DIRECT USE GEOTHERMAL APPLICATIONS FOR BRAZED PLATE HEAT EXCHANGERS

DIRECT USE GEOTHERMAL APPLICATIONS FOR BRAZED PLATE HEAT EXCHANGERS

Prepared For:

U. S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, ID 83401

Contract No. DE-FG07-90ID 13040

Prepared By:

Kevin Rafferty, P.E.

Geo-Heat Center
Oregon Institute of Technology
3201 Campus Drive
Klamath Falls, OR 97601

DISCLAIMER STATEMENT

This report was prepared with the support of the U. S. Department of Energy (DOE Grant No. DE-FG07-90ID 13040). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the view of DOE.

TABLE OF CONTENTS

1. Introduction 1

2. Brazed Plate Heat Exchangers 3

Construction 3

Application Considerations 5

Heat Exchanger Material Cost 7

Brazed Plate Heat Exchanger
Performance in Geothermal Fluids 9

Life Cycle Costs 11

3. Conclusions 14

LIST OF FIGURES

Figure 1. Use of a Heat Exchanger..... 1

Figure 2. Plate and Frame Heat Exchanger..... 3

Figure 3. Brazed Plate Heat Exchanger..... 4

Figure 4. Cost for Plate and Frame Heat Exchanger..... 8

Figure 5. Cost for Brazed Plate Heat Exchanger..... 8

Figure 6. Combined Costs..... 9

LIST OF TABLES

Table 1. Brazed Plate Heat Exchanger Application Limitations..... 2

Table 2. Test Site Fluid Chemistry..... 10

Introduction

Most geothermal fluids used for direct use purposes contain various chemical species which can be detrimental to conventional materials of construction. For this reason, the standard design practice is to isolate the geothermal fluid from the balance of the system through the use of a heat exchanger as illustrated in Figure 1 (ASHRAE, 1991). In the majority of applications, the plate and frame heat exchanger has been the design of choice for this duty. Plate and frame heat exchangers offer many advantages for geothermal applications including their availability in corrosion resistant materials (stainless steel) at reasonable cost. In addition, this design permits disassembly for cleaning or the addition of plates to accommodate increased heating loads. The units are very compact and efficient with heat transfer rates 3 to 10 times those of shell and tube exchangers (ASHRAE, 1991).

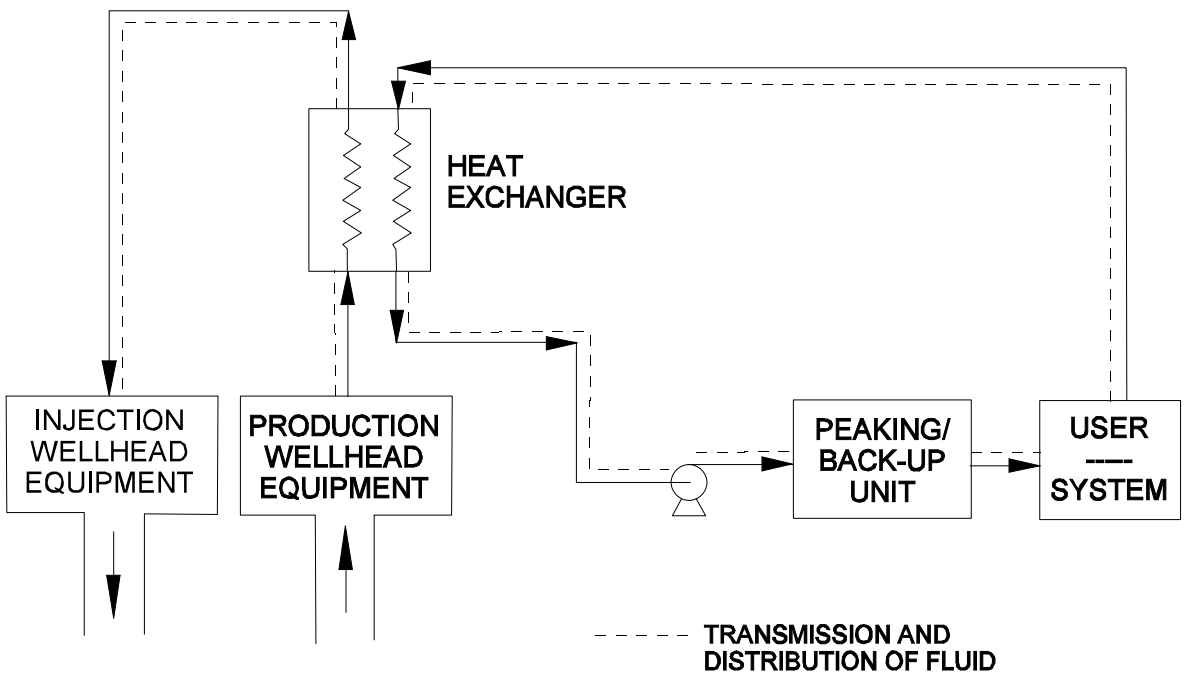

Figure 1.

In very small applications (less than approximately 20 ft^2 heat transfer area), however, the cost of plate and frame heat exchangers becomes uneconomical. These applications would include the space and domestic hot water heating for residences and small buildings, and small commercial and industrial process applications.

Recently, a low-cost version of the plate heat exchanger, the brazed plate heat exchanger has become available. Due to their simpler construction, these units can be economically produced in very small sizes. Considering the reduced cost (as little as 40% of a plate and frame unit for the same duty), these exchangers could greatly enhance the economics of small direct use geothermal systems.

Brazed plate heat exchangers, as the name implies, are manufactured using copper to braze the heat transfer plates together. The question at hand is whether this copper material will demonstrate an acceptable life in the geothermal fluids to which it will be exposed. The object of this report is to examine whether brazed plate heat exchangers will be an economical choice for small direct use systems.

The results of failure analysis conducted on brazed plate heat exchangers exposed to three different geothermal fluids is presented along with information on design considerations, equipment cost and life cycle costs for brazed plate heat exchangers.

BRAZED PLATE HEAT EXCHANGERS

Construction

As the name implies, brazed plate heat exchangers differ from the more common plate and frame exchangers in the method used to attach the plates. As shown in Figure 2, plate and frame exchangers are characterized by heavy steel end plates which along with the tie bolts, compress the individual plates together. Sealing between each plate and between the fluid passages and the atmosphere is provided by elastomeric gaskets on either side of each plate.

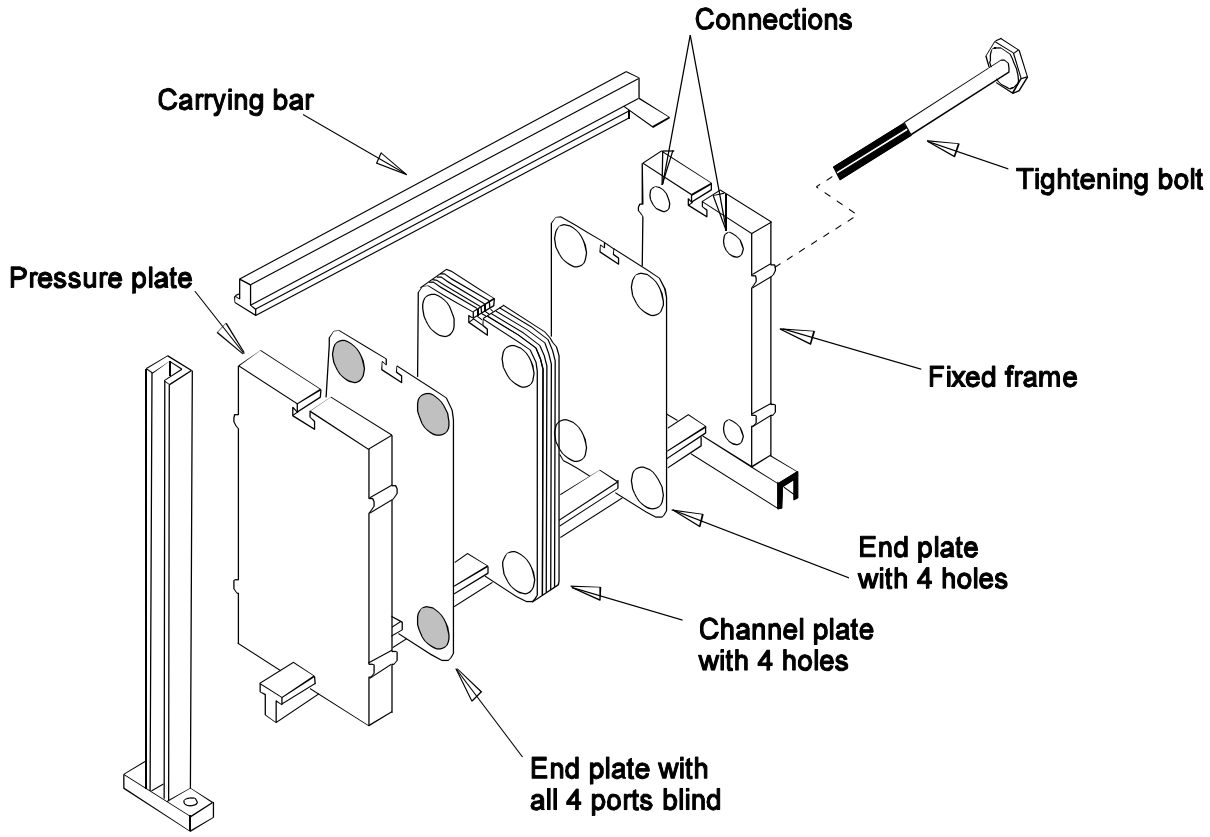

Figure 2. Plate and Frame Heat Exchanger (Rafferty and Culver, 1991).

The brazed plate unit as shown in Figure 3 eliminates the end plates, bolts, and gaskets from the design. Instead, the plates are held together by brazing with copper. This results in a much less complicated, lighter weight and more compact heat exchanger. The simpler design also results in greatly reduced cost.

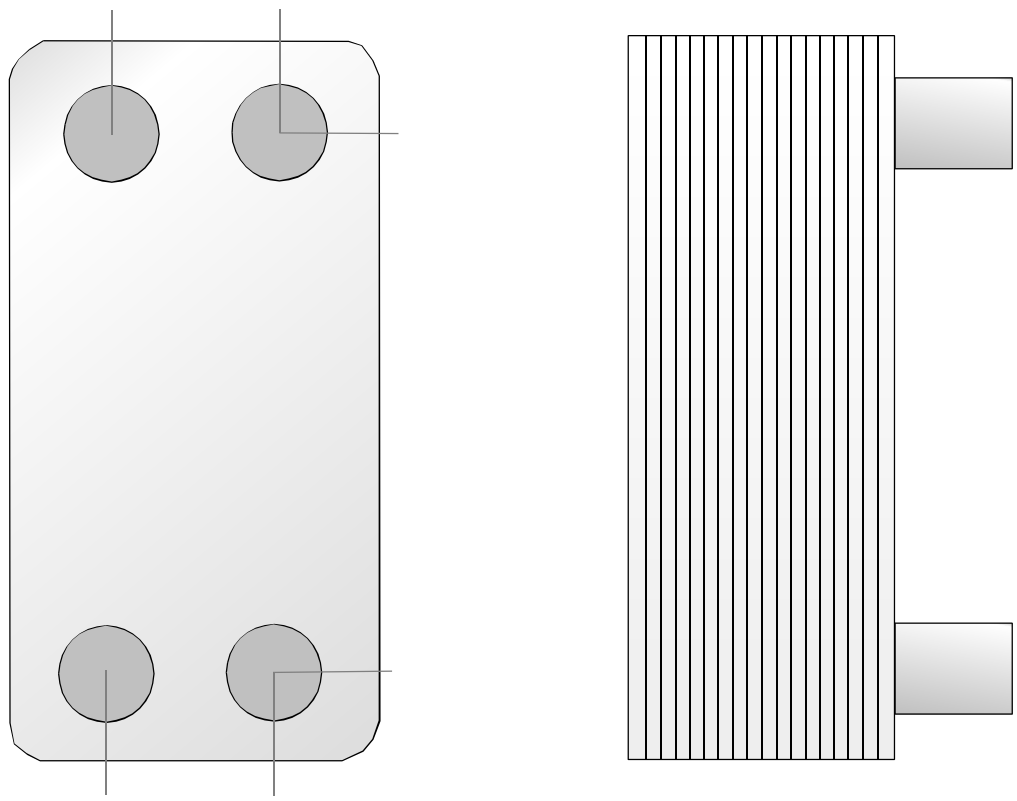

Figure 3. Brazed plate heat exchanger.

On the negative side, the brazed plate approach eliminates some of the advantages of the plate and frame design. In terms of maintenance, the brazed plate units cannot be disassembled for cleaning or for the addition of heat transfer plates as bolted units can.

Most importantly, however, the brazing material is copper. Since most geothermal fluids contain hydrogen sulphide (H_2S) or ammonia (NH_3) copper and copper alloys are generally avoided in geothermal system construction. The situation with brazed plate heat exchangers is especially critical due to the length (less than one tenth) of the braze material and length (a few tenths of an inch) of the brazed joints.

Application Considerations

In addition to the material related questions, there are also issues related to the standard configuration of brazed plate heat exchangers.

Physical size of the exchangers limits application flow rates to approximately 100 gpm (although one manufacturer produces units capable of 200 gpm). Maximum heat transfer area is limited to 200 ft^2. Heat transfer rates are similar to those of plate and frame heat exchangers and range from 800 - 1300 Btu/hr ft^2 ^oF in most applications (SWEP, 1980)(ITT, 1988).

The major design consideration for brazed plate exchangers is that standard units are manufactured in only single pass flow arrangement for both hot and cold fluids. This influences the ability of the exchanger to achieve close approach temperatures in certain applications.

This limitation is best illustrated through the Number of Transfer Units (NTU) approach to heat exchanger analysis. The NTU is a dimensionless value which characterizes the performance of a heat exchanger based upon the log mean temperature difference and the temperature change occurring in the unit. It can be expressed as follows:

$$NTU = \Delta Tm/LMTD$$

where ΔTm =the largest temperature change occurring to a fluid in the heat exchanger

LMTD =log mean temperature difference

$$, \frac{?t_1 \ \& \ ?t_2}{ln\left(\frac{?t_1}{?t_2}\right)}$$

Δt_1 = greater temperature difference between hot and cold fluids

Δt_2 = lesser temperature difference between hot and cold fluids

An example best illustrates the use of these values.

Consider a heat exchanger in which geothermal fluid enters the hot side at 180° and cools to 140°. Process water enters the cold side at 100° and is raised to 150°.

For this case:

$\Delta Tm = 150 - 100 = 50^{o}$

$$LMTD = \frac{(140 - 100) - (180 - 150)}{\ln \frac{(140 - 100)}{(180 - 150)}}$$

$= 34.8^{o}$

NTU $= 50^{o}/34.8$

$= 1.44$

Consider a second case in which we wish to heat the process water to a temperature closer to the geothermal fluid.

Geothermal (hot) side	180° - 140°
Process (cold) side	175° - 125°

For this case:

$\Delta Tm = 175 - 125 = 50^{o}$

$$LMTD = \frac{(140 - 125) - (180 - 175)}{\ln \frac{(140 - 125)}{(180 - 175)}}$$

$= 9.1^{o}$

NTU $= 50/9.1$

$= 5.49$

The importance of the NTU value lies in the fact that heat exchangers are capable of generating a given NTU for each fluid pass. The value is dependent upon their specific construction. For plate heat exchangers, depending upon plate design, an NTU of 0.6 to 4 per pass is generally possible.

Using a conservative value of 3, this would place a upper limit on the type of application to which single pass brazed plate heat exchangers could be applied. Of our two examples, only the first would be within the capabilities of a brazed plate heat exchanger.

Table 1 provides a broader view of the affect of this limitation in single pass performance.

Table 1. Brazed Plate Heat Exchanger Application Limitations (Based on an NTU of 3.0 per pass)

ΔTm	LMTD				
	2	5	10	15	20
10	5	2	1	0.67	0.5
20	10	4	2	1.33	1.0
30	15	6	3	2.0	1.5
40	20	8	4	2.67	2.0
50	25	10	5	3.33	2.5
60	30	12	6	4.0	3.0

The line indicates the limits of the brazed plate units based on an NTU of 3.0 per pass. Applications which fall above the line would be within the capabilities of brazed plate units; while, applications below the line would require a multiple pass heat exchanger.

In summary, brazed plate heat exchangers would in most cases be limited to applications characterized by greater than 10° log mean temperature differences, flows of less than 100 gpm and heat transfer area of less than 200 ft^2.

Heat Exchanger Material Cost

As discussed above the low cost of the brazed plate heat exchanger is its most attractive feature. Since heat exchanger cost is influenced by a host of factors including hot and cold side fluid flows and temperatures, it is most useful to discuss costs in terms of heat transfer area.

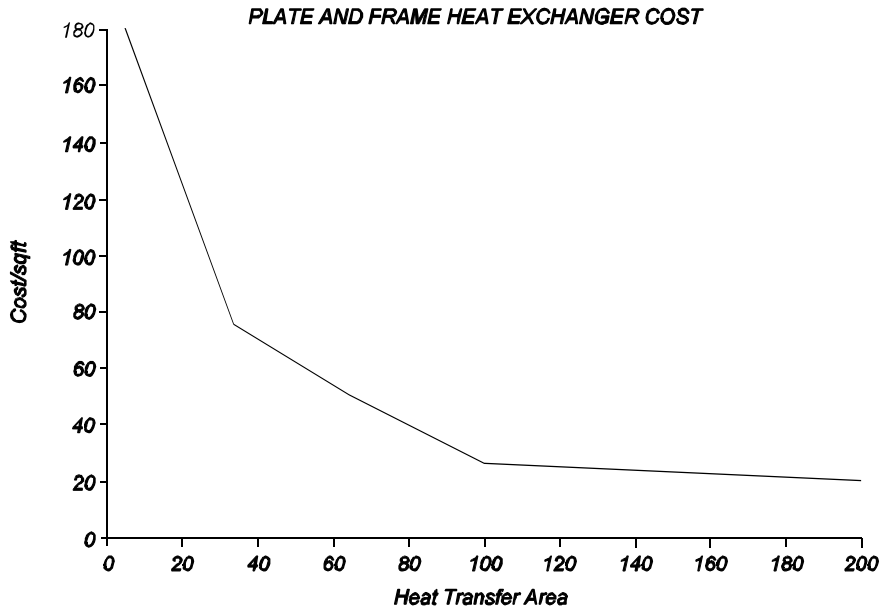

Figure 4.

Figure 4 provides a plot of the cost for plate and frame heat exchangers in $/ft^2 of heat transfer area versus area. It is apparent that the nature of their construction results in a steeply increasing cost curve below approximately 40 ft^2 of area.

Figure 5 presents the same data for brazed plate heat exchangers. As indicated, a similar curve holds for these units; however, it is offset toward lower costs.

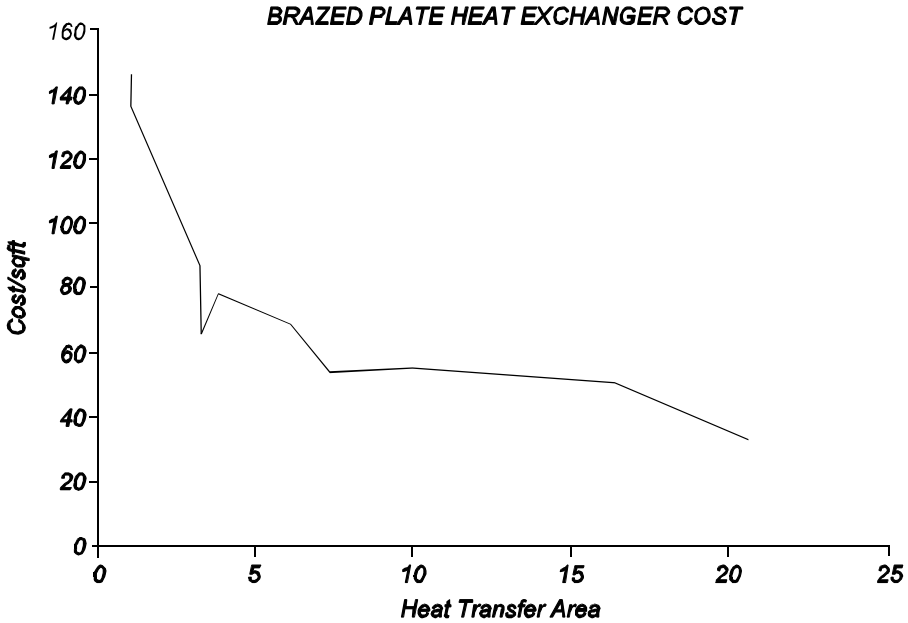

Figure 5.

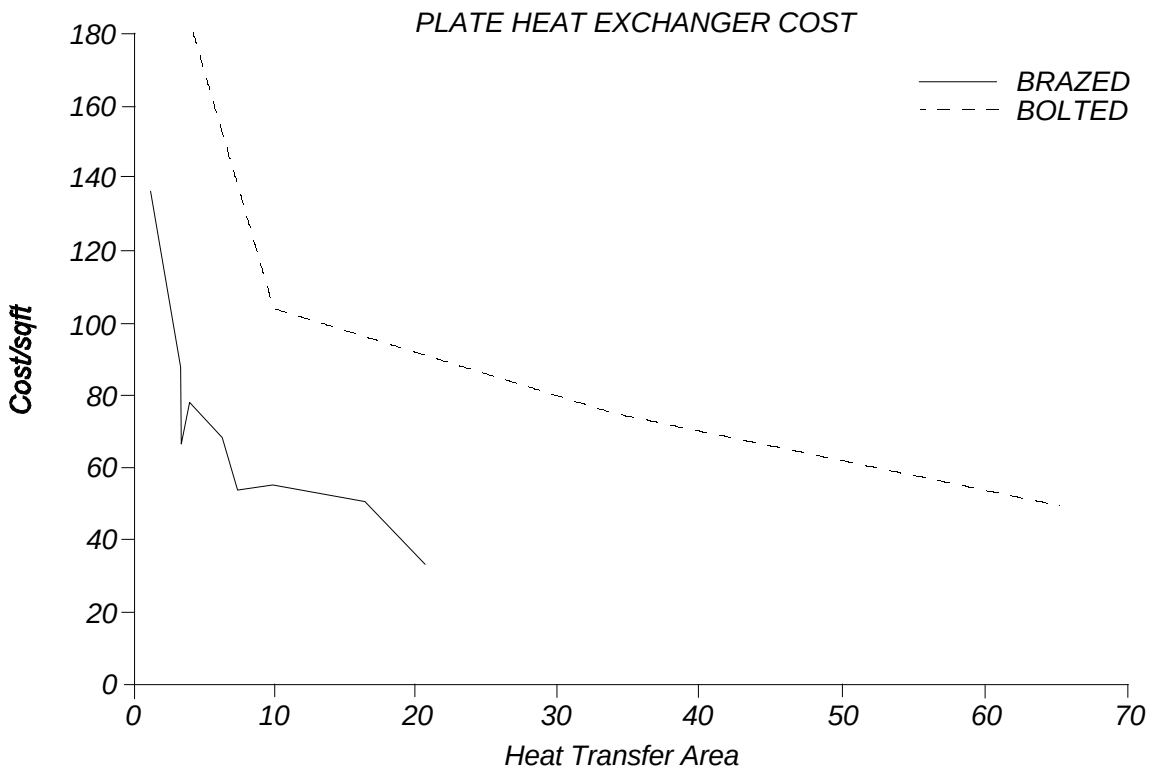

Figure 6.

Costs for both types of exchangers are combined on Figure 6 for units of less than 65 ft^2 heat transfer area. It is apparent that brazed plate units offer a significant savings for exchangers in the 2 - 30 ft^2 size range.

Brazed Plate Heat Exchanger Performance in Geothermal Fluids

A key factor in the determination of the economics of brazed plate heat exchangers is their expected service life in geothermal fluids. In order to evaluate this issue, plate heat exchangers were placed in service in three different geothermal fluids. The three locations for the installations (Boise, ID; Pagosa Springs, CO and Klamath Falls, OR) were chosen specifically due to the previous experiences with copper in geothermal fluids at these sites. Fluid chemistry for the three locations are detailed in Table 2.

Table 2

Test Site Fluid Chemistry*

	Klamath Falls, OR	Boise, ID	Pagosa Springs, CO
H_2S	0.5 - 1.5	0.3	5.0
Temp.	193°	176°	140°
TDS	795	290	3160
pH	8.6	8.2	6.7
Ca	26.0	2.0	240.0
F	1.50	14.0	N/A
Cl	51.0	10.0	160.0
CO_3	15.0	4.0	0
HCO_3	20.0	70.0	810.0
Na	205.0	90.0	640.0
K	1.50	1.6	87.0
SO_4	330.0	23.0	1520.0
SiO_2	48.0	160.0	61.4

*All values in mg/L except temperature (°F) and pH

In the past, the performance of copper tubing in Boise geothermal fluids has been good with water-to-air heating coils (with copper tubes) lasting as long as 10 years (Griffiths, 1990). In Klamath Falls, failure of copper tubing has occurred in approximately half this time with leaks reported in as little as 5 to 7 years. Pagosa Springs fluids have demonstrated the most aggressive reaction to copper with some failures as early as 2 years of service (Martinez, 1990). In all cases, these failures have been traced to corrosion promoted largely by hydrogen sulphide (H_2S). H_2S is present to some extent in virtually all geothermal fluids.

In order to evaluate the influence of fluid chemistry on the braze material, a test program involving four heat exchangers was developed. Three of the units were exposed to the geothermal fluid and a fourth was used as a control. In each location, the heat exchanger was connected to a continuous source of geothermal fluid with a flow rate of approximately 1 gpm. The Boise unit remained in place for 46 weeks, the Klamath Falls unit for 55 weeks and the Pagosa Springs exchanger for 26 weeks. All four heat exchangers were then forwarded to an engineering firm specializing in materials analysis. The full reports which resulted are attached as Appendix 1.

The initial findings of these reports suggested that minimum life of the exchangers, based upon the observed corrosion rates, would be in the range of 6 to 10 years for the Boise and Klamath Falls units, and 5 years for the Pagosa Springs unit.

Subsequent review of the individual fluid flow paths in the heat exchangers revealed that corrosion of the key joint areas would proceed from only one side of the joint rather than both sides of the joint as originally assumed. As a result, minimum expected life would be approximately doubled in both cases to 12 years for the Boise and Klamath Falls units and 10 years for the Pagosa Springs heat exchanger. A letter, amending the original reports, to this affect is attached to this report as Appendix 2.

Clearly the rate of corrosion of the brazed joints within the test heat exchangers was much slower than the most serious corrosion of tubing products observed previously at the test sites.

Based on this limited testing, brazed plate heat exchangers of the design similar to these should demonstrate a minimum service life of 12 years in fluids of less than 1 ppm H_2S and 10 years in fluids of 1 to 5 ppm H_2S.

Life Cycle Costs

The decision between a brazed plate heat exchanger and a plate and frame heat exchanger for a particular application includes considerations of a variety of issues. These would include: capital cost of the exchangers, service life of the exchangers, discount rate, maintenance requirements, installation costs and inflation rate.

Capital cost of the two types of exchangers was discussed earlier in this report. Based on the data presented, brazed plate heat exchanger first cost is on the order of 50% that of similarly sized plate and frame units.

Expected service life (minimum) for brazed plate exchanger in the fluids considered for this report would be in the range of 10 to 12 years. Service life for a plate and frame heat exchanger is less well publicized. According to the 1992 ASHRAE Handbook of Applications, shell and tube heat exchangers have a medium service life of 24 years. Because plate and frame heat exchangers are constructed of stainless steel in most of the fluid flow paths, it is reasonable to expect that they would have a service life somewhat longer than (steel and copper) shell and tube exchangers. In the absence of any long term data on service life of plate and frame exchangers in geothermal fluid applications, a value of 30 years will be used in this report for comparison to brazed plate units.

For cost comparison, a discount rate of 8% will be used for determining present value. It is customary in economic analysis to use a discount rate which approximates the rate which the owner is

earning on other investments. For the general case considered in this report, no owner exists. As a result, a discount rate which approximates the current cost of capital will be used.

Maintenance of heat exchangers whether plate and frame or brazed plate amounts to primarily removal of deposits from the heat transfer surfaces on a periodic basis. For the plate and frame unit, this consists of loosening the tie bolts, sliding the plates out, manually cleaning them, and reassembling the unit. For small heat exchangers, this task can be accomplished by one worker in approximately 2 - 3 hours depending upon the number of plates. For the brazed plate exchanger, cleaning would have to be done by circulating a fluid through the unit until the fouling is removed. The process would be similar to cleaning of a water cooled condenser on a refrigeration unit. In all likelihood, the task would be contracted out for the size heat exchanger in question. For the size exchanger considered in this report, a 2-hour service call should be sufficient for the task.

Based on current rates of $40 per hour for refrigeration service and $30 per man hour for in-house maintenance staff, the difference in maintenance costs for cleaning amounts to only about $5. Assuming this task is required on intervals of only 2 to 5 years, the difference between the two types of exchangers can be disregarded in the economic analysis.

Using the above discussed assumptions, a present value comparison of the two types of exchangers can be accomplished as follows:

For the 10-year minimum life brazed plate heat exchanger, a new heat exchanger would have to be purchased in years 10 and 20 in order to provide the same 30 years of service as the plate and frame heat exchanger. We will assume an installation cost of 20% of the heat exchanger equipment cost.

Inflation rate:	3%	BPHX cost = x
Discount rate:	8%	PFHX cost = y
Installation cost:	20% of equipment cost	
BPHX life:	10 years	
PFHX life:	30 years	

Year	BPHX	PFHX
0	1.2x	1.2 y
10	1.2x	
20	1.2x	

For the BPHX, because costs are incurred in years 10 and 20, these costs must be converted to present value for accurate comparison to the PFHX costs. To do this, the effect of

inflation is considered to arrive at a future cost for the exchanger and then the discount rate is used to bring the cost back to present value.

Year 10 cost = 1.2x

		F/P,3,10
Correct for effect of inflation:	1.2x	(1.344)

		F/P,3,10	P/F,3,10
Correct to present value:	1.2x	(1.344)	(.4632)

The present value of replacing the exchanger in year 10 is then = 1.2 * 1.806 * .4632x

= .747x

Similarly the value of replacing the exchanger in year 20 is:

= 1.2 * 1.806 * .2146x

= .465x

The total present value of the costs associated with the BPHX is the sum of the year 0, year 10 and year 20 costs or

= 1.2x + .747x + .465x

= 2.412x

The cost of the plate and frame heat exchanger is simply 1.2y since it requires no replacement over the 30-year period.

Based on these figures, it is possible to define the break-even cost of the brazed plate heat exchanger in terms of the plate and frame heat exchanger as follows:

$$2.412x = 1.2y$$
$$x = (1.2/2.412)y$$
$$x = .498y$$

That is, the brazed plate heat exchanger (at a 10-year minimum life) is the correct economic choice if it costs 49.8% or less of the cost of the plate and frame heat exchanger.

If the above procedure is represented for the 12-year minimum life heat exchanger, a value of 50.6% results.

Based on the economic assumptions in this report, brazed plate heat exchangers are the clear economic choice at capital costs of 50% or less of the cost of an equivalent plate and frame heat exchanger. This assumes that the costs of replacement will be borne by the

same entity responsible for the capital cost of the system. For situations in which a separate entity is responsible for the maintenance of the system, brazed plate heat exchangers would be the choice at higher capital cost percentages.

Conclusions

Brazed plate heat exchanger were placed in three geothermal fluids (Klamath Falls, OR; Boise, ID; and Pagosa Springs, CO) in order to determine the effect of H_2S on braze material. Based on subsequent analysis, it appears that the rate of corrosion of the braze material is much slower than corrosion of copper tube materials in the same fluids. Minimum expected life of the heat exchangers based on these corrosion rates is reported to be 12 years in fluids of less than 1 ppm H_2S and 10 years in fluids of less than 5 ppm.

Based on these expected lives, and using a 3% inflation rate and 8% discount rate, brazed plate heat exchangers are a clear economic choice in which the capital cost is 50% or less of the cost of a plate and frame heat exchanger for the same duty.

Due to their single pass design, brazed plate heat exchangers are generally limited to approach temperatures of 10° or greater. Size limitations restrict applications to 100 gpm and/or 200 ft^2 heat transfer surface area.

References

ASHRAE, Handbook of Applications, Chapter 29, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, 1991.

Griffiths, R., Mechanical Engineer, Boise Warm Springs Water District. Personal communication, 1990.

ITT-Bell and Gossett, product literature. New Honeycomb™ Brazed Plate Heat Exchangers. ITT Corporation, Buffalo, NY, 1988.

Martinez, J. D., Geothermal Superintendent, City of Pagosa Springs, CO. Personal communication, 1990.

Rafferty, K. and Culver, G., Chapter 11 - Heat Exchangers, Geothermal Direct Use Engineering and Design Guidebook, Oregon Institute of Technology - Geo-Heat Center, Klamath Falls, OR, 1991.

SWEP, product literature - Compact Brazed Plate Heat Exchangers, SWEP International, Ladskoma, SWEDEN, April 1989.

APPENDIX I

M E I-Charlton, Inc.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201-2499
(503) 228-9663
FAX (503) 228-4065

ENGINEERS AND SCIENTISTS solving problems through APPLIED RESEARCH, CONSULTING ENGINEERING AND CHEMISTRY

TO: Oregon Institute of Technology
Geo-Heat Center
Attention: Kevin Rafferty, PE
3201 Campus Drive
Klamath Falls, OR 97601-8801

CLIENT NO.: B23409

REFERENCE NO.: 5703032

DATE: 27 Apr 1992

SUBJECT: METALLURGICAL EVALUATION OF THREE BRAZED PLATE HEAT EXCHANGERS

MEI-Charlton, Inc. has examined three brazed plate heat exchanger to evaluate the effects of service and to estimate the useable lifetime of the units. A fourth unit is still in service at the Pagosa Springs, Colorado facility and will be evaluated later.

All three units were labeled SWEP, LANDSKRONA, MADE IN SWEDEN. The units were made of Type 316 stainless steel with copper braze joints. The individual units were identified as follows:

CONTROL	Type	B10*010
	Serial Number	8912-12010-3321
	Size	11½ X 4½ X 1¼ inches
	Unused	
BOISE	Type	B10*010
	Serial Number	8912-12010-2617
	Size	11½ X 4½ X 1¼ inches
	Service Location	City of Boise
	Installed	February 26, 1991
	Removed	January 5, 1992
	Service Time	46 weeks
OIT	Type	B15*010
	Serial Number	19010-13010-2564
	Size	18¼ X 3 X 1 inches
	Service Location	OIT
	Installed	January 7, 1991
	Removed	January 27, 1992
	Service Time	55 weeks

Our following conclusions are based on visual examination, scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS)[1], and metallographic examination:

1. The copper brazed joints exposed to the geothermal fluid were corroded in both the Boise and OIT units. The stainless steel surfaces were not corroded.

   1.1 In the Boise unit, the braze joints were generally attacked on the surfaces and preferentially attacked along the interfaces between the braze joint material and the stainless steel plate material.

   1.2 In the OIT unit, the braze joints were generally attacked only. They had no interface preferential attack.

   1.3 In both the Boise and OIT units, the most severely corroded braze joints have lost material to a depth of approximately 0.010 inch in 1 year. If the corrosion continues at the same rate, it would penetrate to the joint center in approximately 4 years and can cause internal geothermal fluid leaks in 6 to 10 years.

2. The corrosion products adhering to the joints in the Boise unit had a different composition than the OIT unit.

   2.1 In the Boise unit, the corrosion products were primarily copper oxides with minor amounts of iron and chromium oxides.

   2.2 The Boise unit also contained a film of mineral deposits made up primarily of iron, copper, zinc and silicon compounds with lesser amounts of sodium, aluminum, sulfur, calcium and manganese. These minerals were probably derived from dissolved solids in the geothermal fluid and/or transfer corrosion products from other components of the system.

   2.3 In the OIT unit, the corrosion products were copper and sulfur compounds with moderate amounts of iron, chromium, nickel, silicon and tin.

   2.4 The OIT unit had very small amounts of mineral deposits.

---

[1]Semiquantitative; detection excludes elements with atomic numbers 1-10.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

3. The secondary/domestic water passages in the Boise and OIT units had no corrosion or deposits.

4. The unused control unit had no corrosion or deposits and was used as a comparison basis for the evaluation of units from service.

5. In the brazing operation in all units, copper has penetrated the stainless steel plate grain boundaries to a depth of 0.002 inch. The subsequent corrosion of the copper has left open, unbonded grain boundaries in the plate surfaces. These may, at a later time, be sites of intergranular corrosion and/or crack initiation.

6. The chemical composition of the exchanger plate material was comparable to the specified composition of Type 316 stainless steel.

7. The braze joint material was 96-percent copper with small amounts of manganese, iron, chromium, and nickel.

Details of our examination and findings are given in the following captions and figure. If you have questions or need further testing, please let us know.

REGISTERED PROFESSIONAL ENGINEER 9365 OREGON JULY 22, 1977 DURGAM G. CHAKRAPANI

Ralph A. Hudson, PE
Account Director

RDW:jg
3 copies

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

Figure 1 (12101) Control Unit As Received

This photograph shows the heat exchanger identified as the Control Unit. Its identifying marks were:

Type	B10*010
Serial Number	8912-12010-3321
Size	11½ X 4½ X 1¼ inches

This heat exchanger was the same type as the City of Boise unit. It was not installed but kept as an unused test control. This unit contained no corrosion or deposits and was in the as-manufactured conditon.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

FIG. 1 (12101)

Figure 2 (12102) City of Boise Unit As Received

This photograph shows the heat exchanger identified as the City of Boise unit. Its identifying marks were:

Type	B10*010
Serial Number	8912-12010-2617
Size	11½ X 4½ X 1¼ inches
Service Location	City of Boise

It was installed 26 February 1991 and removed 5 January 1992. Total service time was 46 weeks. The inlet and outlet ports for the geothermal water and domestic water are shown by white and black arrows, respectively.

Figure 3 (12103) OIT Unit As Received

This photograph shows the heat exchanger identified as the OIT unit. Its identifying marks were:

Type	B15*010
Serial Number	19010-13010-2564
Size	18¼ X 3 X 1 inches
Service Location	OIT

It was installed January 7, 1991 and removed January 27, 1992. Total service time was 55 weeks. The inlet and outlet ports for the geothermal water and domestic water are shown by white and black arrows, respectively.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

FIG. 2

(12102)

FIG. 3

(12103)

Figure 4 (12104) Boise Unit, Hot Inlet Port

This photograph shows the internal surfaces of the hot geothermal fluid inlet port of the heat exchanger from the City of Boise system. The surfaces were coated with a red/yellow film of deposits.

The deposits were primarily a mixture of corrosion products and geothermal minerals and consisted of iron, copper, zinc and silicon compounds with lesser amounts of sodium, aluminum, sulfur, calcium and manganese. These deposits were probably derived from dissolved solids in the geothermal fluid and corrosion products from other components of the system.

A few green-colored deposits were on the fitting-to-plate brazed joint (arrow). These deposits consisted primarily of copper and sulfur.

Figure 5 (12105) Boise Unit, Hot Outlet Port

This photograph shows the internal surfaces of the hot geothermal fluid outlet port of the heat exchanger from the City of Boise system. These surfaces had conditions similar to the inlet port with a somewhat thicker film of deposits.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

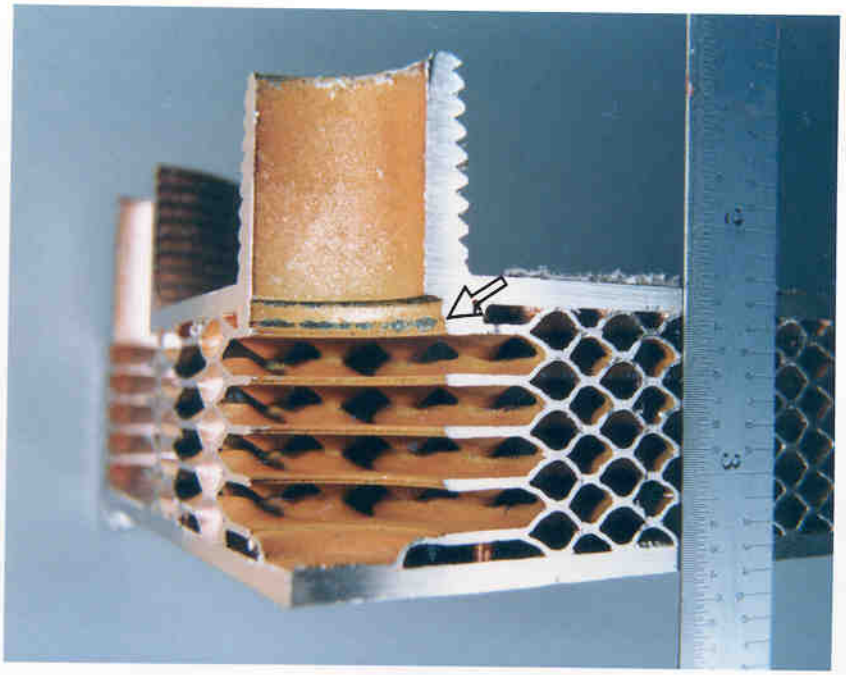

FIG. 4

(12104)

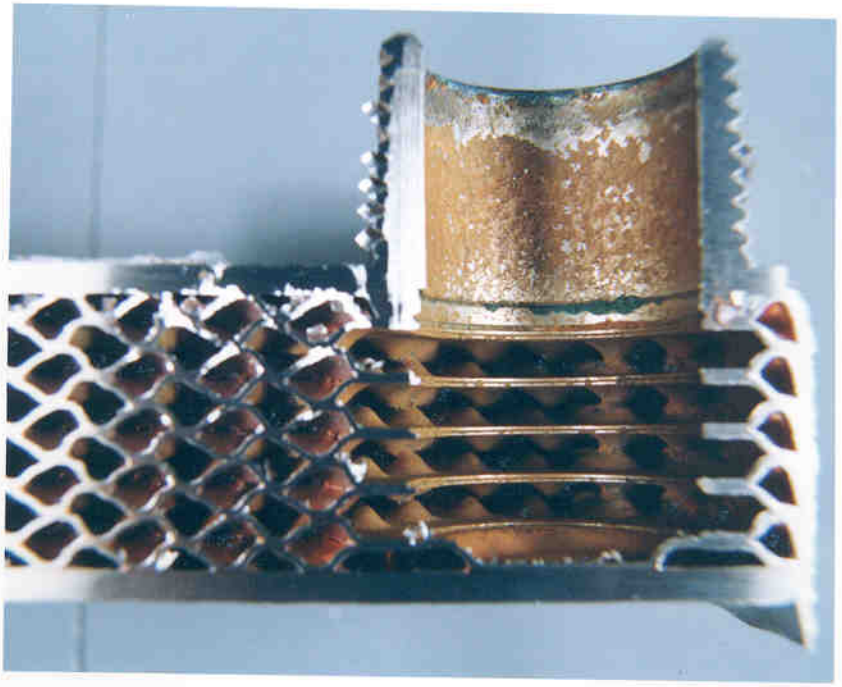

FIG. 5

(12105)

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

Figure 6 (12106) Boise Unit, Hot Outlet Port

This photograph is a magnified view of a brazed plate joint in the outlet port area. The deposits on the joint were a mixture of corrosion products from the joint braze metal and mineral deposits. The corrosion products were primarily copper oxides with minor amounts of iron and chromium.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

FIG. 6 (12106)

Figure 7 (12107) OIT Unit, Inlet Port

This photograph shows the internal surfaces of the hot geothermal fluid inlet port of the heat exchanger from the OIT system. The surfaces were coated with an irregular black film of corrosion products. The corrosion products were copper and sulfur compounds with moderate amounts of iron, chromium, nickel, silicon and tin.

Figure 8 (12108) OIT Unit, Hot Inlet Port

This photograph shows the internal surfaces of the hot geothermal fluid outlet port of the heat exchanger from the OIT system.

These surfaces had conditions similar to the inlet port. The thickest accumulations of the black corrosion deposits were around the fitting-to-plate brazed joints.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

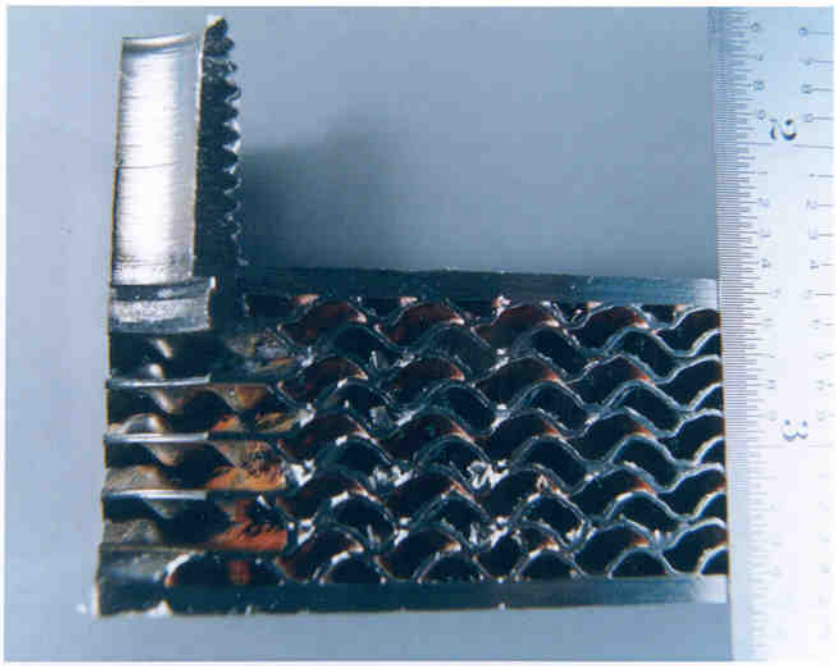

FIG. 7

(12107)

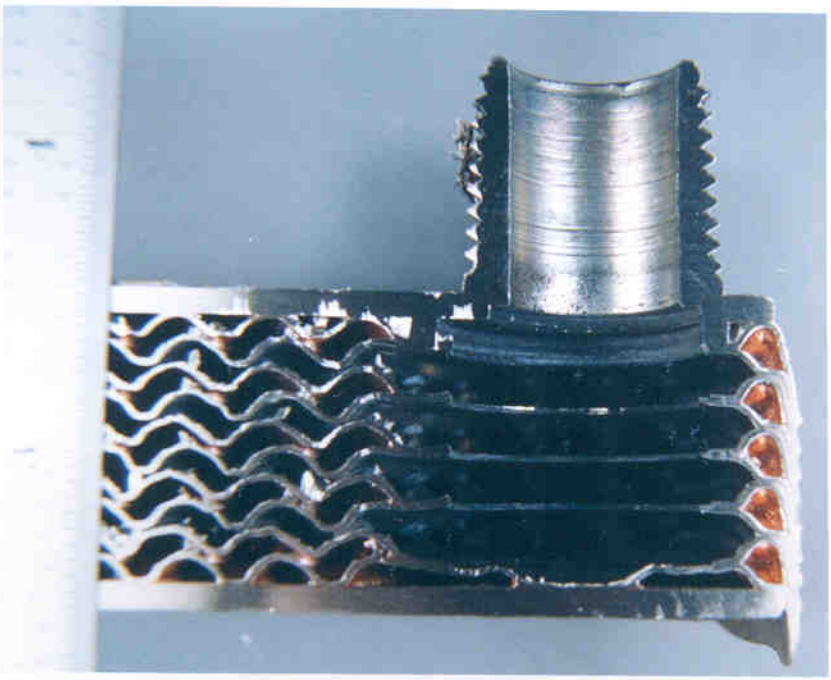

FIG. 8

(12108)

Figure 9 (12109) OIT Unit, Hot Outlet Port

This photograph is a magnified view of a brazed plate joint in the outlet port area. The deposits on the joint were corrosion products from the joint braze metal. The corrosion products were copper and sulfur compounds with moderate amounts of iron, chromium, nickel, silicon and tin.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

FIG. 9 (12109)

Figure 10 (10493) 3X Boise Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows a longitudinal cross section of the outlet port area of the Boise unit. The OIT unit had a similar appearance. The fitting-to-plate joint is on the upper right.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

FIG. 10 (10493)

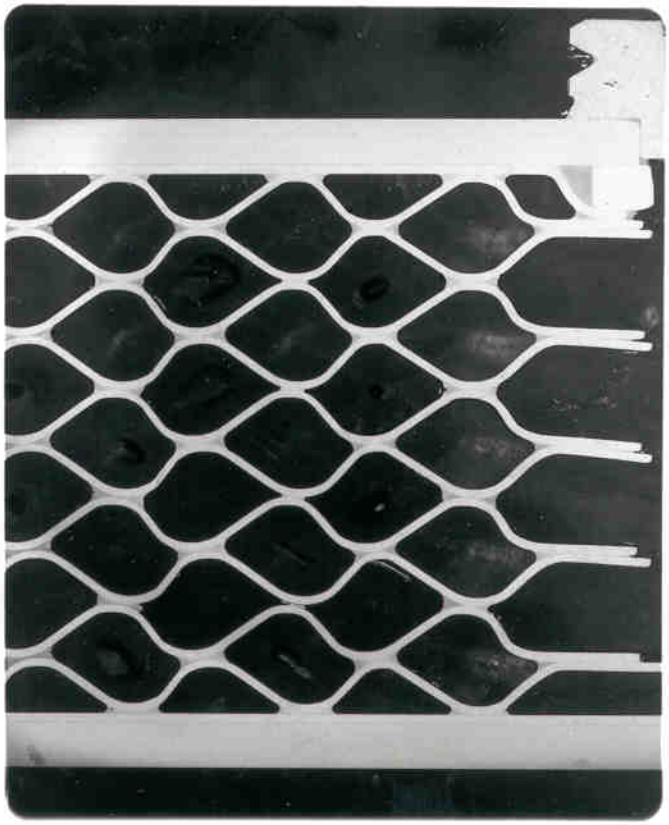

Figure 11 (10503) 11X Boise Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows detail of the Boise unit outlet fitting-to-plate joint. The fitting is on top. The thick section below the fitting is the outer plate. The nearly square rectangle is the spacer ring. The three thin sections on the bottom are the first three corrugated heat transfer plates. These members were all made of stainless steel.

The gray material between the steel members is the copper braze material. The braze metal on the right was exposed to the geothermal fluid and has preferentially corroded (arrow) at an approximate corrosion rate of 10 mils per year. Joints like these could leak in 6 to 10 years. The stainless steel surfaces exposed to geothermal water did not show any corrosion.

Figure 12 (10494) 8X Boise Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows brazed joints between the corrugated, stainless steel heat transfer plates in the heat exchanger core. These joints were located where the plate corrugation peaks crossed the peaks of the adjacent plates. The corrugations crossed at an included angle of approximately 50 degrees. The brazed joints were approximately 0.08 inch wide. The plate braze joints could corrode to failure in 4 years if the braze corrosion continues at the observed rate.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

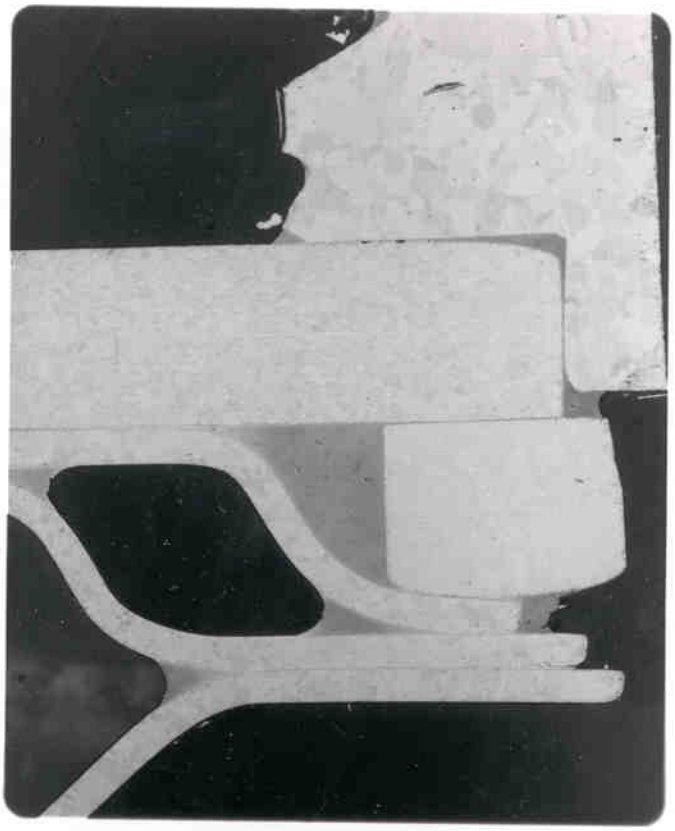

FIG. 11

(10503)

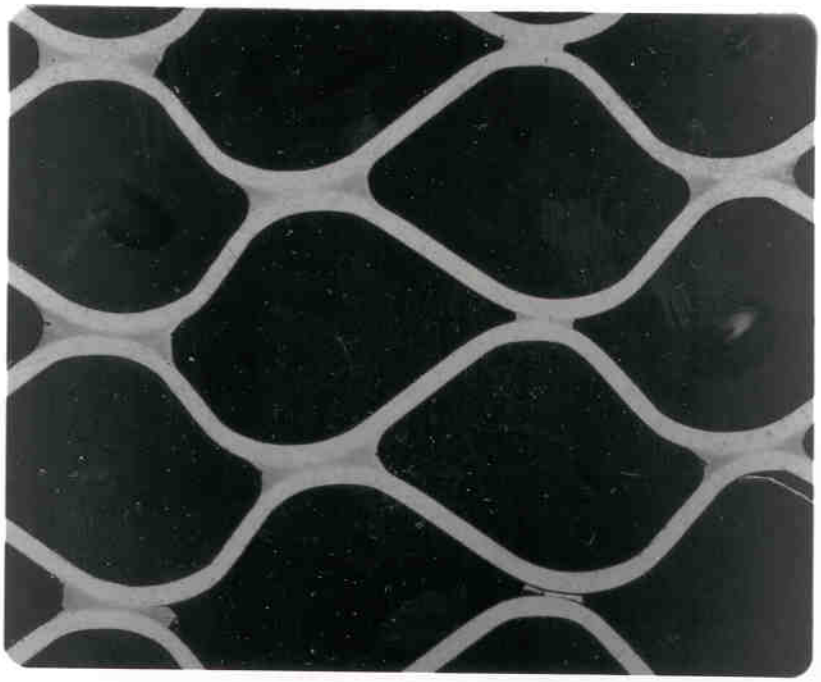

FIG. 12

(10494)

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

Figure 13 (10491) 100X Boise Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows a brazed joint in a secondary/domestic water passage of the Boise unit. This joint had no corrosion deposits. The copper braze filler metal was securely bonded to the stainless steel plates and a smooth, generous fillet formed on the joint surface.

The chemical composition of the plate material was comparable to the specified composition of Type 316 stainless steel. The braze joint material was 96-percent copper with small amounts of manganese, iron, chromium, and nickel.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

FIG. 13 (10491)

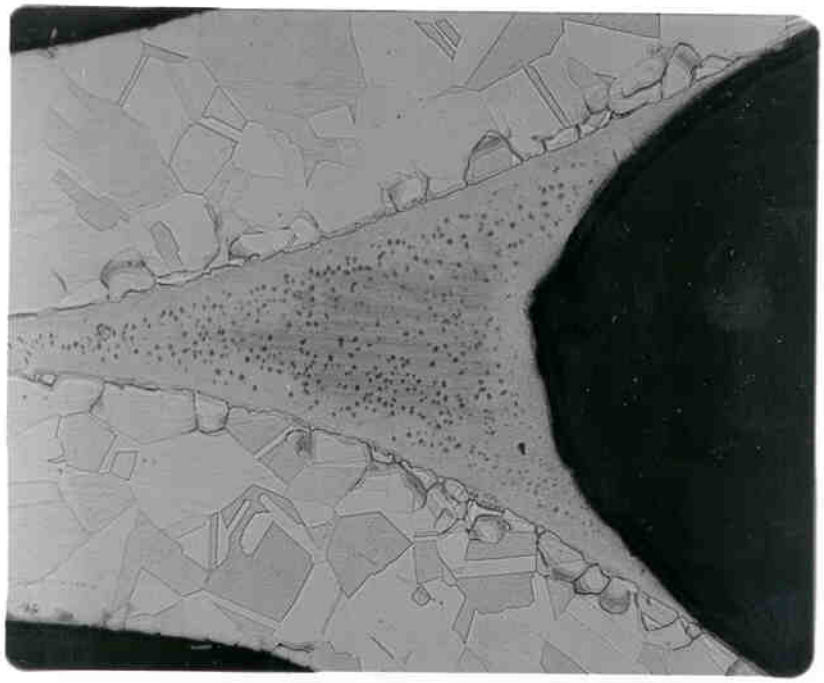

Figure 14 (10486) 100X Boise Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows a brazed joint in a primary/geothermal fluid passage in the Boise unit. Corrosion resulting from exposure to the geothermal fluid has attacked the copper braze material to a depth of approximately 0.01 inch.

The copper brazed joints were generally attacked on the surfaces and preferentially attacked along the interfaces between the copper braze joint material and the stainless steel plate material. The stainless steel plate did not corrode.

Figure 15 (10492) 100X Boise Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows a brazed joint in a primary passage in the Boise unit where the interface corrosion has penetrated entirely through the joint. Only one instance of this condition was observed in the sample, but it serves to illustrate the eventual outcome of continued corrosion of the copper brazed joints.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

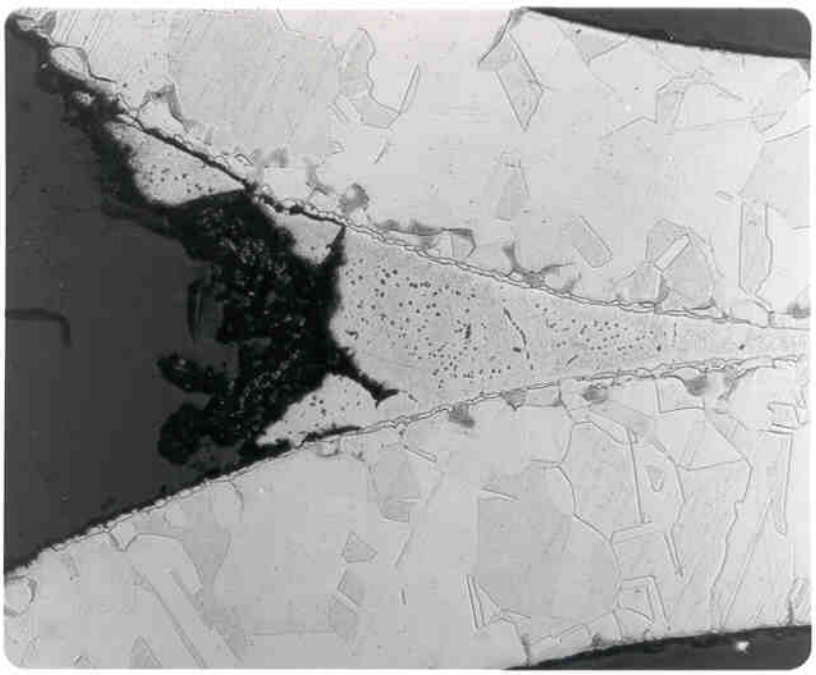

FIG. 14

(10486)

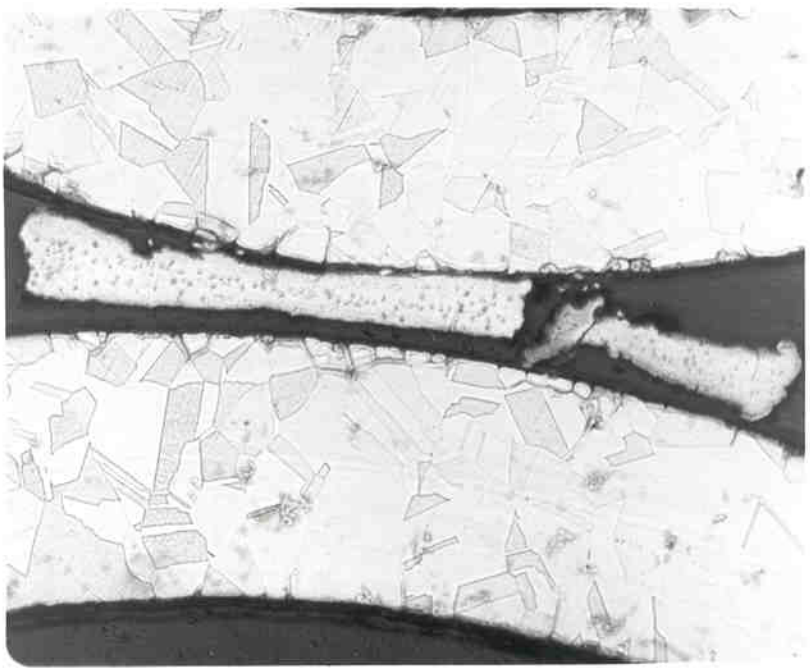

FIG. 15

(10492)

Figure 16 (10488) 500X Boise Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows detail of the preferential corrosive attack along the joint-to-plate interface. The presence of copper in the stainless steel grain boundaries has allowed the corrosion to attack the plates, leaving open, unbonded grain boundaries in the plate surfaces. These may, at a later time, be sites of intergranular corrosion and/or crack initiation, but do not show active corrosion at this time.

Figure 17 (10500) 100X OIT Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows a brazed joint in a primary/geothermal fluid passage in the OIT unit. Corrosion resulting from exposure to the geothermal fluid has attacked the copper braze material to a depth of approximately 0.01 inch.

The copper brazed joints were generally attacked on the surfaces but not preferentially attacked along the interfaces.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

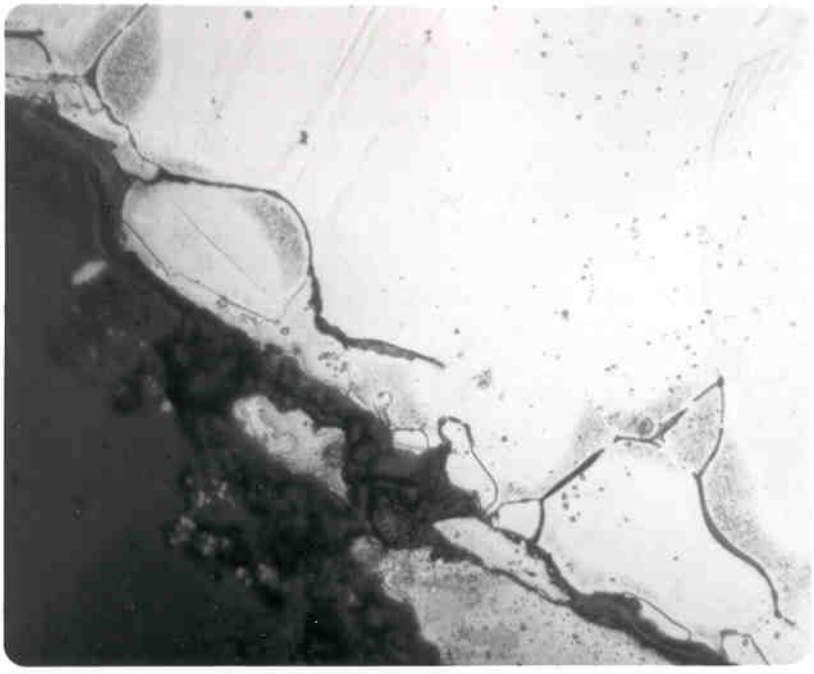

FIG. 16

(10488)

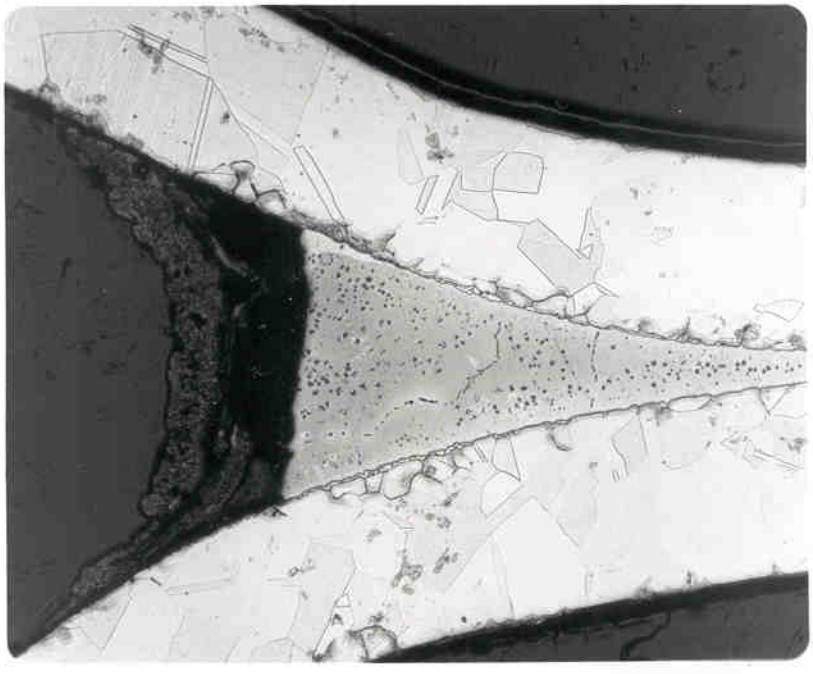

FIG. 17

(10500)

Figure 18 (10501) 500X OIT Unit Etchant: Electrolytic Oxalic Acid

This photomicrograph shows the joint-to-plate interface in the OIT unit. This unit did not have preferential interface attack.

Figure 19 (10502) 2000X OIT Unit Scanning Electron Microscope (SEM) Etchant: Electrolytic Oxalic Acid

This scanning electron micrograph shows a stainless steel grain boundary near the joint-to-plate interface where copper has penetrated from the brazing operation.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

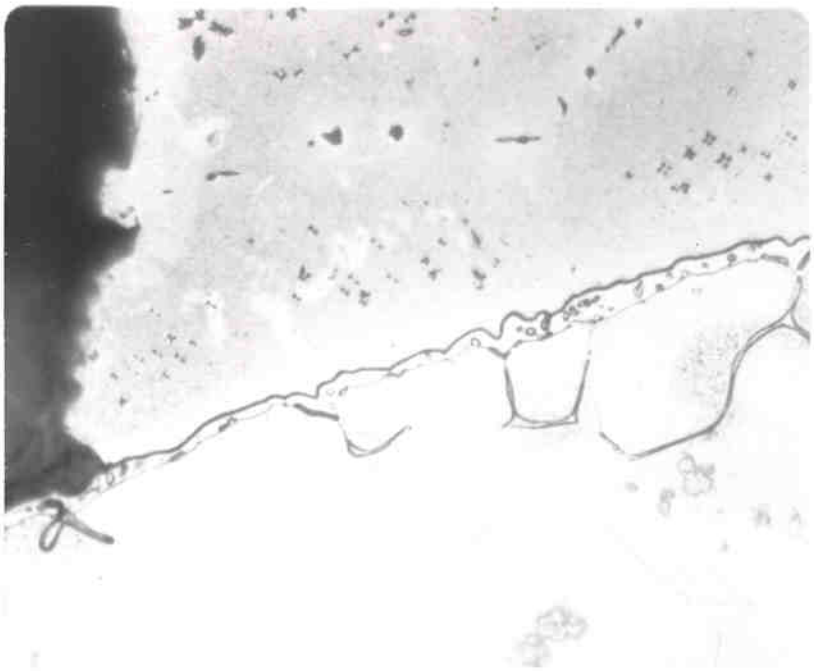

FIG. 18

(10501)

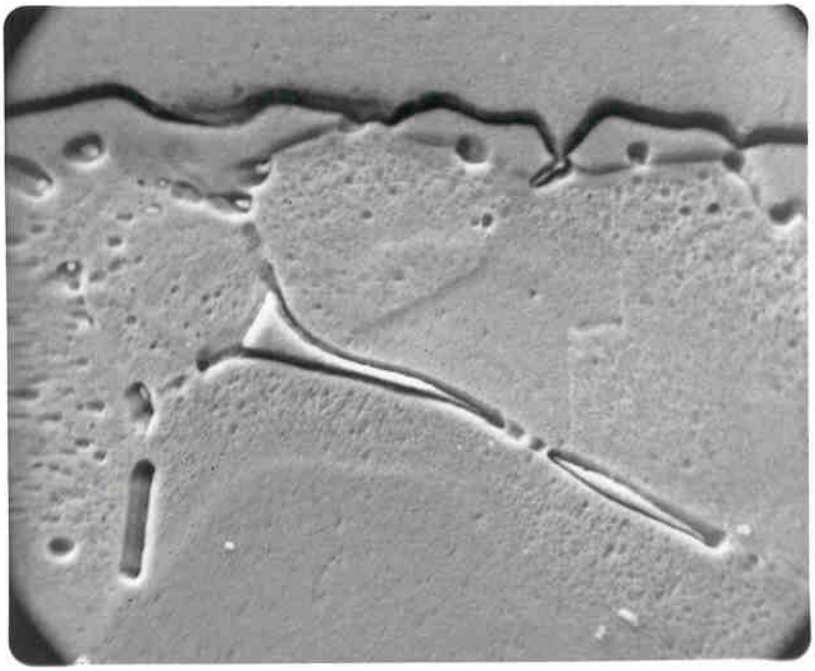

FIG. 19

(10502)

APPENDIX II

M E I-Charlton, Inc.

2233 S.W. CANYON ROAD
PORTLAND, OR 97201-2499
(503) 228-9663
FAX (503) 228-4065

ENGINEERS AND SCIENTISTS solving problems through APPLIED RESEARCH, CONSULTING ENGINEERING AND CHEMISTRY

TO: Oregon Institute of Technology
Geo-Heat Center
Attention: Kevin Rafferty, PE
3201 Campus Drive
Klamath Falls, OR 97601-8801

CLIENT NO.: To be issued
REFERENCE NO.: 5804032 (5703032)
DATE: 11 Dec 1992

SUBJECT: METALLURGICAL EVALUATION OF BRAZED PLATE HEAT EXCHANGERS REPORT II: FOURTH UNIT

MEI-Charlton, Inc. had previously examined three brazed plate heat exchangers to evaluate the effects of service and to estimate the useable lifetime of the units (Report 5703032). This is the fourth unit from service at the Pagosa Springs, Colorado facility.

This unit was labeled SWEP, LANDSKRONA, MADE IN SWEDEN. Like the others, it was Type 316 stainless steel with copper brazed joints. The unit was identified as follows:

Type	B10*010
Serial Number	8912-12010-3323
Size	11½ X 4½ X 1¼ inches
Service Location	Pagosa, Colorado
Installed	March 24, 1992
Removed	September 21, 1992
Service Time	26 weeks

Our following conclusions are based on visual examination, scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS)[1] analysis, and metallographic examination:

1. The copper brazed joints exposed to the geothermal fluid were corroded. The stainless steel surfaces were not corroded.

   1.1 The joints were generally attacked on the surfaces and preferentially attacked along the interfaces between the joint material and stainless steel plate material.

[1]Semiquantitative; detection excludes elements with atomic numbers 1-10.

1.2 The most severely corroded joints have lost material to a depth of approximately 0.033 inch in 1 year. If the corrosion continues at this rate, it would penetrate to the joint centers in approximately 3 years, and could cause external geothermal fluid leaks in about 5 years. The corrosion rates were greater than in the Boise and OIT units (Report 5703032).

2. The corrosion products adhering to the joints had a different composition than either the Boise or OIT units. The compositional differences are attributed to differences in the geothermal mineral compositions at the respective locations.

   2.1 The corrosion products consisted primarily of copper and sulfur with less amounts of iron, arsenic, and nickel, and traces of aluminum, manganese, and calcium.

   2.2 A film of deposits was in all geothermal fluid passages, consisting of the same elements found in the corrosion products, plus some chromium. However, the percentage of arsenic was much higher. These materials were probably derived from minerals and corrosion products dissolved or suspended in the geothermal fluid.

3. The secondary/domestic water passages had no corrosion or deposits.

4. In the brazing operation, copper penetrated the stainless steel plate grain boundaries to a depth of 0.003 inch. The subsequent corrosion of the copper left open, unbonded grain boundaries in the plate surfaces. At a later time, these may be sites of intergranular corrosion and/or crack initiation.

5. The chemical composition of the plate material was comparable to the specified composition of Type 316 stainless steel.

6. The brazed joint material was 96-percent copper with small amounts of manganese, iron, chromium, and nickel.

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

Details of our examination and findings are given in the following captions and figures. If you have questions or need further testing, please let us know.

Expires: 12-31-93

Ralph A. Hudson, PE
Account Director

RAH:jg
3 copies

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

Figure 1 (14184) Pagosa Unit As Received

This photograph shows the Pagosa heat exchanger. This brazed plate heat exchanger was the same type as the previously tested City of Boise unit. It was installed 24 March 1992 and removed 21 September 1992. Service time was 26 weeks.

The inlet and outlet ports for the geothermal water and domestic water are shown by the white and black arrows.

Figure 2 (14185) Hot Inlet Port

This photograph shows the internal surfaces of the hot geothermal fluid inlet port. The surfaces were coated with a thin film of gray-black deposits with a thick yellow-gray corrosion scale on the plate-to-plate brazed joints. This scale consisted primarily of copper and sulfur with less amounts of iron, arsenic, and nickel, and traces of aluminum, manganese, and calcium.

The gray-black deposits had the same elements and some chromium, but the percent of arsenic was much higher. In many areas on the brazed joints the scale had broken off.

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

FIG. 1

(14184)

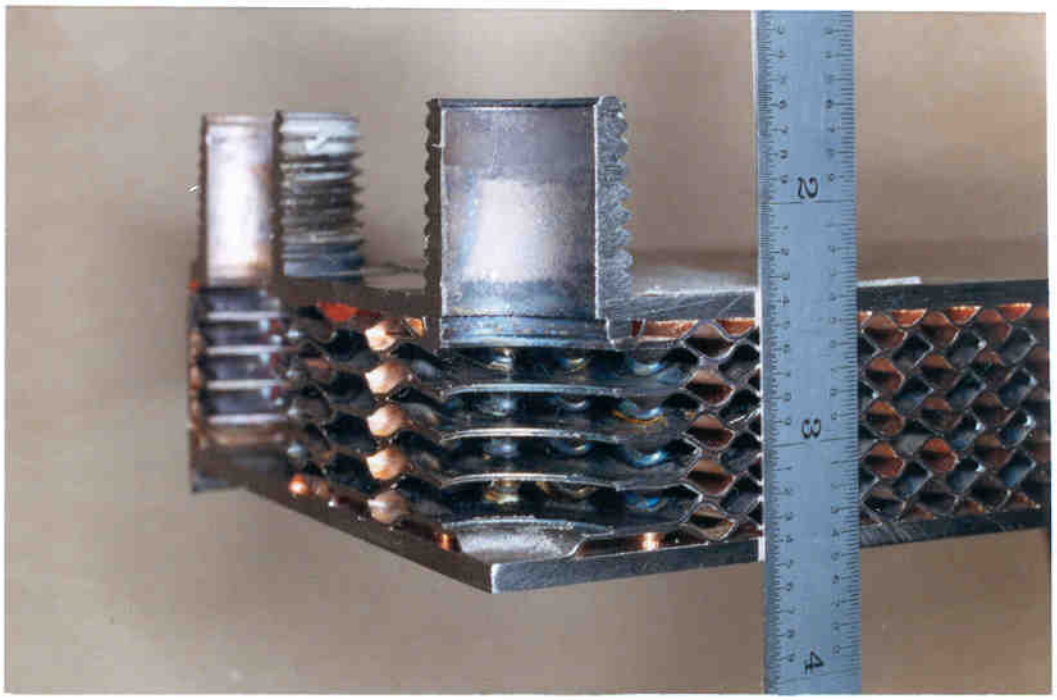

FIG. 2

(14185)

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

Figure 3 (14180) Hot Outlet Port

This photograph shows the internal surfaces of the hot geothermal fluid outlet port. The surfaces had the same conditions as the inlet port, but the corrosion scale on the brazed joints was more intact and continuous.

Figure 4 (14181) 10X Hot Inlet Port

This photograph is a magnified view of two brazed joints in the inlet port area showing the corrosion scale and areas of the braze where the scale had broken off. The corrosion scale was primarily copper and sulfur, with less amounts of iron, arsenic, nickel, aluminum, manganese, and calcium.

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

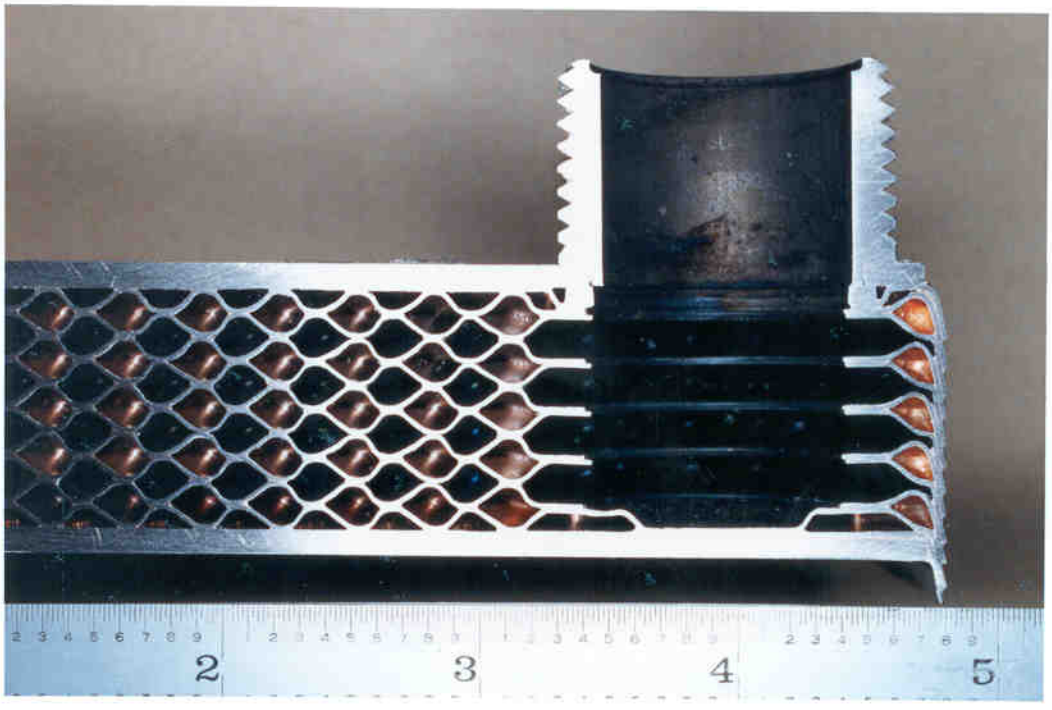

FIG. 3

(14180)

FIG. 4

(14181)

Figure 5 (14182) 10X Hot Outlet Port

This photograph is a magnified view of a brazed joint in the hot outlet port area. The corrosion scale in the joint was intact, but had started to peel from the plates and braze metal, and will eventually break off.

The cracks along the edge are between the scale and stainless steel.

Figure 6 (14183) Hot Outlet Port

This photograph shows a gap between the outlet port fitting and top plate. This joint was not completely filled by braze metal. Its depth and extent of corrosion are shown in Figures 8 and 14.

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

FIG. 5

(14182)

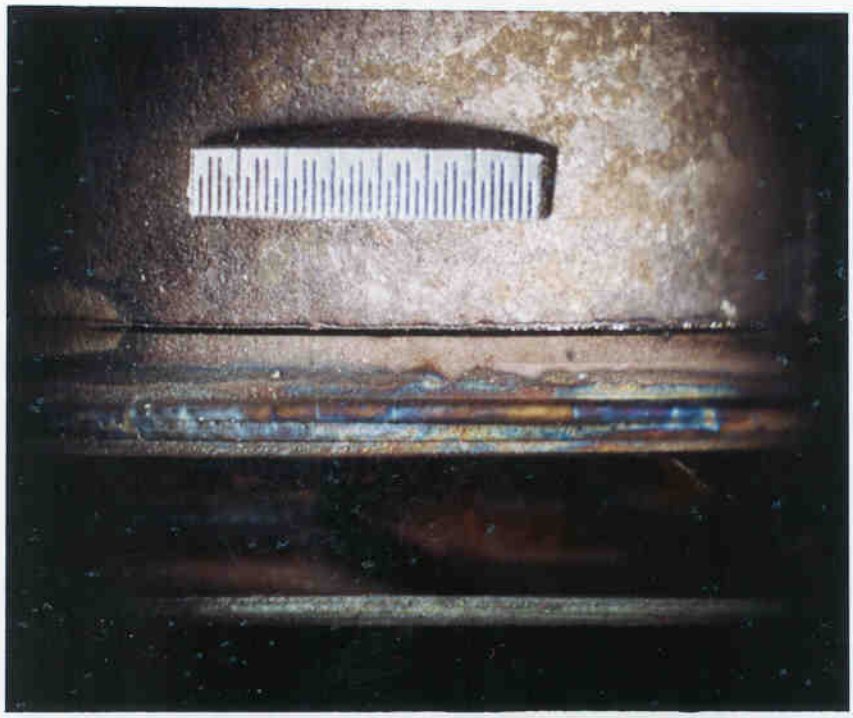

FIG. 6

(14183)

Figure 7 (13542) Hot Outlet Port Etchant: Electrolytic Oxalic Acid

This photomicrograph shows a transverse cross section in the area of the hot outlet port. A layer of corrosion scale is visible on both sides of the inner plate-to-plate copper brazed joints.

Details of the joint (arrow) are shown in Figures 9 and 10.

Figure 8 (13541) Hot Outlet Port Etchant: Electrolytic Oxalic Acid

This photomicrograph, like that of the figure above shows a transverse cross section in the area of the hot outlet port and includes the outlet port fitting.

A gap between the fitting and top plate is shown by the top arrow.

Corrosion of the side wall plate-to-plate braze is visible (bottom arrow). Both features are examined in Figures 11 and 12.

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

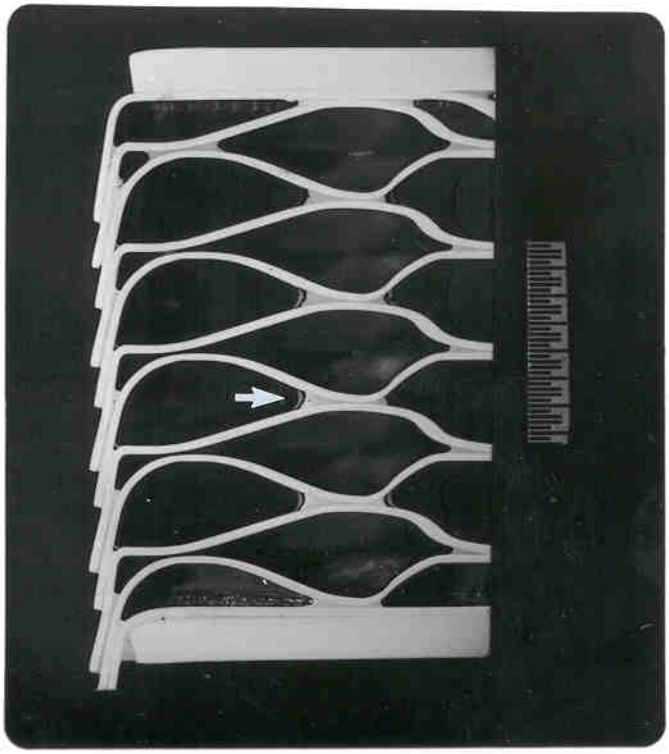

FIG. 7

(13542)

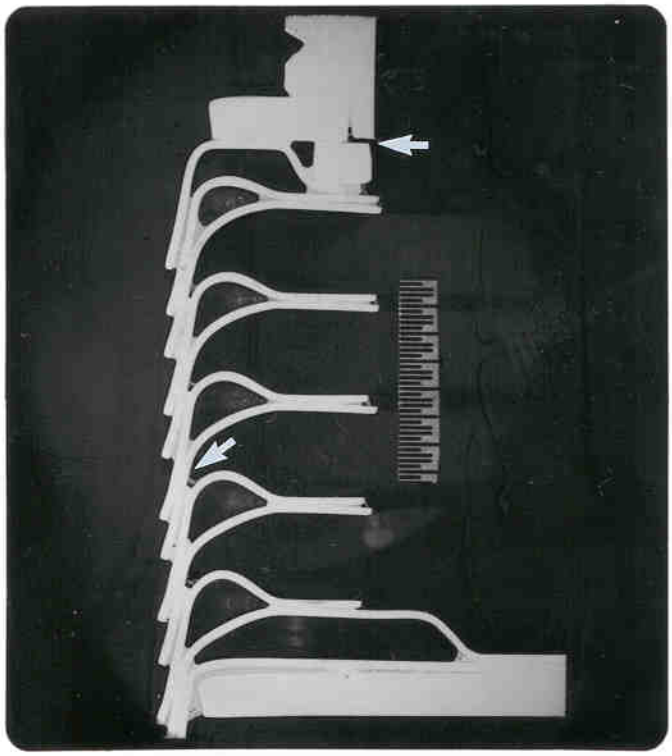

FIG. 8

(13541)

2233 S.W. CANYON ROAD
PORTLAND, OR 97201

Figure 9 (13535) 50X Etchant: Electrolytic Oxalic Acid

This photomicrograph shows detail of the brazed joint shown by the arrow in Figure 7. This joint is in a geothermal fluid passage, and corrosion from contact with this fluid has attacked the copper braze metal to a depth of approximately 0.014 inch.

The corrosion products consisted primarily of copper and sulfur, and the corrosion rate was approximately 0.33 inch per year. At this rate, such joints could fail in as little as 3 years.

These joints, like those of the Boise unit, were attacked primarily on the braze metal surfaces exposed to geothermal fluid, but some preferential attack along the copper-to-stainless steel interface was also present.

The stainless steel showed no evidence of corrosion, but some copper in grain boundaries uncovered by corrosion of the braze metal has been attacked, leaving open grain boundaries in the plate surfaces. These may be future sites for intergranular corrosion and/or crack initiation.

Figure 10 (13536) 300X Etchant: Electrolytic Oxalic Acid

This photomicrograph is a magnified view of the preferential attack of the copper braze metal along the copper-to-stainless steel interface. Open grain boundaries in the plate surface due to attack of intergranular copper are visible. No active corrosion of the stainless steel has occurred.

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

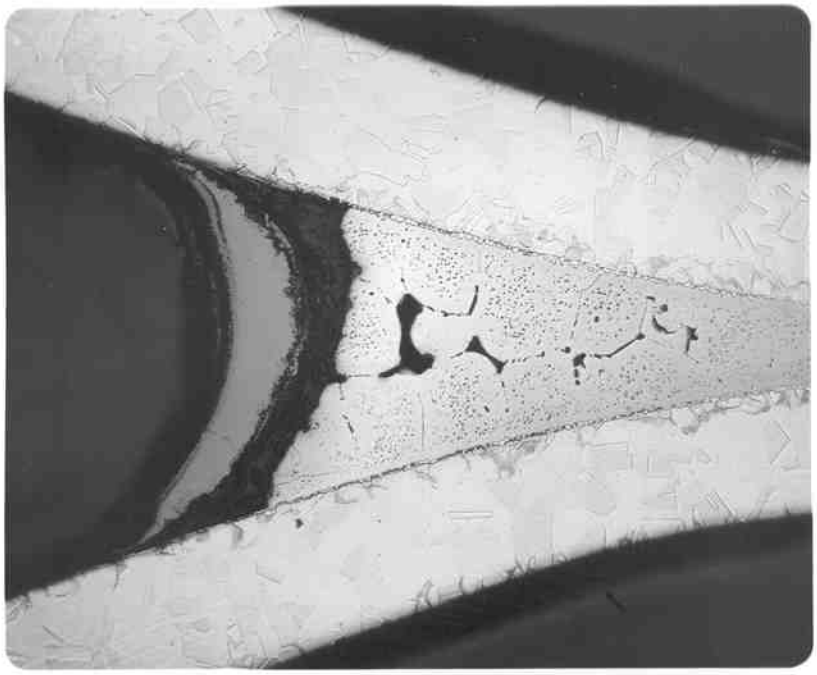

FIG. 9

(13535)

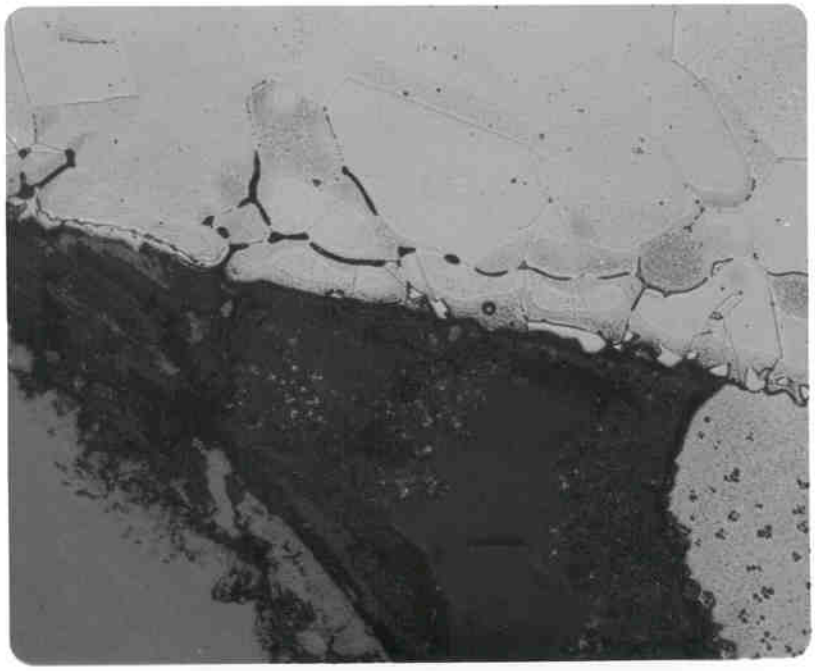

FIG. 10

(13536)

Figure 11 (13540) 50X Etchant: Electrolytic Oxalic Acid

This photomicrograph shows detail of the side wall joint in the hot outlet area shown by the bottom arrow in Figure 8.

Corrosion has attacked the copper braze metal to a depth of approximately 0.02 inch. Because this attack is on only one side of the joint, failure would take much longer than failure of internal geothermal passage joints and would not be the limiting factor in unit life.

Figure 12 (13539) 50X Etchant: Electrolytic Oxalic Acid

This photomicrograph shows detail of the gap between the hot outlet mounting port and the top plate shown by the top arrow in Figure 8.

Though some corrosion was present, the primary cause of the gap appears to be mechanical mismatch. Again, with attack occurring only on one side of the braze, this joint would not be the limiting factor in the unit's life.

2233 SW CANYON ROAD
PORTLAND, OR 97201-2499

FIG. 11

(13540)

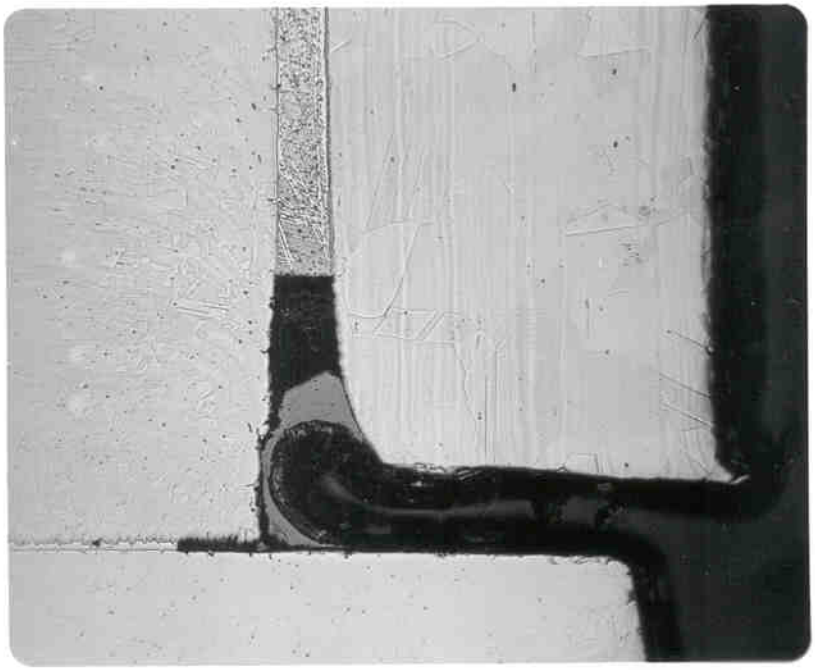

FIG. 12

(13539)