Thermal Characterization of Ground and Surface Waters at the UpJohn Company's Portage Road Manufacturing Facility

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THERMAL CHARACTERIZATION OF GROUND AND SURFACE WATERS AT
THE UPJOHN COMPANY'S PORTAGE ROAD MANUFACTURING FACILITY

by

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William K. Hunsberger
This study focused on thermal characteristics of the ground water and recharged surface water at The Upjohn Company’s (now Pharmacia and Upjohn) Portage Road manufacturing facility. Major objectives were: (a) a compilation and graphical evaluation of historical lower aquifer ground water temperatures; (b) estimates of thermal energy introduced into the ground water system through recharge from Upjohn Pond, and predictions of future production well discharge temperatures; (c) an evaluation of hydraulic conductivity related to changes in water density and viscosity influenced by variable temperature; and (d) the stratigraphy beneath Upjohn Pond.

Records reveal increasing ground water temperatures through time in response to the recharge of non-contact cooling water at the site. Three methods were employed and estimated thermal input via Upjohn Pond to be 1.81E+10, 7.71E+10, and 1.38E+11 BTU’s. Future discharge temperatures are predicted to be 53.2 by 1997. The temperature of the recharging pond water is a significant factor in the value of the hydraulic conductivity. The stratigraphy beneath the pond indicates the basal pond clay layer and the upper aquitard are separate lithologic units.
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INTRODUCTION

Ground water plays a major role in the dissipation of heated non-contact cooling water at the Upjohn Company’s Portage Road manufacturing facility. The use of ground water for this purpose is desirable for several reasons. The resource is readily available in sufficient quantities, ambient ground water temperature at this location is low enough to allow for efficient heat exchange, and a natural basin (Upjohn Pond) exists for recharge of the non-contact cooling water. Additionally, the use of natural ground water for cooling has advantages over mechanical cooling. Energy utilized in mechanical cooling is avoided, fuel resources are conserved, and negative ecological impacts associated with energy generation are minimized.

Increased production coupled with plant expansions have led to increasing volumes of ground water withdrawn for use as non-contact cooling water. The proper management of non-contact cooling water at the Portage Road facility should include a sound understanding of the past thermal ground water performance so that future practices may be assessed. A comprehensive understanding of the thermal ground water system at the site would provide an improved framework within which specific ground water management evaluations can be made. This study is intended to be one component helping to further this understanding.
In order to provide information for resource and plant operations management, the Upjohn Company has conducted previous evaluations concerning non-contact cooling water at the Portage Road facility. Among these, WAPORA (1984) reported on the thermal influence of non-contact cooling water discharges to Portage Creek. Other investigations (Michigan State University, 1992) have focused upon the hydrological and biological properties of Upjohn Pond. This evaluation utilized these reports as significant sources of information.

The primary objectives of the thermal evaluation are defined as follows:

1. To compile relevant existing historical data concerning the thermal ground water regime and Upjohn Pond at the Portage Road manufacturing facility.

2. Prepare and evaluate site contour maps depicting the thermal history of ground water resources at the site.

3. Construct a generalized thermal budget of the Portage Road facility with particular emphasis on changes in aquifer thermal storage.

4. Present methods which may be used to estimate future lower aquifer temperatures.

5. Through the use of existing cross sections (Facility RFI, STS Consultants, Ltd., 1991) present the hydrostratigraphy in the area adjacent to Upjohn Pond in an effort to establish the relationship between the uppermost aquitard, and the clay layer underlying the pond’s basin.

6. Examine the temporally-influenced properties of the recharging pond water and their effects upon hydraulic conductivity and recharge.
A majority of the data and information necessary to achieve these goals has been obtained from a variety of existing sources. In addition to the studies noted above, company production well temperature and volumetric discharge records were examined for their relevance to this study. Conclusions reached here are strongly dependent upon the reliability of the existing data. Additional field data gathered for this study was minimal, primarily consisting of water temperature measurements recorded during the spring of 1994.

Review of the water records from 1957 to the present enables the identification of trends in the thermal state of the lower aquifer at the site. A steady increase in production well discharge temperature is noted from 1957 to 1981 with minor increases and decreases superimposed upon the broader increasing trend. From 1984 to 1988, a distinct increase in discharge temperature is observed, possibly related to changes in non-contact cooling water management. After 1988, and until the present time, the temperature increase has been reversed. Again, operational changes in recharge of non-contact cooling water at the site may be responsible for this change.

Isothermal contour maps of the site reveal other aspects of the thermal evolution of the lower aquifer. The centers of largest ground water withdrawal are also noted as the areas of highest discharge temperature. This suggests that the transfer of thermal energy in the lower aquifer is controlled primarily by advection.

Using records of production well discharge and recorded well temperatures, the removal of thermal energy for the year 1991-1992 was estimated. During this year, 2.24E+11 BTU's were extracted through pumping. This is compared to
estimations of $1.81\times10^{10}$, $7.71\times10^{10}$, and $1.38\times10^{11}$ BTU's recharged to the lower aquifer using the MEYER, contouring, and WAPORA methods respectively. Of these three methods, the contouring procedure is thought to be the most reliable. Each method assumed an ambient ground water temperature of $51.0^\circ F$, and the current high pond (6.0 mgd) and low pond (4.5 mgd) recharge rates. An additional scenario of constant recharge at 7.0 mgd was undertaken and outlined in a later section. Using the contouring method as the preferred energy input, thermal storage in the lower aquifer has declined by $1.47\times10^{11}$ BTU's for the year 1991-1992, and $1.13\times10^{11}$ BTU's for the year 1992-1993.

Prediction of future discharge temperatures with the available information is difficult. One solution may be the extrapolation of the long term temperature trend identified at the site. This method suggests that discharge temperatures will decline from their high in 1988 to approximately $53.2^\circ F$ by 1997, and then increase at a rate of $0.025^\circ F$ thereafter. An exponential decline model was also evaluated and shows a decline to $53.3^\circ F$ by 1999. In a practical sense, each of these methods yields comparable results.

The role of variable water temperature in regard to recharging non-contact cooling water was examined to improve future estimates of recharge rates. The hydraulic conductivity of the sediments, through which infiltration takes place, is temporally controlled by changes in the density and viscosity of the recharging water. Upjohn Pond can be expected to recharge water that varies throughout the year from $32^\circ F$ to nearly $85^\circ F$. Over this wide range of fluid temperatures, differences in water
density and viscosity are significant enough to effect substantial changes in the hydraulic conductivity of the sediment-water system. Any given value of hydraulic conductivity can potentially be reduced during the winter, by as much as 43% from its value during the summer period. This has potentially important implications for projected recharge scenarios.

Although a more detailed evaluation may provide more refinement of the thermal state of the ground water system at the Portage Road facility, this investigation provides information useful in the management of the company’s non-contact cooling water. More accurate estimations of input energy are possible with additional measurements of pond water temperatures. Future records of discharge temperatures and volumes will allow company personnel to monitor the impacts of future recharge management.
SITE GEOLOGY AND HYDROSTRATIGRAPHY

The Portage Road facility lies regionally within an area dominated by outwash of glaciofluvial origin bordered on the west by the Kalamazoo Moraine. These extensive deposits form a gently undulating plain with surface drainage to the northwest. Outwash was deposited by streams flowing off the ice of the Lake Michigan lobe as it stood behind the Kalamazoo Moraine. As the outwash plain extends to the east, a more northerly source area exists, with material originating from the Tekonsha Moraine, likely contributing to the glacial deposits in the region. Till related to the advance responsible for the Tekonsha moraine is likely to be present beneath the outwash at the site.

The area is underlain by the Coldwater shale and has local bedrock relief of up to 100 feet, due to a generally northwest trending buried valley (Facility RFI, STS Consultants, Ltd., 1991). This irregularly-sloping surface has resulted in outwash thicknesses from 250 feet to nearly 350 feet. Reports indicate the Coldwater Shale forms an impermeable lower boundary to the glacial aquifers in the area, with hydraulic conductivities of the shale reported in the range of $10^{-8}$ cm/s (Facility RFI, STS Consultants, Ltd., 1991). This value is up to five orders of magnitude lower than the reported hydraulic conductivities of the upper and lower aquifers at the site.
Two aquifers have been identified within the boundaries of the Upjohn facility. The upper aquifer is generally less than 50 feet thick and its saturated thickness varies across the site. Areal distribution of the upper aquifer is uncertain outside of the site boundaries. The underlying aquitard is fairly continuous in the eastern portion of the site, whereas west of Portage Road it may be discontinuous or unidentified (Facility RFI, STS Consultants, Ltd., 1991). With increasing distance west of Upjohn Pond, near centers of ground water withdrawal, the saturated thickness of the upper aquifer thins due to the influence of pumping. In certain locations within the site boundaries, the upper aquifer may have been dewatered completely. At locations adjacent to Upjohn Pond, the most significant source of recharge in the area, saturated thicknesses of up to 50 feet have been reported. Reportedly, sediments comprising the upper aquifer can be broadly characterized as containing a greater clay percentage and poorer sorting than those of the lower aquifer.
HISTORICAL DATA COMPILATION

An effort was made to accumulate and compile the existing data pertaining to ground water and surface water temperatures at the site. Company records of historical production well discharge temperatures provided the major source of information for this study. The focus of the evaluation of historical temperature records was to present in graphical form the thermal evolution of the ground water system through time. Included within this was the identification of trends in lower aquifer temperatures. This information would prove to be useful in understanding the past behavior of the ground water system, and to assist in the formulation of future non-contact cooling water management practices.

Since 1957, the Water Department at the Upjohn Company has collected temperature measurements of its production wells. Data provided for this study covers the years 1957 to 1994, with the exception of the years 1982 and 1983. The absence of the two years introduces a gap in what would otherwise be a continuous record. From 1957 to 1981 production well temperature data was available biannually. The first set of measurements was collected in February of the year, with the second set following in August of the same year. This provides a consistent means to examine seasonal influences of temperature upon the aquifer system. Beginning around 1980, monthly temperatures were recorded for the production wells.
Examination of the data set shows that some of the water temperature data are not complete for each production well. The number of discrepancies and omissions discovered during this investigation is considered small. It is felt that the existing records present a reasonably accurate picture of water temperatures at the facility.

A majority of the records examined reveal that well temperatures were recorded to an accuracy of 0.1 degree Fahrenheit. Exceptions to this are noted for the three year interval from 1980 through 1982 when temperatures were recorded to an accuracy of 1 degree Fahrenheit. This is a relatively small period of time compared to the entire record. Serious limitations are not imposed by the presence of this difference in the degree of accuracy of temperature measurements. Operator and methodology differences are unlikely to cause substantial deviations in measured production well discharge temperatures. Even though there is some uncertainty regarding specific individual records, the validity of the data for long term trend determination is sound.

The majority of the temperature measurements were obtained from production wells, with some additional measurements from monitoring wells. The monitoring well measurements were collected during RCRA quarterly sampling at the site. Records of historical well temperatures provided by Upjohn for this study were entered into a computer database which greatly facilitated data processing and evaluation.
The temperature history of each production well has been graphically evaluated. Time vs. temperature plots are provided in Appendix A. Examination of these graphs is very useful in understanding the thermal history of this site. Analysis of the graphs reveal several trends. One, a seasonal influence is apparent in the discharge temperatures of individual wells. Secondly, temperatures recorded during the winter months, as expected, are lower than those recorded during the summer. The magnitude of this difference is variable from one well to another, and one year to another, but a one degree Fahrenheit change per year is common for many wells at the site. A number of wells demonstrate temperature changes significantly less than one degree. Lastly, longer-term trends are clearly reflected in the graphs. Without exception the long-term trend for each well shows an increase in lower aquifer temperature.

Wells in the northern well field show either a very slight increase in temperature through time or none at all. At production well locations other than the north well field, much greater increases in water temperature are exhibited through time. As noted previously, the rates of temperature increase are strongly dependent upon their location. Figure 1 illustrates a representative example of differing temperature trends from production wells screened in the lower aquifer. Production well 26 is located in the north well field approximately 400 feet north of Bishop Road. This plot shows well 26 is located in the north well field approximately 400 feet north
Figure 1. Time Vs. Temperature Profiles of Production Wells 26 & 32.
of Bishop Road. temperatures predominantly between 51.0 and 52.0 °F through time.
Seasonal fluctuations are distinguishable along with several periods where
temperatures decreased, presumably in response to climatic changes. In general, these
wells demonstrate areas where the temperature of the lower aquifer have remained
relatively stable through time. This indicates that the influence of recharged thermal
energy at these locations has been minimal.

In contrast, well 32 (Figure 1) located within the west well field, displays
trends evident in many other production wells elsewhere at the site. Well 32
demonstrates a pronounced temperature increase from 1982 to 1988, followed by a
sharp drop in temperatures since 1988. Seasonality and climatic influence is evident in
this plot also, but is superimposed upon the long-term temperature trend increase and
the shorter-term temperature increase and decrease.

Temperature increases of 0.2 °F per year is common for many wells. An
exception to this exists in production wells lying in the northern end of the west well
field. Here, wells 31, 32, 33, 36, and 38 show a much steeper rate of temperature
increase from around 1984 to 1988. Temperatures of individual wells in the west well
field have been observed to rise as much as 1.0 degree Fahrenheit per year. From
1988 to the present, the discharge temperatures of these wells has been steadily in
decline.
A method of assessing the thermal history of the Portage Road facility is to examine the change in average production well discharge temperature through time. Figure 2 is a time vs. temperature plot of production wells that are now in use, or have been used in the past. Caution should be exercised in the interpretation of this figure. Values plotted represent averages of the reported production well temperatures available for each year. February and August readings were used to determine the yearly temperature averages. Prior to 1981 these two months accounted for a well’s entire temperature record. After 1981, measurements were taken with greater frequency, but the additional measurements were omitted in regard to the averaging process to retain continuity with previous years. This method of averaging neglects volumetric discharge of individual wells so that a single year’s average temperature as plotted on the graph may not represent the average water temperature pumped for that year. Volumetric pumping records of each well through time were not available for this type of analysis. This limits the interpretation of this plot, but generally yields a qualitative delineation of the thermal history of pumping discharge.

Even with these qualifications, general temperature trends are distinguishable. Over the entire 24-year period, 1957 to 1981, discharge temperatures increased gradually. The average rate of discharge temperature increase for this period was determined to be 0.025 °F per year. The 24-year trend is most likely the result of increasing volumes of heated non-contact cooling waters recycled to the aquifer.
Figure 2. Average Production Well Temperatures 1957-1994. Long-Term Trend in Bold Line, Regression Curve Fits Dotted.
producing a gradual increase in thermal storage within the aquifer. Temperatures from 1957 to 1967 experienced a gradual rise, while from 1967 to 1982, this trend was reversed. These minor trends may be the result of a combination of climatic influences and variable thermal inputs from plant operations. After the temperature record gap from 1981 to 1984, a sharp increase in temperature is observed. The cause for this may be due to changes in cooling water management practices (increased volumes, higher recharge temperatures, or differing locations of recharging water). The apparent site-wide average rise in temperature appears to have reached a peak in 1988. After 1988, average discharge temperatures have been decreasing from production wells at the site.

As indicated, the highest ground-water temperatures occur from wells within the west well field. These increases are thought to be the result of previous non-contact cooling water management practices at the site. For a period of time, approximately 1960 to 1990, a portion of non-contact cooling water was discharged into several small recharge basins adjacent to Upjohn's Building 88, located west of Portage Road. Recharge from these basins has been reported to have reached two to three million gallons per day during some years. These basins are situated within the extreme northern portion of the cone of depression formed by the west well field. They are positioned such that recharge from them is likely to mix with water extracted from wells in the northern end of the west well field. Consistent with this scenario, the greatest historical temperature increases existed in the northern end of the west well field and may have caused the rapid increase in temperature noted after 1981. It is
probable that elevated temperatures observed in the west well field are the result of both thermal inputs from Upjohn Pond and the Building 88 recharge basins.

Increases in water temperatures achieved a maximum in 1988, and afterward began to decrease. This decline in well discharge temperature continues through the recent data. The start of the decline roughly coincides with the cessation of the Building 88 basins as sites of non-contact cooling water recharge. From these observations, a strong association can be inferred between the operation of the Building 88 recharge basins and the elevated temperatures within the west well field.

Using the temperature vs. time trends outlined in Figure 2, and assuming that pumping and non-contact cooling water recharge volumes and temperatures remain constant, a rough prediction of future temperatures is possible. A prediction of time and temperature can be made by identifying the intersection of the extrapolated long-term trend with the decreasing trends noted since 1988. This process suggests that the average production well temperature will have decreased to approximately 53.2 °F by 1997. Thereafter, temperatures are predicted to rise at an approximate rate of 0.025 °F per year. This rise reflects the average long-term increase of thermal storage in the lower aquifer resulting from plant operations. An accurate projection based on this method of analysis is dependent upon the validity of the time vs. temperature relationship following linear increases and decreases. As discussed previously, the presentation of average well temperatures weighted to discharge volume may improve this estimate somewhat.
Isothermal Contours of Lower Aquifer Temperatures

A thermal summary of the site is also presented using isothermal contour maps. Reported well temperatures from February and August are contoured at ten-year intervals, beginning in February of 1960. These maps are useful in a qualitative overview of the thermal evolution of the system. Over time, 42 wells have been utilized for water production at the Portage Road facility. These wells have generally been concentrated at certain locations on the site. Additionally, the number of wells producing at any one time has been variable. These factors introduce a considerable amount of spatial variability into the contouring process. The first attempt at contouring was accomplished using a commercial contouring software package, Surfer for Windows version 1.0. The results obtained from Surfer were considered to be generally acceptable but in need of refinement. Due to a lack of even spatial distribution, it became necessary to manually edit the Surfer contour maps to provide a more reasonable representation of aquifer temperatures through time. Plates 1-8 show the inferred spatial distribution of lower aquifer temperatures for the period of 1960 through 1990, at ten-year intervals. These contours were constructed attempting to represent the actual data without introducing any bias to the known locations of non-contact cooling water recharge.

Evaluation of the 1960-1990 contours demonstrates the thermal changes within the lower aquifer that have occurred at the Portage Road facility through time. When contours of an individual year are considered, seasonal influences upon
temperatures are evident, just as they are when individual well histories are examined. Slight increases in August temperatures over February temperatures are noted, reflecting the influence of higher recharge temperatures during the summer period.

The most dramatic effect revealed by the contour maps is the spatial influence of pumping upon production well discharge temperatures. Pumping produces a cone of ground water depression at the Portage Road facility superimposed upon the natural flow system. This system is defined by the effects of induced recharge and ground water removal by pumping. The potentiometric surface is currently influenced by recharge from Upjohn Pond and by the spatial distribution of production wells at the site.

Seasonal variations in the site thermal gradients do not appear to strongly influence lower aquifer temperatures. As demonstrated in the contour maps, substantial temperature differences exist in the west well field. Pumping from the lower aquifer within the west well field generally occurs within a single zone. Within the west well field, production wells are screened within an interval between 755 and 695 feet above MSL, and are constructed with screens that are predominantly between 30 and 40 feet in length. The homogeneity of screened intervals contrasts with the wide range of lower aquifer temperatures to indicate that the differences in lower aquifer temperatures are not the result of thermal stratification within the aquifer. Instead, the distribution of temperatures within the lower aquifer seems to be directly related to the spatial relationship between thermal sources and areas of ground water extraction.
Understanding the influences of the sources of thermal input and extraction, along with rates of thermal loading, is necessary to the explanation of the contour diagrams. Examination of the isothermal contour plots through time shows different patterns of temperature distribution. These shifts seem to be related to spatial changes in centers of ground water withdrawal. In general, the spatial distribution of aquifer temperature is related to the hydraulics of the system; whereas, the ground water temperature is dependent upon the temperature and volume of the recharging water. Hydraulic properties of the aquitard, separating the upper and lower aquifer at the site, also exhibit some control on water temperature. In a single aquifer system, recharged non-contact cooling water would move relatively directly to areas within the aquifer where it can be removed through pumping. As discussed in a later section, it is believed that mixing of recharged water with lower aquifer water is limited at the Portage Road facility by the presence of the aquitard. The introduction of an aquitard, producing an upper and lower aquifer system, serves as a barrier to flow and mixing. In this system, heated recharge moves more slowly through the aquitard. This promotes heat loss by the recharged water to the overlying sediments and produces attenuated mixing with the cooler lower aquifer. The presence of the aquitard, as a barrier to vertical flow between the upper and lower aquifers, causes a delay in the thermal impact to the lower aquifer in areas adjacent to Upjohn Pond. This effect of the aquitard limits the mixing between the upper and lower aquifers. Observations of increasing aquifer temperatures with distance from the source of thermal loading (Upjohn Pond) are explained by this process.
Contour maps of 1960 show a thermal distribution which reflects that pumping was concentrated west and northwest of the pond, and in the north well field near Bishop Road. Maximum temperatures occur in a small area south of Upjohn's Building 41. It is believed that the principal recharge source at this time was Upjohn Pond, although some minor contribution from the basins may have been possible. At this time the absence of production wells near the Building 88 allowed the thermal energy introduced via the basins to be advected down gradient off the site. Maximum reported temperatures at this time are below 56 °F. Thermal distributions in 1970 show a shift in the distribution of production wells. Withdrawals now also come from the west well field in addition to the north and south well fields. Maximum temperatures have increased to over 57 °F in both the north and west well field. The Building 88 recharge basins may also be influencing temperatures in the western-most wells of the northern well field at this time. Some thermal energy originating from the Building 88 basins is now captured by wells in the west well field. Wells in the southern well field appear to display lesser effects of warm recharge from Upjohn Pond as temperatures here do not exceed 54.1 °F. Temperature distributions seen on 1980 contour maps show a large temporal change between the February and August periods. Aquifer temperatures from February of this year are the lowest of any reported through the 36 year record. Temperatures of 48 and 49 °F are commonly reported for this month. This point in time is near the end of a short-term temperature decline that had been occurring since 1977. This decline is reflected in essentially every individual production well at the facility. Climatic records show this time
interval possessing below average annual temperatures, the suspected cause for these low ground water temperatures.

Aquifer temperatures of August 1980 are closer to previous conditions. In the northern end of the west well field, elevated temperatures (up to 58.8 °F) are observed. These are the likely result of heated recharge originating from the Building 88 basins. Thermal contours of 1990 temperatures show distributions similar to those that developed in earlier years in the northern and southern well fields. Starting approximately in 1990, the Building 88 basins reportedly no longer operated as recharge ponds. From 1990 on, elevated temperatures in the west well field, above the thermal influence of Upjohn Pond, are believed to be the result of residual heat conducted to aquifer materials from prior heated recharge originating from the Building 88 basins.

Examination of temperature contours and individual well graphs at the Portage Road facility, reveal lower aquifer temperatures increasing through time. The isothermal contour maps show the spatial distribution of increased ground water temperatures to be a function of fixed locations of recharge areas, and the variations through time of the pumping centers. Therefore, the contour maps reveal the advective movement of heated ground water at the site. This seems to demonstrate that advection dominates over conduction in the transport of thermal energy within this system. The expected result of the concentration of pumping at an area is to increase flow velocities between Upjohn Pond and the centers of withdrawal. This
condition serves to decrease the mixing of the recharged water with the existing aquifer fluids.
TEMPERATURE MEASUREMENTS

In an effort to better understand at this site, the movement of infiltrated surface waters to the ground water system, a limited number of temperature measurements were recorded. Of particular interest is the vertical distribution of temperatures within the ground water system at a given point. This may also serve as a qualitative indication of the degree of mixing that occurs between the thermally variable surface recharge, and the existing aquifer water.

A thermal profile through the ground water system can be obtained in two ways. The first, consists of recording aquifer temperatures in the screened interval of wells within a well nest. In this way aquifer temperatures at various vertical positions can be measured. This approach can be limiting considering the small number of well nests existing on site, and the irregular vertical distribution of individual well screens within a well nest. A second method consists of temperature profiling; measurements recorded at regular intervals within a single well. The use of individual monitoring wells for profiling is attractive in that wide coverage of the site is possible. Vertical temperature profiling within a single well raises an important question of whether temperatures recorded at various vertical points within the well casing representative of the actual aquifer temperature. By a comparison between these two approaches, the reliance on single well temperature profiling was verified by a field study.
Temperature profiles were taken at a location north of Upjohn Pond on April 4th and June 14th of 1994. This nest consists of piezometers 5B-5E, monitoring wells MW 129, MW 129A, MW 131, and MW 132. Temperatures in MW 132 were recorded starting below the static water level at approximately 10 foot intervals during the April 4th survey, and at 25 foot intervals on June 14th. Temperatures were also recorded at elevations representing the center of well screens in the remaining wells within this nest. This yields a continuous trace of temperature vs. depth for MW 132, and point measurements at screened intervals from other wells. Figure 3 illustrates the resulting vertical temperature profile obtained during the June 14th survey at the north well nest. Similar results were obtained from the survey of April 4th. Profiling results indicate that at this site, that differences in well casing materials do not seriously effect aquifer temperature measurements.

Temperatures recorded from the individual monitoring wells are in close agreement to those obtained from the vertical profiling of MW 132. Correlation of temperatures between the two measurement methods is strong. Therefore, the use of interval logging of an individual well for the purpose of delineating temperature is considered reliable at this site. With this procedure, it is possible to use single monitoring wells to delineate aquifer temperatures. Information gained using this technique would be useful for a numerical thermal model of the site, or for additional isothermal mapping. Additionally in other situations, if a thermal gradient exists between surface waters and ground water, this technique might prove useful for the determination of discharge/recharge relationships.
Figure 3. Vertical Temperature Profiles of North Well Nest. MW 132 Represents Continuous Profiling. Temperatures in Other Wells Recorded Within Their Screened Intervals.
Profiles logged during this study are presented in Figure 4, and reflect the conditions of April 4, 1994. Interaction between recharging water and ambient ground water is expected to exhibit temporal variability. For example, large seasonal ground water temperature fluctuations would be associated with recharged pond water. Summer recharge increases the temperature of shallow ground water, whereas winter recharge decreases shallow ground water temperatures. Curves of individual wells in Figures 3 and 4 show the influence of cool surface water being recharged during the spring of this year. A portion of the lower temperatures can be attributed to direct recharge from snowmelt and heat loss from the aquifer to the cooler overlying sediments. The greatest amount represents water supplied from Upjohn Pond, still cool, from the winter period.

Shallow (upper aquifer) monitoring wells, MW 154, MW 155, DF 12A, and CW 34, exhibit the most striking influence of pond recharge. Ground water temperatures at the water table in this group of wells range from 40 to 50 °F. With the exception of DF 12A, temperatures increase with depth to values of 50 to 55 °F. In monitoring well DF 12A ground water temperature initially decreases, then reverses and increases to the approximate temperature observed at the water table. This well ranges in temperature from 38 to 40 °F making it the coolest well in the figure. Another monitoring well not shown in this figure, DF 15, yielded a temperature of 33.5 °F during this survey. This low temperature is similar to those reported for MW 133 (January of 1993) during the RCRA quarterly sampling. The temperatures recorded from DF 12A and DF 15 support evidence from the Kellogg Biological
Figure 4. Thermal Profiles of Selected Monitoring Wells at the Portage Road Facility on 4/4/94.
Station study that indicate high rates of recharge taking place within the western and southwestern regions of the pond.

Monitoring wells PZ 8, MW 147, and MW 159 are completed in the lower aquifer, and with the exception of PZ 8, are at greater distances from the pond. The locations of DF 12A and PZ 8 are near enough to each other to collectively represent a continuous 200 foot thermal profile of temperature distribution through both aquifers at this location. Further evidence supporting thermal mixing is demonstrated by the combination of these two curves. As shown in Figure 3 after temperatures increase with depth, a reversal occurs where decreasing temperatures then occur. In MW 132 this point of inflection correlates with the aquitard separating the two aquifers. This is also believed to be the cause of the temperature reversals noted in PZ 8. The aquitard appears to restrict mixing between the ground water of the two aquifers. With distance from the thermal input source, greater mixing occurs and distinct temperature changes within a profile are less pronounced. This is reflected in the thermal profiles of MW 147 and MW 159.

Thermal profiling at the Portage Road site reveals the effects of mixing between the two aquifers. The shape of the temperature vs. elevation curve is strongly dependent upon the position of the monitoring well relative to Upjohn Pond and upon the local stratigraphy.
THERMAL ANALYSIS

Central to the objectives of this study is the estimation of a thermal energy budget encompassing the following:

1. Energy introduced into the ground water system through recharge of site surface waters.

2. Energy removed from the ground water system through discharge from production wells.

In this regard, two methods have been employed to estimate the amount of thermal input and output occurring at the site. This section presents the methodology of these analyses and summarizes their results.

A single year of data (water year October 1, 1991, to September 30, 1992) was chosen for analysis. The choice of time interval was made to coincide with the period of data collection of the Kellogg Biological Station study (1992), a primary source of information used in this investigation.

Throughout this study thermal energy is expressed as the BTU’s where 8.33 BTU’s are gained (lost) in raising (lowering) one gallon of water one degree Fahrenheit. Before an analysis can be undertaken, a reference temperature must be chosen for purposes of energy comparison. Rheaumes (1990) reported an average ground water temperature of 52.1 °F for 46 wells measured in Kalamazoo County. Examination of the thermal history of the site indicates that a temperature of 52.1 °F may be too high. It is evident that background ground water temperatures do vary
through space and time at the Portage Road facility. A more site-specific value was estimated to be 51.0 °F for the ambient ground water temperature at the site. The assignment of 51.0 °F as the reference temperature is warranted based upon historical records of the Portage Road facility provided by The Upjohn Company. Differences between the county-wide averages and the temperature value observed at this site may be attributed to the specific hydrogeologic unit measured. The 51.0 °F estimate at this site is based on the lower aquifer while the Kalamazoo County average is thought to represent aquifer systems of differing hydrostratigraphic units. In subsequent selected analyses, higher reference temperatures were also evaluated for purposes of comparison.

Construction of a thermal budget involves the evaluation of the inputs to, and outputs from, the system. The performance of the system is defined as the quantity of energy gained or lost when the system is changed from the reference temperature to a specified temperature. An estimate of thermal output from the ground water system has been obtained from the product of volumetric discharge from production wells and recorded well temperatures. Other mechanisms operate to remove thermal energy from the system. These included the conduction of thermal energy to basement bedrock, conduction through porous media into the vadose zone, convective heat transfer in the vapor phase through the vadose zone, and possible heat energy advected out of the system. It is assumed here that these mechanisms play a minor role in energy lost from the ground water system and consequently are not evaluated.
Thermal Energy Removal Through Production Well Discharge

Thermal energy removed through production well pumping for 1991-1992 is presented in Table 1, and for 1992-1993 in Table 2. Reported monthly well temperatures were weighted with well discharge to determine BTU’s removed by pumping for each well. A yearly total was obtained from the monthly totals of energy removed through pumping. Determination of energy output for the year 1992-1993 is less certain than for the previous year. Pumping volumes for this interval are complete, but many production well temperatures were not recorded. For those records missing, an attempt was made to estimate their value. The procedure used to accomplish this was a simple linear interpolation between known temperature values. It is generally observed that individual wells do not fluctuate greatly from month to month supporting the use of the simple estimates of production well temperatures.

Although average discharge temperature varies by only 0.1 °F, other differences exist between these two years. During 1991-1992, 9.6 billion gallons of water was extracted for an average of 26.3 million gallons per day. The following year, 1992-1993, pumping had been reduced to a total of 7.9 billion gallons, or 21.6 million gallons per day. 1992-1993 discharge was reduced 14.7% from that of 1991-1992. Examination of pumping records reveal that production wells 32 and 33 were off line for several months. These two wells are among the group of wells in the west well field that discharge at the most elevated temperatures. Discharge from the two wells for 1991-1992 was more consistent with previous years because both wells
Table 1

Thermal Energy and Water Volumes Extracted Through Discharge
From Production Wells 1991-1992

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>Volume (gal)</td>
<td>Temperature (°F)</td>
<td>BTU's @ 51.0</td>
</tr>
<tr>
<td>October 1991</td>
<td>8.56E+08</td>
<td>53.0</td>
<td>1.41E+10</td>
</tr>
<tr>
<td>November 1991</td>
<td>7.89E+08</td>
<td>52.9</td>
<td>1.27E+10</td>
</tr>
<tr>
<td>December 1991</td>
<td>8.17E+08</td>
<td>53.8</td>
<td>1.93E+10</td>
</tr>
<tr>
<td>January 1992</td>
<td>8.25E+08</td>
<td>54.3</td>
<td>2.26E+10</td>
</tr>
<tr>
<td>February 1992</td>
<td>7.95E+08</td>
<td>54.2</td>
<td>2.11E+10</td>
</tr>
<tr>
<td>March 1992</td>
<td>7.76E+08</td>
<td>54.3</td>
<td>2.11E+10</td>
</tr>
<tr>
<td>April 1992</td>
<td>7.78E+08</td>
<td>54.1</td>
<td>1.98E+10</td>
</tr>
<tr>
<td>May 1992</td>
<td>7.87E+08</td>
<td>54.1</td>
<td>2.04E+10</td>
</tr>
<tr>
<td>June 1992</td>
<td>7.91E+08</td>
<td>54.2</td>
<td>2.11E+10</td>
</tr>
<tr>
<td>July 1992</td>
<td>8.08E+08</td>
<td>52.5</td>
<td>9.93E+09</td>
</tr>
<tr>
<td>August 1992</td>
<td>8.03E+08</td>
<td>54.1</td>
<td>2.08E+10</td>
</tr>
<tr>
<td>September 1992</td>
<td>7.89E+08</td>
<td>54.2</td>
<td>2.09E+10</td>
</tr>
<tr>
<td>Total</td>
<td>9.61E+09</td>
<td>54.2</td>
<td>2.24E+11</td>
</tr>
<tr>
<td>Average</td>
<td>8.01E+08</td>
<td>53.8</td>
<td>1.87E+10</td>
</tr>
</tbody>
</table>

operating during each month of the year. By using wells 32 and 33 less in 1992-1993 a reduction in thermal energy removal occurred as compared to that of the previous year. Removal of total thermal energy decreased by 14.7% from 1991-1992 to 1992-1993. However, when measured as energy removed per unit volume of discharge, 1991-1992 yields 23.3 BTU/gallon, while the value of 1992-1993 is 24.2 BTU/gallon. A possible explanation for the difference between the two years may be the influence of greater discharge during 1991-1992. Under this pumping regime, an expanded cone of ground water depression in the west well field would draw additional water from fringe areas less affected by thermal sources.
Table 2

<table>
<thead>
<tr>
<th>Month</th>
<th>Volume (gal)</th>
<th>Temperature (°F)</th>
<th>BTU’s @ 51.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1992</td>
<td>7.68E+08</td>
<td>54.0</td>
<td>1.92E+10</td>
</tr>
<tr>
<td>November 1992</td>
<td>6.68E+08</td>
<td>53.8</td>
<td>1.56E+10</td>
</tr>
<tr>
<td>December 1992</td>
<td>6.24E+08</td>
<td>54.0</td>
<td>1.56E+10</td>
</tr>
<tr>
<td>January 1993</td>
<td>6.37E+08</td>
<td>54.0</td>
<td>1.59E+10</td>
</tr>
<tr>
<td>February 1993</td>
<td>5.89E+08</td>
<td>54.0</td>
<td>1.47E+10</td>
</tr>
<tr>
<td>March 1993</td>
<td>6.11E+08</td>
<td>53.7</td>
<td>1.37E+10</td>
</tr>
<tr>
<td>April 1993</td>
<td>5.50E+08</td>
<td>53.7</td>
<td>1.24E+10</td>
</tr>
<tr>
<td>May 1993</td>
<td>6.85E+08</td>
<td>53.6</td>
<td>1.48E+10</td>
</tr>
<tr>
<td>June 1993</td>
<td>6.84E+08</td>
<td>53.7</td>
<td>1.54E+10</td>
</tr>
<tr>
<td>July 1993</td>
<td>6.82E+08</td>
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<td>1.70E+10</td>
</tr>
<tr>
<td>August 1993</td>
<td>7.22E+08</td>
<td>54.2</td>
<td>1.92E+10</td>
</tr>
<tr>
<td>September 1993</td>
<td>6.87E+08</td>
<td>54.1</td>
<td>1.77E+10</td>
</tr>
<tr>
<td>Total</td>
<td>7.91E+09</td>
<td></td>
<td>1.91E+11</td>
</tr>
<tr>
<td>Average</td>
<td>6.59E+08</td>
<td>53.9</td>
<td>1.59E+10</td>
</tr>
</tbody>
</table>

The estimates of thermal output via the production wells presented here will serve as a basis for thermal input comparison. A hypothetical two-year trend of reduced thermal energy recovery is also employed in a later section for estimates of future thermal conditions.

Thermal Energy Inputs From Upjohn Pond Estimated Using the MEYER and WAPORA Methods

To arrive at a meaningful thermal budget for the facility, a reasonable estimate must be made of energy introduced into the ground water system. The primary
pathway of heat transfer to ground water at the Portage Road site consists of surface water recharge from Upjohn Pond. The Kellogg Biological Station study (MSU, 1992) included a delineation of relative infiltration within Upjohn Pond based on seepage meter measurements taken of the pond bottom. Based upon a hydrologic budget, recharge for 1991-1992 was estimated to be 4.5 million gallons per day for the "low pond" period (April 1 to November 30), and 6.0 million gallons per day for a "high pond" (December 1 to March 31). This study employs the estimated infiltration rates outlined in the KBS study for a weighting of thermal energy input from the pond.

Two methods were used to estimate the temperature of recharged non-contact cooling water. The first method is expanded into two different approaches to arrive at thermal inputs. In the first method, pond water temperature is determined through a one dimensional analytical solution which estimates water temperature vs. distance from a line source. The second technique uses a combination of measured pond water temperatures with estimated values to determine thermal input. Comparison of the three estimates is used to establish reasonable limits of energy input to the ground water system.

Spatial discretization of infiltration rates within Upjohn Pond is viewed as a rectangular body with a length to width ratio of 7:4, closely approximating the actual pond. Twenty eight sub-regions are identified, each measuring 366 x 366 feet, for individual areas of 133,956 ft$^2$ (3.1 acres) each. Collectively the pond area covers 3,750,768 ft$^2$ (86.1 acres). Specific sub-regions are assigned relative rates of infiltration based on the Kellogg Biological Station study. Their positions relative to
the non-contact cooling water inlet channel have been preserved, as well as the total area of each infiltration class. Use of this basemap in conjunction with pond temperatures obtained from analytical solutions enables the prediction of not only the volumetric recharge, but also the thermal input from the recharge. This simplified conceptualization of Upjohn Pond necessitates some assumptions. First, flow within the pond is considered steady and uniform, proceeding as a front from the inlet boundary to the outlet boundary. The inlet and outlet are not point sources and sinks as in the real pond, but lines sources and sinks, each 1,464 feet in length. Internal pond circulation is ignored as a process that distributes heat energy in this analysis. Lastly, the assumption is made that the pond behaves as a channeled conduit (stream). Determination of pond temperature is achieved through the use of an analytical solution. In its application to Upjohn Pond, temperature varies as an exponential function of the distance from the thermal source, the pond’s cooling water inlet, to any point along the flow path at distance from this source. The formulation of the relevant relationship follows.

\[ T_x = T_e + (T_0 - T_e) e^{-\frac{ax}{v}} \]  

Eq. 1

where \( \alpha = \frac{K}{\rho C_p h} \)  

Eq. 2

and
\( \rho \) = density of water (62.4 lb / ft³)

\( C_p \) = specific heat of water (1 BTU / lb-°F)

\( h \) = mean depth of water (ft)

\( v \) = mean horizontal velocity of water (ft / day)

\( T_\text{ix} \) = initial water temperature (°F)

\( T_e \) = equilibrium temperature (°F)

\( e \) = base of natural logarithm

\( K \) = heat exchange coefficient (BTU / ft²-°F)

\( x \) = distance of horizontal water movement (ft)

\( T_x \) = temperature of water at point x (°F)

This analytical solution has been employed previously by WAPORA Inc. during their study of Portage Creek for The Upjohn Company. In that application, creek temperatures were predicted as distance increased from inlet of non-contact cooling water to the stream. This report expands upon that attempt and uses a similar methodology to estimate the temperatures of water recharged from the pond.

Before resulting thermal input values are presented, an abbreviated discussion of the foundation of Eq. 1 is warranted. For an in-depth review of this material, the reader is referred to Edinger and Geyer (1965). The variables of particular interest in Eq. 1 and Eq. 2 are \( K \), the heat exchange coefficient, and \( T_e \), the equilibrium temperature. They are taken from evaporation models where \( T_e \) is defined as the water surface temperature for which the net rate of heat exchange equals zero. Under this condition the quantity of energy gained by the water body is balanced by the
amount of energy lost from the water. This is rare in natural surface waters. Most generally, heat energy is in a state of movement, either to or from the water body, in an effort to achieve a state of thermal equilibrium. If its temperature is below $T_e$, the water body approaches equilibrium by warming. At temperatures above $T_e$, cooling of the water body occurs to achieve equilibrium. The heat exchange coefficient $K$, represents the rate at which the transfer of heat energy proceeds across the air and water interface. Units for the equilibrium temperature are degrees Fahrenheit, those of the heat exchange coefficient are BTU/ft$^2$.°F-day.

Determining $T_e$ and $K$ is not straightforward and requires that evaporation be evaluated through an energy budget approach. When this is done, the equilibrium temperature and the heat exchange coefficient can then be back calculated. Thus, realistic site-specific values of $T_e$ and $K$ are obtained and available for evaluation. Reportedly, WAPORA Inc. obtained values of $T_e$ and $K$ by back calculations of Eq. 1 using field measured stream temperatures. The application of these back calculated stream values to temperature profiles in Upjohn Pond, a recharging surface water body, may introduce some degree of error.

Values of $T_e$ and $K$, from the WAPORA study are reported seasonally and are presented in Table 3. This table also includes equilibrium temperatures and heat
Table 3

Equilibrium Temperatures and Heat Exchange Coefficients Used in the WAPORA and MEYER Methods

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_e</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WAPORA</td>
<td>25</td>
<td>78</td>
<td>77</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>143</td>
<td>81</td>
<td>143</td>
<td>56</td>
</tr>
<tr>
<td>MEYER</td>
<td>29</td>
<td>74</td>
<td>64</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>112</td>
<td>36</td>
<td>79</td>
</tr>
</tbody>
</table>

exchange coefficients developed later in this report labeled as “MEYER”. The MEYER values are included here but explained later in this section.

The equilibrium temperature and heat exchange coefficient can also be derived using site-specific climatic data. An approach of this type is requires a great degree of highly specific climatic data. In order to arrive at values of $T_e$ and $K$, an evaporation model must be chosen and partially evaluated. Several such models exist and contain empirical relationships which are based on Dalton’s law (Dingman 1993), given as follows.

$$H_e = (b_0 + b_1W)(e_s - e_a)$$

Eq. 3

where
\[ H_e = \text{heat energy lost through evaporation} \]

\[ b_0 \text{ and } b_1 = \text{empirical constants} \]

\[ W = \text{wind speed} \]

\[ e_s = \text{saturation vapor pressure} \]

\[ e_a = \text{measured air pressure} \]

Each model differs primarily in the empirical constants \(b_0\) and \(b_1\). These constants are obtained through back calculation of the complete evaporation formula. Data required for these calculations includes site measurements of absorbed radiation, air temperature, air vapor pressure, wind speed, measured net rate of heat exchange and measured surface temperatures. The Upjohn Company has compiled climatic data on-site since October 1991. This provides much of what would be required to determine site specific values of \(T_e\) and \(K\). However, the lack of measured net rate of heat exchange and measured surface temperatures prohibits that computation. The climatic data does allow for an evaluation to be made if \(b_0\) and \(b_1\) are taken from one of the empirical relationships. This is the approach adopted for this investigation.

Values of \(b_0\) and \(b_1\) are assumed to be those used in the MEYER formulation (Edinger and Geyer, 1965) of Eq. 3. In this expression, \(b_0 = 73\) and \(b_1 = 7.3\). Choice of this particular evaporation model is subjective. Wind speed in the MEYER formula is taken as a monthly average which works well with the data collected at the site. Another important parameter found in these empirical formulas is the height at which the air speed is recorded. Air speed measurements are taken at 25 ft. (7.5 m) for the MEYER relationship. Wind speed is recorded at 32.8 ft. (10 m) above ground level at
the Portage Road meteorological station. The height difference can be assumed to introduce some unknown error into the calculations, but a relationship that measures wind speed at a height nearer to 32.8 ft. than the MEYER formula is unknown.

The MEYER coefficients in combination with the site’s climatic records enabled an estimation of $T_e$ and $K$ for Upjohn Pond. Values obtained from these calculations have previously been presented in Table 3 as the MEYER equilibrium temperatures and heat exchange coefficients. Substantial variations are evident when comparing the WAPORA and MEYER coefficients. Differences are even more apparent when the coefficients are applied to predict pond infiltration temperatures.

The necessity of obtaining values of the equilibrium temperature and the heat exchange coefficient is apparent from their inclusion in Eq. 1. The equation is used to predict pond temperatures within various regions of the pond possessing varying rates of infiltration. When this is done, a prescribed volume of water at a specific temperature enters the ground water system. In this way the thermal energy input to the aquifer is estimated. The total energy input is the sum of the energy input for all sub-regions of the pond. Two recharge scenarios are identified and evaluated in this study. In the first scenario, the low pond (April 1 to November 30), the pond recharged the aquifer at a rate of 4.5 mgd. During high pond (December 1 to March 31) conditions, recharge occurred at 6.0 mgd. These conditions approximate those described during the Kellogg Biological Station investigation. A second scenario is evaluated where recharge remains constant at 7.0 mgd throughout the year. This rate
was chosen to evaluate thermal inputs for possible future pond management evaluations. Assumptions used in the computation of Eq. 1 are as follows:

1. Pond area 86.1 acres
2. Average pond depth (@ 4.5 mgd) 3.0 ft.
3. Average pond depth (@ 6.0 mgd) 4.0 ft.
4. Average water velocity (@ 4.5 mgd) 183 ft./day
5. Average water velocity (@ 6.0 mgd) 137 ft./day
6. Retention time 14.0 days

Table 4 summarizes the thermal inputs for the MEYER and WAPORA estimation methods. These values were obtained by implementing WAPORA and MEYER values of $T_e$ and $K$ into Eq. 1. For the recharge scenario that approximates present conditions (high pond 6.0 mgd, low pond 4.5 mgd), energy introduction ranges from 3.78 billion BTU’s using the MEYER coefficients, to 136 billion BTU’s using the WAPORA values. Constant recharge at 7.0 million gallons per day yields a thermal input of 55 billion BTU’s with MEYER coefficients whereas the WAPORA coefficients increase the system by 196 billion BTU’s. Clearly the estimated thermal recharge input is highly sensitive to the choice of the equilibrium temperature and heat exchange coefficient. This demonstrates the strong control that climatic conditions impart upon thermal energy transfer at the site. One measure of the impact of heated recharge water onto the hydrogeologic system at the Portage Road facility is a
Table 4

Non-Contact Cooling Water Recharge, Pond Temperatures, and Thermal Energy Input to Ground Water Using the MEYER and WAPORA Equilibrium Temperatures and Heat Exchange Coefficients

<table>
<thead>
<tr>
<th></th>
<th>High Pond @ 6.0 mgd</th>
<th>Yearly @ 7.0 mgd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Pond @ 4.5 mgd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recharge (gal)</td>
<td>Recharge (gal)</td>
</tr>
<tr>
<td>Winter</td>
<td>5.44E+08</td>
<td>6.30E+08</td>
</tr>
<tr>
<td>Spring</td>
<td>4.10E+08</td>
<td>6.42E+08</td>
</tr>
<tr>
<td>Summer</td>
<td>4.14E+08</td>
<td>6.44E+08</td>
</tr>
<tr>
<td>Fall</td>
<td>4.14E+08</td>
<td>6.44E+08</td>
</tr>
<tr>
<td>Total</td>
<td>1.78E+09</td>
<td>2.56E+09</td>
</tr>
</tbody>
</table>

Ground Water Recharge and Thermal Input for WAPORA Values of $T_e$ and $K$

<table>
<thead>
<tr>
<th></th>
<th>High Pond @ 6.0 mgd</th>
<th>Yearly @ 7.0 mgd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Pond @ 4.5 mgd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recharge (gal)</td>
<td>Recharge (gal)</td>
</tr>
<tr>
<td>Winter</td>
<td>5.44E+08</td>
<td>6.30E+08</td>
</tr>
<tr>
<td>Spring</td>
<td>4.10E+08</td>
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<td>Summer</td>
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<td>Fall</td>
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<tr>
<td>Total</td>
<td>1.78E+09</td>
<td>2.56E+09</td>
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</tbody>
</table>

Comparison between the energy input to the system through current operations and an estimation of thermal energy input if unheated ground water were recharged. The results of the WAPORA computations are compared to a hypothetical pond receiving unheated ground water.
This hypothetical scenario is assumed to be under the influence of the same hydrological parameters, with the exception of inflow temperature. Equilibrium temperatures, and heat exchange coefficients are identical to the heated recharge evaluation (WAPORA method) and inflow temperature is set at 51.0 °F.

Recalculation of the WAPORA method adjusted to a reference temperature of 51.0 °F yields a total natural energy input of 1.39E+11 BTU's as compared to 1.96E+11 BTU's delivered through facility operation. This exercise reveals that a natural body of water similar to Upjohn Pond, not receiving non-contact cooling water, still contributes 1.39E+11 BTU's of thermal energy to the ground water system. The addition of thermal energy from the operation of the Portage Road facility to this pond increases the thermal input by only 29%. The analysis of this scenario suggests that basin size, morphometry, capacity, and residence time are the major impacts regarding thermal energy introduced into the ground water system through recharge.

Thermal Energy Input Estimated Through Contoured Thermistor Data

The final method used for thermal input estimation utilizes in part, actual pond temperatures recorded during the Kellogg Biological Station investigation of Upjohn Pond. From April to September of 1992, an array of thermistors and data loggers operative in Upjohn Pond. This system produced a record of the dinural and seasonal variation of water temperatures within the pond. Average pond temperatures used in
the contouring method were determined from the spatial weighting of hourly
temperature measurements. Average seasonal pond temperatures were contoured
within the pond and then superimposed upon the Kellogg Biological Station relative
infiltration map to produce a thermally weighted estimate of infiltration. As in
previous methods, a prescribed volume of water at an estimated temperature can be
determined and used to calculate energy input to ground water.

Thermistor arrays recorded pond temperatures in the latter portion of the
April, May, and June, (spring season) and, the early portion of the July, August, and
September (summer season). Seasonal pond temperatures are averaged using
available thermistor records. The spring thermistor record contained 45% of the
number of possible measurements for the period, while summer contained 68% of the
possible measurements.

Temperature data is more concentrated in the northern section, near the
cooling water inlet and less so in the southern region near the outlet. This affects
average water temperatures to the extent that the influence of greater thermal
fluctuations observed from the southern thermistor stations is reduced. The spring and
summer seasonal temperature averages are also thought to represent temperatures that
are to some degree higher than those that actually exist. This data skew is introduced
from the timing of data collection intervals in each season. Spring averages omit the
month of April entirely and over one half of the May period. This artificially raises the
average temperature through the omission of cooler pond temperatures that exist in
April. Similarly, the summer season is averaged neglecting somewhat cooler water temperatures in September.

In addition to the warm season measurements, cold season pond temperatures were recorded on February 6 and 12 of 1991. The cold season temperature measurements were used to determine the winter average. It is quite likely that the average winter pond temperature may be in error due to the lack of a larger data set. The absence of other winter pond temperature measurements necessitates the sole use of the February 6 and 12 data. Also problematic is the estimation of average fall pond temperatures. This season is represented by estimated values only. The method of estimation chosen for this period relies upon meteorological records collected at Upjohn. Figure 5 shows the average air temperatures from October of 1991 to May of 1994 collected at the Portage Road facility. This plot indicates that during the spring and fall seasons, the rate of change of air temperatures is at its maximum. The average air temperature for the fall season is closely approximated by taking the arithmetic average of the highest and lowest monthly air temperatures. It is further assumed that pond water temperatures exhibit a response similar to the air temperature curve. From meteorological data, a fall water temperature can be estimated by taking the arithmetic average of the highest recorded water temperature (summer) and the lowest water temperature (winter). This method is applied only to the fall seasonal water temperature because it is the lone period where no real data exists. The method could also be applied to the spring season if necessary.
Figure 5. Average Monthly Air Temperatures Reported at the Portage Road Facility, October 1991-May 1994.
After the seasonal water temperatures are estimated, it is possible to compute thermal pond input from the pond in the same manner as that employed in the WAPORA and MEYER methods. Table 5 presents estimates of thermal input as a result of recharge from Upjohn Pond by the available temperature data collected in the pond. The contouring method yields thermal input estimates intermediate between those given by the MEYER and WAPORA calculations.

Comparison of Estimated Thermal Inputs

Three different methods have been employed to estimate thermal input from Upjohn Pond to the ground water system. All attempt to predict the average water temperature recharged by the pond. With known or target values of recharge specified, the quantity of thermal energy entering the system may be estimated. Each method is presented at reference temperatures of 51.0, 52.0, and 53.0 degrees Fahrenheit. As stated earlier 51.0 °F is considered the most representative of lower aquifer temperatures. Energy inputs obtained through its use are used in the thermal budget. The methods used for thermal input estimation, MEYER, WAPORA and contouring, are each limited in their direct application to Upjohn Pond. MEYER and WAPORA calculations are based upon energy budget evaporation models. The MEYER method uses empirical constants that were developed at an unknown location and used at this site. The WAPORA method has been previously applied to this site, but the application of the equilibrium temperature and heat exchange coefficient to Upjohn Pond may be in error. The MEYER and WAPORA methods
Table 5
Non-Contact Cooling Water Recharge, Pond Temperatures, and Thermal Energy
Input to Ground Water Using the Contouring Method.

<table>
<thead>
<tr>
<th>Ground Water Recharge and Thermal Input from Contouring Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pond @ 6.0 mgd</td>
</tr>
<tr>
<td>Low Pond @ 4.5 mgd</td>
</tr>
<tr>
<td>Recharge (gal)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Winter</td>
</tr>
<tr>
<td>5.44E+08</td>
</tr>
<tr>
<td>Spring</td>
</tr>
<tr>
<td>4.10E+08</td>
</tr>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>4.14E+08</td>
</tr>
<tr>
<td>Fall</td>
</tr>
<tr>
<td>4.14E+08</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recharge Temperature = 52.0 °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (gal)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Winter</td>
</tr>
<tr>
<td>5.44E+08</td>
</tr>
<tr>
<td>Spring</td>
</tr>
<tr>
<td>4.10E+08</td>
</tr>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>4.14E+08</td>
</tr>
<tr>
<td>Fall</td>
</tr>
<tr>
<td>4.14E+08</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recharge Temperature = 53.0 °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (gal)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Winter</td>
</tr>
<tr>
<td>5.44E+08</td>
</tr>
<tr>
<td>Spring</td>
</tr>
<tr>
<td>4.10E+08</td>
</tr>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>4.14E+08</td>
</tr>
<tr>
<td>Fall</td>
</tr>
<tr>
<td>4.14E+08</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>
rely upon an idealized pond geometry coupled with a one dimensional flow domain.

The contouring method is based upon site-specific pond water temperatures controlled by advective heat transport, but is limited by the lack of an entire year’s measured temperatures. Table 6 summarizes the results of energy input estimations. For the current recharge scenario, thermal additions differ by 1.36E+11 BTU’s.

The MEYER computation is not considered a reliable indicator of thermal input because the empirical constants used in its formulation do not appear to be well suited to this site. The lowest estimates of thermal input are obtained when using the MEYER computation is applied to this problem. WAPORA calculations and the contouring method are felt to represent better estimates of thermal input.

Table 6

Energy Inputs to Ground Water From the MEYER, WAPORA, and Contouring Methods Including Energy Differences Between Removal (1991-1992) and Input

<table>
<thead>
<tr>
<th>Energy Inputs and Changes in Aquifer Thermal Storage* (reference temp = 51.0 °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pond @ 6.0 mgd</td>
</tr>
<tr>
<td>Energy Input (BTU’s)</td>
</tr>
<tr>
<td>MEYER</td>
</tr>
<tr>
<td>Contoured</td>
</tr>
<tr>
<td>WAPORA</td>
</tr>
</tbody>
</table>

[* Negative values represent increases in aquifer thermal storage]
The contouring method produces a thermal input 44.0% less than the WAPORA method. Even with the data gaps that exist with the contouring method, it is felt to be more representative of actual conditions than the WAPORA method. In the contouring method, data was used to generate recharge temperatures of 65.3 °F for spring, 55.1 °F for fall, 41.5 for winter, and 74.1 for summer. The summer is the only period represented by actual pond measurements. Pond temperatures for the remaining seasons are chosen to yield a conservative estimate of thermal input. Using these temperatures, a thermal input balance using the contouring method was obtained. It is reasonable to assume that the contouring method yields the most reliable estimates of energy input because it is based upon observed pond temperatures. The WAPORA method also produces reasonable estimates but is more limited than the contouring method due to its dependence upon calculated model parameters that are unverified in their application to the pond.

If greater accuracy is desired for thermal input predictions using the contouring method, thermistor arrays or periodic manual measurements of pond temperatures would be helpful. In particular data from the fall and winter seasons would improve the estimates of pond temperatures for these periods.

As suggested, 51.0 °F should serve as a reasonable approximation of the ambient lower aquifer temperature at the Portage Road facility. This reference temperature serves as a baseline from which all energy inputs and extractions are measured. However, if this assignment is in error, or if regional hydrogeologic or climatic factors change the ambient aquifer temperature, it is useful to adjust the
energy balance to account for these changes. Incremental increases in pond recharge are presented which range from present conditions (5.0 mgd), to recharge that approximates total facility water usage (25.0 mgd). Combinations of variable reference temperatures and recharge yield a range of net energy inputs and changes in thermal aquifer storage and are presented in Table 7.

As expected, at a given reference temperature the total energy input increases by a factor of five from the low to high recharge scenarios. Energy inputs decrease by approximately 15% at a particular recharge rate as the reference temperature increases.

Table 7


<table>
<thead>
<tr>
<th>Recharge (mgd)</th>
<th>Energy Input (BTU's)</th>
<th>Net Change In Thermal Storage (BTU's)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference Temperature (°F)</td>
<td>Reference Temperature (°F)</td>
</tr>
<tr>
<td>5</td>
<td>51.0</td>
<td>52.0</td>
</tr>
<tr>
<td>10</td>
<td>1.03E+11</td>
<td>8.74E+10</td>
</tr>
<tr>
<td>15</td>
<td>2.05E+11</td>
<td>1.75E+11</td>
</tr>
<tr>
<td>20</td>
<td>3.08E+11</td>
<td>2.62E+11</td>
</tr>
<tr>
<td>25</td>
<td>4.10E+11</td>
<td>3.49E+11</td>
</tr>
</tbody>
</table>

[*Negative values represent increases in aquifer thermal storage]

by one degree. Changes in thermal storage significantly vary through the recharge scenarios. Negative values in table 7 indicate increases in thermal storage in the lower aquifer. At recharge rates above 10.0 mgd at 51.0 °F, and above 5.0 mgd at 52.0 °F,
aquifer thermal storage increases at each reference temperature, and approaches \(-293\) billion BTU's at total recharge of 25.0 mgd. Extracted energy is assumed to be \(2.24\times10^{11}, 1.44\times10^{11},\) and \(6.41\times10^{10}\) BTU's at 51.0, 52.0 and 53.0 °F respectively.

**Net Energy Balance**

Before a comparison between input and extracted energy is made, it is important to note that in the context of this study, thermal inputs were assumed to originate solely from Upjohn Pond. This assumption neglects any thermal energy that is introduced elsewhere on the site. Comparison of the thermal energy removed by pumping and the energy recharged by Upjohn Pond shows a net decrease in thermal energy storage within the lower aquifer. Using the contouring method value, net thermal energy reduction was \(1.47\times10^{11}\) BTU's from 1991-1992 and, \(1.13\times10^{11}\) BTU's from the 1992-1993 pumping year. This indicates that aquifer temperatures, that have been previously elevated through thermal input from the Building 88 recharge basins, are presently in decline. It is interesting to note that even at a higher pond recharge of seven million gallons per day, \(8.00\times10^{10}\) BTU's would be removed above the amount of energy recharged. In regard to this thermal analysis, it is unlikely that average production well temperatures will continue to rise in the near future. Large scale additions of energy to the system can be expected to increase thermal storage, but a continuous recharge scenario of 7.0 million gallons per day at 196 billion BTU's per year (the most liberal estimate) is not expected to increase discharge temperatures above present levels.
PROPOSED MECHANISM OF EVALUATING AQUIFER ENERGY REDUCTION

In a previous section a simple linear trend was employed to predict future average production well water discharge temperatures. This assumes that increases and decreases in production well water temperatures respond quickly to changes in site recharge and at constant rates. However, a linear decline in aquifer thermal energy is only an assumption, and has not been verified. Another method is desirable to predict the reduction in production well discharge temperature.

When energy is stored in a mass which is then exposed to an environment at a cooler temperature, Newton’s Law of Cooling predicts that the mass will cool quickly at first, and then asymptotically approach the temperature of the environment. This is the foundation of the approach employed here to estimate future aquifer temperatures.

This additional predictive tool is a variation of Eq. 1, earlier applied to the prediction of temperature as a function of distance. In that case, Eq. 1 is used for pond temperature estimations. As used for the estimation of pond temperatures employing the WAPORA and MEYER methods, the temperature of the mass versus distance follows an exponential decay curve. The main assumption for future production well discharge temperature prediction is that lower aquifer temperatures also follow an exponential decay curve. A further assumption is that volumetric
discharge remains constant through time. To achieve this, Eq. 1 has been modified with time being substituted for distance, resulting in Eq.

\[ T_{t+\Delta t} = T_a + (T_t - T_a)e^{\alpha \Delta t} \]

where \( \alpha = c(E_{\text{out}} - E_{\text{in}}) \)

and

\[ T_t = \text{temperature at time } t \ (\degree F) \]
\[ T_a = \text{ambient aquifer temperature (\degree F)} \]
\[ \Delta t = \text{time increment (1 yr)} \]
\[ e = \text{base of natural logarithm (2.718)} \]
\[ c = \text{empirical constant (-2.31E-13)} \]
\[ E_{\text{out}} = \text{energy extracted from the system (BTU's)} \]
\[ E_{\text{in}} = \text{energy input to the system (BTU's)} \]

Alpha represents the thermal decay constant. Graphically it is determined from the evaluation of average site production well temperatures, yielding a value of -0.034. Mathematically it is defined as the product of an empirical constant “c”, and the difference between extracted and input thermal energy. The difference in energy removals and inputs is taken as 1.46E+11 BTU’s. This is the amount of energy removal during the period of 1991-1992, and the input value determined earlier using the contouring method of energy input estimation. From this, the value of “c” is empirically determined to be -2.31E-13. The constant “c” is assumed to be a constant for the Portage Road facility. The formulation of \( \alpha \) allows for future refinement of production well discharge estimations. Energy differences may be modified as new
energy removals and/or inputs are determined. These differences then can reflect proposed changes in non-contact cooling water disposal practices or changes in well production.

Figure 6 shows the relationships between the long term average thermal increase on the site, observed average production well temperature since 1988, and predicted exponential temperature decline obtained from the evaluation of Eq. 4. This plot suggests that the aquifer temperature will decline to approximately 53.3 °F by the first quarter of 1999. In the earlier linear interpolation, discharge temperature was predicted to decline to 53.2 °F by 1997.

In a practical sense, the difference in predicted temperature between the linear and exponential models is negligible. The close agreement in discharge temperature obtained using the two methods suggests that thermal energy decline at the facility follows relatively uncomplicated processes. The major uncertainty in this exercise is the validity of the long-term temperature trend. Extrapolation of this trend beyond 1981 implies that past practices at the facility continue without drastic increases of input thermal energy. For this reason this prediction may potentially be in error.
Figure 6. Projected Production Well Discharge Temperature Assuming Exponential Decline in Thermal Energy.
Recharge from Upjohn Pond to the ground water system is controlled by the hydraulic properties of the materials underlying the pond. The Kellogg Biological Station study produced a relative infiltration map based upon a sampling of seepage meter readings. This map served as the basis for thermally weighting relative recharge rates in this report. Although seepage meter studies provide estimates of spatially dependent recharge, they do not define the spatial relationships of the geologic units beneath the pond.

Information from available well logs and soil borings were examined and incorporated into geologic cross sections of Upjohn Pond and the immediate vicinity to gain a better understanding of the site's geology. Of particular interest in this regard is the relationship between the clay unit directly underlying the peat deposits in the pond (pond clay) and the upper aquitard present at the site. Borings taken during the Kellogg Biological Station study established the thickness of pond sediments and peat layer, along with the elevation of the upper surface of the basal clay. The thickness of the clay has not been determined. An accurate characterization of the clay layer thickness would provide refinements of infiltration rates based upon estimates of the spatial distribution of hydraulic conductivity within the pond.

Plates 9 and 10 represent cross sections beneath Upjohn Pond generated from the available drilling logs and soil borings. In areas beneath the pond, clay bottom elevations and aquitard elevations are uncertain and were extrapolated from adjacent...
logs and borings. Borings adjacent to the pond indicate minor relief on the aquitard surface therefore interpolation between control points may be used as a reasonable estimate. The position of the bottom of the pond clay layer is less certain. The maximum thickness of this layer was assumed to be 10 feet and is considered a liberal estimate of the units thickness based on the general glacial environments identified in the area. No data exists to verify the thickness of the clay, but in general, infills to closed depressions follow a consistent pattern of sedimentation with deposits generally thinning away from a depositional center. Using the maximum thickness (10 feet), the pond clay and the aquitard exhibit an estimated separation of 10 feet. A clay layer, with thickness of 20 feet at the depositional center is required to produce contact between the two units.

The cross sections support seepage meter results and indicate that infiltration from the pond to the ground water system occurs at variable rates within the pond basin. A portion of the pond water is recharged directly through the peat and basal clay. Water movement below the clay is thought to occur as a combination of saturated and unsaturated flow. Sands and silty sands form a zone of relatively higher permeability which is more pronounced along the western and southern pond boundaries. Though spatially smaller, a large percentage of the total recharge may occur within these marginal areas.

Recharge beneath Upjohn Pond proceeds in a manner consistent with the proposed mechanism outlined earlier in this report. Infiltration from the pond is initially introduced to the upper aquifer. Mixing with the lower aquifer is restricted by
the aquitard in most areas. However, in the southern pond region, pumping from W 39 and W 40 may influence recharge such that water movement through the aquitard may be promoted. Evidence for this is found in the pumping records of these wells which show elevated discharge temperatures and larger than average seasonal water temperature fluctuations.
TEMPORAL INFLUENCE ON GROUND WATER RECHARGE

Normally the application of Darcy's Law to ground water flow assumes isothermal conditions. The dynamics at the Portage Road facility clearly indicate that consideration of changes in water density and viscosity are warranted. This section briefly reviews the non-isothermal properties of water and how they may influence estimates of recharge from Upjohn Pond.

Darcy's Law (Eq. 5) is familiar to geologists and engineers working evaluating the sub-surface laminar flow of water. However, factors that determine the proportionality constant of flow, the hydraulic conductivity, are often unevaluated within varying hydrogeological environments.

\[
q = - K \left[ \frac{dh}{dl} \right]
\]

Eq. 5

where

- \( q \) = specific discharge (L / T)
- \( K \) = hydraulic conductivity (L / T)
- \( dh \) = head difference (L)
- \( dl \) = change in length of flow path (L)
A specific value of hydraulic conductivity is a function of both the media, and the fluid contained within it (Strack, 1989). The hydraulic conductivity term in Eq. 5 can be further expanded to demonstrate its dependence upon fluid density and viscosity. Eq. 6 establishes the variables and constants, and the relationship that defines the hydraulic conductivity within a hydrogeological environment.

\[ K = \frac{\kappa \rho g}{\mu} \]  

Eq. 6

where

- \( K \) = hydraulic conductivity (L / T)
- \( \kappa \) = intrinsic permeability (L^2)
- \( \rho \) = density of the fluid (M / L^3)
- \( g \) = acceleration of gravity (L / T^2)
- \( \mu \) = dynamic viscosity (M / L·T)

The intrinsic permeability is a property of the media alone and remains constant. Water recharged from Upjohn Pond varies both in density and dynamic viscosity as the temperature of the pond changes in response to climatic influences. This causes the hydraulic conductivity of the pond bottom sediments to change through time. In this way, volumetric ground water recharge from Upjohn Pond is controlled temporal influences.

To illustrate, consider a uniform pond bottom with an average hydraulic conductivity of 5.00E-10 m s\(^{-1}\) at 25 °C (77.0 °F). Water density and viscosity at this
temperature are found to be 997.08 kg m\(^{-3}\) and 8.905E-04 kg m\(^{-1}\) s\(^{-1}\) respectively. Rearranging and solving Eq. 6 yields an intrinsic permeability for the pond bottom sediments of 4.56E-17 m\(^2\). Furthermore, assume the limits of pond recharge temperature to extend from 3.0 °C (37.4 °F) during the winter, to 25.0 °C (77.0 °F) in the summer. At the high recharge temperature, the value of hydraulic conductivity equals 5.00E-10 m s\(^{-1}\). Evaluation of Eq. 6 to include the values of water density and viscosity at 3.0 °C (37.4 °F) reveal that the hydraulic conductivity has decreased to 2.76E-10 m s\(^{-1}\). In this scenario, seasonal changes in the temperature of the recharging water produce a range in hydraulic conductivities that vary by 44.8% throughout the year.

Darcy's Law states that discharge is proportional to the value of the hydraulic conductivity, which has been demonstrated to be controlled by temperature. Under conditions of constant head within the pond, volumetric recharge will fluctuate along with pond water temperature. This is illustrated using pond temperatures determined from the contouring of quarterly averaged thermistor data. When summer recharge (74.1 °F) is assumed to occur at 7.0 mgd, fall recharge (55.1 °F) is reduced by 23.4% to 5.4 mgd, winter recharge (36.1 °F) is then reduced by 44.1% to 3.9 mgd, and spring recharge (65.3 °F) is reduced by 11.5% to 6.2 mgd. Ground water recharge from the pond had been assumed to proceed at a rate of 7.0 mgd, for a yearly total of 2.55 billion gallons. However, when the system is adjusted to account for the effects of variable recharge temperature, the yearly total is reduced to 2.05 billion gallons.
Clearly this has important implications for the management of recharged non-contact cooling water at the site. Estimates of yearly volumetric recharge from Upjohn Pond will be in error when the hydraulic conductivity is assumed to remain constant. As previously applied in the Michigan State-KBS study, pond recharge was determined through the use of a hydrologic budget approach which can ignore the effects of variable hydraulic conductivity. However, when these recharge determinations are based upon direct hydraulic computations employing the spatial distribution of pond bottom infiltration, the temporal control on hydraulic conductivity by variable water densities and viscosities must be considered.
CONCLUSIONS

Examination of temperature data provided by Upjohn reveals that increasing amounts of thermal energy have been recovered from production wells at the Portage Road facility. The source of this thermal loading is heated non-contact cooling water previously recharged to the aquifer system at the site. Recharge has been focused at Upjohn Pond and several basins near Upjohn’s Building 88. Currently the Building 88 ponds are not sources of recharge, but their thermal effects may still be reflected in the temperature of ground water extracted in the west well field.

A review of the thermal histories of the production wells has led to their assignment into two groups. The first group of wells shows a slow but steady increase in discharge temperature through time. The second group has experienced significant increases and decreases in water temperature since 1981. Average production well discharge temperature has risen by approximately 0.025 °F per year since 1957. From 1984 to 1988 average water temperature increased at the rate of 0.38 °F per year, presumably in response to greater thermal input from the Building 88 recharge basins. Since 1988, the average discharge temperature has declined at the rate of 0.14 °F per year. This decline may be attributed to the cessation of the Building 88 basins as sources of recharge.
Evaluation of the observed trends leads to an estimation of future production well discharge temperature. In the absence of major changes in the management of non-contact cooling water recharge, and assuming a linear decline in temperature, average water temperature is projected to decline to 53.2 °F by 1997. After this time, water temperatures are expected to increase by 0.025 °F per year, to some point of dynamic equilibrium.

Isothermal contour maps of the site demonstrate the geometric relationship between thermal recharge sources and pumping centers. Areas of elevated lower aquifer temperatures strongly correlate with potentiometric depressions created by ground water withdrawal.

The nature of thermal mixing of recharge water with ambient aquifer water is controlled by advective ground water flow and the stratigraphy at the site. Recharge water is first introduced to the upper aquifer and moves slowly through the aquitard to the lower aquifer where it is removed through pumping. Where it is present, the aquitard acts to spatially dampen the thermal influences of recharge areas.

The quantity of heat energy recovered in production well discharge was determined. For the year 1991-1992, 2.24E+11 BTU’s of energy were extracted by pumping at an average temperature of 53.8 °F. During the following year, 1992-1993, energy removal was 1.91E+11 BTU’s at 53.9 °F.

Three methods were used to estimate the thermal input to the ground water system by Upjohn Pond. Two of these, the MEYER and WAPORA methods use a similar recharge mechanism differing only by equilibrium temperatures and heat
exchange coefficients. MEYER values resulted from an attempt to derive site specific values based upon climatic data collected at the Portage Road facility. WAPORA equilibrium temperature and heat exchange coefficients are thought to be superior to coefficients (MEYER) computed during this study. The last method of thermal input estimation uses a set of pond temperatures collected during a study of Upjohn Pond by the Kellogg Biological Station of Michigan State University. KBS pond temperature data were augmented with reasonable estimates to arrive at a yearly total energy input.

Annual thermal energy input estimates are 1.81E+10 (MEYER), 7.71E+10 (contouring) and, 1.38E+11 (WAPORA) BTU's. These values are based upon recharge of 6.0 mgd from December 1 to March 31 and 4.5 mgd during the remainder of the year. Even without a full data set of pond temperatures, the contouring method is thought to be the most accurate of the three methods considering its reliance upon recorded pond water temperature data.

An additional recharge scenario is presented during which recharge occurs at a steady yearly rate of 7.0 mgd. Thermal inputs at this recharge rate give energy inputs of 54.8, 144.0, and 196.0 billion BTU's for the MEYER, contoured, and WAPORA methods respectively.

These values of recharged energy were compared to the 244.0 billion BTU's that were removed during 1991-1992. At the most liberal estimate where recharge occurs at 7.0 mgd, an excess of 50 billion BTU's would be removed for that period. The high level of energy extracted reflects remnant thermal energy stored in the lower aquifer. This storage may have resulted from the operation of recharge basins adjacent
to Building 88. Even though total site recharge volumes at the time these basins were in use were comparable to volumes currently being recharged, the manner of their introduction may have increased energy storage in the lower aquifer. The use of a larger receiving body for non-contact cooling water appears to facilitate energy transfer to the atmosphere.

An exponential decline in lower aquifer temperature is presented as an alternative to the linear decline trend. The exponential method predicts future temperatures which are in close agreement with the previous estimation. Exponential decline predicts a water temperature of 53.3 early in 1999, as opposed to a prediction of 53.2 by 1997 obtained from the linear trend. The close agreement in predicted aquifer temperatures suggests that either of these methods appear to be reliable estimators.

The temporal influence of recharged water temperature was examined. This review demonstrated that volumetric recharge from Upjohn Pond is substantially affected through changes in hydraulic conductivity as water viscosity and density change through time. Recharge can be reduced up to 43.5% in response to changes in physical properties of infiltrating water. It is recommended that subsequent recharge evaluations consider the effects of hydraulic conductivity due to the variable temperature of recharging water.
Appendix A

Time vs. Temperature Graphs of Production Wells
Chronological Temperature Profile of Production Well 1.
Chronological Temperature Profile of Production Well 2.
Chronological Temperature Profile of Production Well 5.
Chronological Temperature Profile of Production Well 6.
Chronological Temperature Profile of Production Well 7.
Chronological Temperature Profile of Production Well 8.
Chronological Temperature Profile of Production Well 9.
Chronological Temperature Profile of Production Well 11.
Chronological Temperature Profile of Production Well 12.
Chronological Temperature Profile of Production Well 13.
Chronological Temperature Profile of Production Well 14.
Chronological Temperature Profile of Production Well 15.
Chronological Temperature Profile of Production Well 16.
Chronological Temperature Profile of Production Well 17.
Chronological Temperature Profile of Production Well 18.
Chronological Temperature Profile of Production Well 19.
Chronological Temperature Profile of Production Well 20.
Chronological Temperature Profile of Production Well 22.
Chronological Temperature Profile of Production Well 23.
Chronological Temperature Profile of Production Well 24
Chronological Temperature Profile of Production Well 25.
Chronological Temperature Profile of Production Well 26.
Chronological Temperature Profile of Production Well 27.
Chronological Temperature Profile of Production Well 29.
Chronological Temperature Profile of Production Well 40.
Chronological Temperature Profile of Production Well 41.
Chronological Temperature Profile of Production Well 42.
Chronological Temperature Profile of Production Well 43.
Chronological Temperature Profile of Production Well 44.
Chronological Temperature Profile of Production Well 45.
Chronological Temperature Profile of Production Well 46.
Chronological Temperature Profile of Production Well 47.
Appendix B

Vertical Temperature Profiles of Monitoring Wells
Temperature profiles of CW 11, CP 2, DF 21, MD, 2 & MW 138 taken 4/4/94.
Temperature profiles of CW 28, CW 29 & CW 34 on 4/4/94.
Temperature profiles of PZ 1A, PZ 1B, PZ 3A, PZ 3B & DF 12A on 4/4/94.
Temperature profiles of LA 2, LA 3 & MW 113 taken 4/4/94.
Temperature profile of DF 15 taken on 7/7/94.
Temperature profiles of PZ 8, MW 147, MW 154, MW 155 & MW 159 on 4/4/94.
REFERENCES CITED


LEGEND

- PRODUCTION WELL

W 1 Well ID

55.3 Temperature in Degrees F.

PLATE 1
LOWER AQUIFER TEMPERATURES
FEBRUARY 1960

THE UPJOHN COMPANY — PORTAGE FACILITY
Section 14, T. 3 S., R. 11 W.
City Of Portage
Kalamazoo County, Michigan

Data Supplied By The Upjohn Company
PLATE 3
LOWER AQUIFER TEMPERATURES
FEBRUARY 1970
THE UPJOHN COMPANY - PORTAGE FACILITY
Section 14, T. 3 S., R. 11 W.
City Of Portage
Kalamazoo County, Michigan
PLATE 4
LOWER AQUIFER TEMPERATURES
AUGUST 1970
THE UPJOHN COMPANY – PORTAGE FACILITY
Section 14, T. 3 S., R. 11 W.
City Of Portage
Kalamazoo County, Michigan

LEGEND
• PRODUCTION WELL
W 1 Well ID
55.3 Temperature in Degrees F.

UPJOHN POND
Bishop Ave.

Plate Map Adapted From Abrams Aerial Survey Corporation Map
Date Of Photography March 20, 1990

Data Supplied By The Upjohn Company
A2497

LEGEND
• PRODUCTION WELL
W 1 Well ID
55.3 Temperature in Degrees F.
PLATE 5
LOWER AQUIFER TEMPERATURES
FEBRUARY 1980
THE UPJOHN COMPANY – PORTAGE FACILITY
Section 14, T. 3 S., R. 11 W.
City Of Portage
Kalamazoo County, Michigan
PLATE 6
LOWER AQUIFER TEMPERATURES
AUGUST 1980
THE UPJOHN COMPANY – PORTAGE FACILITY
Section 14, T. 3 S., R. 11 W.
City Of Portage
Kalamazoo County, Michigan
Data Supplied By The Upjohn Company

LEGEND
@ PRODUCTION WELL
W 1 Well ID
52.7 Temperature In Degrees F.
PLATE 7
LOWER AQUIFER TEMPERATURES
FEBRUARY 1990
THE UPJOHN COMPANY – PORTAGE FACILITY
Section 14, T. 3 S., R. 11 W.
City Of Portage
Kalamazoo County, Michigan

LEGEND
@ PRODUCTION WELL
W Well ID
50.8 Temperature in Degrees F.

Base Map Adapted From Abrams Aerial Survey Corporation Map
Data Photography March 20, 1990
Center Ave.
Data Supplied By The Upjohn Company

A2497
PLATE 8
LOWER AQUIFER TEMPERATURES
AUGUST 1990
THE UPJOHN COMPANY – PORTAGE FACILITY
Section 14, T. 3 S., R. 11 W.
City Of Portage
Kalamazoo County, Michigan

LEGEND
• PRODUCTION WELL
W 1 Well ID
52.7 Temperature in Degrees F.

Base Map Adapted From Abrams Aerial Survey Corporation map
Date Of Photography March 20, 1990

Data Supplied By The Upjohn Company

A2497
PLATE 10
CROSS SECTION B TO B'
THE UPJOHN COMPANY – THERMAL STUDY
Portage, Michigan

Horizontal Scale
Vertical Exaggeration = 20 : 1