PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

A Desktop Review of Calculation Equations for Geothermal Volumetric Assessment

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ABSTRACT

The volumetric method has been used for geothermal resource assessment since it was proposed by USGS in 1970s. While the originally proposed calculation method has been in practice, two other calculation equation sets have also been used under the name of volumetric method or heat-in-place. Different ranges of numerical value for three variables of reference temperature, heat-electricity converting efficiency and/or recovery factor are selected for those methods, most of them without clear explanations on why or how those are selected. As calculation results of geothermal electricity capacity largely depend on these three variables, resource assessments without describing clear explanations may sometimes have resulted in unclear conclusions; with what conditions could an investor get this much electricity energy? Or is this feasible for our field?

This paper reviews the origins of reference temperatures, heat-converting efficiency and recovery factor being adopted by the three different calculation methods, thereby, clarifies their applicability and limitations for use. Through the review, we pointed out a small but theoretically fundamental modification should be necessary to the original USGS method. We also found that recovery factor being used by the three equation sets should be used as a temperature dependent variable in theory, although it was originally defined as an independent of reservoir temperate.

Key words: Geothermal volumetric method, resource assessments, recovery factor, utilization factor, conversion factor, triple point temperature

1. INTRODUCTION

The notes of the acronyms and symbols used in the text are given after the main text.

1.1 Background

Electricity capacity of geothermal reservoir available largely depend on underground resource conditions. Thus, more reliable resource assessment can only be made after investing underground conditions by test well drilling. However, investors are usually eager to know approximate capacity even before test well drilling to decide whether they should invest on test well drilling or not. Volumetric geothermal resource assessment method, as it is simple and easy to use at this stage, has thus been practiced for this type of needs as well as at various later development stages.

The method was first proposed by USGS in1970s. The method aims to assess *geothermal resource* that is defined as the portion of the accessible resource base that can be recovered as useful heat under *current and potential* economic and technological conditions. When assessing electricity capacity by this method, practitioners may determine underground conditions since the other factors (variables) are pre-recommended by USGS (1978) assuming assessment is made for field in USA. However, many resource assessment reports for fields in other countries do not clearly mention this condition. To make matters more complicated, there are three different calculation equation sets including the original USGS calculation method. We name the other two as the USGS expansion method and the Prevailing method. Among those three, the Prevailing method uses different value range of "reference temperature", heat-conversion efficiency and different value range of recovery factor from the other two USGS based calculation methods. We have not yet located explanatory descriptions on why those values have been selected for the Prevailing method. Since such variables as reference temperature, heat-conversion efficiency and recovery factor shall largely affect the calculation results, clear explanations on why the value range of these variables are selected have to be described in resource assessment reports. With sufficient information, investors may be able to fully utilize resource assessment reports.

In this paper, we reviewed the origin of these variables, which enabled us to clarify applicability and limitations of the present calculation methods. Also, through this review, we pointed out a small but a fundamental modification to be needed for the original USGS method just for theoretical conformity.

1.2 Scope of Work

We limited our scope of work to the widely-used three methods that include temperature conditions as controlling factors. We do not intend a comprehensive review report that deals with many other methods. Most of our reviews are focused on clarifying theoretical backgrounds, and applicability and limitations of these three methods.

1.3 Definitions and conditions for the volumetric assessments

This paper follows the basic definitions and conditions originally given by the USGS method, unless otherwise specifically described; that is, geothermal fluid in reservoir is assumed to be liquid phase, because that "for all hot-water system, we assume the initial wellhead condition to be saturated liquid, mainly because a fluid that is all liquid has a smaller entropy value than a two-phase fluid with the same enthalpy. Thus, the Available work assuming liquid water is greater than any two-phase mixture of the same enthalpy and is an appropriate reference condition" (Muffler, 1978). Also, we assume geothermal fluid should possess thermodynamic characteristic of water unless otherwise described.

2. REVIEW OF THE CALCULATION EQUATIONS OF THE USGS METHOD (1978)

2.1 Equations used by the USGS method

2.1.1 Thermal energy stored in reservoir

The USGS method gives the following equation to estimate thermal energy originally stored in reservoir (Muffler, 1978).

$$\mathbf{q_{rsv} = C_v V(t_{rsv} - t_{ref})\ [kJ]} \qquad \textbf{Eq. 1}$$[1]

Eq. 1 expresses heat available when temperature changes from $\mathbf{t_{rsv}}$ to $\mathbf{t_{ref}}$.

2.1.2 A clarification of "reference temperature"

The term "reference temperature" in **Eq. 1** is a temporarily fixed point of temperature that serves as "starting point" or "datum point" for measurement. It is a rather general term to which a different temperature may be assigned depending on issues under consideration. Further, there are other nomenclatures[2] used for "reference temperature" in geothermal volumetric resource assessments. It is sometimes ambiguous unless specifically and consistently defined in a paper.

As for the geothermal volumetric resource assessments, the USGS method describes that a temperature **15 ℃** is selected to $\mathbf{t_{ref}}$ in **Eq. 1**, because that it is the mean annual surface temperature and for simplicity is assumed to be constant for the entire United States (Muffler, 1978). For this specific purpose, we re-write **Eq. 1** with suffix "amb" denoting "ambient temperature condition" as:

$$\mathbf{q_{rsv} = C_v V(t_{rsv} - t_{amb})\ [kJ]} \qquad \textbf{Eq. 2}$$

This equation will be proved not to be thermal energy *stored* in reservoir before extracted but thermal energy *available under ambient temperature condition after extracted from reservoir*. Explanations are given in Section 2.4.

2.1.3 Calculation equation for mass of fluid

Together with **Eq. 1**, the USGS method gives the following two equations to calculate mass of fluid available *at wellhead*. We use the simble $\mathbf{R_{g\_amb}}$ and $\mathbf{h_{amb\_L}}$, rather than $\mathbf{R_g}$ and $\mathbf{h_{ref}}$ used in the USGS method (Muffler, 1978), to correspond to the change made above

$$\mathbf{R_{g\_amb} = q_{WH}/q_{rsv}\ [\text{-}]} \qquad \textbf{Eq. 3}$$

$$\mathbf{m_{WH\_L} = q_{WH}/(h_{WH\_L} - h_{amb\_L})\ [kJ]} \qquad \textbf{Eq. 4}$$[3]

Although the three equations are basic for the USGS method to estimate thermal energy in reservoir, we have noted that they need to be re-examined from thermodynamic definition point of view. Discussions on this issue will be given in Section 2.4 after reviewing definitions of recovery factor and Available work presented by the USGS method.

2.2 Definition of recovery factor and its implication

Recovery factor is defined as "the ratio of geothermal energy recovered at wellhead, to the geothermal energy originally in the reservoir: it reflects the physical and technological constraints that prevent all the geothermal energy (>15 ℃) in the reservoir from being extracted; the value of recovery factor is assumed to include the relatively small energy and friction losses that occur in the wellbore as the reservoir fluid rises to the surface. In relation to the definition of recovery factor, estimation of $\mathbf{h_{WH\_L}}$ assumes isenthalpic flow in wellbore; that is, no heat is lost by conduction as the water comes to the surface (Muffler, 1978).

The deffinitions for $\mathbf{R_g}$ and $\mathbf{h_{WH\_L}}$ together with the assumption that fluid in wellbore is liqud phase, result in the following relations.

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[1] **Eq. 1** is proved to be thermal energy available *under reference temperature condition.* We will provide explanations in section 2.3.

[2] For the volumetric method, other terminologies are sometimes used, which may have this temperature ambiguous; please refer to 4.1.

[3] **Eq. 4** is proved to be against definition of thermodynamics. Explanation will be given in section 2.4.

$$\mathbf{t_{rsv}} = \mathbf{t_{WH}}\ [^\circ\mathbf{C}],\quad \mathbf{h_{WH\_L}} = \mathbf{h_{rsv\_L}}[\mathbf{kJ/kg}] \qquad \textbf{Eq. 5}$$

2.3 Available work

The USGS method describes Available work (Exergy energy) as:

$$\mathbf{W_A} = \mathbf{m_{WH\_L}}\{(\mathbf{h_{WH\_L}} - \mathbf{h_{0\_L}}) - \mathbf{T_0}(\mathbf{s_{WH\_L}} - \mathbf{s_{o\_L}})\}\ [\text{kJ}]\text{ or }[\text{kW}] \qquad \textbf{Eq. 6}$$

It describes that two likely choices are $\mathbf{T_0}$ equal to ambient (15℃; 288.15 K) in the USA or to condenser temperature (say, 40℃; 313.15 K), and that it prefers to use **15**℃ in order to keep $\mathbf{W_A}$ a maximum value and thus the most appropriate reference value (Muffler, 1978). We change the suffixes to make this point clear:

$$\mathbf{W_{A\_amb}} = \mathbf{m_{WH\_L}}\{(\mathbf{h_{WH\_L}} - \mathbf{h_{amb\_L}}) - \mathbf{T_{amb}}(\mathbf{s_{WH\_L}} - \mathbf{s_{amb\_L}})\}\ [\text{kJ}]\text{ or }[\text{kW}] \qquad \textbf{Eq. 7}$$

Further, **Eq. 7** is specifically represented with numerical values by the following equation.

$$\mathbf{W_{A\_USA}} = \mathbf{m_{WH\_L}}\{(\mathbf{h_{WH\_L}} - 62.98) - 288.15(\mathbf{s_{WH\_L}} - 0.2245)\}\ [\text{kJ}]\text{ or }[\text{kW}] \qquad \textbf{Eq. 8}$$

It is evident that the Available work given by **Eq. 8** is the maximum work converted from the heat energy recovered *at the wellhead* in the USA or in *the regions* where the surrounding ambient temperate is 15℃ (288.15K). Thus, we the USGS method represented by **Eq. 8** is *a region-specific method*.

2.4 Review of the equation for mass at the wellhead

Combination of **Eq. 2**, **Eq. 3**, **Eq. 4** and **Eq. 5** results in:

$$\mathbf{m_{WH\_L}} = \mathbf{R_g C_v V(t_{WH} - t_{amb})/(h_{WH\_L} - h_{amb\_L})}\ [\mathbf{kJ}] \qquad \textbf{Eq. 9}$$

Examine **Eq. 7** and **Eq. 9** together, and we note those appear to be as if the mass having the temperature $(\mathbf{t_{WH}} - \mathbf{t_{amb}})$, not $\mathbf{t_{WH}}$, and specific enthalpy $(\mathbf{h_{WH\_L}} - \mathbf{h_{amb\_L}})$, not $\mathbf{h_{WH\_L}}$, is sent into power cycle represented by the term in the curly brackets, indicating exergy per unit mass, of the right-side term of **Eq. 7**. This is not in greement with definition of specific enthalpy; the mass sent into power cycle should be of the initial temperature $\mathbf{t_{rsv}} = \mathbf{t_{WH}}$ and specific enthalpy $\mathbf{h_{rsv\_L}}$=$\mathbf{h_{WH\_L}}$. Moreover, **Eq. 9** is the equation that shows that mass of fluid available at well head (m_{WH_L}) should vary depending on ambient temperature, which is totally unexplanable.

We note, in the first place, **Eq. 4** is against the definition of specific enthalpy. The definition is that "specific enthalpy is calculated by taking the total enthalpy of the system and dividing it by the total mass of the system. It is written mathematically as: h = H/m; where h is the specific enthalpy, H is the enthalpy of the system, and m is the total mass of the system"[4]. The term $(\mathbf{h_{WH\_L}} - \mathbf{h_{amb\_L}})$ of **Eq. 4** is no longer the specific enthalpy of the mass at wellhead unless $\mathbf{h}_{\text{amb\_L}} = \text{zero}$ (Takahashi & Yoshida, 2016). We provided an illustrative exploratory notes in the **Appendix**-A to give an additional explanation.

2.5 Introducing the triple point temperature to the geothermal volumetric assessment method

2.5.1 Modification of original equations of USGS method.

We introduce "triple point temperature" to solve the issue above. "Triple point" is defined to be the pressure-temperature condition at which three phases (solid, liquid, and gas phases) of a substance co-exist. The triple point temperature is the minimum temperature, at which the liquid can exist. Working fluid in practical thermal utilization systems (such as steam-engines) are not always working (moving) below this temperature because gas or liquid phase changes to solid phase directly below this temperature[5]. As for water, the temperature is defined to be 0.01 ℃ (273.16 K), pressure be 0.00061 MPa, specific entropy and enthalpy of liquid phase are zero and virtually zero[6] respectively.

With the triple point temperature, we re-write **Eq. 2**, **Eq. 3** and **Eq. 4** as follows:

$$\mathbf{q_{rsv\_trp}} = \mathbf{C_v V(t_{rsv} - t_{trp})}\ [\mathbf{kJ}] \qquad \textbf{Eq. 10}$$

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[4]http://www.calculator.org/property.aspx?name=specific%20enthalpy; for an example

[5] For this reason, this is the base reference temperature for steam-turbines.

[6] Precisely describing, the specific enthalpy of water at the triple point temperature is defined as $\mathbf{h_{trp\_L}}$=0.00061 kJ/kg, which is verturally zero in pracitice.

$$\mathbf{R_{g\_trp} = q_{WH}/q_{rsv\_trp}\ [\text{-}]} \qquad \text{Eq. 11}$$

$$\mathbf{m_{WH\_L} = q_{WH}/(h_{WH\_L} - h_{trp\_L}) = q_{WH}/h_{WH\_L}\ [kJ]} \qquad \text{Eq. 12}$$

Combination of **Eq. 10**, **Eq. 11** and **Eq. 12** results in:

$$\mathbf{m_{WH\_L} = R_{g\_trp} C_v V (t_{WH} - t_{trp})/h_{WH\_L}\ [kJ]} \qquad \text{Eq. 13}$$

Eq. 10 represents thermal energy *inherently stored in reservoir*; which shall be estimated before consideration of ambient temperature at which thermo-utilization system is to be used. Recovery factor represented by **Eq. 11** agrees with the descriptive definition "the ratio of geothermal energy recovered at wellhead, to the geothermal energy *originally (inherently)* in the reservoir". Those three equations (**Eq. 10**, **Eq. 11** and **Eq. 12**) are all in agreement with assumptions made for the volumetric method as well as thermodynamics. We name this set of equation as *modified USGS method*.

In addition, **Eq. 2** shall be reservoir thermal energy available *under surrounding ambient temperature condition* (refer to Appendix). To emphasize this point we could re-write **Eq. 1** and **Eq. 2**, with the triple point temperature as follows.

$$\mathbf{q_{rsv_{ref}} = C_v V\{(t_{rsv} - t_{trp}) - (t_{ref} - t_{trp})\}\ [kJ],\ (t_{rsv} \geq t_{ref},\ t_{ref} \geq t_{trp})} \qquad \text{Eq. 14}$$

$$\mathbf{q_{rsv\_amb} = C_v V\{(t_{rsv} - t_{trp}) - (t_{amb} - t_{trp})\}\ [kJ],\ (t_{rsv} \geq t_{amb},\ t_{amb} \geq t_{trp})} \qquad \text{Eq. 15}$$

Only when $\mathbf{t_{ref} = t_{trp}}$, **Eq. 14** shall represent thermal energy *inherently store in reservoir*; i.e. the thermal energy that is *independent of reference or ambient temperature*.

2.5.2 Impacts on the past assessments

The above re-examination has been made only for theoritical comformity with thermodynamics, for a basic understanding of the geothermal volumetric assessment method. Discrepancies between calculation results caused from this theoretical adjustment, however, will be neglegibly small because $\mathbf{t_{rsv}}$ is far greater than $\mathbf{t_{amb}}$ and $\mathbf{t_{trp}}$ ($\mathbf{t_{rsv} \gg t_{amb} \approx t_{trp}}$), and $\mathbf{h_{rsv\_L}}$ also far greater than $\mathbf{h_{amb\_L}}$ and $\mathbf{h_{trp\_L}}$ ($\mathbf{h_{rsv\_L} >> h_{amb\_L} \approx h_{trp\_L}}$). Thus, this revision will not affect past estimations conducted by the USGS method.

2.6 Re-writing the definition of recovery factor

The definition of the recovery factor presented in Section 2.2., has to be re-written, by replacing 15 ℃ with $\mathbf{t_{trp} = 0.01\ ℃}$ for theoretical conformity; that is, "recovery factor reflects the physical and technological constraints that prevent all the geothermal energy **(>$\mathbf{t_{trp} = 0.01\ ℃}$)** in the reservoir from being extracted".

2.7 Electricity

The USGS method gives the following equation for calculation of the electrical energy.

$$\mathbf{E_{USGS} = \eta_{u\_USGS} W_{A\_USA}\ [kJ]\ or\ [kW]} \qquad \text{Eq. 16}$$

A key point to estimate the electrical energy to be converted from the thermal energy recovered at wellhead is how the "utilization factor" ($\mathbf{\eta_{u\_USGS}}$) should be selected.

2.8 Utilization factor of the USGS method

2.8.1 Utilization factor presented by USGS(1978)

The heat-electricity conversion factor of the USGS method named as "utilization factor" was first given based on theoretical calculation. For the calculation, a DFC-PC was assumed to convert as larger part of recovered thermal energy as possible to electricity because the volumetric method was originally proposed to assess *geothermal resource* that was defined as the portion of the accessible resource base. Calculation procedure is that: Firstly, the theoretical work is calculated by the equation-15 on page 24 of the Nathenson (1975) with the following conditions: (a) the pressures of the first and second separator are 6.0 and 0.9 bar-a respectively, (b) condenser temperature is 40 °C, and (c) turbine-generator efficiency is 0.7; Secondly, the Available work in the USA is calculated by **Eq. 8** (Muffler, 1978); Lastly, utilization factor is calculated by the following equation.

$$\mathbf{\eta_{u\_USGS} = \eta_{exg} W_{theoritical(DFC-PC)} / W_{A\_USA}} \qquad \text{Eq. 17}$$

The conditions are summarized in Table 1.

Table 1 Conditions for Calculation of the Utilization Factor of the USGS method (1978)

Conditions for the Utilization factor

・ Power cycle	DFC-PC
・ Pressure of the first separator	6.0 bar-a
・ Pressure of the second separator	0.9 bar-a
・ Condenser temperature	40℃
・ Ambient temperature	15℃
・ Turbine-generator efficiency	0.70
Note: Those conditions were given by Nathenson (1975) and Muffler P. (1978).	

The figure 6 on p.26 of the Muffler (1978) represents variation of utilization factors for several conversion technologies. We calculated numerical values of utilization factors for both cases of DFC-PC and SFC-PC (Table 2). It shows that: (i) the approximate utilization factor 0.4 is numerically confirmed to be applicable; (ii) discrepancy of the utilization factor between DFC-PC and SFC-PC becomes larger as fluid temperature decreases. Based on this figure, a numerical value 0.4 is chosen as the representative utilization factor for hot water system in the USA.

Note that Muffler, (1978) describes that the value of 0.4 is applicable only when the reference conditions for calculation (Table 1 shown above) are used.

Table 2 Comparison of utilization factors of DFC-PC and SFC-PC

t_{WH}(°C)	200	225	250	275	300	325
η_{u_dbl} (a)	0.37	0.39	0.41	0.41	0.41	0.41
η_{u_sgl} (b)	0.22	0.28	0.32	0.35	0.36	0.37
(a)/(b)	1.7	1.4	1.3	1.2	1.1	1.1

η_{u_dbl} : Utilization factor of DFC-PC, assuming the first separator=6.0 bar-a, the second separator=0.9 bar-a;

η_{u_sgl}: Utilization factor of SFC-PC, assuming the separator =6.0 bar-a.
For both, condenser=40 ℃, the average ambient temperature=15℃, turbo-generator efficiency η_{exg} = 0.70 are given.

2.8.2 Utilization factor reviewed by USGS (2008)

The original USGS method was reviewed by the USGS (Williams, et al., 2008). It describes that a compilation of η_{u_USGS} for existing geothermal power plants producing from liquid-dominated systems over a wide range of temperature confirms η_{u_USGS} equal to approximately 0.4 above 175 ℃. The figure that demonstrates this point is presented in Figure 1 below.

We note, however, that the data in Figure-1 varies in a wider range from 0.3 to 0.5 approximately above 175 ℃, and that the utilization factor $\eta_{u\_USGS} = \mathbf{0.4}$ was allowed to vary over this range in the resource estimation equation used with Monte Carlo method (Williams, written comm., 2017).

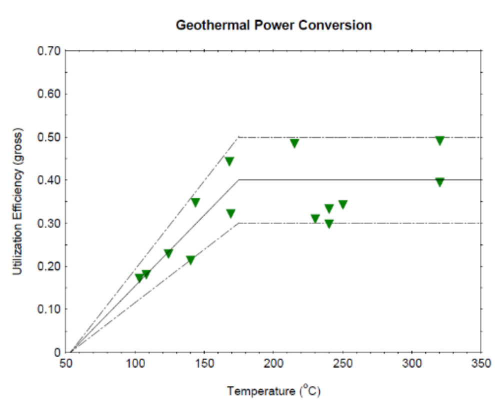

Figure 1 Geothermal Power Conversion (the figure provided by the courtesy of C.F. Williams, 2017)

2.8.3 Issues on applicability of utilization factor

Utilization factor will largely be dependent on many factors that include the efficiency of the basic power plant design, the resource temperature, the concentration of dissolved gases in the reservoir fluid, and the condition of plant maintenance. Thus, the proposed utilization factor 0.4 based on actual performance records (Williams, et al., 2008)) is useful for assessments of reservoir thermal energy in a broad region where conditions will vary from plant to plant. It may be prudent, however, that probabilistic parameter ($\boldsymbol{\eta_{u\_USGS} = 0.4 \pm 0.1}$, uniform distribution, for an example) together with Monte Carlo method should be used to cope with inevitable variations.

On the other hand, however, we are sometimes requested to assess geothermal energy of a very specific reservoir in a very specific region with a specific type of power plant, for a decision of monetary investment before drilling of test wellbore. For this specific purpose, we consider it necessary to select a (range of) plant-specific utilization factor assuming a set of specific conditions such as plant type and temperature conditions, with uncertain factors to be included as probabilistic parameters. Thus, we would emphasize that practitioners shall have proper understandings on the applicability and the limitations of utilization factor, and shall select an appropriate value depending on purposes they should use for.

2.9 Other issue

The USGS method includes variables of specific enthalpy and entropy in its exergy calculation by **Eq. 7**. Those are temperature-dependent variables, therefore, shall be included as functions of the fluid temperature when used with Monte Carlo method. This conversion may be laborious for field practitioners for immediate use.

3. REVIEW OF THE CALCULATION EQUATIONS OF THE EXTENSION METHOD (2002)

3.1 Equations used

Sanyal, et al. (2002) describe a different calculation approach to obtain the Available work. It is an extension of concept originally presented by the USGS method. We name it the Extension method.

3.2 Available Work ($\mathbf{W_{A\_ext}}$)

<u>3.2.1 Equations used for the Extension method</u>

There are a set of equations presented. We describe a summary of these equations below.

$$\mathbf{W_{A\_ext}} = \mathbf{R_{g\_amb} V} \left(\frac{\mathbf{C_V}}{\mathbf{C_{f\_rsv}}}\right) \mathbf{W}[\mathrm{kJ}] \text{ or } [\mathrm{kW}] \qquad \textbf{Eq. 18}$$

$$\mathbf{dW = dq}\left(\mathbf{1} - \frac{\mathbf{T_{amb}}}{\mathbf{T_{rsv}}}\right) [\mathbf{kJ/kg}] \qquad \textbf{Eq. 19}$$

$$\mathbf{dq = C_{f\_avg} dT} \ [\mathbf{kJ/\ kg}] \qquad \textbf{Eq. 20}$$

Note that $\mathbf{C_{f\_rsv}}$ in **Eq. 18** is the specific heat of the fluid in reservoir at temperature $\mathbf{T_{rsv}}$, whereas $\mathbf{C_{f\_avg}}$ in **Eq. 20** is the average specific heat of the fluid for the temperature change $\mathbf{dT}$, i.e. from $\mathbf{T_{rsv}}$ to $\mathbf{T_{amb}}$.

<u>3.2.2 Practical calculation equations</u>

Because **Eq. 19** and **Eq. 20** include differential terms, the equations are not for immediate uses. We, thus, derive a practical equation by combining **Eq. 18**, **Eq. 19**, and **Eq. 20** and then integrating the combined equation; resulting in:

$$\mathbf{W_{A\_ext}} = \mathbf{R_{g\_amb} V}\left(\frac{\mathbf{C_V}}{\mathbf{C_{f\_rsv}}}\right)\mathbf{C_{f\_avg}}\{(\mathbf{T_{rsv}} - \mathbf{T_{amb}}) - \mathbf{T_{amb}} \ln\left(\frac{\mathbf{T_{rsv}}}{\mathbf{T_{amb}}}\right)\} \ [\mathbf{kJ}] \text{ or } [\mathbf{kW}] \qquad \textbf{Eq. 21}$$

For the calculation of the Available work by Eq. 21, Sanyal, et al. (2002) choose $\mathbf{T_{amb} = 288.15\ K}$ (15°C), same as the USGS method; i.e. a region specific Available work.

Note that **Eq. 21** does not include the issues regarding theoretical unconformity and laborious conversion of specific enthalpy and entropy to temperature-dependent functions, discussed in Section 2.4 and 2.9.

<u>3.2.3Average fluid specific heat $\boldsymbol{C_{f\_ave}}$</u>

Because the mass at wellhead is expressed by the following equation;

$$\mathbf{m_{WH\_L}} = \mathbf{R_{g\_amb} V}\left(\frac{\mathbf{C_V}}{\mathbf{C_{f\_rsv}}}\right) [\mathrm{kg}] \qquad \textbf{Eq. 22}$$

Eq. 21 is re-written as:

$$\mathbf{W_{A\_ext}} = \mathbf{m_{WH\_L} C_{f\_avg}}\{(\mathbf{T_{rsv}} - \mathbf{T_{amb}}) - \mathbf{T_{amb}} \ln\left(\frac{\mathbf{T_{rsv}}}{\mathbf{T_{amb}}}\right)\} \ [\mathbf{kJ}] \text{ or } [\mathbf{kW}] \qquad \textbf{Eq. 23}$$

Comparison of **Eq. 6** and **Eq. 23** gives;

$$\{(\mathbf{h_{WH\_L}} - \mathbf{h_{amb\_L}}) - \mathbf{T_{amb}}(\mathbf{S_{WH\_L}} - \mathbf{S_{amb\_L}})\} = \mathbf{C_{f\_avg}}\{(\mathbf{T_{rsv}} - \mathbf{T_{amb}}) - \mathbf{T_{amb}} \ln\left(\frac{\mathbf{T_{rsv}}}{\mathbf{T_{amb}}}\right)\} \qquad \textbf{Eq. 24}$$

When specific numerical values are given to $\mathbf{T_{rsv}}$ and $\mathbf{T_{amb}}$, enthalpies and entropies in **Eq. 24** will be given from the steam table; then $\mathbf{C_{f\_avg}}$ is uniqly determined. A numerical calculation shows, for an example, when $\mathbf{T_{res}}$ ranges from **200** ℃ **(473.15 K)** to **300** ℃ **(573.15 K),** then the corresponding $\mathbf{C_{f\_ave}}$ shall be in a range from 4.33 (kJ/kg) to 4.70 (kJ/kg) as a function of $(\mathbf{T_{rsv}} - \mathbf{T_{amb}})$; the average may be 4.46 (kJ/kg) that gives the best approximation that satisfys **Eq. 24**. Note that for $\mathbf{T_{rsv}} \geq 533.15$ K (260 ℃), $\mathbf{C_{f\_avg}/C_{f\_rsv}}$ falls below 90 %; a consideration may be given if the same average value (4.46 kJ/kg) or different values should be selected for the average specific heat.

3.3 Electricity

Electricity is calculated by the virtually same equation as **Eq. 16**, as:

$$\mathbf{E_{ext} = \eta_{u\_ext}\, W_{A\_ext}} \qquad \textbf{Eq. 25}$$

3.4 Utilization factor of the Extension method

The Extension method chooses various sets of utilization factor and the ambient temperature; for examples: (i) $\mathbf{\eta_{u\_ext}}$**= 0.45**, $\mathbf{t_{amb}}$**=30**℃ used for an assessment in Nicaragua (Sanyal, et al., 2002); (ii) $\mathbf{\eta_{u\_ext}}$**= 0.45**, $\mathbf{t_{amb}}$**=15** ℃ used for California of the USA, with explanation that advances in plant efficiency since the publication of Circular 790 (1978) justify a default value of 0.45 (GeothermEx, Inc., 2004); (iii) $\mathbf{\eta_{u\_ext}}$**= 0.477**, $\mathbf{t_{amb}}$**=30** ℃ (this is named as "rejection temperature[7]") for Philippines (Sanyal & Sarmiento, 2005). As for the case (ii) above, we confirmed, by numerical calculations, that the Extension method assumes the turbo-generator efficiency of 0.77.

It seems to be that the Extension method chose utilization factor depending on conditions of each power plant or the region where the power plant was to be constructed, although it is not explicitly described.

3.5 Issues - Applicability

The Extension method does not include the issues that are included in the original USGS method discussed in Section 2.4 and 2.9. On the other hand, proper understandings on the applicability and the limitations of the utilization factor are necessary to select utilization factor.

4. REVIEW OF THE CALCULATION EQUATIONS OF THE PREVAILING METHOD

4.1 Equation used

A calculation equation based on a seemingly different concept from the USGS and the Extension method has often been practiced. We name this method the Prevailing method. The equation of the Prevailing method uses is given below for the reservoir thermal energy available at wellhead (Axelsson, et al., 2013; Houssein, 2010; Pastor, et al., 2010; Ernst & Youg ShinNihon LLC, et,. al, 2011; Sarmiento & Bjornsson, 2007; for examples).

$$\mathbf{q_{WH\_prv} = R_{g\_prv} C_v V (t_{rsv} - t_{ref})\ [kJ]} \qquad \textbf{Eq. 26}$$

4.2 "Reference temperature" used

The method assigns a much higher "reference temperature ($\mathrm{t_{ref}}$)" such as 180 ℃. We are not able to identify a written reference that explains why such high reference temperature is selected. Explanations are provided through discussions with practitioners that the reference temperature is the one at which the geothermal fluid is no longer self-flowing out of wellbores. The reference temperature used for the Prevailing method is therefore regarded as the minimum temperature at which geothermal fluid ceases self-flowing out from wellbore. This temperature is sometimes named as "cut-off temperature" (Grant & Bixley, 2011), "rejection temperature" (AGEA; AGEG, 2010), "abandonment temperature" (Ernst & Youg ShinNihon LLC, et,. al, 2011), "base temperature" (SKM, 2002).

The selection of this reference temperature excludes heat below this temperature from resource assessment; it is no longer based on the same concept as the one adopted by the USGS method. We therefor replace $\mathrm{t_{ref}}$ in **Eq. 26** with $\mathrm{t_{ref\_prv}}$, then;

$$\mathbf{q_{WH\_prv} = R_{g\_prv} C_v V (t_{rsv} - t_{ref\_prv})\ [kJ]}\ ,\ (\mathbf{t_{prv}} = 180\ ℃ \text{ for an example}) \qquad \textbf{Eq. 27}$$

4.3 Electricity

Electricity available is given using conversion factor $\mathbf{\eta_{C\_prv}}$ as follows.

$$\mathbf{E_{prv} = \eta_{C\_prv}\, q_{WH\_prv}\ [kJ]\ or\ [kW]} \qquad \textbf{Eq. 28}$$

[7] The "rejection temperature" is defined as the average annual ambient temperate by the same first author in a different paper (Sanyal, et al., 2002).

4.4 "Conversion efficiency" of the Prevailing method

The heat-electricity conversion factor used in the Prevailing method has usually be named as "conversion factor". The many reports we referred use the conversion factor in a range from 0.10 to 0.15, as an independent variable in Monte Carlo method (refer to the five references in Section 4.1). Other reports use the following linear equation as the conversion efficiency (AGEA; AGEG, 2010; SKM, 2002).

$$\eta_{c\_prv} = 0.0484\, t_{res} - 0.5096 \text{ [-]} \qquad \textbf{Eq. 29}$$

A calculation with the **Eq. 29** using fluid temperature ranging from 200 ℃ to 300℃ gives the η_{c_prv} ranging from 0.09 to 0.14, similar values given as indepedent variables described above.

Srmiento & Steingrimsson (2011) presents the correlation between thermo-conversion efficiency and reservoir temperater in their figure 3 quationg Bodvarrson (1974) and Nathenson (1975). We confirmed, by a numerical calculation, that **Eq. 29** is a linear approximation of conversion factor (η_{c_prv}) for fluid temperature ranging from 200 ℃ to 300℃, shown in figure 12 of Nathenson (1975), assuming a DFC-PC of the same conditions given in Table 1.

The conversion factor of Nathenson (1975), being different from the USGS method, is calculated by the following equation.

$$\eta_{c\_prv} = \eta_{exg} W_{theoritical(DFC-PC)\_unit} / (h_{WH\_L} - h_{amb\_L}) \text{ [-]} \qquad \textbf{Eq. 30}$$

The denominator of **Eq. 30** is the "Available heat" itself in the ambient condition, not "Available work (excergy)" given by the USGS method (**Eq. 6**). This is the reason the conversion factor of the Prevailing method is different from the utilization factor for the USGS method.

Note, although **Eq. 26** does not include ambient-temperature, the conversion factor (η_{c_prv}) is determined with the pre-conditions given in Table 1 including pre-determined ambient temperature condition; thus, the Prevailing method should be *ambient-temperature dependent*.

4.5 Issues - Applicability

The conversion factor is given purely based on the conditions listed in Table 1; if a power plant of power cycle such as a SFC-PC and/or with different pressure/temperature conditions and/or in different ambient temperature conditions are selected, a suitable utilization factor and/or turbine-generator efficiency should be assigned.

In addition, conversion factor shall not be used as an independent variable when used with Monte Carlo method, but shall be used as fluid temperature dependent variable expressed by **Eq. 29** for a logical conformity.

5. DISCUSSIONS ON RECOVERY FACTOR

5.1 Different ranges of recovery factor used for the USGS and the Extension method

5.1.1 Recovery factor of the USGS method

Muffler & Cataldi (1978) presented in their fig.8 the following relation to give numerical value of recovery factor, with a note that "the relation between the two is little more than a guess". The USGS method (Muffler, 1978) proposed R_{g_amb}=0.25 as a first approximation. They also commented that "in real field situation, recovery factor probabley never exceeds 25%".

$$R_{g\_amb} = 2.5\emptyset_e \text{ [-]} \qquad \textbf{Eq. 31}$$

After years, Sanyal, et al. (2004) proposed numerical values ranging from 0.03 to 0.17 based on operation data of geothermal power plants; Williams, et al. (2008) and Williams (2014) proposed values from 0.08 to 0.20 for fracture dominated reservoir and from 0.10 to 0.25 for sediment hosted reservoir. In all cases, the recovery factor has been considered as a factor that is not dependent on reservoir temperature.

5.1.2 Range of recovery factor of the Prevailing method

On the other hand, the Prevailing method has used much larger recovery factors, i.e. R_{g_prv} ranging from 0.13 to 0.30 approximately (refer to the references presented in Section 4.1). SKM (2002) uses **Eq. 31** by taking typical void space values of 0.08, 0.10, 0.12 (min., mode, max.), giving recovery factor of 0.2, 0.25 and 0.3, respectively. Being same as the USGS method, the recovery factor used by the prevailing method has been considered independent of reservoir temperature. In addition to this application, this method uses much larger "reference temperature (such as t_{ref_prv}=180℃)" to further *exclude* unrecoverable heat energy below this temperature. This "reference temperature" acts as if another "recovery factor".

5.1.3 Issues regarding the recover factor

As was observed in the forgoing sections, the USGS Method has applied different recovery factors and 'reference temperatures' from those of the Prevailing Method, although that recover factor is defined as "recovery factor reflects the physical and technological constraints that prevent all the geothermal energy ($>t_{trp} = 0.01$ ℃) in the reservoir from being extracted" as stated in section 2.6. Here are two issues that (i) why different recovery factors have been used by each method, and (ii) what is the relation of the two different calculation methods. We clarify the issues by using mathematical equations in the following sections.

5.2 Examinations on reservoir-temperature dependency of recovery factors

5.2.1 The USGS Method - Examinations on temperature dependency of recovery factor

Combination of **Eq. 10**, **Eq. 11** and **Eq. 12** gives a calculation equation of recovery factor of the modified USGS method (refer to section 2.5 of this paper) , as:

$$\mathbf{R_{g\_trip}} = \frac{\mathbf{m_{WH\_L}}(\mathbf{h_{WH\_L}} - \mathbf{h_{trp\_L}})}{\mathbf{C_v V}(\mathbf{t_{rsv}} - \mathbf{t_{trp}})} \text{ [-]} \qquad \textbf{Eq. 32}$$

Because the three factores of $\mathbf{m_{WH\_L}}$, $\mathbf{C_v}$, and $\mathbf{V}$ are regarded as constants (or probablistic parameters in Monte Calro method) when dealing with a single reservoir (or a group of reservoirs as one unit of reservoir), **Eq. 32** indicates that $\mathbf{R_{g\_trip}}$ is a simple function of reservoir temperature. To assess its sensitity to a variation of temperater, we calculated "*relative recovery factors* ($\boldsymbol{Relative\_R_{g\_trp(t)}}$)" at various reservoir temperatures, by representing $\boldsymbol{Relative\_R_{g\_trp(t)} = \alpha}$ at $\mathbf{t_{rsv}}$=300 ℃; the results are presented in Table 3. This table reaffirms that the $\mathbf{R_{g\_trp}}$ should virtually be independent of reservior temperature as originaly defined by the USGS.

Table 3 Relative recovery factor of the <u>modified</u> USGS method

$\mathbf{t_{rsv}}$ ℃	200	225	250	275	300	325
Relative_$\mathbf{R_{g_trp(t)}}$	0.95α	0.95α	0.97α	0.98α	1.00α	1.03α
Relative recovery factors of the USGS method are presented, representing $R_{g\_trp(300)} = \alpha$ at t_{rsv}=300 ℃.						

We also calculated Revive recovery factors for the original USGS method using the following equation by representing $\boldsymbol{Relative}\_\mathbf{R_{g\_amb(t)}} = \boldsymbol{\alpha'}$ at $\mathbf{t_{rsv}}$=300 ℃;

$$\mathbf{R_{g\_amb}} = \frac{\mathbf{m_{WH\_L}}(\mathbf{h_{WH\_L}} - \mathbf{h_{amb\_L}})}{\mathbf{C_v V}(\mathbf{t_{rsv}} - \mathbf{t_{amb}})} \text{ [-]} \qquad \textbf{Eq. 33}$$

Table 4 shows the result that gives almost the same numerical values as the ones in Table 3.

Table 4 Relative recovery factor of the <u>original</u> USGS method

$\mathbf{t_{rsv}}$ ℃	200	225	250	275	300	325
Relative_$\mathbf{R_{g_amb(t)}}$	0.95$\boldsymbol{\alpha'}$	0.96$\boldsymbol{\alpha'}$	0.97$\boldsymbol{\alpha'}$	0.98$\boldsymbol{\alpha'}$	1.00$\boldsymbol{\alpha'}$	1.03$\boldsymbol{\alpha'}$
- Relative recovery factors of the USGS method are presented, by representing $R_{g\_amb(300)} = \alpha$ at t_{rsv}=300 ℃, t_{abm}=15℃.						

From the above, $\mathbf{R_{g\_amb(t)}}$ of the original USGS method may be virtually constant as has been practiced. Furthermore, we may consider $\mathbf{R_{g\_trp(t)}} \approx \mathbf{R_{g\_amb(t)}}$, because:

$$\frac{\mathbf{R_{g\_amb(t)}}}{\mathbf{R_{g\_trp(t)}}} = \left[\frac{\left(\mathbf{h_{WH_L}} - \mathbf{h_{amb_L}}\right)}{(\mathbf{t_{rsv}} - \mathbf{t_{amb}})}\right]\left[\frac{(\mathbf{t_{rsv}} - \mathbf{t_{trp}})}{\left(\mathbf{h_{WH_L}} - \mathbf{h}_{\boldsymbol{trp}_\mathbf{L}}\right)}\right] \approx \mathbf{1} \qquad \textbf{Eq. 34}$$

Where $\mathbf{t_{rsv}} \geq 200$ ℃, $\mathrm{t_{amb}} = 15$ ℃, $\mathrm{t_{trp}} = 0.01$ ℃

5.2.2 The Prevailing method - Examinations on temperature dependency of recovery factor

Since **Eq. 26** for the Prevailing method is comparative to **Eq. 10** of the modified USGS method, recovery factors of the Prevailing method may be calculated by **Eq. 35** below.

$$\mathbf{R_{g\_prv}} = \frac{\mathbf{m_{WH\_L}}(\mathbf{h_{WH\_L}} - \mathbf{h_{ref\_prv\_L}})}{\mathbf{C_v V}(\mathbf{t_{rsv}} - \mathbf{t_{ref\_prv}})} \text{ [-]} \qquad \textbf{Eq. 35}$$

Similar to Table 3 and Table 4, we calculated the recovery factors at various temperatures for the Prevailing method, representing $\mathbf{Relative\_R_{g\_prv(t)}} = \beta$ at $\mathbf{t_{rsv}} = 300$ ℃ with the reference temperature $\mathbf{t_{ref\_prv}} = 180$℃. The results are shown in the second row of **Table 5.** It is obvious that the recovery factor for the Prevailing method shall be a variable dependent on reservoir temperature, contrary to the original definition given by the USGS method.

The second row of Table 5 shows the maximum value of a range of recovery factor given as a probabilistic variable, corresponding to the reservoir temperature in the same column of Table 5 which should be determined as the maximum temperature of a range given as another probabilistic variable. For an example, if reservoir temperature is in a range having the maximum 300 ℃, then the recovery factor shall be given in a range having the maximum of β. Referring to the references given in Section 4.1 and SKM (2002), we temporarily select $\beta = 0.3$[8] at $\mathbf{t_{rsv}} = 300$ ℃, then the maximum recovery factor for each reservoir temperature is given in the third row of Table 5.

Table 5 Relative recovery factors and recovery factors at various reservoir temperatures for the Prevailing method

$\mathbf{t_{rsv}}$ ℃	200	225	250	275	300	325
Relative $\mathbf{R_{g\_prv(t)}}$	0.2β	$0.5\,\beta$	$0.7\,\beta$	$0.8\,\beta$	β	$1.2\,\beta$
Max.$\mathbf{R_{g\_prv(t)}}$	0.07	0.14	0.20	0.25	0.30	0.35
Relative $\mathbf{R}_{g\_prv(t)}$ at reservoir temperatures t ℃ are given in the second row, by representing $\mathbf{R_{g\_prv(t)}} = \beta$ for $\mathbf{t_{rsv}}$=300 ℃. Each maximum recovery factor at each reservoir temperatures, is given in the third row, by representing $\text{Max.}\,\mathrm{R_{g\_prv(300)}} = 0.3$ at t_{rsv}= 300 ℃.						

5.2.3 Linear approximation of recovery factors of the Prevailing method

The maximum recovery factors and reservoir temperatures shown in Table 5 may be approximated in a linear relation.

$$\boldsymbol{Max}.\mathbf{R_{g\_prv(t)}} = \boldsymbol{\beta}(\mathbf{0.007\ t_{rsv}} - 1.101), \qquad \boldsymbol{\beta} = \mathbf{0.3} \qquad \textbf{Eq. 36}$$

On the other hand, recovery factor usually is given as a probabilistic variation with a range (minimum, mean or most likely, maximum) in the Monte Carlo method, but it shall not be negative values in any cases. To satisfy this condition, when the range of uncertainty of recovery factor is represented as $2X_{unc}$ (=Max. $\mathrm{R_{g\_prv(t)}}$ - Min. $\mathrm{R_{g\_prv(t)}}$), then, $2X_{unc}$ shall be defined by the following equation.

$$\mathbf{2}\boldsymbol{X_{unc}} \leq \boldsymbol{\beta}\{\mathbf{0.007}\ \boldsymbol{Min}.\mathbf{t_{rsv}} - \mathbf{1.101})\}, \qquad \boldsymbol{\beta} = \mathbf{0.3} \qquad \textbf{Eq. 37}$$

Consequently, minimum recovery factor shall be the following condition to maintain $Min.\mathrm{R_{g\_prv(t)}} \geq$ zero

$$\boldsymbol{Min}.\mathbf{R_{g\_prv(t)}} = \boldsymbol{\beta}(\mathbf{0.007\ t_{rsv}} - 1.101) - \mathbf{2}\boldsymbol{X_{unc}}, \qquad \boldsymbol{\beta} = \mathbf{0.3} \qquad \textbf{Eq. 38}$$

With **Eq. 37** and **Eq. 38**, the mean recovery factor is given by:

$$\mathbf{Mean}.\mathbf{R_{g\_prv(t)}} = \boldsymbol{\beta}\{(\mathbf{0.007\ t_{rsv}} - \mathbf{1.101}) - \frac{\boldsymbol{X_{unc}}}{\boldsymbol{\beta}}\}[\text{-}], \qquad \boldsymbol{\beta} = \mathbf{0.3} \qquad \textbf{Eq. 39}$$

A combination of **Eq. 37**, **Eq. 38** and **Eq. 39** gives the following **Eq. 40** that gives temperature dependent realistic recovery factor that may be used together with Monte Carlo method.

$$\mathbf{R_{g\_prv(t)}} = \boldsymbol{\beta}\{(\mathbf{0.007\ t_{rsv}} - \mathbf{1.101}) - \frac{\boldsymbol{X_{unc}}}{\boldsymbol{\beta}}\} \pm \boldsymbol{X_{unc}}\ [\text{-}], \quad \boldsymbol{\beta} = \mathbf{0.3} \qquad \textbf{Eq. 40}$$

X_{unc} in **Eq. 40** may be given as a probablistic variation in the Monte Calro method within the range given by **Eq. 37**.

Just for an intial reservoir assessment, **Table 6** presents sample calculation equations for reservoir with Min. $\mathrm{t_{rsv}}$, assuming $X_{unc} = \frac{\boldsymbol{\beta}}{2}(0.007\ Min.\mathrm{t_{rsv}} - 1.101)$, $\boldsymbol{\beta} = \mathbf{0.3.}$ For examples; if the range of Min.$\mathrm{t_{rsv}}$ is assumed to be 225 ℃, use the equation #2 (resulting in $\mathbf{R_{g\_prv(t)}}$ from zero to 0.25), or if Min.$\mathrm{t_{rsv}}$ is estimated to be 275 ℃ to 300 ℃, take equation #4 (resulting in $\mathbf{R_{g\_prv(t)}}$ from zero to 0.30).

[8] We assume 0.3 here just for a typical example because our basic assumption for this paper is for liquid dominated. We note however that $\mathrm{R_{g\_prv(t)}}$ would be over 0.3 for some cases, particularly for vapor dominated reservoirs. We do not deal a case of vapor dominated reservoir in this paper.

Table 6 Sample equations for recovery factor for the Prevailing method for the case $\boldsymbol{\beta} = \mathbf{0.3}$

#	Min. $\mathbf{t_{rsv}}$℃	$\mathbf{R_{g\_prv(t)}}$
1	200	$\mathbf{R_{g\_prv(t)}} = (0.0021\,\mathbf{t_{rsv}} - 0.375) \pm 0.045$
2	225	$\mathbf{R_{g\_prv(t)}} = (0.0021\,\mathbf{t_{rsv}} - 0.401) \pm 0.071$
3	250	$\mathbf{R_{g\_prv(t)}} = (0.0021\,\mathbf{t_{rsv}} - 0.428) \pm 0.097$
4	275	$\mathbf{R_{g\_prv(t)}} = (0.0021\,\mathbf{t_{rsv}} - 0.454) \pm 0.124$
5	300	$\mathbf{R_{g\_prv(t)}} = (0.0021\,\mathbf{t_{rsv}} - 0.480) \pm 0.152$
6	325	$\mathbf{R_{g\_prv(t)}} = (0.0021\,\mathbf{t_{rsv}} - 0.506) \pm 0.179$
Condition: $\boldsymbol{\beta} = 0.3$, and $X_{unc} = \frac{\boldsymbol{\beta}}{2}(0.007\,t_{rsv} - 1.101)$ Note: These equations will give Min. $\mathbf{R_{g\_prv(t)}}$ of zero. If readers judge Min. $\mathbf{R_{g\_prv(t)}}$> zero, determine the second and third otherwise.		

5.3 Relation of $\mathbf{R_{g\_amb(t)}}$ of the USGS method and $\mathbf{R_{g\_prv(t)}}$ of the Prevailing method

5.3.1 Assumptions

It is reported that both the USGS method and the Prevailing method have been used succesfully in fields (C.F. Williams, 2014 for the USGS method; Sanyal, et al., 2004 for the Extension method; Z F Sarmiento and Björnsson, 2007 for the Prevailing method). In other words, both methods should give the same resource assessment results *if they were to be used for one geothermal reservoir.* This assumption is expressed by the following three equations:

$$\mathbf{q_{WH\_15}} = \mathbf{R_{g\_amb(t)} C_v V (t_{rsv} - 15)}\ [\mathbf{kJ}] \qquad \textbf{Eq. 41}$$

$$\mathbf{q_{WH\_180}} = \mathbf{R_{g\_prv(t)} C_v V (t_{rsv} - 180)}\ [\mathbf{kJ}] \qquad \textbf{Eq. 42}$$

$$\mathbf{q_{rsv\_15}} = \mathbf{q_{rsv\_180}} \qquad \textbf{Eq. 43}$$

Obviously, in order to maintain the relation of **Eq. 43**, $R_{g\_amb(t)}$ in **Eq. 41** shall defer from $R_{g\_prv(t)}$ in **Eq. 42**. In the following section, we attempt to examine mathematical relation of $R_{g\_amb(t)}$ and $R_{g\_prv(t)}$. The basic assumptions are summarized below.

i. **Eq. 41** and **Eq. 42** should give the same calculation result,

ii. Recovery factors for each method shall be within the range being currently practiced for each; i.e. $\mathbf{R_{g\_amb(t)}}$ is from 0.03 to 0.25, $\mathbf{R_{g\_prv(t)}}$ be from 0.13 to 0.30

5.3.2 Relation of $\mathbf{R_{g\_amb(t)}}$ and $\mathbf{R_{g\_prv(t)}}$

To compare the recovery factors, the mathematical relation of the recovery factors of the both method is expressed by combination of **Eq. 41**, **Eq. 42** and **Eq. 43**, as:

$$\frac{\mathbf{R_{g\_prv(t)}}}{\mathbf{R_{g\_amb(t)}}} = \frac{(\mathbf{t_{rsv}} - \mathbf{15})}{(\mathbf{t_{rsv}} - \mathbf{180})}\ [\text{-}] \qquad \textbf{Eq. 44}$$

The relations for various reservoir temperatures calculated by **Eq. 44** are given in Table 7. Note, that $R_{g\_prv(t)}/R_{g\_amb(t)}$ is not in a linear relation.

Table 7 Relation of recovery factor between the USGS method ($\mathbf{R_{g\_amb(t)}}$) and the Prevailing method ($\mathbf{R_{g\_prv(t)}}$)

$\mathbf{t_{rsv}}$ ℃	200	225	250	275	300	325
$\frac{R_{g\_prv(t)}}{R_{g\_amb(t)}}$	9.3	4.7	3.4	2.7	2.4	2.1

5.3.3 Ranges of $\mathbf{R_{g\_amb(t)}}$ and $\mathbf{R_{g\_prv(t)}}$

With the results given in Table 5 and Table 7, we may calculate the *maximum* recovery factors of $\mathbf{R_{g\_amb(t)}}$ and $\mathbf{R_{g\_prv(t)}}$ *at various reservoir temperatures* assuming Max. $\mathbf{R_{g\_prv(300)}}$=0.3 (at $\mathbf{t_{rsv}}$300 ℃), as shown in Table 8.

Table 8 Comparison of recovery factors $R_{g\_pr(t)}$ and $R_{g\_amb(t)}$ at various reservoir temperatures

t_{rsv} °C	200	225	250	275	300	325
Max. $R_{g\_prv(t)}$	(0.07)	0.14	0.20	0.25	0.30	(0.35)
Max. $R_{g\_amb(t)}$	(0.01)	0.03	0.06	0.09	0.13	(0.16)

Max. $\mathbf{R_{g\_prv(300)}}$=0.3 is assumed.
Recovery factors in parentheses may be out of the range being practiced. Since $R_{g\_prv(325)}$=0.35 is out of the range, the corresponding $R_{g\_amb(325)}$=0.16 should be out of the range, based on the conditions made in Section 5.3.1.

It shows that maximum recovery factors of the USGS method (Max. $\mathbf{R_{g\_amb(t)}}$) ranges from 0.01 to 0.16, whereas the ones of the Prevailing method (Max. $\mathbf{R_{g\_prv(t)}}$) does from 0.07 to 0.35, *both reservoir temperature dependent*. Note that the numerical value of recovery factor of the USGS method is surprisingly close to the ones proposed by Sanyal, et al. (2004) though the approaches are completely different; whereas rather smaller than those proposed by Williams, et al. (2008) and Williams (2014).

5.3.4 Interpretations on the Recovery factor of the USGS method.

From the discussion of the above section, the recovery factor of the USGS method should be regarded as being reservoir-temperature dependent if the assumptions presented in the Section 5.3.1 should be accepted. As this is inconsistent with the method employed to derive the recovery factor for the USGS method, they may be interpreted as due to reason of a difference between the models for when a reservoir is to be abandoned. That is; in the Prevailing method, a reservoir is to be abandoned when the wellbores cease self-flowing at a certain lower temperature; i.e., the thermal energy below this temperature will be *un-recoverable*, unless a pumping system should be installed, which may be unrealistic for flash type power plants; whereas the USGS method may have assumed otherwise that needs to be clarified.

A tentative interpretation may be that the originally proposed recovery factor 25 % of the USGS method has been reduced based on operation results over years (Section 5.1.2). This may be because the USGS method has adjusted (reduced) the numerical values of recovery factor to exclude the all unrecoverable heat including the heat below self-flowing temperature while maintaining an original concept of $\boldsymbol{t_{ref} = t_{amb} = 15}$**℃.** On the other hand, the Prevailing method has adjusted (increased) the reference temperature from $\mathbf{t_{ref}} = \boldsymbol{t_{ref\_prv} = 15}$℃ to$\mathbf{180}$℃ while maintaining another original concept of the recovery factor expressed by **Eq. 31**.

Further studies of this matter may be related to both of definition and practical use of the recovery factor, together with various heat transfer mechanisms underground, which is out of scope of this paper.

5.4 Summary and Discussions for the Section 5

1. If recovery factor of the USGS method is reviewed separately from the one of the Prevailing method, it should not be reservoir-temperature dependent, whereas the recovery factor of the Prevailing method is reservoir-temperature dependent.
2. If the recovery factor of the USGS method is reviewed together with the one of the Prevailing method, it should be reservoir-temperature dependent. It may be beneficial to use the original USGS method with temperature-*independent* recovery factor and the slight theatrical modification if assessment should include schemes with fluid pumping-up facility, whereas the USGS or Prevailing method with temperature-*dependent* recovery factor may be convenient for schemes with no fluid pumping up facility.
3. If the conclusion 2 above should not be accepted, either or both calculation method/s may have to be re-examined.
4. Examinations on applicability and limitations with field data shall be awaited.

7. SUMMARY AND CONCLUSIONS

7.1 Calculation equation sets

There have been used three sets of calculation methods for the geothermal volumetric methods. Practitioners shall be aware that different numerical values for heat-electricity conversion factor and recovery factor have been used depending on methods selected.

7.2 Triple point temperature adopted to the USGS method (1978)

Slight modifications are given to the USGS method (1978) for theoretical conformity using the triple point temperature. However, consequence of this modification will negligibly be small to the past assessments by the USGS method.

7.3 Utilization factor or conversion efficiency

"Utilization factor" for the USGS method (1978) and the Extension method, and "Conversion efficiency" for the Prevailing method are given originally based on a DFC-PC with a set of specific pressure-temperature conditions together with the average ambient temperature of 15 ℃ in the USA. Continuous efforts have been given to review the utilization factor of the USGS and the Extension method. Proper understanding shall be required to select a proper (range of) value. On the other hand, the Prevailing method has kept using the factor of the original concept. Careful considerations shall be required if this is applied for reservoir of different conditions.

7.4 Recovery factor

The recovery factor for the USGS method is proved to be fluid-temperature independent as originally defined if considered separately from the Prevailing method; on the other hand, the recovery factor for the Prevailing method is revealed to be fluid-temperature dependent, which needs attentions when used with Monte Carlo method.

Given both calculation equations should provide the same assessment results for one geothermal reservoir, the USGS recovery factor should be regarded as being fluid temperature dependent, ranging from 0.03 to 0.13 for fluid temperature from 225 ℃ to 300 ℃. Attentions need to be required when the USGS and the Extension method are to be used.

ACKNOWLEDGEMENT

This is a continuation of our research on the calculation equations of the geothermal volumetric method. We therefore would like to express our greatest appreciations to all who have supported us in conducting this research, whose names are presented in the previous papers (Takahashi & Yoshida, 2016). Special thanks to Dr. C. F. Williams, who provided useful comments and an original figure; to Prof. Hirofumi Muraoka, who always encourages us to continue the research, to all our colleagues for helpful discussions and suggestions, to Nippon Koei Co., Ltd for supporting us to continue this research and to the reviewers who provided us with very useful and helpful comments and suggestions.

APPENDIX A

We made three illustrations to explain the reservoir heat available at wellhead, and the reservoir heat available in surrounding ambient conditions. Assume here recovery factor shall be one (1) or 100%.

A-1. Heat available at wellhead.

A-1.1 Note for Fig.A-1.1:

Assume that we collect, into a closed box at wellhead, geothermal fluid having mass $\boldsymbol{m_{WH}}$, temperature $\boldsymbol{t_{WH}}$, and specific enthalpy $\boldsymbol{h_{WH}}$. The box at wellhead is perfectly adiabatic to the surrounding environment. The heat sent into the box should be $\boldsymbol{q_{WH} = m_{WH}h_{WH}}$ as per thermodynamics.

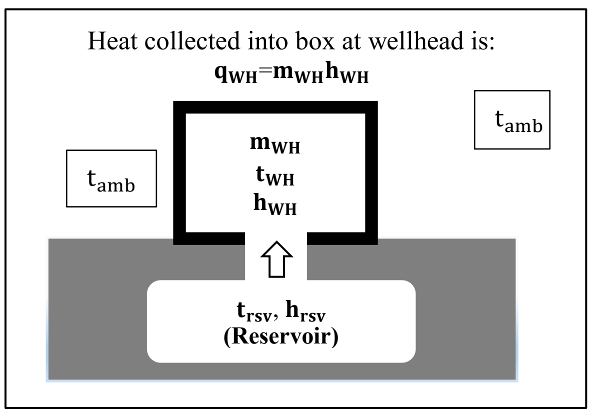

Fig. A-1.1 Thermal energy collected in box at wellhead

A-1.2 Note for Fig. A-1.2:

We stop the fluid flow from the reservoir to the box, and replace the “roof” with perfectly heat conductive material; release the heat, not allowing the fluid going out, from the “roof” of the box to the surrounding environment having temperature $\boldsymbol{t_{amb}}$ until equilibrium state reaches between the environment and the fluid in the box. Assume the temperature of the surrounding environment will not change due to this operation.

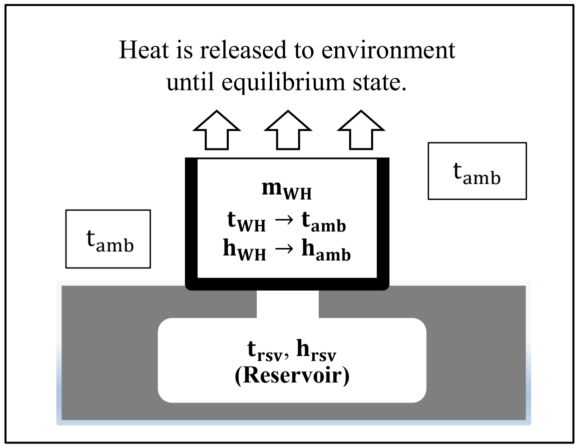

Fig. A-1.2 Heat releasing from the box to the surrounding environment

A-1.3 Note for Fig.A-1.3:

When the equilibrium conditions have reached, the temperature and specific enthalpy in the box have changed from $\mathbf{t_{WH}}$ to $\mathbf{t_{amb}}$ and from $\mathbf{h_{WH}}$ to $\mathbf{h_{amb}}$ respectively. The mass of fluid remains same as $\mathbf{m_{WH}}$. Thus, the released heat to the environment should be $\boldsymbol{q_{rsv\_amb}}$ $=\mathbf{m_{WH}}(\mathbf{h_{WH}}\text{- }\mathbf{h_{amb}})$, representing *the maximum heat available from the box (i.e. the wellhead) to the surrounding environment.* Note that this is different from the heat sent into the box at wellhead: $\mathbf{q_{WH}} = \mathbf{m_{WH}h_{WH}}$.

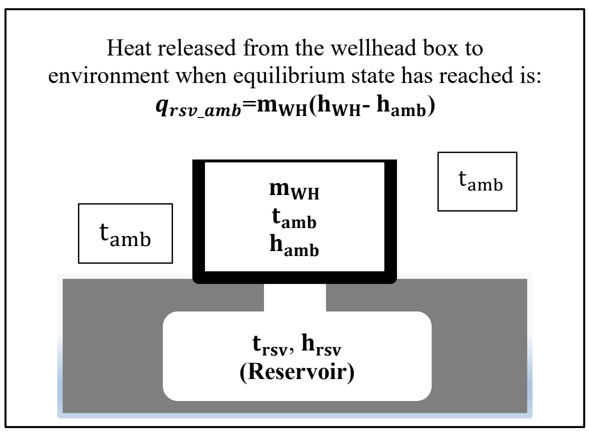

Fig. A-1.3. Heat in the box and heat released to the environment ($\boldsymbol{q_{rsv\_amb}}$) when equilibrium state has reached.

A-2. Heat sent into heat utilization system.

Based on the illustrative explanations made above, we present another illustration showing a simplified heat utilization system in the Fig.A-2.1.

Note for Fig. A-2.1*:* Assume that the heat utilization system should be a Carnot cycle (no heat losses due to such reasons as conduction, vortex, friction, leakage, vibration and/or others). From Fig. A-1.1, -1.2, and -1.3, it is evident that the heat sent into the system in Fig. A-2.1 should be heat collected at the box $\boldsymbol{q_{WH}}=\mathbf{m_{WH}}\ \mathbf{h_{WH}}$ and the heat released from the system to the environment be $\boldsymbol{q_0}=\mathbf{m_{WH}}\ \mathbf{h_0}$. Thus, the heat consumed by the system shall be $\Delta\mathbf{q}=\mathbf{m_{WH}}(\mathbf{h_{WH}}\text{- }\mathbf{h_0})$, $(\mathbf{t_0} \geq \mathbf{t_{amb}}$ and $\mathbf{h_0} \geq \mathbf{h_{amb}})$. For the extreme case, the system *could* consume the input heat ($\boldsymbol{q_{WH}}=\mathbf{m_{WH}}\ \mathbf{h_{WH}}$) until the temperature of the fluid is lowered down to $\mathbf{t_{amb}}$. Thus, the maximum heat that can be theoretically consumed to is $\boldsymbol{q_{rsv\_amb}} = \mathbf{m_{WH}}(\mathbf{h_{WH}}\text{- }\mathbf{h_{amb}})$. Note again this is not the heat that is sent into the system of $\boldsymbol{q_{WH}}=\mathbf{m_{WH}}\ \mathbf{h_{WH}}$, which is not yet affected by the surrounding ambient temperature. Compare the $\boldsymbol{q_{rvs\_amb}}$ $=\mathbf{m_{WH}}(\mathbf{h_{WH}}\text{- }\boldsymbol{h_{amb}})$ with the right-side term of **Eq. 4;** it is evident that the term represents the maximum heat is not equal to the $\boldsymbol{q_{WH}}$ that denotes the heat available at the wellhead before sent into the power cycle.

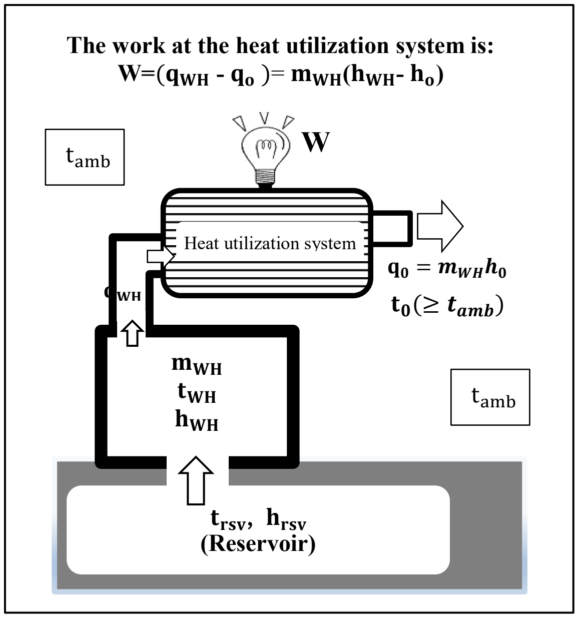

Fig. A-2.1 A simplified heat utilization system (a Carnot cycle)

ABBREVIATION AND ACRONYMS

DFC-PC: Double flash condensing power cycle
SFC-PC: Single flash condensing power cycle
USGS: U.S. Geological Survey

SYMBOLS

$\mathbf{C_{f\_avg}}$**:** Average specific heat of fluid between the reservoir temperature from T_0 to T_{res} [kJ/kg/K]
$\mathbf{C_{f\_rsv}}$: Specific heat of fluid at reservoir temperature [kJ/kg/K]
$\mathbf{C_r}$: Specific heat of rock (used in equation of $\mathbf{C_v}$**)** [kJ/kg/K]
$\mathbf{C_v}$: Average volumetric specific heat of the reservoir at temperature $\mathbf{T_{res}}$ [kJ/m^3/K], $C_V = \rho_r C_r(1-\varphi) + \rho_f C_{f\_rsv}$
dq: Function defined by **Eq. 20**
dT: Differential form of the temperature change from $\mathbf{T_{rsv}}$ to $\mathbf{T_0}$.
dW: Differential form of available work, defined by Eq. 19
E: Electric energy calculated by the proposed method by this paper [kJ] or [kW]
$\mathbf{E_{USGS}}$: Electric energy calculated by the USGS method [kJ] or [kW]
$\mathbf{E_{ext}}$**:** Electric energy calculated by the Extension method [kJ] or [kW]
$\mathbf{E_{prv}}$**:** Electric energy calculated by the Prevailing method [kJ] or [kW]
$\mathbf{h_{0\_L}}$**:** Specific enthalpy of fluid in luiqid phase at final state [kJ/kg]
$\mathbf{h_{cd\_L}}$**:** Specific enthalpy of fluid in luiqid phase in condenser [kJ/kg]
$\mathbf{h_{sp\_s}}$**:** Specific enthalpy of fluid in steam phase in separator [kJ/kg]
$\mathbf{h_{sp\_L}}$**:** Specific enthalpy of fluid in liquid phase in separator [kJ/kg]
$\mathbf{h_{0\_L}}$**:** Specific enthalpy of fluid in liquid phase at final state [kJ/kg]
$\mathbf{h_{amb\_L}}$**:** Specific enthalpy of fluid in liquid phase at ambient temperature [kJ/kg]
$\mathbf{h_{rsv\_L}}$**:** Specific enthalpy of fluid in liquid phase in reservoir [kJ/kg]
$\mathbf{h_{trp\_L}}$**:** Specific enthalpy of fluid in liquid phase at the triple point condition [kJ/kg]
$\mathbf{h_{ref\_prv\_L}}$**:** Specific enthalpy of fluid in liquid phase at temperature $\mathbf{t_{ref\_prv}}$ [kJ/kg]
$\mathbf{h_{WH\_L}}$**:** Specific enthalpy of fluid in liquid phase at wellhead [kJ/kg]
$\mathbf{m_{WH\_L}}$**:** Mass of fluid in liqude phase at wellhead [kg]
$\mathbf{q_{rsv}}$: Thermal energy originally in reservoir defined by **Eq. 1**; the right-side term of **Eq. 1** is re-defined by this paper to be reservoir thermal energy available under reference temperature condition [kJ]
$\mathbf{q_{rsv\_amb}}$: Reservoir thermal energy available under surrounding ambient temperature $\mathbf{t_{amb}}$ condition [kJ]
$\mathbf{q_{rsv\_ref}}$: Reservoir thermal energy originally defined by USGS (1978); it is redefined by this paper as reservoir thermal energy available under reference temperature condition (refer to **Eq. 14**).

$\mathbf{q_{rsv\_trp}}$: Reservoir thermal energy inherently stored in reservoir [kJ]
$\mathbf{q_{WH}}$: Thermal energy available at wellhead, that sent into power cycle [kJ]
$\mathbf{q_{WH\_15}}$: Thermal energy recovered at wellhead for USGS method ($t_{amb} = 15°C$); this is theoretically unexplainable [kJ]
$\mathbf{q_{WH\_180}}$: Thermal energy recovered at wellhead for the Prevailing method ($t_{prv} = 180°C$) [kJ]
$\mathbf{R_g}$: Recovery factor defined by **Eq. 3**[-]
$\mathbf{R_{g\_amb}}$: Recovery factor defined by the USGS method ($t_{amb} = 15°C$), equal to $\mathbf{R_g}$ [-]
$\mathbf{R_{g\_amb(t)}}$: Recovery factors at reservoir temperatures t°C used by the USGS method [-]
$\mathbf{R_{g\_prv}}$: Recovery factor used by the Prevailing method [-]
$\mathbf{R_{g\_prv(t)}}$: Recovery factor at reservoir temperature t°C used by the Prevailing method [-]
$\mathbf{R_{g\_trp}}$: Recovery factor defined with the triple point temperature [-]
$\mathbf{s_{sp\_s}}$: Specific entropy of fluid in steam phase in separator [kJ/ (kg K)]
$\mathbf{s_{cd\_L}}$: Specific entropy of fluid in liquid phase in condenser [kJ/ (kg K)]
$\mathbf{s_{WH\_L}}$: Specific entropy of fluid in liquid phase at wellhead [kJ/ (kg K)]
$\mathbf{s_{0\_L}}$: Specific entropy of fluid in liquid phase at final state [kJ/ (kg K)]
$\mathbf{T_o}$: Fluid temperature of the final state in Kelvin [K]
$\mathbf{T_{amb}}$: Fluid temperature of ambient temperature in Kelvin [K]
$\mathbf{T_{cd}}$: Fluid temperature at condenser in Kelvin [K]
$\mathbf{T_{rsv}}$: Reservoir temperature in Kelvin [K]
$\mathbf{t_0}$: Temperature of fluid at final state [°C]
$\mathbf{t_{amb}}$: Ambient temperature proposed by USGS method [°C]
$\mathbf{t_{cd}}$: Condenser temperature [°C]
$\mathbf{t_{ref\_prv}}$: Reference temperature used by the Prevailing method, probably the minimum temperature for self-flowing condition [°C]
$\mathbf{t_{ref}}$: Reference temperature [°C]
$\mathbf{t_{sp}}$: Separator temperature [°C]
$\mathbf{t_{rsv}}$: Reservoir temperature [°C]
$\mathbf{t_{trp}}$: Triple point temperature 0.01 °C for water
$\mathbf{t_{WH}}$: Temperature of the fluid at wellhead [°C]
V: Volume of the reservoir [m^3]
W: Thermodynamic work defined by **Eq. 19**
$\mathbf{W_A}$: Available work (exergy) [kJ] or [kW]
$\mathbf{W_{A\_amb}}$: Available work (exergy) when reference temperature is ambient temperature [kJ] or [kW]
$\mathbf{W_{theoritical(DFC-PC)}}$:Theoritical work generated by a double flash condensing power cycle
$\mathbf{W_{theoritical(DFC-PC)\_unit}}$:Theoritical work, generated by a double flash condensing power cycle, per unit mass of fluid
$\mathbf{W_{A\_USA}}$: Available work in the USA (**$\mathbf{t_{ref}}$=15** °C) ([kJ] or [kW])
$\mathbf{W_{A\_ext}}$: Available work for the Extension method ([kJ] or [kW]
$\mathbf{X_{unc}}$: Range of uncertainty of recovery factor included in equation as a part of probabilistic variable for Monte Carlo method

GREEK SYMBOLS

$\boldsymbol{\eta_{C\_prv}}$: Coversion efficiency for the Prevailing method
$\boldsymbol{\eta_{exg}}$: Turbin-generator efficiency (exergy efficiency) [-]
$\boldsymbol{\eta_{u\_ext}}$: Utilization efficiency for the Extension method [-]
$\boldsymbol{\eta_{u\_USGS}}$: Utilization factor proposed for the USGS method [-]
$\boldsymbol{\eta_{u\_dbl}}$: Utilization factor for double flash condensing power cycle [-]
$\boldsymbol{\eta_{u\_sgl}}$: Utilization factor for single flashi condensing power cycle plant [-]
$\boldsymbol{\rho_r}$: Density of rock (used in the equation of $\mathbf{C_v}$) [kg/m^3]
$\boldsymbol{\rho_f}$: Density of fluid of at temperature T (used in the equation of $\mathbf{C_v}$) [kg/m^3]
$\emptyset_e$: Effective porosity [-]
$\boldsymbol{\varphi}$: Reservoir porosity (used in the equation of $\mathbf{C_v}$) [-]

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