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POWER-CYCLE STUDIES FOR A GEOTHERMAL ELECTRIC
PLANT FOR MX OPERATING BASES

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ABSTRACT

Binary geothermal plants were investigated for providing electrical power for MX missile bases. A number of pure hydrocarbons and hydrocarbon mixtures were evaluated as working fluids for geothermal resource temperatures of 365, 400, and 450°F. Cycle thermodynamic analyses were conducted for pure geothermal plants and for two types of coal-geothermal hybrid plants. Cycle performance results were presented as net geofluid effectiveness (net plant output in watts per geofluid flow in lbm/hr) and cooling water makeup effectiveness (net plant output in watts per makeup water flow in lbm/hr). A working fluid containing 90% (mass) isobutane/10% hexane was selected, and plant statepoints and energy balances were determined for 20MW(e) geothermal plants at each of the three resource temperatures. Working fluid heaters and condensers were sized for these plants.

It is concluded that for the advanced plants investigated, geothermal resources in the 365 to 450°F range can provide useful energy for powering MX missile bases.

CONTENTS

	Page
ABSTRACT	i
1. INTRODUCTION	1
1.1 Objectives	1
1.2 Background	1
2. SUMMARY	4
2.1 Cycles Evaluated	4
2.2 Results of Cycle Evaluation	4
2.3 Geothermal Plant Definition	7
3. RESOURCE ASSUMPTIONS	9
4. ADVANCED BINARY CYCLE STUDY RESULTS	13
4.1 Binary Cycle Description and Evaluation Base	13
4.2 Power Cycle Performance with Pure Hydrocarbon Working Fluids, 365°F Resource	15
4.3 Power Cycle Performance Comparison of Hydrocarbon Mixtures, 365°F Resource	20
4.4 Power Cycle Performance Comparison, 400°F Resource	23
4.5 Power Cycle Performance for 450°F Resource	28
4.6 Power Cycle Analysis Conclusions	31
5. HYBRID COAL-GEOTHERMAL PLANT CONCEPTS	34
5.1 Hybrid Plant, Geothermal Feed Water Heating	34
5.2 Hybrid Plant, Bottoming Cycle	37
5.3 Hybrid Cycle Study Conclusions	38
6. 20MW(e) ADVANCED BINARY PLANT DEFINITION	39
6.1 Power Cycle Description	39
6.2 Heat Balance and Heat Exchanger Sizing Basis	39
6.3 Heat Exchanger Configurations	44
6.4 Heat Exchanger Design Conclusions	46
7. REFERENCES	49

TABLES

1. Summary of Assumed Resource Data	10
2. Cycle Performance Summary	33

CONTENTS (Cont'd)

	Page
3. Comparison of Hybrid Plant with Geothermal and Coal Plants for a 365°F Resource	36
4. Heat Balance for 20MW(e) MX Geothermal Plant for a 365°F Resource using 90% Isobutane/10% Hexane	41
5. Heat Balance for 20MW(e) MX Geothermal Plant for a 400°F Resource using 90% Isobutane/10% Hexane	42
6. Heat Balance for 20MW(e) MX Geothermal Plant for a 450°F Resource using 90% Isobutane/10% Hexane	43

FIGURES

1. Performance of Advanced Binary Systems	5
2. Silica Deposition Temperature	12
3. Schematic Diagram of Advanced Binary Electrical Power Plant	14
4. Cycle Performance for 365°F Geothermal Resource with Isobutane Working Fluid	16
5. Schematic Diagram of Advanced Binary Electrical Power Plant with a Recuperator	18
6. Cycle Performance for 365°F Geothermal Resource with Isopentane Working Fluid	19
7. Cycle Performance for 365°F Geothermal Resource with 90% (mass) Propane/10% Isopentane Working Fluid	21
8. Cycle Performance for 360°F Geothermal Resource with 80% (mass) Propane/20% Isopentane	22
9. Cycle Performance for 365°F Geofluid Resource with 88% (mass) Isobutane/12% Isopentane	24
10. Cycle Performance for 365°F Geothermal Resource with 90% (mass) Isobutane/10% Hexane Working Fluid	25
11. Cycle Performance for 400°F Geothermal Resource with Isobutane Working Fluid	26
12. Cycle Performance for 400°F Geothermal Resource with Isopentane Working Fluid	27

CONTENTS
(Cont'd)

13. Cycle Performance for 400°F Geothermal Resource with 88% (mass) Isobutane/12% Isopentane Working Fluid	Page 29
14. Cycle Performance for 400°F Geothermal Resource with 90% (mass) Isobutane/10% Hexane Working Fluid	30
15. Baseline Coal-Fired Steam Plant	35
16. MX Binary Power Plant: 20MW Module	47

1.0 INTRODUCTION

1.1 Objectives

The overall purpose of the effort summarized in the present report was to evaluate the feasibility of producing electricity for MX operating bases using geothermal energy. Preconceptual thermodynamic studies were conducted to investigate various types of geothermal power plants. (Thermodynamic analysis of potentially applicable plant configurations has been found to serve as an excellent "screening" function preceeding detailed costing and economic evaluation of selected plants.) Economic evaluation was not made in this preliminary study.

Specific objectives were to: (1) investigate, use of various plant working fluids for several geothermal resources; (2) investigate, preliminarily, the sensitivity of water usage to the various plant concepts and working fluids; (3) conduct preliminary thermodynamic assessments of combined fossil and geothermal "fueled" plants; and (4) present a preliminary plant schematic, plant state points, and heat exchanger sizes for each of the better performing plants for several resource conditions.

1.2 Background

In Reference 1, "Geothermal Energy for MX Operating Bases", brief background material was presented pertaining to categories of geothermal resources, types of conventional geothermal plants, and some overall economic considerations. Reference 1 concluded that for the geothermal resources expected at potential operating bases, binary cycles should produce electricity more economically than flash steam cycles; accordingly, binary cycles were selected for the present evaluation.

Power Plant Features. In a binary geothermal cycle, working fluid is vaporized in a heat exchanger, utilizing energy from the geofluid. The working fluid vapor drives a turbine and then passes through a condenser where heat is rejected, conventionally to cooling water, and then to the atmosphere.

The condensate is collected, pumped to the heater pressure (approximately turbine inlet pressure), and the cycle is repeated.

Binary geothermal plants have been designed using working fluids consisting of a single chemical substance; light hydrocarbons such as isobutane, or isopentane are frequently chosen. Analyses at EG&G (Reference 2) and elsewhere have shown that mixtures of these hydrocarbons can result in significantly improved geofluid utilization effectiveness (net electrical energy produced per unit weight of geofluid) for simple binary cycles. Based on those results both pure and mixed light hydrocarbons have been evaluated as candidate working fluids for the advanced binary plants investigated here.

Geofluid Supplied to Plant. Of the geothermal resource types, summarized in Reference 1, liquid dominated hydrothermal resources in the temperature range between about 360 and 450°F are expected for the Milford, Utah and Coyote Springs, Nevada bases. At the present time production well pumps, which keep the geofluid in a liquid state, are not fully developed; therefore, for this analysis it was assumed that pumps would not be used, and some 5 to 10% of the geofluid would be allowed to flash into steam within the wellbore as it flows to the surface. The thermodynamic cycles investigated were tailored to be compatible with the flashing of the geofluid.

Cooling Water Makeup. The resulting cycles will produce condensed steam which can serve to provide a fraction of the required cooling-water makeup (replaces cooling water which has evaporated in the cooling tower). Because of the inherently low thermal efficiency of the geothermal cycles (limited by the relatively low resource temperatures), a larger amount of cooling water makeup is required for a geothermal plant than for a comparably sized nuclear or fossil fueled plant, and makeup water in excess of the flashed-steam condensate produced by the plant is needed. In areas having a shortage of "clean" water to be used for cooling water makeup, the amount of required makeup water is particularly important, and must be considered in an economic evaluation and final cycle selection. Tradeoffs between net power produced and makeup water required must eventually be conducted when the cost of makeup cooling water is known for a given resource location. To provide preliminary information for such a subsequent

analysis, the performance comparisons of cycles presented here include the quantity "cooling water utilization effectiveness," watt hours/lbm makeup cooling water, as well as geofluid utilization effectiveness, watt hours/lbm geofluid. The cooling water evaluation tradeoffs, themselves, have not been made.

2.0 SUMMARY

2.1 Cycles Evaluated

Evaluations were made for binary cycles using several pure and mixed hydrocarbon working fluids for resource temperatures of 365, 400 and 450°F. The working fluids analysed included isobutane, isopentane, 90% propane/10% isopentane (by mass), 80% propane/20% isopentane, 88% isobutane/12% isopentane, and 90% isobutane/10% hexane. These fluids were selected based on results of the studies of Reference 2 which was conducted for pumped wells. Cycles investigated included those which correspond to a 10°F pinch point temperature difference in the heaters, as well as those which expel the geofluid at temperatures sufficiently high to prevent silica precipitation and subsequent injection-well damage (on the order of 160°F for the 365°F resource).

Two types of hybrid coal-geothermal cycles were included in the study for the 365°F resource temperature, and compared with the geothermal cycles. The first of these, initially studied by the City of Burbank, uses the energy from the geofluid for feedwater preheating in a conventional steam cycle (replacing turbine bleed feedwater heating). The second incorporates a bottoming binary cycle in conjunction with a relatively simple steam cycle, where the working fluid in the bottoming cycle is vaporized using energy both from the geofluid and from the condensing steam from the steam cycle. Working fluids investigated for the bottoming cycle were isopentane and 90% propane/10% isopentane.

2.2 Results of Cycle Evaluations

Overall results of the binary geothermal cycle analyses are shown in Figure 1 as geofluid (brine) effectiveness (net plant power in watts, per unit brine flow, in lbm/hr) for the best performing cycle plotted versus resource temperature. The results are shown as circles for cycles having 10°F heater pinch points, and as triangles for cycles whose brine outlet temperatures were held above the silica precipitation limit. These results are compared with the performance of dual-flash steam systems (solid lines), and more conventional binary plants using pure hydrocarbon working fluids (dashed lines), which do

Figure 1. Performance of Advanced Binary Systems Relative to Conventional Systems

not have brine outlet temperature limits imposed. For the 365°F resource temperature, for example, a large improvement in geofluid effectiveness (near 30%) is shown for the advanced binary plant relative to the more conventional binary plants. This improvement results in a substantial reduction in the size of the well field required for a given plant capacity, and therefore, a significant potential reduction in the cost of electricity (up to perhaps 15%) relative to electricity costs predicted for the conventional flash steam and binary plants as shown in Reference 1.

The primary conclusions concerning the advanced binary concept are:

1. Geofluid effectiveness can be increased over the conventional binary and flash steam cycles by the appropriate choice of working fluid for a flashing resource (as was shown in Reference 2 for a pumped resource).

2. The "best" working fluid for a flashing resource is not necessarily the same as for a pumped resource having the same downhole temperature because different wellhead temperatures, and therefore different maximum cycle temperature, will result.

3. For the 365°F resource as a reference, mixtures of 80% propane/20% pentane and 90% isobutane/10% hexane showed comparable geofluid effectiveness (within 1 or 2%), the magnitudes being about 5% higher than for pure isobutane, when no minimum temperature constraint was placed on the spent geofluid. At the highest geofluid effectiveness the least cooling water makeup was required for the isobutane/hexane mixture (about 25% less than for the pure isobutane cycle).

4. Regenerative preheating of the working fluid using turbine exhaust was found to be an effective method for achieving good cycle performance while maintaining a brine outlet temperature sufficiently high to prevent silica precipitation. (Although not evaluated here, working fluid preheating with turbine bleed vapor is another approach for regenerative preheating.)

5. With regenerative preheating (turbine exhaust recuperator) the 90% isobutane/10% hexane mixture showed the highest geofluid effectiveness

(for the 365°F resource) when the geofluid outlet temperature was maintained above the silica precipitation temperature (about 20% higher than for the isobutane cycle). At the turbine inlet temperature for highest geofluid effectiveness this cycle required less cooling water makeup (about 20%) than a pure isobutane cycle.

6. Use of regenerative preheating of the working fluid reduced the condenser heat load and cooling water makeup requirements by about 7% for the cases investigated.

7. The two coal-geothermal hybrid plant types investigated were estimated to produce about the same electrical energy (within approximately 2%) as do separate coal and geothermal plants which use the same amounts of coal and geofluid. The hybrid plant which uses geothermal energy for feedwater heating permits a reduction in coal usage of only about 7% relative to an all-coal plant producing about the same power. The hybrid plant which incorporates a binary bottoming cycle appears to be superior in this regard, and can result in a reduction in coal usage of up to 33% relative to the all-coal plant.

2.3 Geothermal Plant Definition

In order to provide preliminary information from which plant costs could be subsequently estimated, state points, heat balances and heat exchanger sizes were determined for a simple advanced geothermal plant for each of three resource temperatures 365, 400 and 450°F. The plants selected utilized the 90% isobutane/10% hexane working fluid, and were sized to produce 20MW(e) net plant power. Pinch points in the heat exchangers were assumed to equal 10°F, resulting in brine outlet temperatures below the silica precipitation limit; for these plants any silica precipitation encountered is assumed to be treated separately from the power plant.

Net plant brine effectiveness for these plants was predicted to be 8.94, 11.73, and 14.40 watt-hr/lbm geofluid for resource temperatures of 365, 400, and 450°F. Heater and condenser sizes are shown in the body of the report;

generally, however, the units were of high fineness ratio in order to be compatible with the countercurrent flow characteristics required to minimize thermodynamic irreversibilities introduced during the heat exchange processes. The working fluid heaters were designed with geofluid on the tube side and working fluid on the shell side of finned tube heat exchangers. The working-fluid condensers had internally finned tubes with working fluid on the tube side to avoid phase separation during condensing of the working fluid.

3.0 RESOURCE ASSUMPTIONS

The nature of a geothermal resource is the primary factor in determining the proper choice of type of power generation cycle and of working fluid. No specific resource has been identified for the MX system application; therefore, a series of hypothetical resources have been used in this study to simulate those expected in the MX application.

It is expected that the resource will have a downhole temperature in the range of 350°F to 450°F. For this study 365, 400, and 450°F were used as typical downhole temperatures, and it was assumed that there would be no production well pumping. The flow will leave the wells partially flashed with steam. The downhole temperatures were defined (rather than wellhead temperature) to produce a consistent thermodynamic comparison with previous work done considering a 360°F wellhead temperature using production pumps. The 360°F wellhead temperature corresponded to a downhole temperature of 365°F.

The typical production well was assumed to be 5,900 feet deep and to have a downhole pressure of approximately 2,500 psia (approximately the static head at the average liquid conditions). From this information downhole water state conditions are established. Because nothing specific is known about well drawdown characteristics for the hypothetical well, it was assumed that the 365°F resource would produce sufficient flow with a wellhead pressure of 100 psia or less. (This pressure was estimated based on the operating wellhead pressure for a number of flashing geothermal wells such as in the Imperial Valley in California.) Wellhead conditions are then determinable and are shown in Table 1. At the higher downhole temperatures, the wellhead pressure was adjusted according to data taken by James.⁽³⁾ James correlated mass velocity, wellhead pressure and enthalpy for a number of geothermal wells flowing in choked, two phase conditions. For wells at different downhole temperatures with the same mass velocity (the same mass flow rate through the same size well casing), the following relationship was found:

$$\frac{P_1}{P_2} = \left(\frac{h_1}{h_2} \right)^{1.148}$$

TABLE 1. SUMMARY OF ASSUMED RESOURCE DATA

	Downhole Temperature °F	Downhole Enthalpy Btu/lb	Wellhead Enthalpy Btu/lb	Wellhead Pressure psia	Wellhead Temperature °F	Wellhead Quality	Silica Limit Outlet Temperature °F
<u>Flashing Flow (Unpumped)</u>							
	365	341.24	333.65	100	327.6	0.0396	160
	400	377.84	370.25	112.7	336.6	0.0708	184
	450	431.52	423.93	131.6	348.3	0.1193	235
<u>Pumped</u>							
	365	341.24	332.53	250	360.0	0.000	160

Using 100 psia and 365°F downhole temperature, the corresponding pressures to give the same mass flow rate through the same size well were determined for the 400 and 450°F resources. These pressures are shown in Table 1.

It should be noted that assumption of the wellhead pressure determines the wellhead saturation temperature, and therefore, the maximum temperature attainable in the thermodynamic cycle (which is related to the cycle geofluid effectiveness). The wellhead pressure also determines the amount of flow which can be obtained from a single well, and therefore, the required number of wells for a given plant. To properly select the wellhead pressure, an economic optimization is required which trades off plant geofluid effectiveness against the number of wells required. This type of optimization was not performed in the present preliminary study. (With the wellhead pressures assumed for this study, the cycle peak temperature for maximum geofluid effectiveness could not be reached for some working fluids.)

All geofluids contain silica (SiO_2), and its potential deposition is of concern. The silica limit temperature is the temperature below which the silica dissolved in the geothermal fluid may be expected to come out of solution and deposit in the plant equipment or the injection well. An estimate of that temperature was obtained using the solubility curve for quartz and amorphous silica shown in Figure 2. At a given downhole temperature, it is assumed that the saturation concentration of silica in solution is attained by dissolving quartz. The temperature below which the silica will precipitate out of solution is taken as the saturation concentration for amorphous silica. On Figure 2 at a downhole temperature of 365°F, the deposition temperature will be 140°F. The silica precipitation limits given in Table 1 include about a 20°F margin.

The resource was assumed to contain a negligible amount of noncondensable gas. The dissolved solids concentration was assumed to have no appreciable effect on thermodynamic properties.

Figure 2. Silica Deposition Temperature

4.0 ADVANCED BINARY CYCLE STUDY RESULTS

Two possible alternative types of electrical conversion systems were investigated: binary systems using pure and mixed hydrocarbon working fluids, and a combined geothermal-fossil fuel plant. This section discusses the binary system.

Previous studies⁽¹⁾ at EG&G have considered cycle optimization when geothermal wells are pumped, thus providing a hot liquid to the plant. With pumped wells, the entire heat removal from the geothermal resource to the plant is sensible. In the present study, it has been assumed that the resource will not be pumped, and the geofluid at the wellhead will be a mixture of liquid water and steam; some of the heat transfer from the resource will be as a result of condensing the vapor which has flashed. The schemes considered here keep the condensed vapor separated from the unflashed liquid so that it can be used as makeup for a wet cooling tower.

4.1 Binary Cycle Description and Evaluation Base

The previous studies⁽²⁾ indicated that single boiling or supercritical cycles will produce geofluid effectiveness (electrical energy produced per unit mass of geofluid) as high or higher than dual or triple boiling cycles if appropriate working fluids are chosen. Because of the application, it was felt that simplicity of the basic unit was important to ensure high system reliability; therefore, only single boiling or single heating supercritical cycles were considered in this study.

Figure 3 is a schematic diagram of the basic cycle. Heat exchanger (3) condenses the vapor geofluid and does the last heating or boiling of the working fluid. Heat exchangers (1) and (2) are in parallel, with the working fluid flow split in the same proportions as the ratio of condensate to the original liquid geofluid. If it is not important to recover the condensed steam for cooling tower makeup, heat exchangers (2) and (3) could be replaced with a single heat exchanger in which the geothermal liquid streams are mixed.

Figure 3. Schematic Diagram of Advanced Binary Electric Power Plant

The analyses considered here would be the same because the flow ratios (mass flow working fluid/mass flow geothermal fluid) are the same for both exchangers. A number of working fluids have been screened, and their performance determined. These include pure fluids such as isobutane and isopentane and mixtures of similiary hydrocarbons.

For this study it was assumed that all heat rejection would be by wet cooling towers. The condensed geofluid was assumed to be used as makeup cooling water. Water for power plant cooling in the basin and range regions is often in short supply and of poor quality (high saline); therefore, water consumption and quality were variables addressed in the study.

4.2 Power Cycle Performance with Pure Hydrocarbon Working Fluids, 365°F Resource

Figure 4* indicates the performance for a cycle using isobutane; geofluid effectiveness is plotted versus makeup water effectiveness. The geofluid effectiveness is the net power produced in watts for each lb/hr of geofluid flow, and the makeup water effectiveness is the net power produced in watts for each lb/hr of makeup cooling water. For these cycle evaluations the parasitic power subtracted from the turbine power includes working fluid pump, and cooling tower fan and pump power values. Consideration of the cooling water makeup adds an additional parameter to the problem, the concentration factor. The concentration factor (cycles of concentration) is defined as the ratio of the total dissolved solids in the circulating (or blowdown) water to that in the makeup water. Two cases have been treated here: first, if the external makeup water is good quality, the concentration factor was taken to be 10 (the curves with this assumption are labeled a-a); second, if the external makeup water is of poor quality, for example, treated geothermal water, the concentration factor was taken to be 5 (the curve with this assumption is labeled b-b). The geothermal condensate is used for makeup in both cases, and its concentration factor was assumed to be 10.

The solid lines in Figure 4 show cycle performance assuming that all heat exchangers have 10°F pinch points. For these curves the geofluid outlet

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*Note: The performance maps are purposely drawn with the same coordinate scales even though the specific range covered by the curves on any one figure is small (for ease in comparing various results).

Figure 4. Cycle Performance for 365°F Geothermal Resource with Isobutane Working Fluid

temperature is below the 160°F limit for silica deposition (for the 365°F resource). The dashed lines represent the performance if the geofluid outlet temperature is maintained at 160°F to eliminate the silica deposition problem. The left extremity of each curve represents the point at which the working fluid turbine inlet temperature is within 10°F of the wellhead temperature. Note that if this temperature could be raised, the geofluid effectiveness would be increased. The assumed geofluid wellhead pressure is, therefore, limiting the performance to some extent for this working fluid.

The isobutane leaves the turbine in a superheated state. There is the possibility of removing some of the superheat from the vapor and using the energy to preheat the liquid before it enters the first heaters. Figure 5 shows this situation, schematically. Regenerative preheating using the turbine exhaust recuperator allows an increase in geofluid effectiveness when the geofluid outlet temperature is maintained at 160°F or above. It has the added benefit of reducing the external cooling load which must be removed in the condenser and cooling tower, and will result in a slightly smaller condenser and cooling tower and a small parasitic work association with cooling. The third set of curves (shown as dash-dot lines) in Figure 4 depicts the performance under these conditions. Note that the geofluid effectiveness is above that for the 160°F limit but below that for 10°F pinch point. For the 160°F geofluid outlet limit, the makeup water effectiveness is higher using the recuperator than without it because of the reduced heat rejection load, and because less geofluid is required for preheating. (Conversely, at a given makeup water effectiveness, the recuperator provides higher geofluid effectiveness.) This appears to be a viable approach for eliminating the silica precipitation problem.

Figure 4 shows, parametrically, how geofluid effectiveness varies with required cooling water makeup. The specific point on a given curve which results in minimum cost of electricity, depends on the relative "costs" of makeup water and geofluid; determination of that point has not been attempted in this study.

Figure 6 shows, in the same format as for Figure 4, cycle performance with isopentane as the working fluid instead of isobutane. The performance in terms of maximum geofluid effectiveness is approximately 20% lower than for the

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Figure 5. Schematic Diagram of Advanced Binary Electrical Power Plant with a Recuperator

Figure 6. Cycle Performance for 365°F Geothermal Resource with Isopentane Working Fluid

isobutane cycle. (Propane also resulted in lower performance than isobutane.) Isobutane appears to be the best of the pure hydrocarbons in this family at the 365°F resource condition. These results are generally consistent with Reference 2.

4.3 Power Cycle Performance Comparison of Hydrocarbon Mixtures, 365°F Resource

Because of the success of mixtures of hydrocarbons shown in studies involving pumped wells, it was decided to investigate binary mixtures of these hydrocarbons. For a 365°F resource with pumped wells, a mixture of 90% by mass propane and 10% isopentane produced the best geofluid effectiveness. Figure 7 shows this working fluid used in cycles with the flashing wells. Note that the performance is not as good as for pure isobutane, because a higher turbine inlet temperature is required with the mixed fluid to maximize performance than can be provided by the flashing well at the assumed wellhead pressure (the curves are still increasing rapidly to the left of the plot). Turbine inlet temperatures higher than those possible with a wellhead pressure of 100 psia would give improved performance; therefore, this is probably not the best working fluid choice for this particular application. Regeneration was not investigated for this working fluid because it is not superheated at the turbine outlet, and differences in temperature between the turbine exhaust and condenser outlet are relatively small for good recuperator operation.

A working fluid with more isopentane will maximize geofluid effectiveness at lower turbine inlet temperatures, and possibly be better for this application. Figure 8 illustrates this point. With a working fluid having 80% propane (mass)/20% isopentane, the geofluid effectiveness is about 5% higher than for isobutane when obtained for 10°F pinch points, and about 2% higher for the 160°F geofluid outlet limit case. Again, desuperheating regeneration was not attempted with this fluid.

The next working fluid choices were first: moving one increment heavier in the primary constituent to isobutane/isopentane, and then second: moving to heavier secondary constituents. Figures 9 and 10 show the results for

Figure 7. Cycle Performance for 365°F Geothermal Resource with 90% (mass) Propane/10% Isopentane Working Fluid

Figure 8. Cycle Performance for 365°F Geothermal Resource with 80% (mass) Propane/20% Isopentane

88% isobutane/12% isopentane and 90% isobutane/10% hexane. When holding 10°F heater pinch points, the values of geofluid effectiveness are higher for the 90% isobutane/10% hexane mixture, giving a 3.4% increase over pure isobutane with water makeup requirements about 25% less than for the isobutane cycle. Both fluids show substantial effects resulting from regeneration (reaching within about 1% of the 10°F pinch point values while maintaining a 160°F outlet geofluid temperature).

For a 365°F resource, the best of the working fluids investigated were 90% isobutane/10% hexane and 80% propane/20% isopentane. The former has the advantage of allowing regeneration if necessary, and also has a lower maximum pressure (500 psia versus 1,000 psia). In addition, cooling water makeup requirements are generally smaller for the isobutane/hexane mixture. Both cycles entail supercritical heating.

4.4 Power Cycle Performance Comparison, 400°F Resource

Figures 11 through 14 show similar results for a 400°F resource. Under the assumption of higher wellhead pressures at higher resource temperatures (as discussed in Section 3.0), the turbine inlet temperatures can increase approximately 13°F. At the higher turbine inlet temperature the peak cycle pressures increase substantially. For this reason, and because the geofluid effectiveness of the 80% propane/20% isopentane mixture was only 1.5% higher (for the 10°F pinch point cases) than that of 90% isobutane/10% hexane, the propane mixtures were not evaluated for the 400°F resource.

As the resource temperature rises, the penalty associated with maintaining the geofluid outlet temperature above the silica deposition limit becomes greater due to two effects. First, with higher resource temperatures, the silica deposition temperature increases; and second, the temperature to which the geofluid could be cooled with a 10°F pinch point decreases. The pure fluids considered illustrate this point (Figures 11 and 12). For an isobutane system with 10°F pinch points, the geofluid effectiveness increased relative to the 365°F resource, while that limited by the silica deposition temperature increased 8%. The increase in performance due to regeneration is smaller for the 400°F resource than for the 365°F.

Figure 9. Cycle Performance for 365°F Geothermal Resource with 80% (mass) Isobutane/12% Isopentane

Figure 10. Cycle Performance for 365°F Geothermal Resource with 90% (mass) Isobutane/10% Hexane Working Fluid

Figure 11. Cycle Performance for 400°F Geothermal Resource with Isobutane Working Fluid

Figure 12. Cycle Performance for 400°F Geothermal Resource with Isopentane Working Fluid

Although isopentane did not perform as well as isobutane in terms of geofluid effectiveness at this temperature (considering with the behavior at 365°F), the makeup water effectiveness was higher than for any other candidate. With a regenerator at maximum geofluid effectiveness, the makeup water effectiveness was between 180 and 210 w-hr/lb makeup (approximately three times that of the other fluids). If makeup water is at a premium, optimization studies conducted during the design phase may influence final working fluid selection.

Figures 13 and 14 depict the performance of mixtures of isobutane with 12% pentane and 10% hexane respectively. The 90% isobutane/10% hexane mixture produced the highest geofluid effectiveness of the mixtures analyzed, and for 10°F heater pinch points resulted in a geofluid effectiveness 15% higher than for the isobutane cycle; the cycle peak pressure was found to be 650 psia. For the isobutane/isopentane mixture, Figure 13 shows that regeneration using the desuperheat of the turbine exhaust resulted in a maximum geofluid effectiveness which regained 21% of the loss in effectiveness incurred by accepting the high geofluid outlet temperature. With a mixed hydrocarbon working fluid, the condensation takes place over a range of temperatures, and the possibility exists for using partial condensation for feed liquid heating. Figure 14 shows that when this is done for the isobutane/hexane mixture, 40% of the loss in effectiveness between the 10°F-pinch-point and the silica-precipitation-limit values of geofluid effectiveness is recovered while maintaining the high geofluid outlet temperature; corresponding improvements in makeup water requirements are also shown.

4.5 Power Cycle Performance for 450°F Resource

Limited evaluation was performed for the 450°F resource condition. The working fluid 90% (mass) isobutane/10% hexane, which was judged, overall, to be the best mixture at 365 and 400°F, was evaluated at several turbine inlet temperatures for the 450°F resource at a wellhead pressure defined as discussed in Section 3. The maximum geofluid effectiveness found was 15.4 watt hours/lbm geofluid; the corresponding cooling water makeup effectiveness was 77 watt-hr/lbm cooling water for the "clean" (10 cycles of concentration) cooling water. For comparison, corresponding values were 12.3 and 61 for the same mixture at the 400°F resource condition. The peak cycle pressure for the 450°F resource was 650 psia, the same as for the 400°F resource.

Figure 13. Cycle Performance for 400°F Geothermal Resource with 88% (mass) Isobutane/12% Isopentane Working Fluid

Figure 14. Cycle Performance for 400°F Geothermal Resource with 90% (mass) Isobutane/10 Hexane Working Fluid

4.6 Power Cycle Analysis Conclusions

The results of this cycle evaluation study indicate:

1. Working fluid mixtures have thermodynamic performance improvements over pure hydrocarbon working fluids for the unpumped (flashing) production well application as was the case for the pumped well case. The choice of working fluid for the flashing well is not necessarily the same as for the pumped well (for the same downhole condition).

2. Differences in geofluid effectiveness with changing resource temperatures are generally less with the flashing wells than the pumped wells because the maximum turbine inlet temperature is limited by the wellhead temperature which changes less for flashing wells than for pumped wells.

3. A penalty in geofluid effectiveness results when limiting the geofluid outlet temperature to ensure against silica precipitation. The hotter the resource, the greater the penalty. This penalty can be partially or totally offset by using the turbine exhaust stream to preheat (regeneratively) the liquid feed from the pump to the first geofluid heat exchanger. For mixtures, regenerative preheating can possibly include partial condensation of the turbine exhaust. Regeneration has the added advantage of decreasing the heat rejection load, and makeup cooling water required (on the order of 10%).

4. Small differences in geofluid effectiveness will exist between pumped and unpumped wells. The magnitude of the difference varies with working fluid, wellhead pressure, etc., and is impossible to quantify, generally. As an example, however, comparing a 96% isobutane/4% heptane cycle utilizing a pumped 365°F resource (Reference 2), with a 90% isobutane/10% hexane cycle utilizing a flashing well at the same downhole conditions, the pumped-well plant would provide about 3% lower net geofluid effectiveness. Both plants were assumed to maintain a geofluid outlet temperature at 160°F, and to utilize turbine exhaust recuperators. (Major advantages of pumped wells are: greatly increased well productivity, reduced geofluid precipitation problems, and elimination of the need for handling two-phase geofluid.)

5. Selection of a cycle and working fluid to produce the minimum cost of electricity requires consideration of the "cost" of cooling water makeup as well as the "cost" of geofluid. If water costs are sufficiently high, the highest geofluid effectiveness point, for example, may not result in the lowest cost of electricity if that cycle requires more makeup water than another.

6. To present a summary of the comparison of the cycles assuming minimal effects of cooling water makeup cost, the following tables (Table 2) show values of highest geofluid effectiveness and corresponding values of makeup water effectiveness at each of the resource conditions for cycles having 10°F heater pinch points, and for cycles having geofluid outlet temperatures equal to the silica precipitation temperature (with recuperators). The values in the tables assume the "clean" (10 cycles of concentration) cooling water makeup, and are shown as net geofluid effectiveness in the upper left corner of each box followed by cooling water makeup effectiveness in the lower right.

Table 2 shows that for the 365°F resource, 90% isobutane/10% hexane and 80% propane/20% isopentane appear to be the two best working fluids evaluated. The 90% isobutane/10% hexane mixture results in almost the same geofluid effectiveness (within 2%) and requires less cooling water makeup (17% less) than does the 80% propane/20% isopentane mixture. The peak cycle pressure is 500 psia for the isobutane/hexane mixture versus 1,000 psia for the propane/isopentane mixture. When the geofluid outlet temperature is held sufficiently high to prevent silica precipitation, the isobutane/hexane mixture would be preferred in all respects.

Of the mixtures evaluated at 400°F, 90% isobutane/10% hexane also resulted in the best cycle performance. This working fluid was selected for plant performance evaluation and preliminary sizing of heat exchangers as discussed in Section 6.

TABLE 2. CYCLE PERFORMANCE SUMMARY

10°F Heater Pinch Points

Working Fluid	Resource Downhole Temperature				
	365°F	400°F	450°F		
Isobutane	8.8 46	10.7 56			
Isopentane	7.0 98	9.3 97			
90 Propane/10% Isopentane	8.6 65				
80% Propane/20% Isopentane	9.3 52				
88% Isobutane/12% Isopentane	9.0 64	11.7 61			
90% Isobutane/10% Hexane	9.1 63	12.3 61	15.4 77		

Geofluid Outlet Temperature at Silica Precipitation Limit

	365°F	400°F	
Isobutane	8.1 54	8.7 65	
Isopentane	7.0 98	8.3 210	
90% Propane/10% Isopentane	8.0 56		
80% Propane/20% Isopentane	8.0 54		
88% Isobutane/12% Isopentane	8.8 59	9.5 76	
90% Isobutane/10% Hexane	9.1 60	10.4 85	

5.0 HYBRID COAL-GEOTHERMAL PLANT CONCEPTS

Another way in which a geothermal resource may be utilized in production of electricity is to be used in conjunction with a coal-fired steam plant. Two concepts have been included in this study: the first, using the geofluid to preheat the feedwater (taking the place of steam bled from the turbine for regenerative feedwater heating), was studied previously in Reference 4. A second concept, studied here, involved using a secondary or bottoming cycle in conjunction with a simple steam cycle. The steam cycle obtains its energy from coal, and the bottoming cycle receives its energy from both the geofluid and the condenser from the steam cycle.

To provide a consistent basis for comparison a baseline coal-fired steam plant was devised against which to measure the utilization of geothermal energy. It was decided that for this small size (20MW net) the plant should be relatively simple. Figure 15 is a schematic design of the cycle. The maximum cycle temperature was taken as 1000°F, a normal operating limit. The high pressure in the cycle was 1,500 psia which is a relatively low pressure, and gave a maximum turbine outlet moisture of approximately 12% without reheating. Three regenerative feedwater heaters were used, providing an increment in feedwater temperature of approximately 125°F. For a plant which produced 20MW(e) net power, the coal requirement was 10.62 tons/hour of 11,500 Btu/lb coal, (assuming a furnace efficiency of 75%). All hybrid schemes were compared to this steam plant, and to the best binary geothermal plant as described in the previous section.

5.1 Hybrid Plant, Geothermal Feedwater Heating

As mentioned previously, one possible use of geothermal energy considered here had been investigated in the City of Burbank study⁽⁴⁾ which used the geofluid to replace the feedwater heaters. The 365°F resource was assumed for the comparisons; for this resource two of the three feedwater heaters can be replaced with heaters utilizing geothermal energy. This system was compared with the baseline coal plant; the results are shown in Table 3.

Figure 15. Baseline Coal-Fired Steam Plant

TABLE 3. COMPARISON OF 20MW(e) HYBRID PLANTS
WITH GEOTHERMAL AND COAL PLANTS FOR A 365°F RESOURCE

	Geothermal Rate (lb/hr x 10 ⁻⁶)	Coal Rate (tons/hr)	Percentage Increase in Power Produced over Separate Plants
Baseline Coal Plant	N/A	10.62	0.0
Baseline Geothermal Plant	2.144	N/A	0.0
Geothermal Feedwater Heating			
No Additional F.W. Heating	0.188	9.91	+1.2
One Stage Additional Heating	0.113	9.87	+1.8
Binary Bottoming Cycle with Geothermal Heating			
Isopentane			
No Steam Cycle F.W. Heating	0.682	7.09	+1.4
One Stage Steam F.W. Heating	0.671	7.04	+2.4
0.9 Propane 0.1 Isopentane			
No Steam Cycle F.W. Heating	0.715	7.23	-1.4
One Stage Steam F.W. Heating	0.703	7.18	-0.4

Also shown in Table 3 is an additional comparison between the hybrid system and a separate geothermal system. The rate of coal burned and the rate of geofluid flow are given for the two 20MW(e) baseline plants. The final comparison to be made is the amount of power that would be generated by the hybrid system over separate coal and geothermal plants with the same coal and geofluid inputs. Table 3 shows that the use of geothermal feedwater heating produces about the same power for the same geofluid and coal usage as the separate baseline plants, but can reduce the coal requirements for producing 20MW(e) by approximately 7%.

5.2 Hybrid Plant - Bottoming Cycle

The other coal-geothermal hybrid system involved a standard steam cycle which rejects heat in the condenser at a high temperature (approximately 330°F) at the point where the steam exists the turbine as saturated vapor. The heat transferred from the steam is used to do the final heating or boiling of a secondary working fluid. The preheating of this working fluid (and possibly some boiling) is accomplished by heat transferred from the geofluid. It appeared that a pure fluid at a subcritical state would better fit the condensing curve of the steam; isopentane was chosen as the first working fluid to be evaluated since the pentane boiling characteristics better "fit" the steam condensation temperature than the other pure hydrocarbons of that family. Table 3 includes the results of this study, and shows that a much larger geofluid flow (and therefore, smaller coal usage) was possible with this arrangement, although the power produced is only slightly higher (1.4%) than can be produced by the separate coal and geothermal plants. (For this arrangement, about 62% of the gross power was produced by the binary bottoming cycle.) Adding a regenerative feedwater heating stage to the steam cycle reduced the geofluid flow required without affecting the coal regeneration, and thereby slightly improved the hybrid performance relative to individual plants (2.4% compared to 1.4%).

One mixture (90% isopentane/10% propane) was evaluated; however, its performance as shown in Table 3 was not as good as for pure isopentane, because the large isothermal heat rejection from the condensing steam to the working fluid is best matched (thermodynamically) by the boiling of a pure fluid.

5.3 Hybrid Cycle Study Conclusions

Although this study was preliminary in nature, certain conclusions can be made:

1. The use of geofluid as a feedwater heater replacing regenerative turbine bleed in a conventional steam cycle decreases the coal consumption and shows a small advantage in the hybrid system over two separate coal and geothermal plants. The amount of geofluid to do this, and thereby the reduction in coal usage, is relatively small (approximately 7% for the 365°F geothermal resource).

2. The use of a bottoming cycle with a relatively simple steam cycle shows more promise. In this configuration more geofluid may be used in a fixed size plant giving a reduction in coal usage of about 33%. The power produced was slightly higher (2.4%) than for individual coal and geothermal plants utilizing the same amounts of coal and geofluid.

3. Mixtures in the bottoming cycle do not appear to give better performance than pure fluids because of the large fraction of heat transferred to the working fluid by the condensing steam at a fixed temperature.

4. The hybrid plant incorporating the bottoming cycle may show promise if a substantial reduction in coal usage proves to be advantageous, and if the power required at a given site exceeds the geothermal plant size for optimum cost of electricity.

6.0 20MW(e) ADVANCED BINARY PLANT DEFINITION

As the next step in the investigation of the use of geothermal energy for powering MX missile bases, the results of the thermodynamic studies presented in Section 4 were used to determine state points, energy balances, and heat exchanger sizes for binary geothermal plants utilizing resources having temperatures of 365, 400 and 450°F.

For this preliminary plant-definition effort, heaters and condensers for the plants were selected consistent with 10°F pinch points. These heat exchangers result in a simple plant configuration (without recuperators) having high performance, but reduce the geofluid outlet temperature below the silica precipitation limit. Subsequent conceptual designs would investigate alternate geothermal plant configurations. Investigation of hybrid coal-geothermal plants was relegated to a position of lesser immediate interest, and further evaluation of those concepts was not undertaken here.

6.1 Power Cycle Description

The cycle selected is shown in Figure 3. Because the wells are not pumped, the well flow will be flashing. The steam is separated from the liquid geofluid and passed through heat exchanger (3) where it is condensed while transferring heat to the hottest working fluid. The condensate from this heat exchanger then flows through heat exchanger (2) where it heats part of the working fluid. The remainder of the working fluid is heated with the unflashed geofluid. Heat exchangers (1) and (2) are similar (the ratio of working fluid to geofluid flow rate is the same in each heater). They are separate only to allow the recovery of the condensed steam geofluid which is used as cooling water makeup. The working fluid is at supercritical pressures in these heaters. It then flows through the turbine and then to the condenser in which the flow is countercurrent to give maximum thermodynamic benefit. The pump completes the cycle discharging to the heaters (1 and 2).

6.2 Heat Balance and Heat Exchanger Sizing Basis

Heat balances and state points to produce 20MW(e) net energy for a

unit were calculated and are given in Tables 4, 5, and 6 for the three different resources. Of the two better performing mixtures found from the cycle analyses of Section 4.3, isobutane/hexane and propane/pentane, the 90% isobutane/10% hexane mixture was selected because of the lower pressures and smaller pumps, as well as lower cooling water makeup requirements. The flows and thermodynamic states were used to size the heat exchangers for this application. Calculations sizing these heat exchangers were made, and the results were confirmed using the HTRI heat exchanger analysis codes ST-4 and CST-1.

Certain design rules were used for the heat exchangers. The geofluid was placed in the tubes of each exchanger because of its possible corrosive nature and probable fouling. It was felt that ease of cleaning was an important criterion for these exchangers on the geofluid side. Additionally, this arrangement allowed for use of external fins on the working fluid side of the exchangers. The convective heat transfer coefficient was lower for the working fluid than for the geofluid so it was expected that use of low fin tubes would be advantageous. Also, because the working fluid side is the clean side, the magnified fouling effect on finned surfaces would be eliminated. This approach placed the higher pressure on the shell side (requiring a thicker, more costly shell), but it was thought that the advantages of this configuration outweighed advantages shown by other configurations.

The condenser, however, was handled in a different manner. The prime concern here was to establish integral condensation (the liquid and vapor phases held in infinite contact throughout the condensation process) which was achieved by placing the condensing fluid inside the tubes. Because of the low heat transfer coefficient for condensation, it was decided to use internally finned tubes to augment the heat transfer. Studies indicated that horizontal heat exchangers performed as well as vertical, so horizontal units were chosen because of the relatively large length of the units.

In order to fully utilize the low temperature resource and resultant close temperature approaches in the heat exchangers, pure countercurrent flow heat exchangers (E-shells) were selected. This configuration provides a higher thermodynamic efficiency than multi-tubepass units which have a combination of counter and co-current flows.

TABLE 4. HEAT BALANCE FOR 20MW(e) MX GEOTHERMAL PLANT
FOR A 365°F RESOURCE USING 90% ISOBUTANE/10% HEXANE

State	Pressure (psia)	Temperature (°F)	Enthalpy (Btu/lbm)	Specific Volume (ft ³ /lbm)	Mass Flow Rate lb/hr x 10 ⁻⁶
1	530.0	84.2	-780.68	.0289	2.680
2	530.0	84.2	-780.68	.0289	2.521
3	530.0	84.2	-780.68	.0289	0.160
4	525.0	283.5	-628.96	.0588	2.521
5	525.0	283.5	-628.96	.0588	0.160
6	525.0	283.5	-628.96	.0588	2.680
7	520.0	300.2	-582.39	.1226	2.680
8	500	296.4	-582.39	.1312	2.680
9	51.4	142.6	-614.52	1.9685	2.680
10	49.4	80.5	-783.92	.0291	2.680
11	100	327.9	333.65	.2112	2.366
12	77.6	310.2	1183.0	5.632	0.141
13	75.6	308.2	278.06	.0176	2.225
14	75.6	308.2	278.06	.0176	.141
15	70.6	138.2	106.20	.0163	2.225
16	70.6	138.2	106.20	.0163	.141
17	50.0	70.0	38.09	.0161	20.981
18	45.0	91.6	59.37	.0161	20.981

Heat Loads: (Btu/hr x 10⁻⁸)
 Heater #1: 3.824
 Heater #2: .243
 Heater #3: 1.248
 Condenser: 4.540

Power: (MW)
 Turbine: 25.24
 Pump: 2.55
 Heat Rejection: 1.69
 Injection Pumping: 0.55
 Generator: 22.24

TABLE 5. HEAT BALANCE FOR 20MW(e) MX GEOTHERMAL PLANT
FOR A 400°F RESOURCE USING 90% ISOBUTANE/10% HEXANE

State	Pressure psia	Temperature °F	Enthalpy Btu/lbm	Specific Volume (ft ³ /lbm)	Mass Flow Rate lb/hr x 10 ⁻⁶
1	680	90.6	-776.82	.0290	2.512
2	680	90.6	-776.82	.0290	2.334
3	680	90.6	-776.82	.0290	0.179
4	675	301.0	-622.18	.0529	2.334
5	675	301.0	-622.18	.0529	0.179
6	675	301.0	-622.18	.0529	2.512
7	670	326.9	-579.44	.0905	2.512
8	650	326.5	-579.44	.0905	2.512
9	51.4	145.1	-614.08	1.7046	2.512
10	49.4	80.5	-781.09	.0293	2.512
11	113.1	336.9	370.75		1.705
12	113.1	336.9	1190.1	3.946	0.121
13	111.1	333.6	304.6	.0178	1.584
14	111.1	333.6	304.6	.0178	0.121
15	106.1	110.1	78.1	.0162	1.584
16	106.1	110.1	78.1	.0162	0.121
17	50	70.0	38.1	.0161	19.696
18	45	91.3	59.4	.0161	19.696

Heat Loads: (Btu/hr x 10⁻⁸)
 Heater #1: 3.609
 Heater #2: .277
 Heater #3: 1.074
 Condenser: 4.195

Power: (MW)
 Turbine: 25.50
 Pump: 3.14
 Heat Rejection: 1.54
 Injection Pumping: .37
 Generator: 21.91

TABLE 6. HEAT BALANCE FOR 20MW(e) MX GEOTHERMAL PLANT
FOR A 450°F RESOURCE USING 90% ISOBUTANE/10% HEXANE

State	Pressure (psia)	Temperature (°F)	Enthalpy (Btu/lbm)	Specific Volume (ft ³ /lbm)	Mass Flow Rate lb/hr x 10 ⁻⁶
1	680	90.6	-776.82	.0290	2.500
2	680	90.6	-776.82	.0290	2.163
3	680	90.6	-776.82	.0290	0.337
4	675	281.8	-645.68	.0435	2.167
5	675	281.8	-645.68	.0435	0.337
6	675	281.8	-645.68	.0435	2.500
7	670	326.9	-579.44	.0905	2.500
8	650	326.5	-579.44	.0905	2.500
9	51.4	145.1	-614.08	1.7046	2.500
10	49.4	80.5	-781.09	.0293	2.500
11	113.1	336.9	423.93	.0293	1.389
12	113.1	336.9	1190.1	3.946	0.187
13	111.1	333.6	304.6	.0178	1.202
14	111.1	333.6	304.6	.0178	0.187
15	106.1	100.6	68.65	.0162	1.202
16	106.1	100.6	68.65	.0162	1.202
17	50	0.0	38.09	.0161	19.600

Heat Loads: (Btu/hr x 10⁻⁸)
 Heater #1: 2.836
 Heater #2: .441
 Heater #3: 1.656
 Condenser: 4.175

Power: (MW)
 Turbine: 25.37
 Pump: 3.13
 Heat Rejection: 1.53
 Injection Pumping: .28
 Generator: 21.80

6.3 Heat Exchanger Configurations

A summary of the heat exchanger configurations is presented in the following paragraphs.

365°F Resource. The working fluid condensers selected for this application are four horizontal E-shell units 8 feet in diameter and 54 feet long connected in parallel. Tubeside condensation is used to encourage integral condensation. Each unit has 5,059, 0.75 inch O.D. tubes of the Noranda type with longitudinal internal fins to augment the inside surface area. The tube material is a 90% copper/10% nickel alloy. The tube pitch is 1.062 inches on a 90° layout angle. No-tubes-in-window baffles (15% cut) were selected to eliminate a tube vibration problem indicated with segmental baffles.

The steam condenser was sized as a single horizontal unit 75 inches in diameter and 49 feet long. Since only a single component is to be condensed, differential condensation is not a problem; however, the steam was condensed on the tubeside so that fins could be used externally to augment the working fluid heat transfer. The unit has 1,983, 1.0 inch O.D. (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. No-tubes-in-window baffles (15.2% cut) were selected to eliminate a tube vibration problem indicated with segmental baffles.

The larger of the two heaters, HX#1, consists of two horizontal E-shell units 72 inches in diameter and 55 feet long connected in series. The units are horizontal with the working fluid on the shellside. Each unit has 1,831, 1.0 inch (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. No-tubes-in-window baffles (15.0% cut) were used to eliminate a tube vibration problem.

The smaller of the two heaters, HX#2, consists of six horizontal E-shell units 15.25 inches in diameter and 20 feet long connected in series. The units are horizontal with the working fluid on the shellside. Each unit has 86, 1.0 inch O.D. (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. Segmental baffles (32.7% cut) were used since tube vibration was not a problem.

400°F Resource. The working fluid condensers selected for this application are four horizontal E-shell units 8 feet in diameter and 50 feet long connected in parallel. As for the 365°F resource, tubeside condensation is used to encourage integral condensation. Each unit has 5,059, 0.75 inch O.D. tubes of the Noranda type with longitudinal internal fins to augment the inside surface area. The tube material is a 90% copper/10% nickel alloy. The tube pitch is 1.062 inches on a 90° layout angle. No-tubes-in-window baffles were selected to eliminate a tube vibration problem indicated with segmented baffles.

The steam condenser was sized as a single horizontal shell unit 63 inches in diameter and 43 feet long. The condensing steam was placed on the tubeside. The condenser has 1,315, 1.0 inch O.D. (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. No-tubes-in-window baffles (17.4% cut) were selected to eliminate a tube vibration problem indicated with segmented baffles.

The larger of the two heaters, HX#1, has three horizontal E-shell units 78 inches in diameter and 45 feet long connected in series. The working fluid was placed on the shellside to take advantage of external fins on the tubes. Each unit has 2,157, 1.0 inch (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. No-tubes-in-window baffles (15% cut) were selected to eliminate a tube vibration problem indicated with segmented baffles.

The smaller of the two heaters, HX#2, consists of six horizontal E-shell units 17 inches in diameter and 28 feet long connected in series. Here too, the working fluid was placed on the shellside to take advantage of external fins on the tubes. Each unit has 713, 1.0 inch (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. Segmented baffles (31.7% cut) were used since tube vibration was not a problem.

450°F Resource. The working fluid condensers selected for this application are four horizontal E-shell units 8 feet in diameter and 50 feet long connected in parallel. Again, tubeside condensation is used to encourage

integral condensation. Each unit has 5,059, 0.75 inch O.D. tubes of the Noranda type with longitudinal internal fins to augment the inside surface area. The tube material is a 90% copper/10% nickel alloy. The tube pitch is 1.062 inches on a 90° layout angle. No-tubes-in-window baffles were selected to eliminate a tube vibration problem indicated with segmental baffles.

The steam condenser was sized as a single horizontal E-shell units 66 inches in diameter and 48 feet long. The condensing steam was placed on the tubeside. The condenser has 1,510, 1.0 inch O.D. (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. No-tubes-in-window baffles (15.62% cut) were selected to eliminate a tube vibration problem indicated with segmental baffles.

The larger of the two heaters, HX#1, has give horizontal E-shell units 52 inches in diameter and 40 feet long connected in series. The working fluid was placed on the shellside. Each unit has 918, 1.0 inch (nominal) Admiralty metal tubes of the external low fin type (19 fins/inch). The tube pitch is 1.312 inches in a 90° layout angle. Segmental baffles (15.7% cut) were used since tube vibration was not a problem.

The smaller of the two heaters, HX#2, has five units 24 inches in diameter and 35 feet long connected in series. The working fluid is on the shellside to take advantage of external low fin type (19 fins/inch). The tube pitch is 1.312 inches on a 90° layout angle. No-tubes-in-window baffles (15% cut) were selected for these limits.

A typical plant layout has been made using these components; a sketch is shown in Figure 16.

6.4 Heat Exchanger Design Conclusions

The following conclusions were reached concerning heat exchanger design.

1. In the geothermal heat exchangers, the geofluid was always taken as the tubeside fluid. This allows for the containment of the corrosive

FIGURE 16. **Mx Binary Power Plant:
20 MW Module**

INEL-S-33 448

geofluid, provides ease of cleaning the geofluid side, and allows for external fins to augment the working fluid heat transfer.

2. In the condenser, the working fluid was taken as the tubeside fluid. This was done in an attempt to ensure integral mixing of the condensing phases. Internal fins were used to augment the tubeside heat transfer.

3. Horizontal condensers were used to minimize the height of the system.

4. Heat exchangers were generally long and thin in order to maintain true countercurrent flow, which means that tubeside flow area and velocity must be controlled for each single pass.

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