has been approximated with linear function given by single parameter $\gamma$=0.03 S/m/°C. Initial reservoir temperature is 10°C.

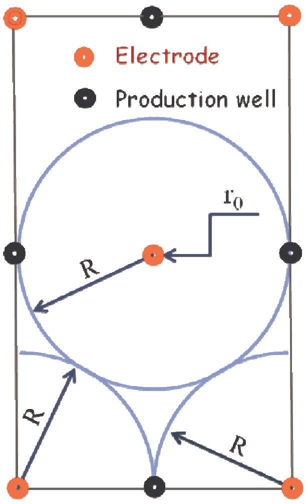

**Figure 4**. Representative areal multi-electrode pattern used for COMSOL simulations: zero potential at 4 production wells, $R$=8m, $r_0$=0.1m.

The case (1) is a reference which shows the departure point for key process parameters. The case (2) takes into account the local variation of electric conductivity with temperature (typically, factor 3-4 at a temperature rise of 100 °C, cf. parameter $\gamma$). Finally, the case (3) represents the EH enhancement via convective heat transfer which results in more uniform and effective heating (cf. [2]). The flow conditions (electrode/well pressure and temperature) were similar to those presented below in subsection 4.3.

Like for any standard thermal method of oil recovery, the main purpose of EH process is to make heavy oil mobile due to rapid viscosity drop at raising temperature. More uniform temperature field improves significantly the sweep efficiency of oil recovery. At last the typical heating time is also important parameter of EH process which can be prohibitive for the process field application. Therefore the heating power and temperature fields as well as their average values will be examined and compared for the three cases under consideration.

The main results of COMSOL modeling are presented in Figures 5 and 6. Total time of EH heating for all three cases was $t_{max}$ =24 months.

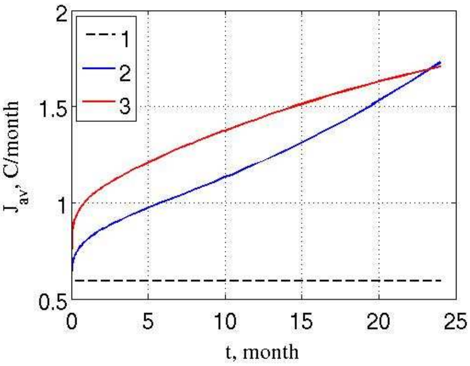

**Figure 5**. Average power of Joule heat release in the multi-electrode element shown in Figure 4: time diagram for three cases under consideration.

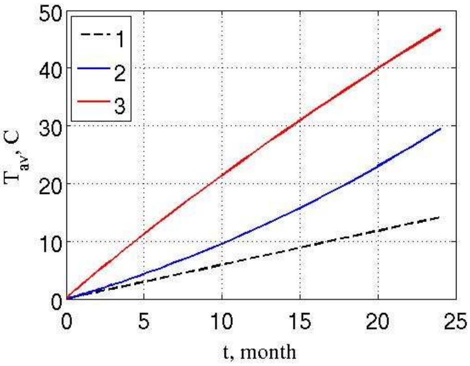

**Figure 6**. Average temperature rise over initial (uniform) temperature in the multi-electrode element shown in Figure 4: time diagram for three cases.

The average power (over the element surface) of Joule heat release, $J_{av}$ , °C/month, is shown for the three cases in Figure 5. As the electrical conductivity remains constant in case 1, so does the power $J_{av}$ (dashed line, Figure 5). Local value of $J$ near an electrode may reach as much as three order of magnitude greater value which demonstrates typical strong non-uniformity of heat release. This is a well-known drawback of EH method.

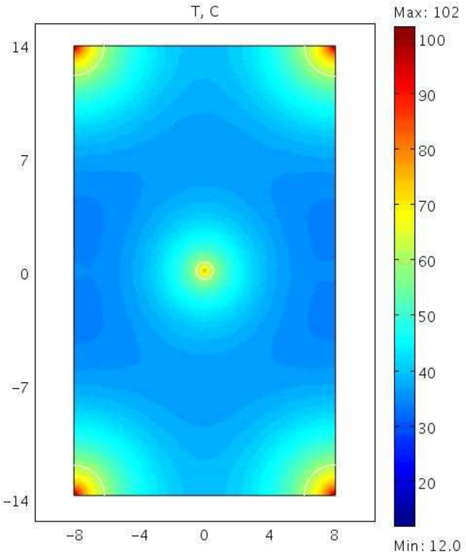

**Figure 7a**. Temperature field at $t=t_{max}$ in case (2); white line contours correspond to 60°C.

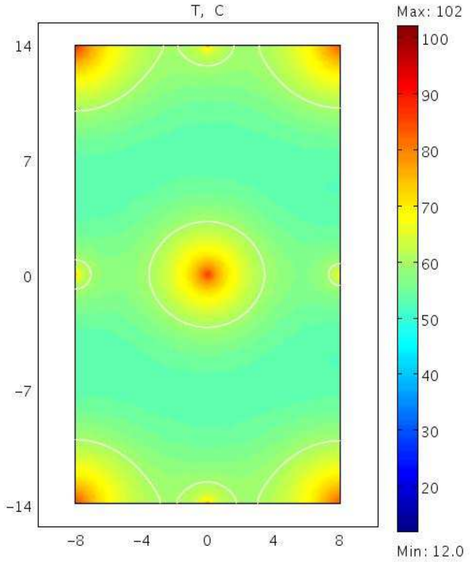

**Figure 7b**. Temperature field at $t=t_{max}$ in case (3); white line contours correspond to 60°C.

When the temperature rises, the electrical conductivity increases locally (case 2 and 3) which leads to electrical current and thus the heating power increase. Due to more uniform temperature distribution in the case (3) (cf. Figures 7a,b) the average power $J_{av}$ becomes even greater than in case (2). Moreover the heating is turned out to be more successful in this case because the variation of temperature results in stronger viscosity variation (cf. equation (8)) which will impact finally the oil sweep efficiency.

The effect of convective heat transfer on temperature distribution is significant. The average temperature rise (over initial temperature) increases most rapidly (red line in Figure 6) while the temperature field remains considerably more uniform in this case (see Figures 7a,b). The time at which the average temperature rise reaches 30°C is about 10 months shorter than in case (2); this factor will evidently depend on imposed flow and temperature conditions.

### 4.3 Coupled simulations

Due to the symmetry of areal element shown in Figure 4, only a lower half of it was used for coupling purposes. Thus the computational domain contains three electrodes and three production wells. Three phase electric potential was applied at the electrodes while the ground potential was given at the wells. The initial reservoir conditions are specified in Table 1. Water injection at 80°C was applied to enhance the reservoir preheating and also to control the temperature in the close vicinity to electrodes. The water injection and production well conditions can be found in Table 2. The total process time is 18 months.

The temperature field at 17 months of EH indicates that the maximum temperature zone has moved from the electrodes to the middle of the element where the oil saturation remains nearly unchanged (Figures 8,9). By this time the oil viscosity has been reduced from $10^6$cP initially to less than 20 cp near the production wells. The oil saturation near the production wells have been reduced from 0.798 to 0.4.

| $T$, °C | $\sigma$, S/m | $S_h$ | $V$, volt | $\mu_h$ , cP |
|---|---|---|---|---|
| 10 | 0.007 | 0.798 | 220 | $10^6$ |

**Table 1.** Initial conditions for coupling problem.

| Pressure, bar | | Flow rate, m3/m/day | |
|---|---|---|---|
| injection, max | production, min | injection, max | production, max |
| 15 | 8 | 1 | 1 |

**Table 2.** Electrode (water injection) and production well conditions of flow.

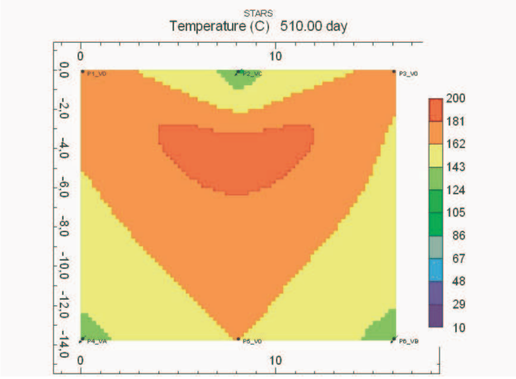

**Figure 8**. Temperature field (in °C) computed by STARS at 510 days of EH.

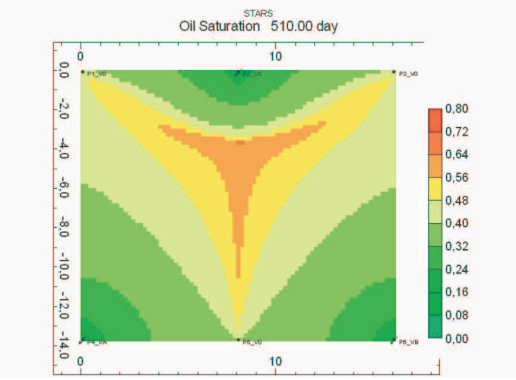

**Figure 9**. Oil saturation field at t=510 days computed by STARS.

## 5. Conclusions

- Fully integrated COMSOL model for electrical heating has been tested and applied successfully for EH field conditions;

- Tentative coupling between COMSOL and STARS has demonstrated that the COMSOL Script options combined with the numerical performance of both simulators constitute a good basis for sequentially coupled computations;

- Both fully integrated and coupling models seem to be promising for numerical implementation.

## 6. References

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## 7. Acknowledgements

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