Medium Deep High Temperature Heat Storage

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ABSTRACT

Heating of buildings requires more than 25 % of the total end energy consumption in Germany. Shallow geothermal systems for indirect use as well as shallow geothermal heat storage systems like aquifer thermal energy storage (ATES) or borehole thermal energy storage (BTES) typically provide low exergy heat. The temperature levels and ranges typically require a coupling with heat pumps.

By storing hot water from solar panels or thermal power stations with temperatures of up to 110 °C a medium deep high temperature heat storage (MDHTS) can be operated on high temperature levels which are characterized by 50 °C to 110 °C. Therefore, heat pumps are not necessary and low temperature space heating systems are not mandatory because MDHTS can be operated in conjunction with classical radiator based high temperature heating systems. Furthermore, storage depths of 500 m to 1,500 m below surface avoid conflicts with groundwater use for drinking water or other purposes. Additionally, the temperature difference between the storage system and the surrounding rocks becomes smaller with increasing depth resulting in a decrease of thermal losses. Permeability is typically also decreasing with greater depth, especially in the crystalline basement therefore conduction becomes the dominant heat transport process. Solar-thermal charging of a MDHTS is a very beneficial option for supplying heat in urban and rural systems.

Feasibility and design criteria of different system configurations are discussed. One system is designed to store and supply heat (300 kW) for an office building. The required boreholes are located in granodioritic bedrock. Resulting from this setup several challenges have to be addressed. The drilling and completion has to be planned carefully under consideration of the geological and tectonical situation at the specific site. In addition to the MDHTS system the results of this drill site will help to characterize potential target horizons for petrothermal systems (Enhanced Geothermal Systems (EGS)) in the nearby Upper Rhine Graben where several deep geothermal projects are already in operation and new ones are planned which target the same geological formations like the one discussed here.

1. INTRODUCTION

Approximately 55 % of the overall energy demand in Germany is due to heating and cooling purposes (Federal Ministry of Economics and Technology, Germany, 29.11.2012). Therefore, especially in this low exergy sector groundbreaking techniques are needed to save energy and reduce greenhouse gas emissions. The combination of different renewable energy sources – solar thermal and geothermal – with already existing district heating systems – combined heat and power station (CHP) – is a very promising new approach to do so.

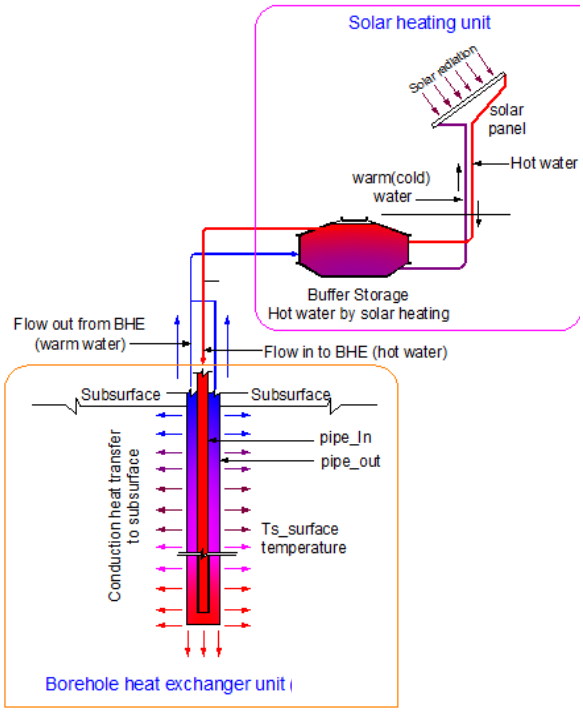


Figure 1: Schematic layout of a geothermal - solar thermal heat storage unit without the use of a heat pump; BHE: borehole heat exchanger (Koju 2012).

In summer excess solar thermal energy is available, while in winter when thermal energy is needed for heating systems its quantity is usually not sufficient. There are different options in terms of thermal storage to cope with the seasonal shift. Besides traditional

storage tanks at the surface and shallow borehole thermal energy storage (Diersch et al., 2011), geothermal heat storage in medium depth is an innovative and yet untested concept. In difference to shallow heat storage systems the proposed approach upgrades the naturally available geothermal energy in the subsurface by means of external heat input. This is done in summer when the space heating load of a building is not required or at the time when surplus energy is available. In winter when other sources of energy are not sufficiently and cheaply available without using heat pumps the thermal energy from the upgraded geothermal reservoir is used for space heating and hot water supply (Fig. 1).

2. HIGH TEMPERATURE BOREHOLE HEAT STORAGE

The proposed system of a medium deep borehole heat exchanger/storage (MDHTS) consists of one or multiple boreholes with depths of 500 m – 1,500 m. A coaxial pipe is implemented in the borehole. In the coaxial pipe a heat carrier fluid is circulated. The fluid is pumped through the outer annulus, absorbs or transfers heat depending on the operation mode of the system and ascents back to the top through a smaller thermally insulated inner pipe. The surrounding rock is therefore utilized as a heat carrier and heat storage, the cementation and borehole wall functions as heat exchange surface. Typically water (in some cases with refrigerant or other additives) is used as heat carrier fluid. Figure 2 shows a schematic of a coaxial 1,000 m deep borehole heat exchanger in summer and winter operation mode.

The advantage of MDHTS over open systems is the closed circulation system which is not allowing a direct contact or mass transfer of heat carrier fluids with the groundwater or subsurface. Geochemical processes like solution and mineralization in the surrounding rock and a direct hydrochemical influence on the groundwater will be prevented. Furthermore, auxiliaries like pumps, etc. on the surface are protected against scaling and corrosion since no mineralized thermal waters are used. Consequently the life time of the system is expected to be higher and the system can be operated more constantly and therefore more economically.

In general deep borehole heat exchangers can be constructed everywhere, due to the fact that neither naturally occurring thermal aquifer systems nor special geological structures are needed. Only in terms of heat storage a very low or better not existing groundwater flow is required so that the induced thermal plume in the vicinity of the deep boreholes is not dissipated.

In contrast to conventional shallow borehole heat exchanger storages the mandatory heat pump is not necessary due to the higher operation temperature levels. Consequently the electric power which is needed to run a heat pump is not required which increases the economic feasibility.

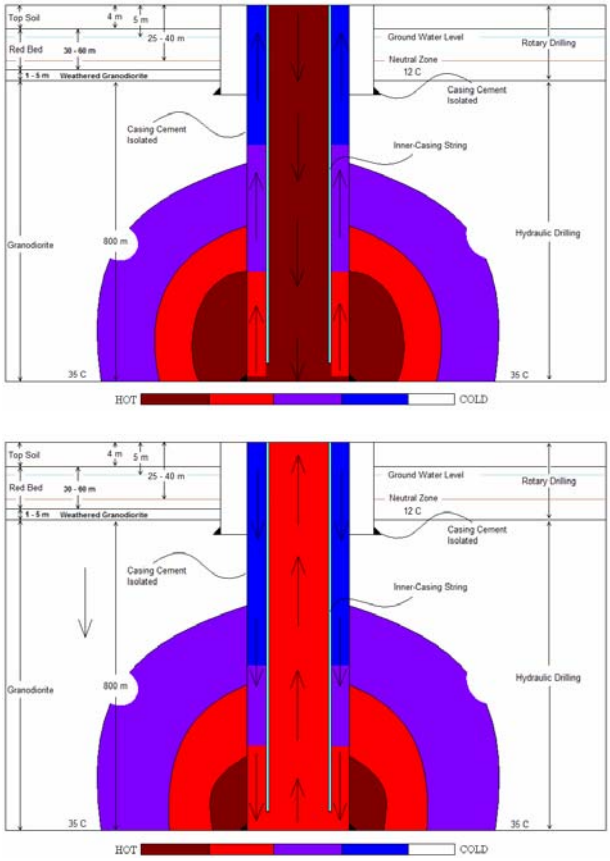


Figure 2: Schematic example of a 1,000 m deep coaxial borehole heat exchanger used as heat storage in summer (top) and winter (bottom), respectively (Thompson, 2011).

The completion depth of 500 m – 1,500 m with higher underground temperatures compared to shallow systems results in lower temperature differences between the heat carrier fluid and surrounding rock. This means a significant decrease of heat losses of the system which makes the system more efficient.

Operating the storage with high temperatures up to 110 °C supplied by solar heating and/or industrial processes/thermal power plants in combination with greater depths will allow backflow temperatures of the geothermal storage of 50 °C – 90 °C depending on the setup of the storage and utilisation scenarios. The supply of constant heating preflow temperatures of 55 °C – 65 °C allows for a feed in to conventional radiator based high temperature heating systems, which are commonly installed in office buildings. Another option is to directly feed in to district heating distribution systems and supply heat for multiple if possible even cascading uses.

To ensure a reliable prognosis for the dimensioning and operation of a geothermal heat storage a detailed knowledge of the petrophysical (conductive heat transfer) as well as the geometrical and hydraulic properties (convective heat transfer) of the borehole

heat exchanger system and its interplay with the subsurface temperature regime is mandatory.

Different kinds of energy flows as well as different storage and utilisation scenarios have to be assessed in the simulation and feasibility studies of such systems. Specific user profiles and economic frameworks are necessary to consider. Figure 3 shows possible coupled system configurations for summer and winter operation for the proposed system.

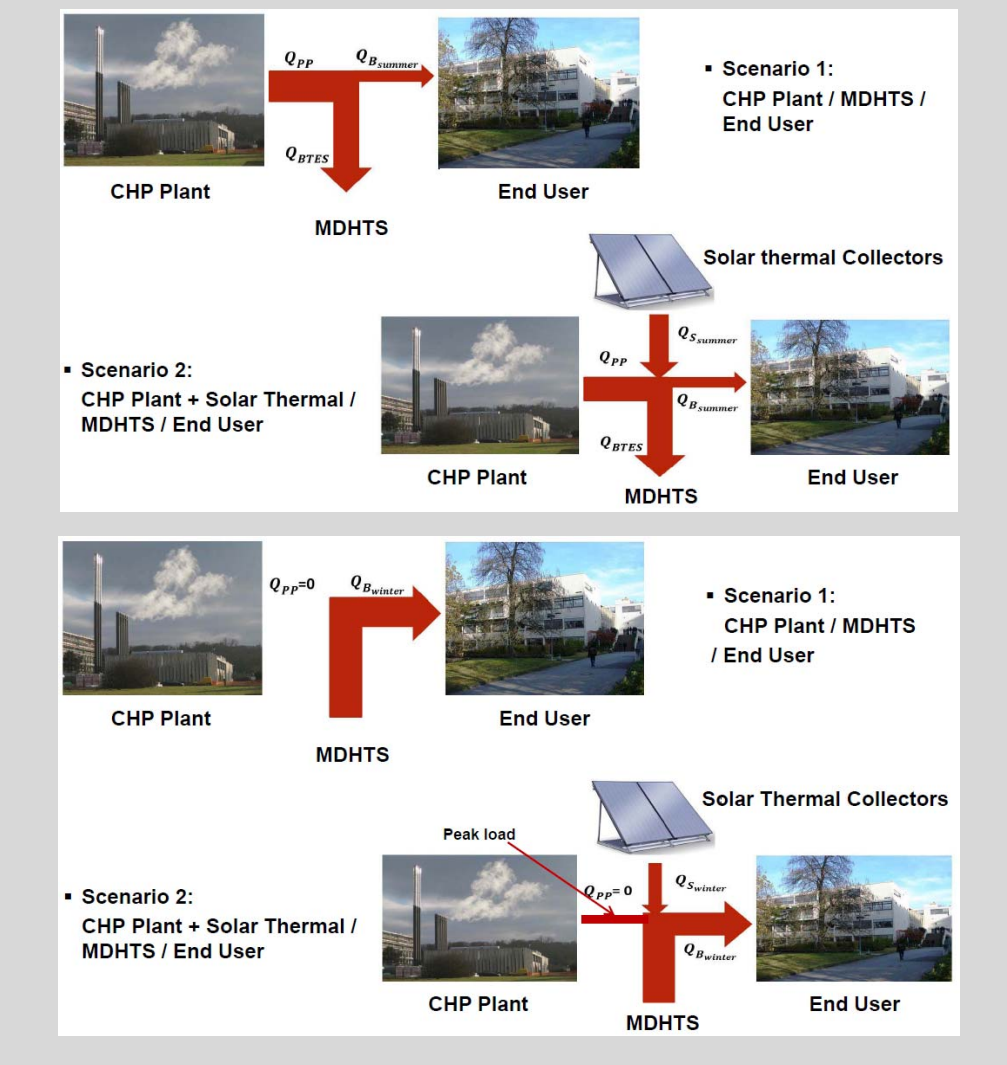


Figure 3: Summer(top) and Winter (bottom) operation scenarios (1) and (2) respectively with coupling of combined heat and power (CHP) plant, solar thermal collectors and medium deep high temperature heat storage (MHDTS) (modified after Homuth et al. 2012)

2.1 Site description – structural geology / hydrogeology

The planned drill site (Darmstadt) is located right at the eastern part of the boundary fault zone of the Upper Rhine Graben. In geological and hydrogeological terms this major fault zone divides the urban area of Darmstadt. A crystalline and Permian fracture controlled aquifer of the Odenwald and Sprendlinger Horst is roughly located in the eastern part of the city and the western part is dominated by a Quaternary porous Aquifer of the sedimentary graben fill of the Upper Rhine Graben (Figure 4).

The Upper Rhine Graben fault system is characterized by steep faults in N-S to NNE-SSW direction, which are showing a displacement of up to 2,000 m. The major N-S fault is accompanied by a complex block mosaic structure (Hoppe & Lang 2007).

The mentioned crystalline formation of the area is mainly consisting of granitic to granodioritic rocks, which are the target formation of the MDHTS site and several planned petrothermal (EGS) projects in the adjacent Upper Rhine Graben. The granodiorite is expected to be very homogenous. The formation permeability is supposed to be very low, so that it is a suitable formation for a MDHTS system.

The lithology of the proposed MDHTS site consists of over 1,000 m granodiorite with a thin weathered layer on top overlaid by some 30 m – 60 m thick Permo-

Carboniferous red bed clastics and volcanoclastics (melaphyre in local nomenclature). The top Quaternary soil layer is about 4 - 5 m thick. Figure 4 illustrates a cross section through the northern Upper Rhine Graben with the nearby planned MDHTS site.

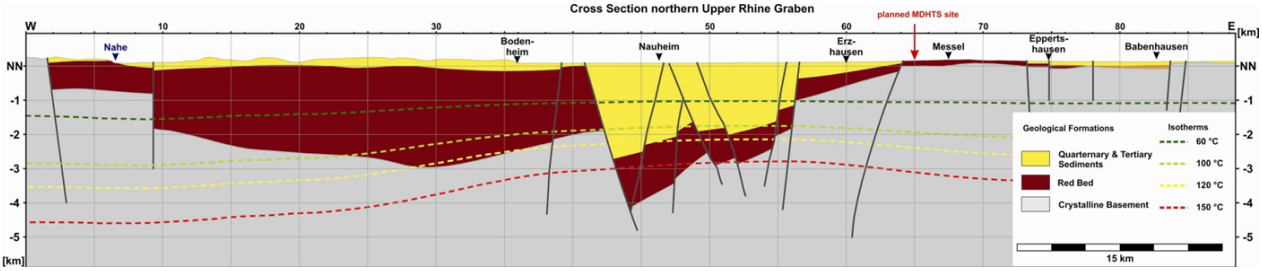


Figure 4: Cross section of the northern Upper Rhine Graben and accompanying graben shoulders (Bär et al 2011)

2.2 Subsurface temperature distribution

Figure 5 shows the temperature distribution in a depth of 1,000 m below surface. The temperature distribution is extracted from the 3D geothermal model of the federal state of Hesse (Bär et al. 2011, Arndt et al. 2011), which includes all available temperature datasets in the region.

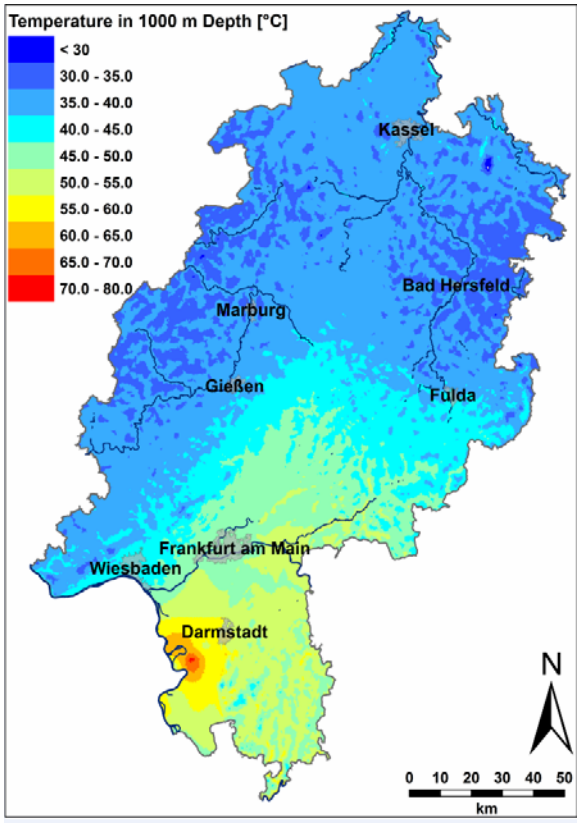


Figure 5: Temperature distribution in 1,000 m depth (Bär 2012)

The data from different nearby deep drill sites shows that the geothermal gradient ranges between 2.6 and 3.9 °C/100 m, depending on the distance and location of the drill site to the Upper Rhine Graben and related major fault zones. So, obviously the geothermal gradient has a significant influence on the temperature in the subsurface of the planned borehole thermal energy storage site.

2.3 Numerical Simulation of the MDHTS

In designing a vertical closed loop borehole heat exchanger, the determination of the necessary BHE depth as well as geometric distribution and amount of boreholes is crucial. Typically, the depth is estimated based on the desired power extraction per unit depth by considering a certain degree of steady state heat transfer from the surrounding subsurface. But due to long term and peak power extraction, during the operation time, the heat flow may change into transient nature. In this stage, either the power level may decrease or the injection temperature relative to the outlet temperature has to be reduced to get the desired heat level.

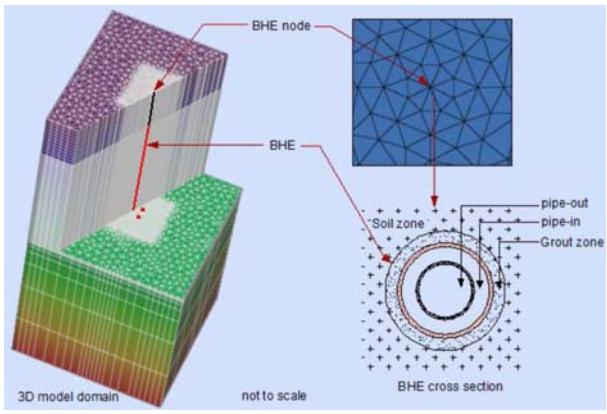


Figure 6: Example of a simulation model of a 1,000 m deep coaxial borehole heat exchanger storage with three drillings (Koju 2012)

To keep the power production within desired levels of production temperature, the suitable BHE depth has to be estimated. This can be done by simulating various computer based numerical or analytical BHE models with different geometrical scenarios and different BHE depths in a given geothermal reservoir. Based on

the output power and production temperature a best fit scenario can be selected. Figure 6 displays a first approach of the box model, which simulates a three borehole thermal energy storage system with a 1,000 m deep coaxial borehole completion. The simulation data is used to optimise the design and completion process as well as to evaluate the best economic scenario for such a coupled system (Figure 7).

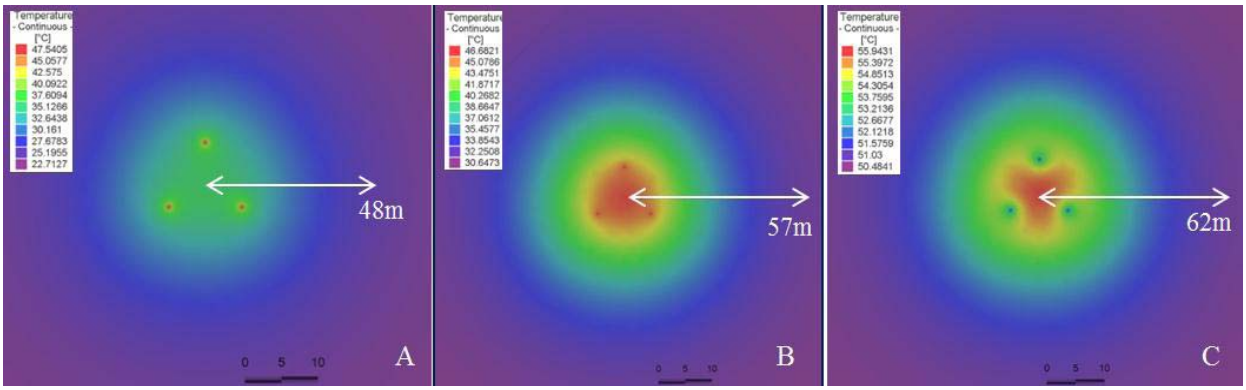


Figure 7: Horizontal extent of thermal influence in geothermal loading of 100 kW (8640 MJ/d) and thermal unloading after 10 years of heat extraction at depth (A) 300 m, (B) 500 m and (C) 1000 m (Koju, 2012)

2.4 Transferability to petrothermal systems in the Upper Rhine Graben

The knowledge of the heterogeneity of the crystalline basement, the hydrogeological conditions and the thermal and geomechanical properties in the vicinity of the Upper Rhine Graben fault system is still insufficient. Further research in this area is strongly needed to understand the system and improve reservoir prognosis.

Figure 8: Map of the earth total magnetic anomalies, formations of the deeper underground displayed in transparent colors, dark colors showing the according outcrop formations (modified after Bär 2012, based on Voges et al. 1993 and Gabriel & Vogel 2010); RH = Rheno-Hercynian; ST = Saxo-Thuringian; NPZ = Northern Phyllite Zone.

Drillings and according geophysical measurements in the transition zone from basin sediment formations to the crystalline basement, which upper sections function as a deep aquifer and potential geothermal (EGS) reservoir, will help to improve the knowledge and petrophysical database. This information is vital for the exploration and design of hydrothermal and petrothermal (EGS) projects in the whole northern Upper Rhine Graben.

A MDHTS system with drillings in the vicinity of the northern Upper Rhine Graben is of special interest, because here the typical geothermal reservoir formations of the Upper Rhine Graben (Muschelkalk and Buntsandstein aquifers) are not present anymore. The transition zone of the Mesozoic sedimentary cover to the Palaeozoic crystalline basement is therefore an important target formation for deep geothermal projects like MDHTS and petrothermal (EGS) systems situated in crystalline basement rocks. About 50 km to the south of the planned MDHTS site – in Landau and Insheim – already two geothermal combined heat and power projects are successfully exploiting the mentioned transition zone and utilizing the geothermal potential of this area.

Additional outcrop studies of the crystalline will help to improve the petrophysical database and give insight on various design criteria like structural elements, geomechanical and hydromechanical properties. With the help of integrating geophysical measurements like seismic, geoelectric and magnetotelluric investigations the results of outcrop analogue studies can be correlated and transferred to greater depth for the same facies in the Upper Rhine Graben. Figure 8 is stating an example for transferring outcrop information of the granodiorite (dark red) to parts of the northern Upper Rhine Graben where the top of the same formation is located in depths of 1.5 km to 4.5 km (light red).

3. CONCLUSIONS

The biggest energy consumption is due to heating and cooling of buildings. Innovative energy saving concepts in this field will have the biggest impact in terms of reducing greenhouse gas emissions. A coupling of solar thermal, geothermal and combined heat and power plants potential in combination with a storage system which fits into the energy flows of already existing district heating systems can be a huge benefit and cost saving factor. Low temperature heating systems cannot be applied everywhere, due to the need of costly renovation measures, consequently

a high temperature storage and heating supply system without the application of a heat pump is needed.

The design and completion of such MDHTS systems is highly depending on the knowledge about the subsurface and the accompanying energy flows from the energy source (solar thermal/thermal power plant/geothermal) to the storage system and back. The estimation of the BHE depth and completion design needs some iterative procedures. Numerical modeling can be used to estimate the required depth of the BHE system by simulating different setups with different BHE depth and BHE parameters.

The investigations on the target formation in the crystalline basement can be used to infer certain rock properties, which are also very important for hydrothermal and petrothermal (EGS) projects located in the adjacent northern Upper Rhine Graben. With the correlation of petrophysical/hydromechanical parameters and geophysical measurements the results can be transferred to greater depths and larger areas in the northern Upper Rhine Graben. Thus the reservoir prognosis for deep geothermal projects in this area can be improved.

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