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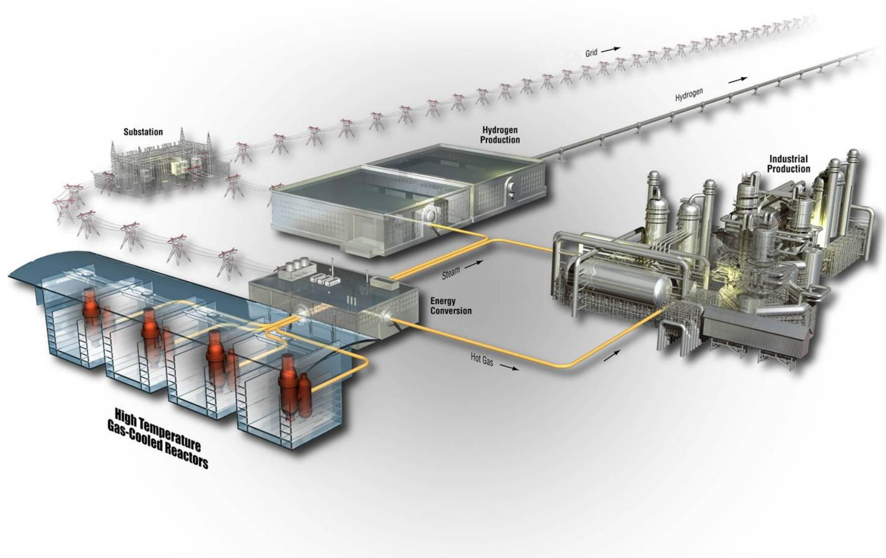
Technical Evaluation Study

Project No. 23843

An Analysis of Fluids for the Transport of Heat with HTGR-integrated Steam Assisted Gravity Drainage



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REVISION LOG

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EXECUTIVE SUMMARY

This technical evaluation (TEV) has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the integration of a high-temperature gas-cooled reactor (HTGR) with conventional chemical processes. This TEV addresses the effectiveness of selected fluids to transfer heat from the HTGR to a remote boiler used within the steam assisted gravity drainage process (SAGD). Two gases: helium and carbon dioxide, two phase changing liquids: water and DOWTHERM A, and one molten salt: FLiNaK were considered in this analysis. It was assumed that the heat is carried from the reactor to a boiler in the field through a 24 inch steel pipeline 25 km long. At the boiler, 11MPa steam is generated. The heat transfer fluid is returned to the HTGR within another 25 km long pipeline. Pressure and heat losses are calculated for each delivery and return pipelines.

Figure S-1 compares the effectiveness of the heat transfer fluids to produce SAGD steam and service the SAGD well pads. Steam and the molten salt FLiNaK perform better than helium, carbon dioxide and DOWTHERM A. The molten salt does not go through a phase change and therefore pressure has no influence on the heat transfer capabilities. At pressures near 20 MPa, steam is the most effective, if the boiler at the well pads has a minimum approach temperature difference of 25°C. The plot indicates that a drop in effectiveness occurs with steam, if the boiler is designed to accommodate a minimum approach temperature difference of 50°C. In the case of the pressure of 24 MPa, the number of well pads decreases from 8.3 to 6. The cost of laying additional pipelines may justify developing larger, more efficient boilers.

The amount of mass for each fluid within the pipelines is shown in Figure S-2. The molten salt, FLiNaK, has the highest mass. Although steam is not the lowest, it is among the gases which require the lowest mass. Considering both figures, steam is the preferred choice within the secondary heat transfer loop. FLiNaK may effectively transfer the heat needed, but it requires much more mass and therefore requires much higher cost and it has undesirable issues with respect to the effects of the salt on pipe materials and the need for a heat trace to prevent solidifying in the pipelines. Water is a readily available fluid and is effective in transferring heat with much less mass.

The number of well pads serviced decreases as the distance between the well pads and the reactor increases, see Figure S-3. For this analysis, the selected heat transfer fluid is steam at a pressure of 17 MPa and a minimum approach temperature difference of 25°C at the well pad boiler.

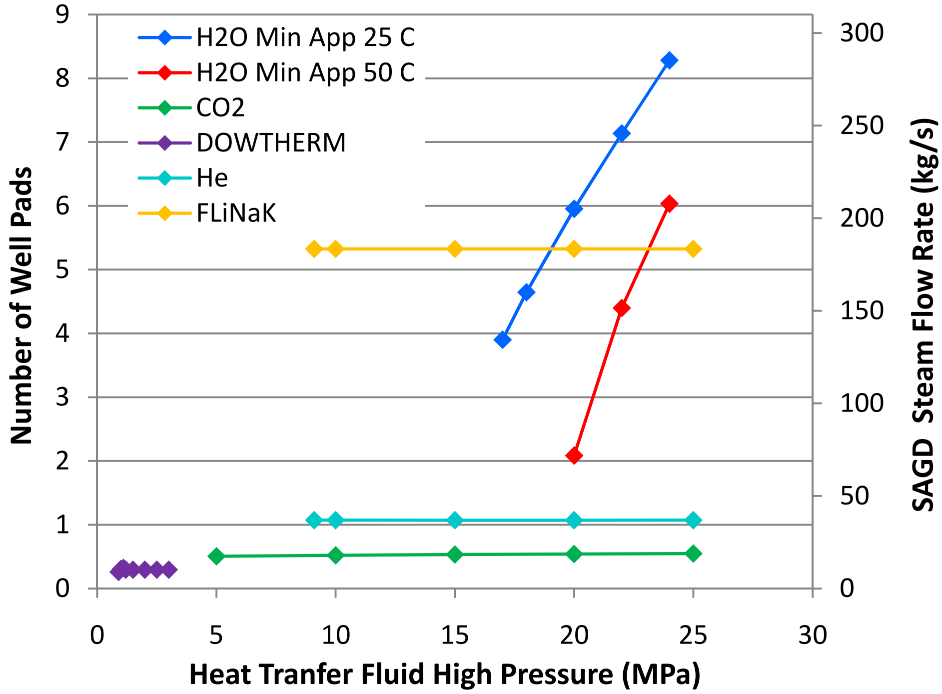

Figure S-1. Number of well pads serviced and SAGD steam production rate for various fluids within a 24" schedule 160 pipeline.

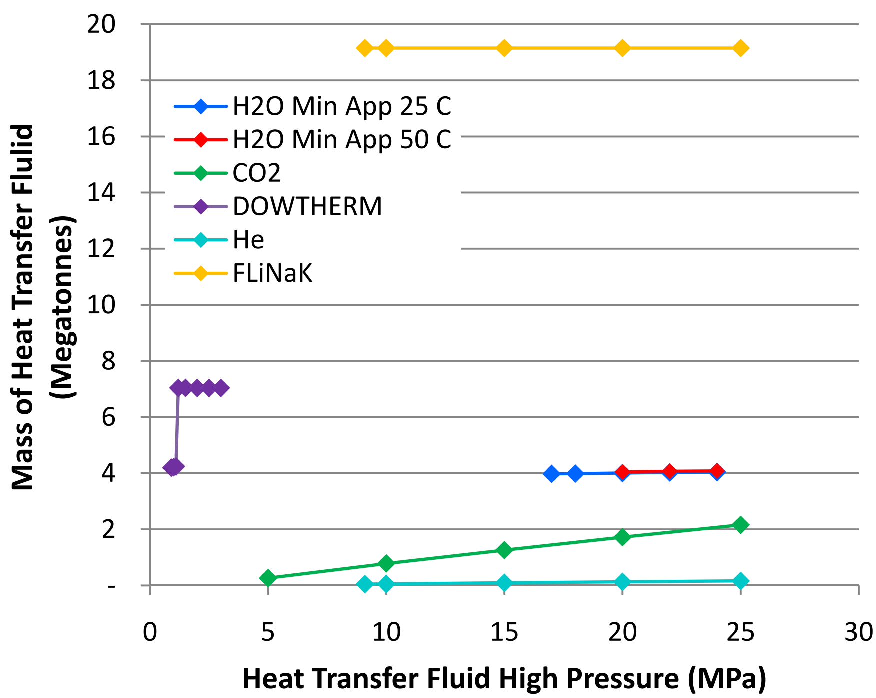

Figure S-2. Mass of heat transfer fluids within the delivery and return lines as a function of maximum heat transfer fluid pressure.

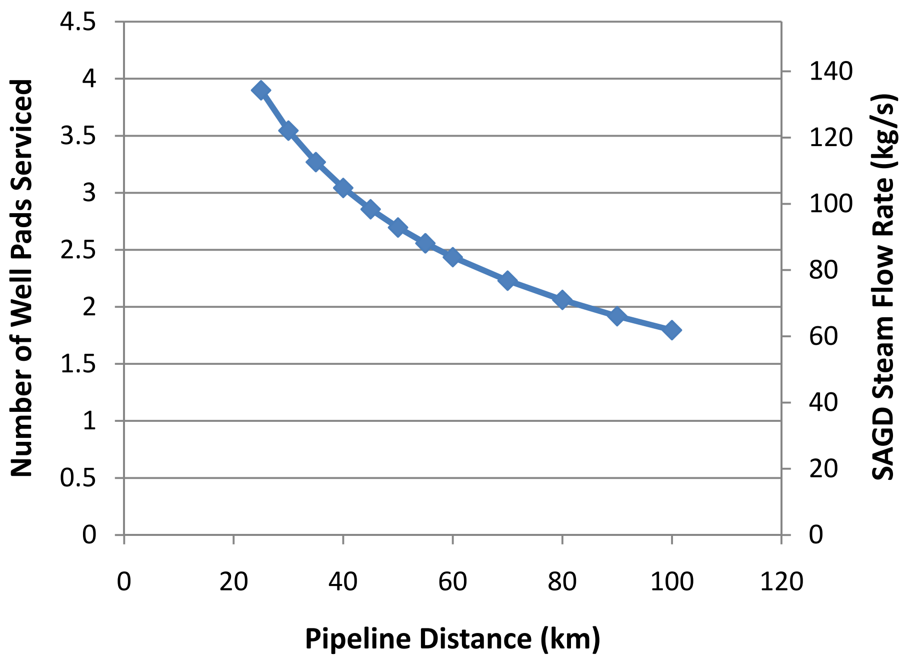

Figure S-3. Number of well pads serviced and SAGD steam flow rate as a function of the pipeline distance between the reactor and the well pads.

CONTENTS

1. INTRODUCTION

This technical evaluation (TEV) is part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the economics of integrating a high-temperature gas-cooled reactor (HTGR) with conventional chemical processes. The NGNP Project is being conducted under U.S. Department of Energy (DOE) direction to meet a national strategic need identified in the *Energy Policy Act of 2005* to promote reliance on safe, clean, economic nuclear energy and to establish a greenhouse-gas-free technology for the production of hydrogen. The NGNP represents an integration of high-temperature reactor technology with advanced hydrogen, electricity, and process heat production capabilities, thereby meeting the mission need identified by DOE. The strategic goal of the NGNP Project is to broaden the environmental and economic benefits of nuclear energy in the U.S. economy by demonstrating its applicability to market sectors not being served by light water reactors.

One process under consideration is the steam-assisted gravity drainage process used to extract bitumen from oil sands. This enhanced recovery technique is used to produce bitumen by injecting pressurized steam into the upper part of a pair of horizontal wells to heat bitumen and reduce its viscosity. The heated bitumen then drains to the lower well where it flows up to the surface. Pipelines are needed to transfer the heat from the reactor to a boiler at the wells. A fluid is needed to carry that heat within the pipelines from the HTGR to the SAGD process. The purpose of this TEV is to study the effectiveness of a variety of fluids to carry the heat and to determine the effect of pipeline distance on the generation of steam at well heads.

2. PROCESS MODEL

Four process models developed using Aspen HYSYS [1] are shown in Figures 2-1 through 2-4. All models have a primary loop with the reactor modeled as a heater, an intermediate heat exchanger (IHX), and a primary circulator. The primary loop is filled with helium at a nominal pressure of 9 MPa. The secondary loops differ, depending on the fluid modeled. If the secondary fluid is a liquid or goes through a phase change at the steam generator, a pump is used to push the heat transfer fluid through the IHX. If the fluid is a gas throughout the entire loop, a compressor is used instead. The fluid passes through the IHX and is transported through the delivery line where the pressure drop and heat loss are calculated. The fluid then passes through the steam generator where the heat is transferred to the water to make 10 MPa steam. The hot steam is cooled to 160°C and 1 MPa to simulate the use of the steam at the well pads of the steam assisted gravity drainage system. Cleanup of the steam is not modeled in this analysis, but 95% of the water is recycled and the remaining water is assumed lost. [2] After the steam generator, the heat transfer fluid is returned to the IHX through a return line where the pressure and heat losses are again calculated. The third model (see Figure 3) was necessary for the molten salt case. The temperature of the molten salt could not fall below 500°C. This constraint produced extra heat in the primary loop that must be transferred so that the reactor inlet temperature is low enough to enter the reactor core. The extra heat was used to generate power using a Rankine steam power cycle. The final model (see Figure 4) uses DOWTHERM A as a fluid. An additional cooler was necessary at the inlet of the pump to allow the pump to run efficiently (isentropic efficiency of 75%). The cooler was necessary for pump pressures over 1 MPa.

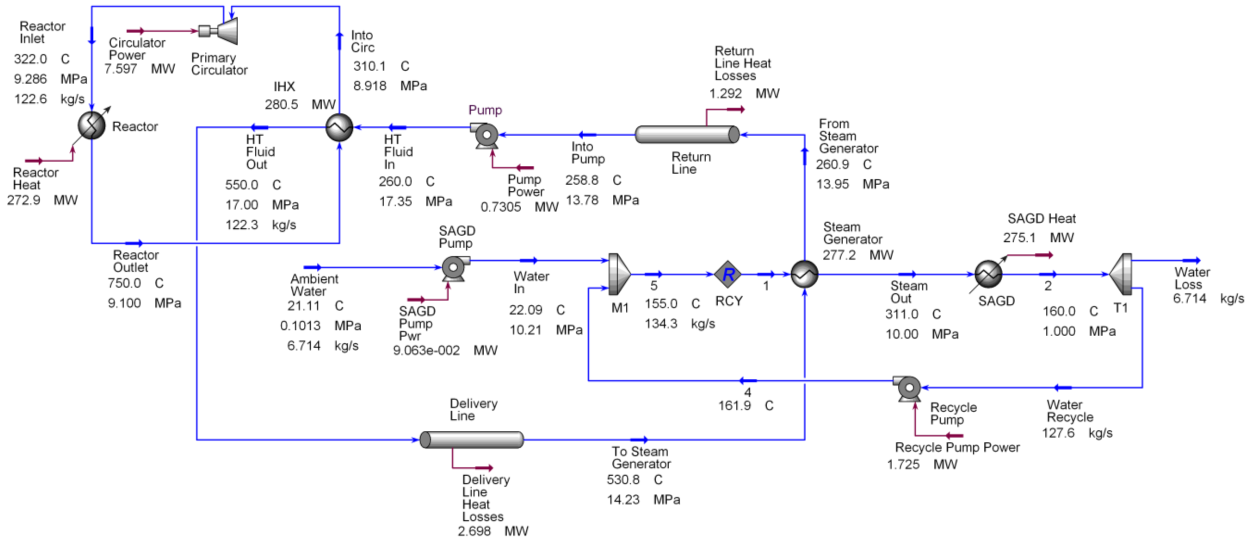

Figure 2-1. Process flow diagram of heat transfer loop from reactor to SAGD well pad. Heat transfer fluid is steam.

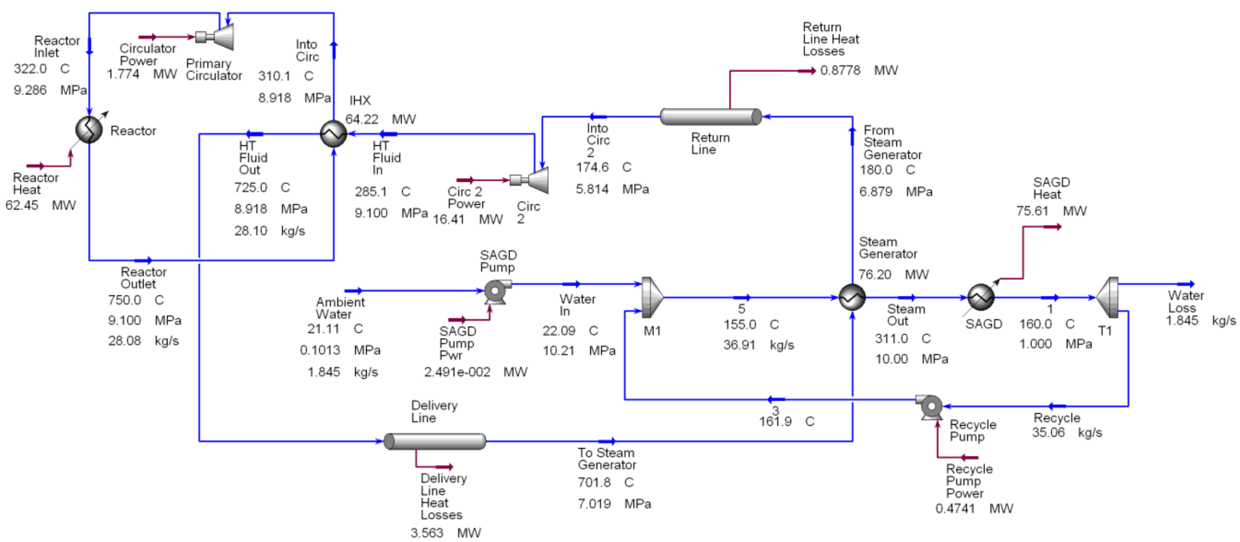

Figure 2-2. Process flow diagram of heat transfer loop from reactor to SAGD well pad. Heat transfer fluid is helium.

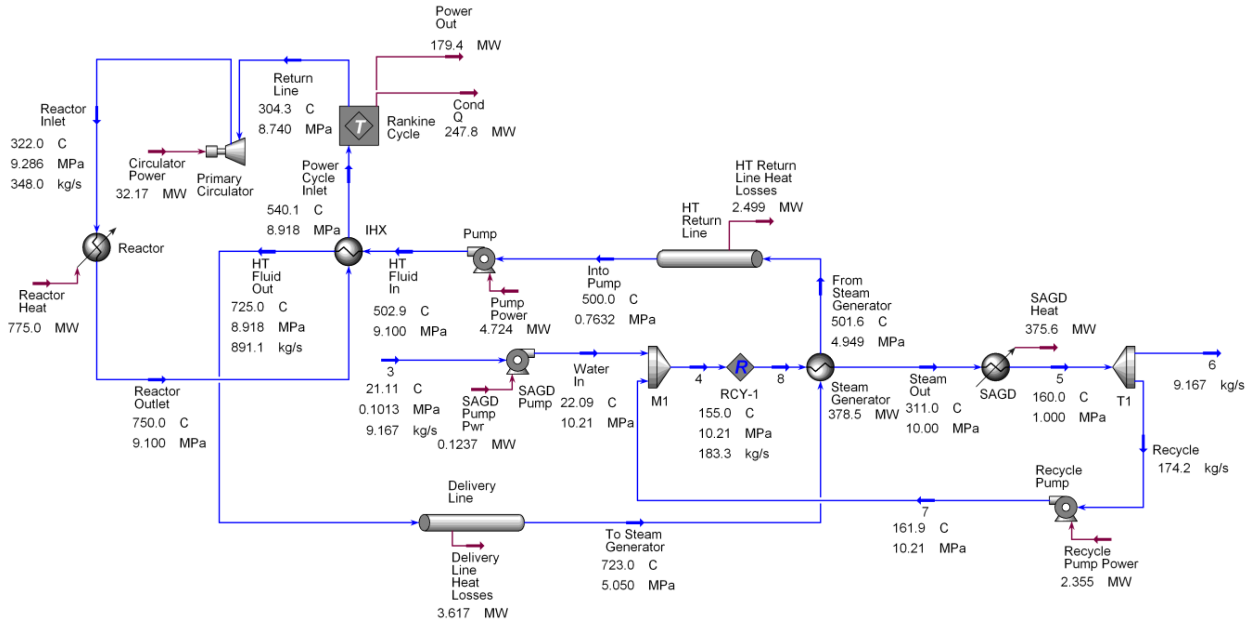

Figure 2-3. Process flow diagram of heat transfer loop from reactor to SAGD well pad. Heat transfer fluid is FLiNaK

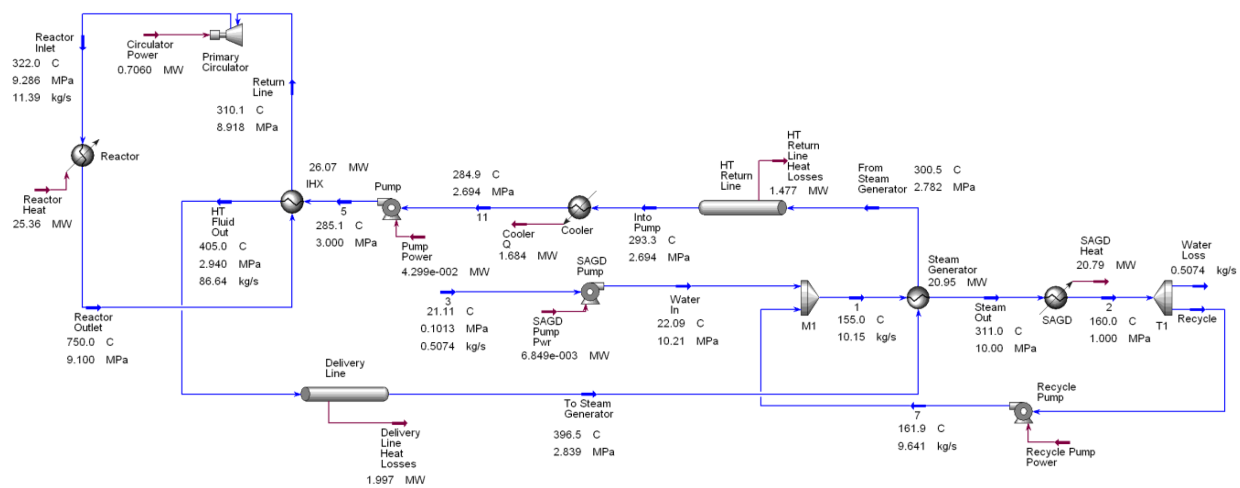

Figure 2-4. Process flow diagram of heat transfer loop from reactor to SAGD well pad. Heat transfer fluid is DOWTHERM A.

The following assumptions apply to analysis of the heat transfer fluids:

- Minimum approach is 25°C (except for additional steam cases in which the minimum approach is 50°C).
- Equivalent distance of 25 km between the reactor and the well pads

- The delivery and return lines are modeled as one 24-inch schedule-160 pipe
- Six inches Aerogel insulation on pipe; thermal conductivity is 0.013 W/m*K
- Air velocity over pipe is 4.5 m/s
- Pipe material is mild steel with roughness of $4.572*10^{-5}$ and thermal conductivity is 45 W/m*K
- Ambient temperature = 2.1°C
- Reactor outlet temperature of 750°C.

ASPEN HYSYS has a pipeline module that can be used to calculate pressure and heat losses within pipelines. The Beggs and Brill (1973) correlation was selected for pressure losses and hydrostatic pressure differences. It is one of the few published correlations capable of handling horizontal or vertical flow directions [3].

The pipe module calculates the heat loss from the pipe by specifying the geometry of the pipe, air velocity over the pipe, insulation thickness, and ambient temperature. The Pro FES option was selected to calculate the heat loss for this analysis [4].

The steam and carbon dioxide properties of Aspen HYSYS were used. The properties were checked using the National Institute of Standards and Technology (NIST) property database. The thermodynamic properties of helium in Aspen HYSYS also correlated well with NIST, but the fluid properties, viscosity, and thermal conductivity were off by as much as a factor of 10. ASPEN HYSYS however can use the ASPEN Plus database and those properties agreed well with the NIST properties. The molten salt properties [5] and the DOWTHERM A [6] properties are not a part of the basic HYSYS database and had to be entered into the hypothetical fluid database. The models were checked to make sure the properties were correct once entered.

3. RESULTS

Figure 3-1 plots the number of well pads that service the various heat transfer fluids as a function of the highest pressure within the heat transfer loop. Corresponding to the number of wells pads is the mass flow rate of the steam generated at the boilers, which is also plotted in Figure 3-1. Both the number of well pads and the steam flow are fairly constant regardless of pressure for all of the fluids except for steam. The CO_2 and helium gases service 0.5 and 1.1 well pads respectively, which corresponds to steam flow rates of 18.3 and 36.9 kg/s respectively. DOWTHERM A performs with an average of 0.3 well pads and a steam flow of 10.2 kg/s. As indicated in the plot, the pressure of the DOWTHERM A is limited because of the limitations of the fluid data provided by DOW chemical. The molten salt, FLiNaK, can service 5.3 well pads with a corresponding steam flow of 183 kg/s.

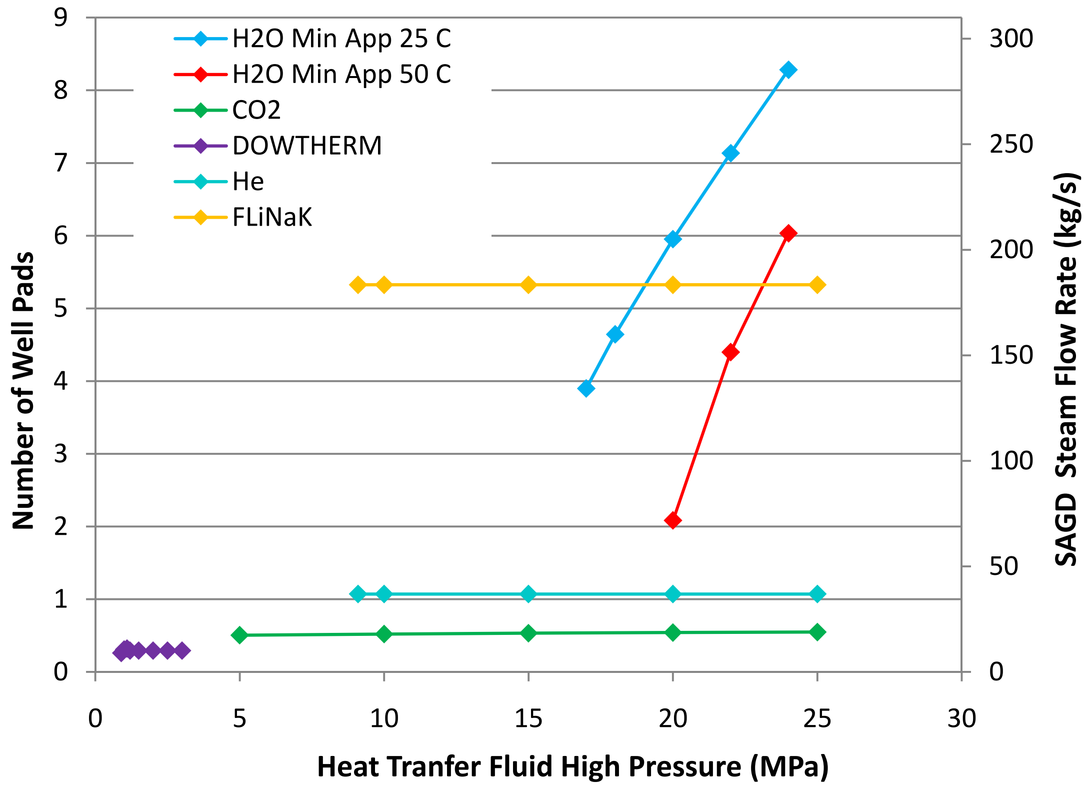

Figure 3-1. Number of well pads serviced and the SAGD steam flow rate as a function of the pressure of the heat transfer fluid.

Higher pressures in the steam cases allow the servicing of more well pads. The pressure of the steam entering the boiler within the heat transfer loop side is 14.2 MPa if the minimum approach temperature difference between the SAGD steam and the heat transfer steam is 25°C. If this minimum approach temperature difference is 50°C, the pressure is 19.4 MPa. In other words, given the pressure of the SAGD steam, the minimum approach temperature difference determines the pressure of the steam entering the boiler on the heat transfer fluid side of the boiler. Higher pressures at the pump outlet of the heat transfer loop allow more steam to flow through the pipelines, which in turn increases the flow of the SAGD steam. If the minimum approach temperature of the steam generator increases, the number of well pads serviced decreases. For example, at the pressure of 20 MPa, the number of well pads decreases from 6 to 2 as the minimum approach temperature difference changes from 25 to 50°C. The steam can service as much as 8.3 well pads with a corresponding SAGD steam flow of 285 kg/s.

A plot was made of the number of pipelines needed to transfer 600 MWt from a reactor using the assumptions outlined above, see Figure 3-2. Steam and FLiNaK have the least number of pipelines. The gases, DOWTHERM A, and FLiNaK have values that are fairly constant. However, higher pressure reduces the number of pipelines needed for the steam cases because the mass flow increases as the pressure increases.

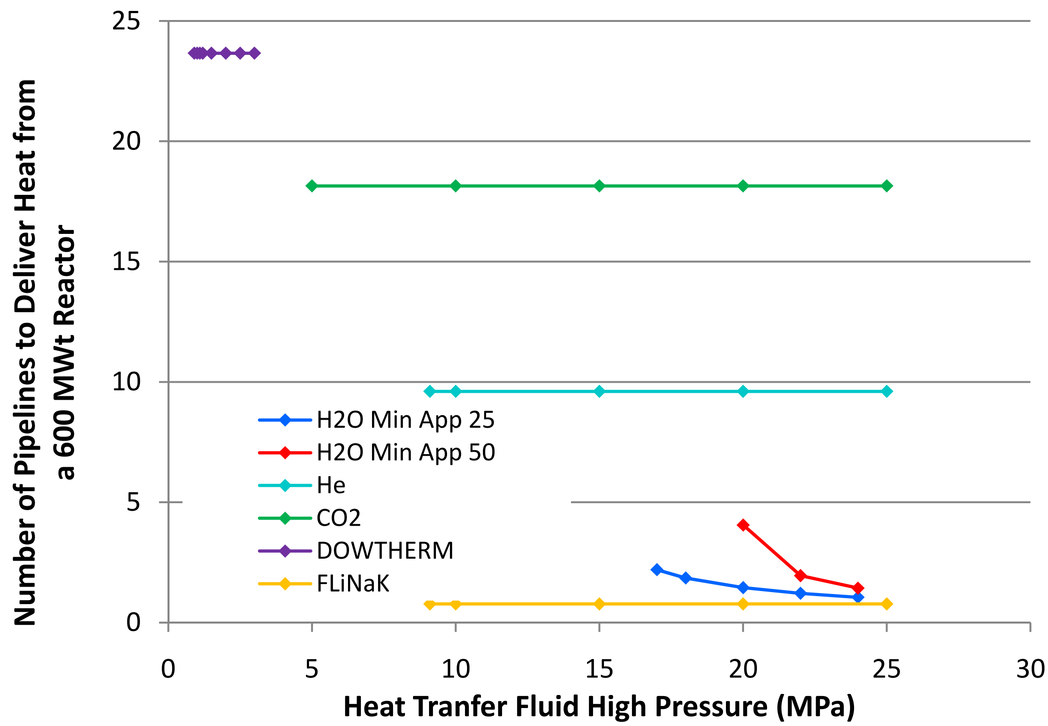

Figure 3-2. Number of pipelines needed to deliver 600 MWt reactor heat.

Figure 3-3 plots the total mass of the heat transfer fluids within the pipelines as a function of the maximum heat transfer loop pressure. As expected, the gases have little mass, which increases as the pressure goes up. CO_2 has a greater mass than helium because it is a larger molecule with a higher density. When DOWTHERM A is a two-phase fluid, it has similar mass to water, but the mass goes up when the DOWTHERM remains a liquid throughout the entire loop. The molten salt FLiNaK requires the most mass.

Heat losses in the pipeline are constant for most fluids and for a given pipeline distance as shown in Figure 3-4. Steam and DOWTHERM A have different heat losses because of the two-phase character of the fluid. Pressure has an effect on two phase flow and can also affect the heat transfer. In all cases, the delivery line loses more heat than the corresponding return line because the average temperature of the fluid in the delivery line is higher than in the return line. FLiNaK has the highest heat loss in the return line because the temperature has to stay above 500°C to prevent solidifying. Helium, carbon dioxide, and FLiNaK have very similar heat losses within the delivery line because these lines have the same maximum temperature of 725°C. Steam and DOWTHERM A have delivery lines with maximum temperatures of 550°C and 405°C respectively.

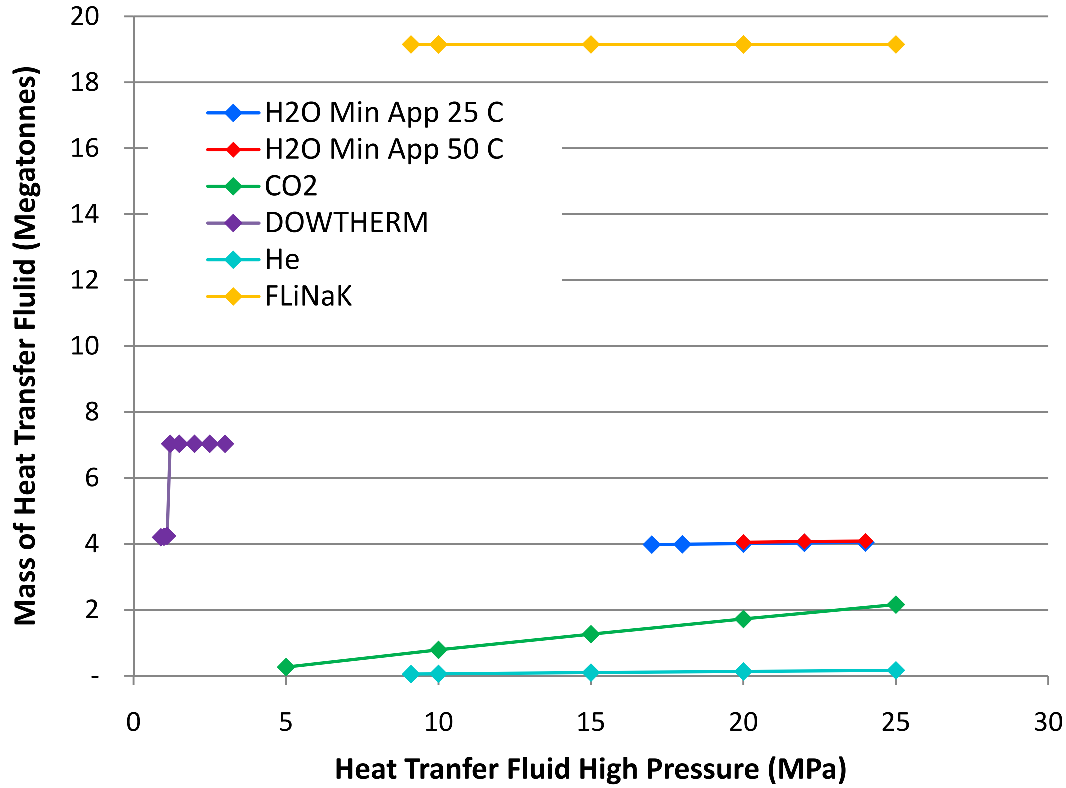

Figure 3-3. Mass of the heat transfer fluids within the delivery and return pipelines as a function of the pressure of the heat transfer fluid.

Figure 3-5 plots the number of well pads serviced using 17 MPa steam as the fluid in the heat transfer loop as a function of the distance from the reactor to the well pads. Pipeline distances up to 100 km can be used to service the well pads. The number of well pads decreases rapidly as the pipeline distance increases at lower pipeline distances. At higher pipeline distances, the number of well pads continues to decrease but at a lower rate. At distances of 25 km, 4 well pads may be serviced, but at 100 km only 1.75 well pads may be serviced.

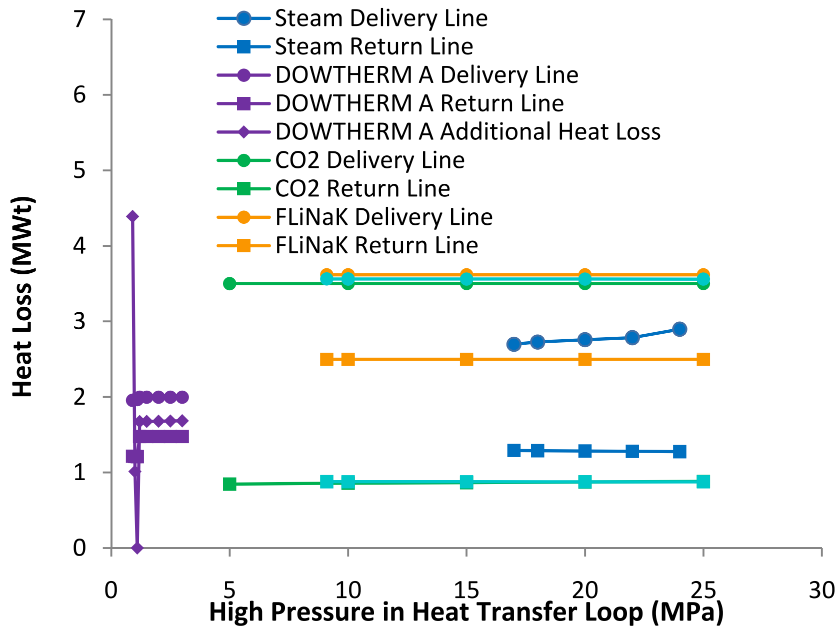

Figure 3-4. Heat losses in delivery and return lines as a function of heat transfer loop pressure for 25 km pipes.

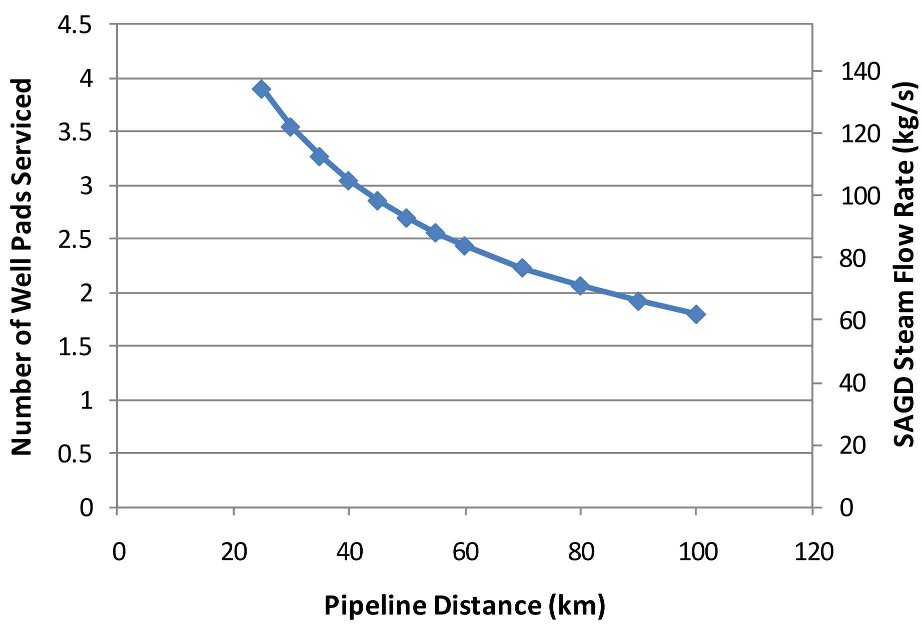

Figure 3-5. Number of well pads served and SAGD steam flow as a function of the pipeline distance from the reactor to the well pads for 17 MPa steam as heat transfer fluid.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the following conclusions are made:

- Considering all factors, steam is the preferred of all alternative heat transport fluids evaluated:
  - High heat capacity, i.e. less pipeline required
  - Total mass required is among the lowest
  - Least expensive
  - Chemically benign
  - Large body of experience
- Organic fluids do not have adequate temperature capability
- Molten salt is not considered acceptable for this application because:
  - Requires heat tracing to prevent solidification
  - Chemically corrosive
  - Expensive
  - Large mass required
- Gases considered do not have sufficient heat capacity.

5. REFERENCES

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