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MODEL BOILER STUDIES ON DEPOSITION AND CORROSION

by

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Etudes sur modèle de chaudière des dépôts et de la corrosion*

par

P.V. Balakrishnan et E.G. McVey

Résumé

Les dépôts qui se forment dans les générateurs de vapeur constituent un lieu de concentration pour les produits chimiques risquant d'être corrosifs pour le métal adjacent. La formation des dépôts a été étudiée dans un modèle de chaudière où de l'eau de mer a été injectée pour simuler l'infiltration qui pourrait se produire à partir des condenseurs refroidis par eau de mer. En utilisant le traitement AVT (All Volatile Treatment) pour contrôler la chimie, on a obtenu des dépôts consistant en sels d'eau de mer et en produits de corrosion. En ajoutant du phosphate de sodium à l'eau de la chaudière, on a constaté que les dépôts contenaient également des phosphates provenant des sels d'eau de mer. Des analyses aux rayons X et des examens au microscope électronique de balayage ont montré que les dépôts se formaient en couches ayant des compositions différentes.

Il n'y a pas eu de corrosion significative des tubes de chaudière en alliage Fe-Ni-Cr sous les dépôts, ni dans les parties ouvertes des tubes, ni dans les entailles. Cependant, l'acier au carbone ayant formé une entaille autour d'un tube se corrodait gravement lorsque l'eau de la chaudière ne contenait pas de phosphate. La corrosion de l'acier au carbone était causée par la présence d'une solution acide de chlorure fortement concentré provenant de l'eau de mer séjournant dans l'entaille. On donne les résultats des calculs théoriques touchant la composition de la solution concentrée.

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ABSTRACT

Deposits in steam generators provide a concentration
site for chemicals which may be corrosive to the adjacent
metal. Deposit formation was studied in a model boiler,
with sea-water injections to simulate the in-leakage which
could occur from sea-water cooled condensers. When All
Volatile Treatment (AVT) was used for chemistry control the
deposits consisted of the sea-water salts and corrosion
products. With sodium phosphate added to the boiler water,
the deposits also contained the phosphates derived from the
sea-water salts. Energy dispersive X-ray analysis and
scanning electron microscopy showed that the deposits were
formed in layers of differing compositions.
There was no significant corrosion of the Fe-Ni-Cr
alloy boiler tube under deposits, either on the open area of
the tube or in crevices. However, carbon steel that formed
a crevice around the tube was corroded severely when the
boiler water did not contain phosphate. The observed
corrosion of carbon steel was caused by the presence of
acidic, highly concentrated chloride solution produced from
the sea-water within the crevice. Results of theoretical
calculations of the composition of the concentrated solution
are presented.

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MODEL BOILER STUDIES ON DEPOSITION AND CORROSION

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In the nuclear steam generators which have experienced
tube leakage, the major cause of leakage has been corrosion.
The world experience on leakage in nuclear steam generators has
been documented in a series of reports by Stevens-Guille and
Hare (1). No corrosion-induced leakage has yet occurred in any
CANDU* steam generator. Development and evolution of steam
generators to higher performance levels require continual study
of failure mechanisms to ensure that the perfect record is
maintained.

Corrosion is more likely to occur in the secondary side
of steam generators. Corrosive reagents may be generated in
the boiler water from impurities present in the feed water.
Impurities may come from leakage at the condenser or from the
make-up water from the water treatment plant. These impurities
concentrate within the steam generators, especially inside
crevices or in porous deposits and may generate an aggressive
environment. The chemical treatment of the secondary water is
meant to control the generation of such environments.

WATER TREATMENT METHODS

Water treatment is intended to reduce corrosion by
increasing the pH and decreasing the dissolved oxygen

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*CANada Deuterium Uranium

concentration. The oxygen concentration is decreased by the addition of a reducing agent, hydrazine, to the feed water. The pH is raised either by the addition of a volatile base to the feed water or a non-volatile base to the steam generator water. Typical reagents for the former treatment - the All Volatile Treatment (AVT) - are ammonia, morpholine and cyclohexylamine. A mixture of di- and tri- sodium phosphates is used in the latter treatment.

The mixture of phosphates is a buffer system which can prevent the water becoming too alkaline or too acidic. It can also precipitate impurities, such as calcium and magnesium salts in a form that can be removed by blow-down. The composition of the mixture is maintained to give a sodium to phosphate molar concentration ratio in the range 2.2:1 to 2.6:1 such that the deposition (hide-out) of sodium phosphate within low-flow areas in the steam generator does not lead to excessively acidic or alkaline conditions in the water. The range of Na/PO_4 ratio for proper operation under this water treatment method - the Congruent Phosphate Treatment (CPT) - was derived from studies on the sodium phosphates-water system (2,3). These studies determined the points of congruent precipitation (where the solution and the precipitate are of the same Na/PO_4 ratio) and the behaviour of the solution (i.e. direction in which the Na/PO_4 ratio changes) during incongruent precipitation.

The AVT method uses a volatile neutralizing amine, such as ammonia, morpholine, or cyclohexylamine, for pH control. These reagents usually provide protection against corrosion for the feed train and, to some extent because of their volatility, for the surfaces exposed to wet steam. However, the low buffering capacity of these weak bases is of little help in preventing chemistry excursions within the steam generator to the acid or alkaline side of neutrality in the

event of a condenser water in-leakage. Moreover, hard scales
have been known to form on tubes from condenser water
impurities in boilers with AVT chemistry control. These hard
scales could impede heat transfer.

This paper describes studies on deposition and corrosion
carried out in a model boiler, with congruent phosphate
treatment as well as all volatile treatment of the boiler water
and with injection of Atlantic sea-water to simulate in-leakage
from sea-water cooled condensers.

THE LOOP AND THE MODEL BOILER

A schematic diagram of the model boiler circuit is given
in Figure 1. The boiler had a single Incoloy-800* U-tube (12.7
mm OD x 1.15 mm wall). The tube had appended to it on one leg
a carbon steel umbrella to create a steam-blanketed region for
studying effects of concentration of impurities in such regions
(Figure 2), and to the other leg devices to simulate different
crevices between tubes and tube support plates. The heat
required to generate the steam in the boiler was derived from
the primary flow through the tube taken from the loop.
The model boiler system included a copper-tubed condenser and a
6 kW heater for preheating the water as it entered the boiler.
The circulation was provided by natural density differences
(natural circulation). The boiler was rated at 40 kW. The
operating conditions of the loop were as listed in Table 1.

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* Incoloy-800 nominal composition (wt%):

Fe	Ni	Cr	Mn	Cu	C	S	Si	Al	Ti
46.0	32.5	21.0	0.75	0.38	0.05	0.008	0.50	0.38	0.38

EXPERIMENTS

The experimental program consisted of three phases. In the first phase the boiler water chemistry was controlled by congruent phosphate treatment while a small amount of sea-water was continuously injected with the make-up water. In the second phase, both the phosphate treatment and the sea-water injection were stopped to see whether the deposits accumulated during the first phase would be cleaned by maintaining all volatile treatment in the absence of ingress of sea-water. The third phase of the program examined the effects of sea-water ingress while the boiler water chemistry was controlled by all volatile treatment.

At the end of each phase the boiler tube was examined visually. Samples of deposit were removed from the tube, both from an open area and from under the carbon steel umbrella. The deposits were analyzed chemically, by X-ray diffraction and by energy dispersive X-ray analysis in a scanning electron microscope (SEM/EDS). The tube and carbon steel umbrella were visually examined for corrosion. After the third phase, a section of boiler tube with the deposit intact on it was examined in detail in the scanning electron microscope.

RESULTS

Congruent Phosphate Treatment - Sea-water Injection (Phase 1)

The secondary water chemistry conditions during this phase were as follows:

pH:	9.8
phosphate:	18 mg PO_4/kg water (average)
chloride (from sea-water):	17 to 55 mg Cl/kg water (32 mg/kg average)
oxygen:	<10 µg/kg (controlled with hydrazine)

The boiler water also contained morpholine (≈6 mg/kg) so that the observed pH of 9.8 corresponded to a sodium to phosphate molar ratio of ≈2.4:1.

After 47 days there was a thick black deposit on the tube. The deposit under the carbon steel umbrella was white. The deposit on the tube appeared to have a soft outer layer with rough texture and a harder, brittle inner layer. Chemical and X-ray powder analyses gave the results in Table 2.

The white deposit under the umbrella probably consisted of sodium phosphates, sodium chloride, magnesium hydroxide, and calcium phosphate. The deposit on the tube consisted mainly of corrosion products from the boiler circuit materials. The copper must have come from the copper tubes in the condenser.

No localized corrosion attack of any kind was observed on the tube anywhere, even inside crevices. The carbon steel of the umbrella also did not show significant corrosion.

All Volatile Treatment - No Sea-water Injection (Phase 2)

Following the visual examination at the end of the first phase and removal of the deposit under the umbrella and small amounts of deposit from the tube for analysis, the boiler was reassembled for the next phase. Sea-water injection and CPT as in Phase 1 were continued for the first 13 days to build up the deposit under the umbrella. The chemistry was then switched over to AVT after stopping the sea-water injection. For the next 13 days the following chemistry conditions were maintained:

pH: 9.8 (with morpholine ≈ 12 mg/kg)
chloride: 1 mg Cl/kg water
oxygen: 10 to 30 μg/kg (hydrazine used for reduction
                          of oxygen)

After 13 days in this phase the deposit had a brownish colour, presumably due to the oxidation of magnetite to haemetite by oxygen which was present at a higher concentration during this phase than during the previous one. The deposit also had a layered structure – an outer loose deposit and two layers of hard, brittle scale. Analyses of the deposit under the carbon steel umbrella and of the deposit on the tube in an exposed area are given in Table 3.

A small portion of the hard deposit removed as one piece was examined microscopically. The deposit appeared under the optical microscope to consist of two layers. The layered feature was not obvious under the scanning electron microscope. The five regions seen in the SEM micrograph (Figure 3) were examined more closely at a higher magnification. Elemental compositions at these regions, determined by energy dispersive X-ray analysis in the scanning electron microscope (SEM/EDS) are shown in Table 4.

The deposit is copper rich near the tube, richer in calcium and magnesium at the outer edge than near the tube and richer in iron in the central regions than at either edge.

The deposits from this phase were not significantly different from those from the first phase. The switchover to AVT did not remove the deposits formed under CPT and sea-water contamination.

No indication of localized corrosive attack was present either on the tube or on the carbon steel umbrella.

All Volatile Treatment – Sea-water Injection (Phase 3)

The deposit was scraped off the boiler tube after the second phase, and the third phase with water treatment by morpholine and sea-water injection was begun. The boiler water chemistry conditions were as follow:

pH: 9.5 to 9.6 (controlled with morpholine)

chloride

(from sea water):   8 to 60 mg Cl/kg (30 mg/kg average)

oxygen: $\leq$10 µg/kg (controlled with hydrazine)

magnesium: 1.5 to 2.3 mg/kg as Mg^{+2}

calcium: 1.4 to 4.3 mg/kg as Ca^{+2}

The pH tended to drift towards the acid side and it required additions of morpholine up to 25 mg/kg water compared to only 12 mg/kg during Phase 2. This behaviour illustrates the acid-forming nature of sea-water.

After 47 days in this phase, the deposit formed was thinner than that formed during the first phase. Both the loose outer layer and the hard inner scales were present. A section of the tube with the deposit intact was examined by the SEM/EDS technique. The optical micrograph and the secondary electron micrograph of the sections are shown in Figures 4a and 4b respectively. The elemental maps of the deposit are given in Figures 5a through 5g which show the distribution of the different elements through the scale. Figure 6 shows a composite elemental X-ray map obtained by tracing the boundaries of major concentration for each element. Four layers are apparent, with similar elemental constituents but different concentration profiles. Figure 7 shows the X-ray spectra collected for each layer. The elemental composition for each of these layers is given in Table 5. The bottom two layers are rich in copper, which may have been deposited on the tube in the metallic state since it is the least electro-positive metal in the system. Iron is more predominant in the middle two layers. The iron may be existing as magnetite. Magnesium, introduced as an impurity with the sea-water, pre-dominates in the top two layers, while calcium, also a

sea-water impurity, is abundant in the outer three layers. Phosphorous is present more or less uniformly. This was not really expected after the AVT phase. Perhaps because of the very long exposure to phosphates that the boiler had, and because the boiler was not chemically cleaned before Phase 3, there probably was enough phosphate hidden out in the system to make its presence felt in the deposits. The trends described above on the elemental X-ray maps are not clearly seen in the analyses listed in Table 5. This may be because the analyses were done on spots within each layer which have compositions different from the overall average in the layer as reflected by the X-ray maps.

Figure 8 shows the carbon steel umbrella used during Phase 3. It was severely corroded. The original wall thickness of 0.57 mm of the neck of the umbrella was completely penetrated in 47 days. This gives an estimate for the corrosion rate of greater than $900 \, mg/(dm^2 \cdot day)$. This very high corrosion rate must have been due to the very high chloride concentration and the acid pH that would have existed in the crevice within the umbrella during the Phase 3 experiment. This contrasts with the lack of appreciable corrosion of carbon steel during Phase 1 when congruent phosphate treatment was used in the presence of sea-water impurities. The non-volatile phosphate buffer system prevented the pH from going to the acid side. The volatile amine, morpholine, which is also only a weak base, and hence un-ionized at the boiler temperature, was inadequate for this purpose during the Phase 3 experiment.

There was no evidence of any localized or general corrosion on the tube (Incoloy-800).

DISCUSSION

Deposition and Corrosion

During the three phases of the study reported here, scales formed in layers. The top layer in all cases was loose, hard and brittle. The layers had similar chemical constituents, but the distribution of these constituents was different for each layer. Huijbregts et al. (4) have made similar observations on the scale formation from sea-water salts on carbon steel boiler tubes. The mechanism of scale formation probably is, as suggested by these workers, the deposition of corrosion products to produce a porous layer under which sea-water salts concentrate and precipitate. The layers of salts could further interact with the corrosion product deposit and make it flaky or otherwise affect its integrity. In the case of carbon steel boiler tubes, there could be interaction with the metal, i.e. increased corrosion as observed by Huijbregts et al. There was no interaction with the Incoloy-800 tube in our studies.
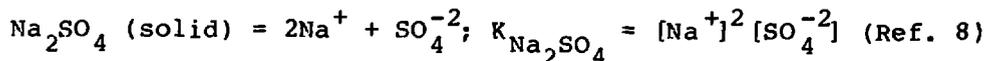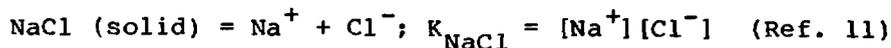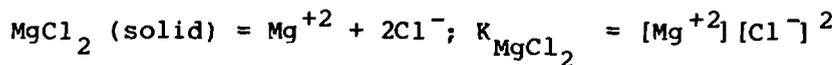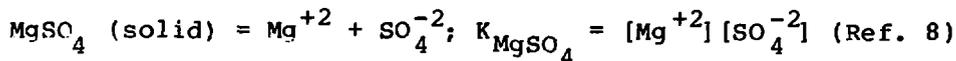
The thick and hard deposit formed from sea-water during Phase 1 indicates definitely that long-term operation of steam generators with sea-water in-leakage is not advisable even with Co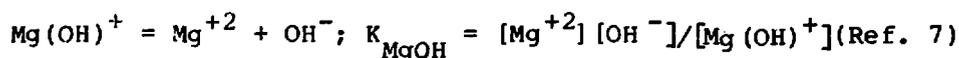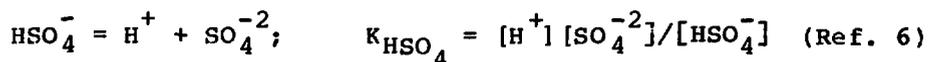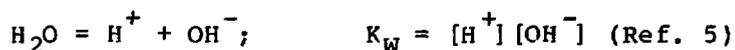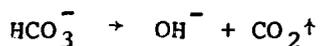ngruent Phosphate Treatment. Thick deposits on tubes provide concentration sites for corrosive chemicals. In addition, they may affect heat transfer adversely. The Phase 2 experiments, in which the water chemistry was switched to All Volatile Treatment from Congruent Phosphate Treatment after stopping the sea-water injection, showed that the scale formed from CPT and sea-water was not cleaned by AVT significantly during 13 days of this phase.

Both AVT and CPT formed deposits of similar thickness (150 µm) from sea-water salts. There was no significant corrosion of the boiler tube with either treatment. Even in the presence of up to 60 mg chloride/kg the Incoloy-800 tube

did not show any signs of pitting with more than 100 days
total exposure. The Phase 3 results show that sea-water salts
lead to the accelerated corrosion of carbon steel components
within crevices when volatile amines only are used for the
water treatment. The observed severe corrosion of carbon steel
is the result of a corrosive environment being generated within
the crevice under the umbrella.

Composition of Concentrated Sea-Water

To determine the nature of concentrated sea-water, the
composition of the concentrate was evaluated theoretically
using the following reactions and equilibria:

$$HCO_3^- \rightarrow OH^- + CO_2\uparrow$$

$$H_2O = H^+ + OH^-; \qquad K_W = [H^+][OH^-] \text{ (Ref. 5)}$$

$$HSO_4^- = H^+ + SO_4^{-2}; \qquad K_{HSO_4} = [H^+][SO_4^{-2}]/[HSO_4^-] \text{ (Ref. 6)}$$

$$Mg(OH)^+ = Mg^{+2} + OH^-; \quad K_{MgOH} = [Mg^{+2}][OH^-]/[Mg(OH)^+] \text{(Ref. 7)}$$

$$CaSO_4 \text{ (solid)} = Ca^{+2} + SO_4^{-2}; \quad K_{CaSO_4} = [Ca^{+2}][SO_4^{-2}] \text{ (Ref. 8)}$$

$$Ca(OH)_2 \text{ (solid)} = Ca^{+2} + 2OH^-; \quad K_{Ca(OH)_2} = [Ca^{+2}][OH^-]^2 \text{ (Ref. 9)}$$

$$CaCl_2 \text{ (solid)} + Ca^{+2} + 2Cl^-; \quad K_{CaCl_2} = [Ca^{+2}][Cl^-]^2$$

$$Mg(OH)_2 \text{ (solid)} = Mg^{+2} + 2OH^-; \quad K_{Mg(OH)_2} = [Mg^{+2}][OH^-]^2 \text{ (Ref. 10)}$$

$$MgSO_4 \text{ (solid)} = Mg^{+2} + SO_4^{-2}; \quad K_{MgSO_4} = [Mg^{+2}][SO_4^{-2}] \text{ (Ref. 8)}$$

$$MgCl_2 \text{ (solid)} = Mg^{+2} + 2Cl^-; \quad K_{MgCl_2} = [Mg^{+2}][Cl^-]^2$$

$$NaCl \text{ (solid)} = Na^+ + Cl^-; \quad K_{NaCl} = [Na^+][Cl^-] \text{ (Ref. 11)}$$

$$Na_2SO_4 \text{ (solid)} = 2Na^+ + SO_4^{-2}; \quad K_{Na_2SO_4} = [Na^+]^2[SO_4^{-2}] \text{ (Ref. 8)}$$

The equilibrium constants, K, are expressed in terms of the activities of the ions involved in the equilibria. Each equilibrium constant was taken from the reference shown in brackets for each equilibrium, as also were the parameters required for evaluating the activity coefficients.

The calculations were carried out starting from the composition of the natural sea-water (Atlantic Ocean) considering it concentrated at 300°C (the highest temperature within the boiler) by arbitrary concentration factors until further concentration did not change any of the ionic concentrations in the water because it became saturated with each of the salts that would precipitate. Table 6 gives the maximum attainable concentration thus calculated. The salts that precipitate at these concentrations are also listed.

Table 6 shows that the concentrated sea-water is of extremely high chloride concentration, with $MgCl_2$ and NaCl as the principal solutes in the solution. It is also acidic ($pH_{25°C}$ = 3.52). Acid solutions of high chloride concentration are known to corrode carbon steel rapidly (12). Thus, the observed severe corrosion of the carbon steel umbrella is a consequence of the concentration of sea water impurities within the crevice under it. The water treatment (AVT - with morpholine) was not capable of neutralizing the acid condition in the water.

SUMMARY AND CONCLUSIONS

Operation of a model boiler with the boiler water on congruent phosphate treatment and with sea-water injection resulted in thick, laminated scales on the tube which consisted of corrosion products from the boiler circuit and solutes from the sea-water. A white deposit was also formed under a

concentrating device (a carbon steel umbrella.) This deposit consisted mainly of sea-water salts and their hydrolysis products. There was no indication of localized corrosion in the boiler during the 47 days of the experiment.

Return to all volatile treatment with morpholine and fresh water after the previous phase of operation with phosphate treatement in the presence of sea-water salts did not reduce the scales on the tube or under the concentrating device significantly in the 13 days of operation in this mode.

All Volatile Treatment in the presence of sea-water impurities resulted in scales on the boiler tube similar to those formed during phosphate treatment. There was no pitting of the Incoloy-800 boiler tube during the 47 days of this phase, but the carbon steel umbrella which formed a crevice around the boiler tube was severely corroded. Calculations have shown that an acidic, highly concentrated chloride solution results from the evaporation of sea-water. The rapid corrosion of carbon steel must be the consequence of the corrosive environment so generated.

All Volatile Treatment is not adequate to prevent corrosion of carbon steel components in steam generators during the in-leakage of acid-forming sea-water. Under these circumstances, the use of non-volatile buffering agents, e.g. the sodium phosphates as in the congruent phosphate treatment, is desirable.

REFERENCES

1. a) Stevens-Guille, P.D., "Steam Generator Tube Failures: A
      World Survey of Water-Cooled Nuclear Power Reactors to
      the End of 1971", AECL-4449, Atomic Energy of Canada
      Limited (1973).

   b) Stevens-Guille, P.D., "Steam Generator Tube Failures:
      World Experience in Water-Cooled Nuclear Power Reactors
      During 1972", AECL-4753, Atomic Energy of Canada Limited
      (1974).

   c) Stevens-Guille, P.D. and Hare, M.G., "Steam Generator
      Tube Failures: World Experience in Water-Cooled Nuclear
      Power Reactors in 1973", AECL-5013, Atomic Energy of
      Canada Limited (1975).

   d) Hare, M.G., "Steam Generator Tube Failures: World
      Experience in Water-Cooled Nuclear Power Reactors in
      1974", AECL-5242, Atomic Energy of Canada Limited (1975).

   e) Hare, M.G., "Steam Generator Tube Failures: World
      Experience in Water-Cooled Nuclear Power Reactors in
      1975", AECL-5625, Atomic Energy of Canada Limited (1976).

2.   Ravich, M.I. and Shcherbakova, L.A., "Nature of the Solid
      Phase Which Crystallizes from Aqueous Solutions of Tri-
      sodium Orthophosphate at High Temperatures", Izvest.
      Sektora. Fiz-Khim. Anal. Inst. Obshchei Neorg. Khim.
      Akad. Nauk. SSSR 26, 248 (1955).

3.   Panson, A.J., Economy, G., Liu, C-T., Bulischek, T.S.,
      "Sodium Phosphate Solubility and Phase Relations Basis
      for Invariant Point Chemistry Control", J. Electrochem.
      Soc. 122 (7), 915 (1975).

4. Huijbregts, W.M.M., Jelgersma, J.H.N. and Snel, A.,
    "Der Einfluß von Warmetransport, Ablagerungen und
    Kondensator leakagen auf die Korrosion in
    Dampferzuengern", VGB Kraftwerketechnik 55, 26 (1975).

5. Fisher, J.R. and Barnes, H.L., "The Ion-Product Constant
    of Water to 350°", J. Phys. Chem. 76, 90 (1972).

6. Marshall, W.L. and Jones, E.V., "Second Dissociation
    Constant of Sulfuric Acid from 25° to 350° Evaluated from
    Solubilities of Calcium Sulfate in Sulfuric Acid
    Solutions", J. Phys. Chem. 70, 4028 (1966).

7. Helgeson, H.C., "Thermodynamics of Hydrothermal Systems
    at Elevated Temperatures and Pressures", Amer. J. Science
    267, 729 (1969).

8. Marshall, W.L., "Thermodynamic Functions at Saturation of
    Several Metal Sulfates in Aqueous Sulfuric and Deutero-
    sulfuric Acids at Temperatures up to 350°C", J. Inorg.
    Nucl. Chem. 37, 2155 (1975).

9. Yeatts, L.B. and Marshall, W.L., "Aqueous Systems at High
    Temperature XVIII. Activity Coefficient Behaviour of
    Calcium Hydroxide in Aqueous Sodium Nitrate to the
    Critical Temperature of Water", J. Phys. Chem. 71, 2641
    (1967).

10. Cohen, P., The Chemistry of Water and Solutions at High
    Temperatures for Application to Corrosion in Power
    Systems", WARD-5788, Westinghouse Electric Corporation
    Advanced Reactors Division, Madison, Pa., USA, page 38
    (1972).

11. Liu, C-T. and Lindsay, W.T., Jr., "Thermodynamics of Sodium Chloride Solutions at High Temperatures", J. Solution Chem. 1, 45 (1972).

12. Potter, E.C. and Mann, G.M.W., "The Fast Linear Growth of Magnetite on Mild Steel in High-Temperature Aqueous Conditions", British Corrosion Journal, 1, 26 (1965).

TABLE 1

OPERATING CONDITIONS OF THE MODEL BOILER SYSTEM

Primary Circuit

Temperature – boiler inlet:	300°C
Pressure:	9.0 MPa
Flow rate:	1.1 to 1.5 kg/s
pH:	10.0 to 10.5 (with LiOH)
Oxygen:	< 5 µg/kg (controlled by catalyzed hydrazine)
Purification flow:	≈10% of the loop flow
Make-up water:	distilled, deionized, deoxygenated water

Secondary Circuit

Temperature – steam:	251°C
– condensate:	95°C
– feed water:	170°C
Steaming rate:	0.063 kg/s
Boiler pressure:	4.1 MPa
Blow down:	≈1% steaming rate

TABLE 2

ANALYSIS OF THE DEPOSITS FROM PHASE 1 (CPT + SEA-WATER)

	Composition (Abundance in Deposit)	
Element	Deposit Under Umbrella	Deposit on Tube
Fe	m	M
Cr	m	m
Cu	M	M
Ni	m	M
Zn	ND	M
Ca	m	m
Mg	M	M
Na	M	m
P	m	M
Si	m	m

M = major
m = minor
ND = not detected

TABLE 3

ANALYSIS OF THE DEPOSITS FROM PHASE 2 (AVT)

	Composition (Abundance in Deposit)	
Element	Deposit Under Umbrella	Deposit on Tube
Fe	m	M
Cr	m	m
Cu	M	M
Mn	M	M
Ni	M	M
Zn	m	M
Ca	m	M
Mg	M	m
Na	M	M
P	M	M
Si	M	m

m = minor
M = major

TABLE 4

ANALYSIS OF THE DEPOSIT FROM THE TUBE AFTER PHASE 2

Region	Composition* (in descending order of concentration)		
	Major	Minor	Trace
1 (metal/scale interface)	Fe,Cu,P,Ca	Mn,Mg	Al,Si,S,Zn
2	Cu,Fe,P,Ca,Mg	Mn	Si,Al,S,Zn
3	Fe,Ca,P,Cu,Mg	S,Mn	Si,Al,Zn
4	P,Mg,Fe,Ca,Cu	Mn	Si,Al,Zn,S
5 (outer edge of scale)	Ca,P,Fe,Mg	Cu,Ba	S,Al,Si,Zn

* for elements, atomic number > 10

TABLE 5

ELEMENTAL WT% (ZAF CORRECTED) COMPOSITION OF LAYERS IN OXIDE/SCALE

Layer →	1	2	3	4
Element ↓	(scale/metal interface)			
Mg				
Range	7.4-13.9	6.0-15.2	12.4-15.8	8.6-22.4
Average	10.4	9.0	13.9	13.6
P				
Range	22.4-31.2	21.6-29.1	28.6-33.7	10.6-35.0
Average	28.3	25.2	30.2	22.1
Ca				
Range	9.7-17.2	13.1-24.0	9.2-13.8	2.0-11.5
Average	12.5	17.6	11.5	5.7
Cr*				
Range	0.9-1.1	0.1-0.3	0.02-0.14	0.03-0.2
Average	1.0	0.2	0.1	0.08
Fe				
Range	18.8-25.6	14.7-27.7	10.3-15.8	4.1-15.4
Average	21.2	23.3	13.1	9.0
Ni*				
Range	0.5-0.8	0.05-0.2	0.0-0.07	0.02-0.1
Average	0.7	0.12	0.05	0.07
Cu				
Range	6.7-13.3	2.5-18.3	0.2-0.6	0.1-2.9
Average	9.7	9.2	0.3	0.7
Total	83.8	84.6	69.2	51.2
Other elements present in trace amounts	Mn,Al,Si,S Zn (Ba or Ti)	Mn,Al,Si,S Zn	Mn,Al,Si,S Zn	Mn,Al,Si,Zn

* Not ZAF corrected. (ZAF is a computer program to calculate
  elemental composition corrected for X-ray generation efficiencies
  and absorption and fluorescence effects)

TABLE 6

MAXIMUM ATTAINABLE CONCENTRATIONS ON EVAPORATING
SEA-WATER AT 300°C

Ions	Concentration (mol/kg)
Ca	0.134
Mg	11.1
Na	6.17
SO_4	0.00389
Cl	28.6
$pH_{25°C}$	3.52

Precipatate:
$CaSO_4$, $Mg(OH)_2$, $MgSO_4$, $MgCl_2$ and $NaCl$

CHEMICAL MAKE-UP
DISTILLED WATER

MAKE-UP TANK

N_2

CHEMICAL MAKE-UP
DISTILLED WATER

SEA-WATER

MAKE-UP TANK

N_2

CONDENSER

MODEL BOILER

6 kW HEATER

8 kW HEATER

15 kW HEATER

25 kW HEATER

TEST SECTION

9 kW HEATER

MAKE-UP PUMP

BLOWDOWN

PRIMARY
SECONDARY
AUXILIARY

MAKE-UP PUMP

PHOS-PHATE TANK
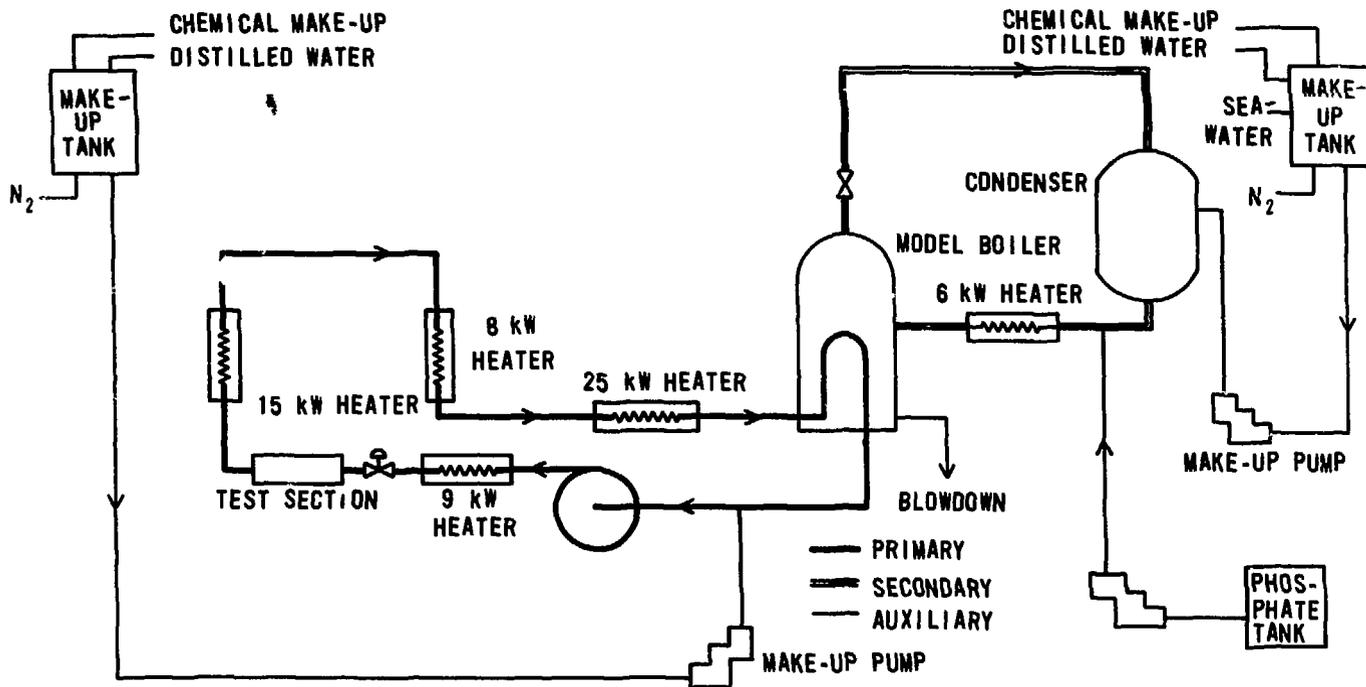
FIGURE 1   SCHEMATIC DIAGRAM OF MODEL BOILER INSTALLATION
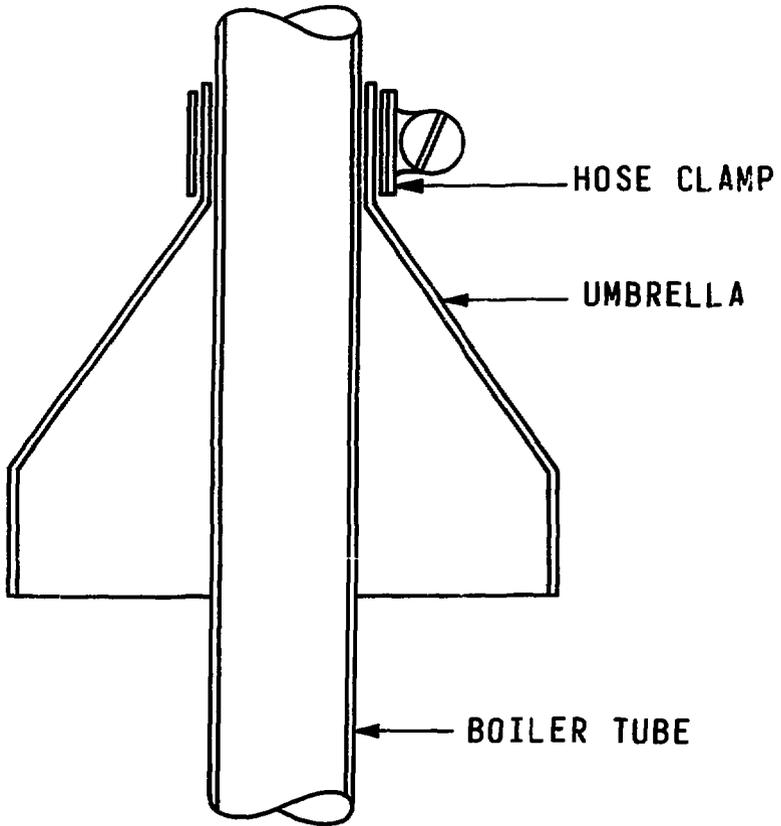
FIGURE 2 SKETCH OF THE CARBON STEEL UMBRELLA
ON BOILER TUBE
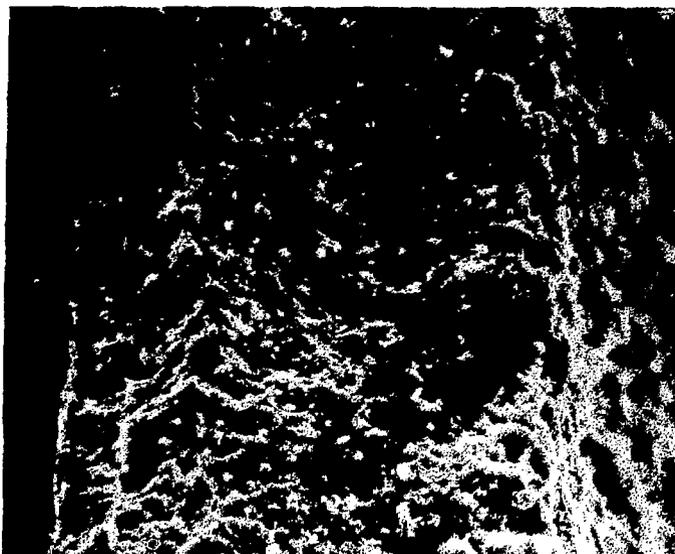
500x

1   2   3   4   5

FIGURE 3   Cross section of scale removed from Incoloy-
           800 tube. Left-hand edge is metal/deposit
           interface.
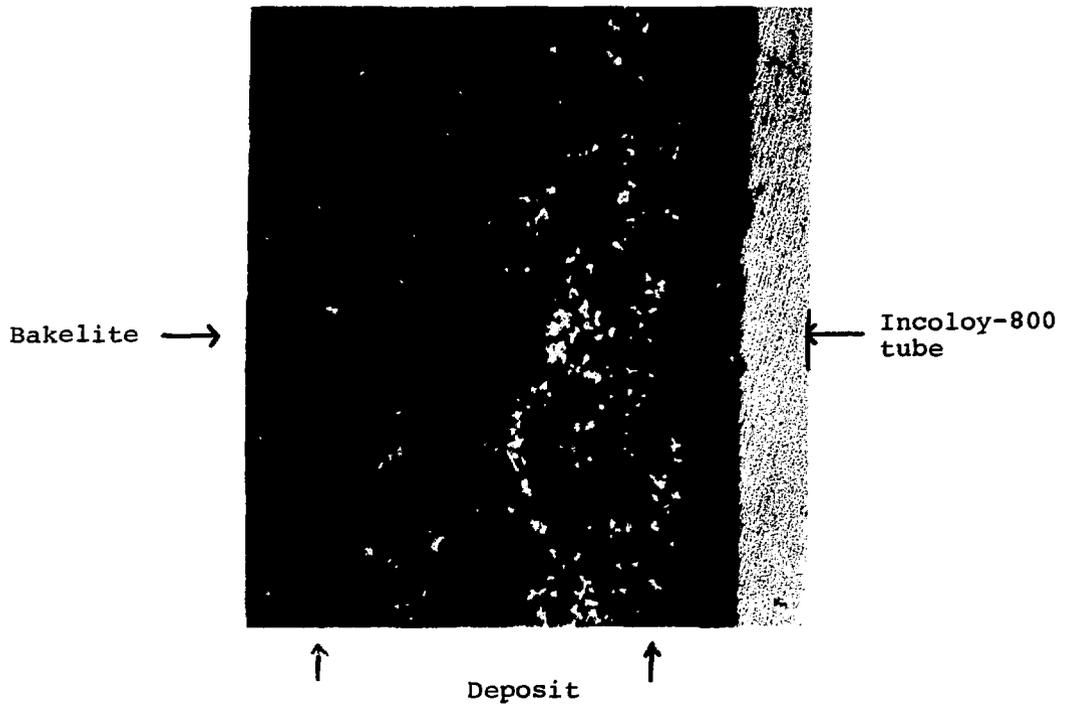
FIGURE 4a   Optical micrograph of deposit   500x
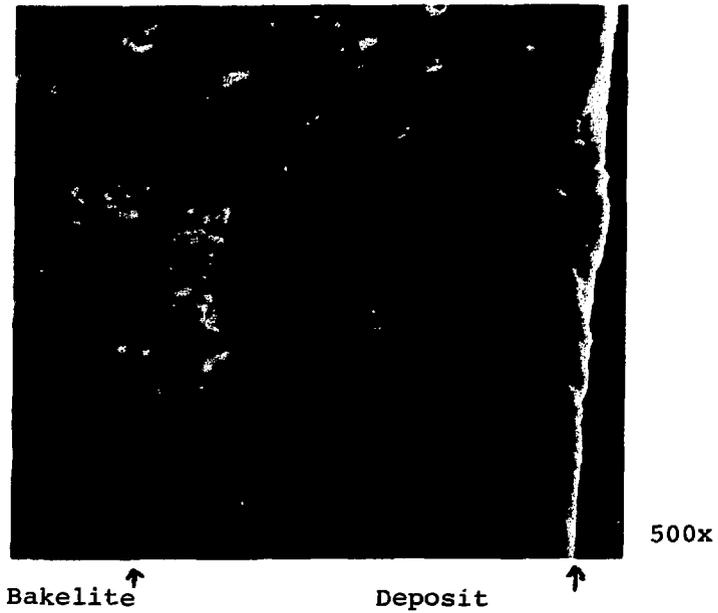
FIGURE 4b   Secondary electron micrograph of deposit

FIGURE 5   Elemental X-ray maps of area shown in Figure 4
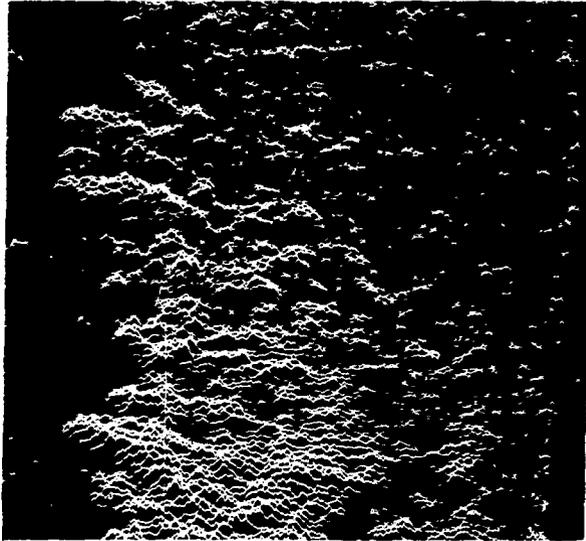
500x

FIGURE 5a   Mg X-ray map. (Changes in intensity and height of
            scan line indicate   increase in concentration.)
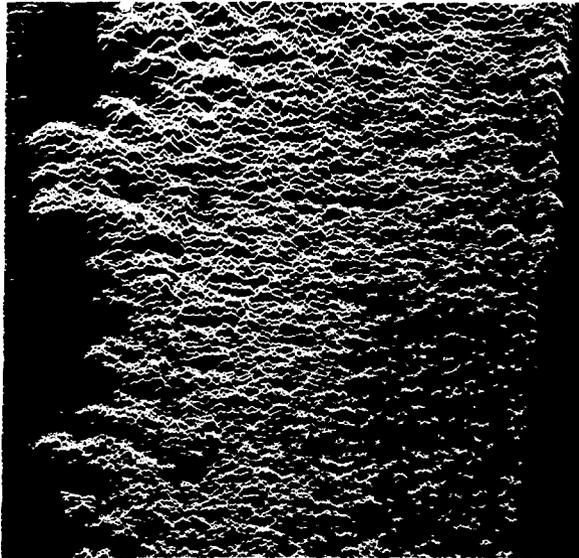
FIGURE 5b   P X-ray map   500x
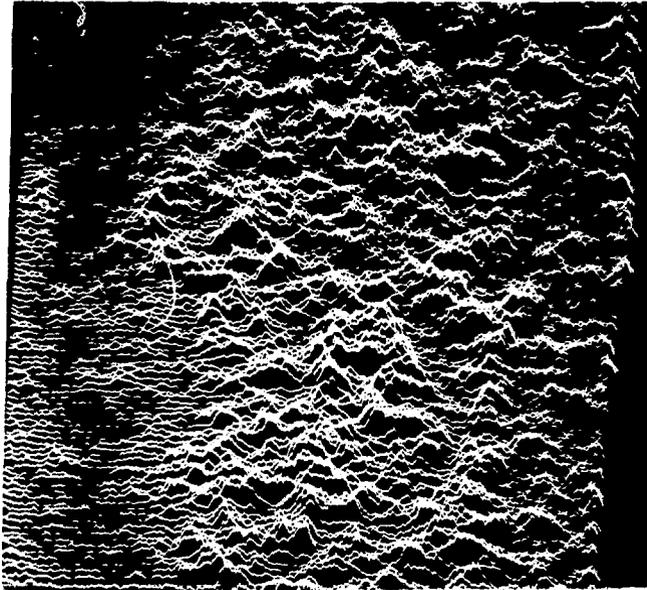
FIGURE 5c   Ca X-ray map   500x

FIGURE 5d   Cr X-ray map   500x
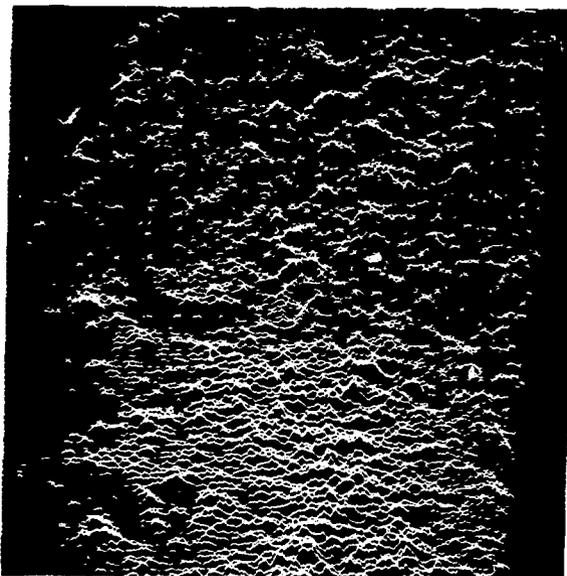
FIGURE 5e   Fe X-ray map   500x
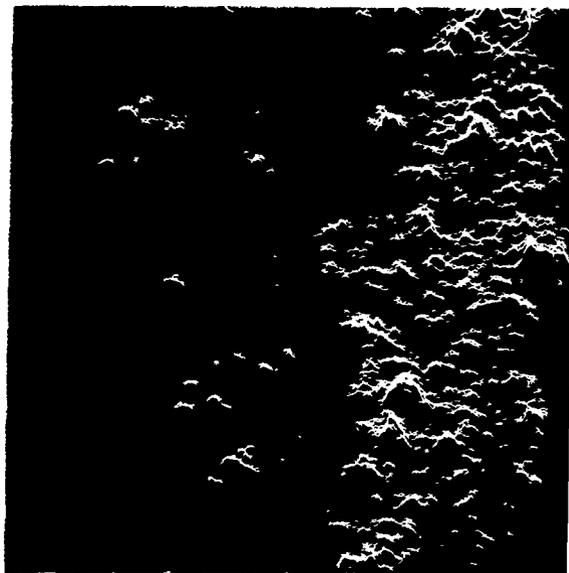
FIGURE 5f   Cu X-ray map   500x
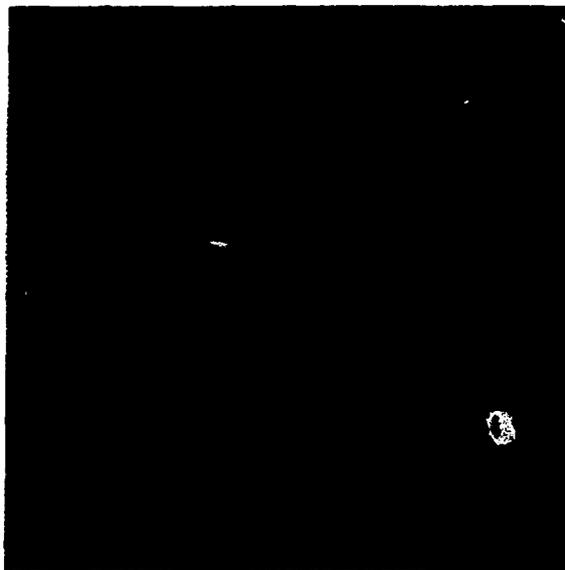
FIGURE 5g   Ni X-ray map   500x
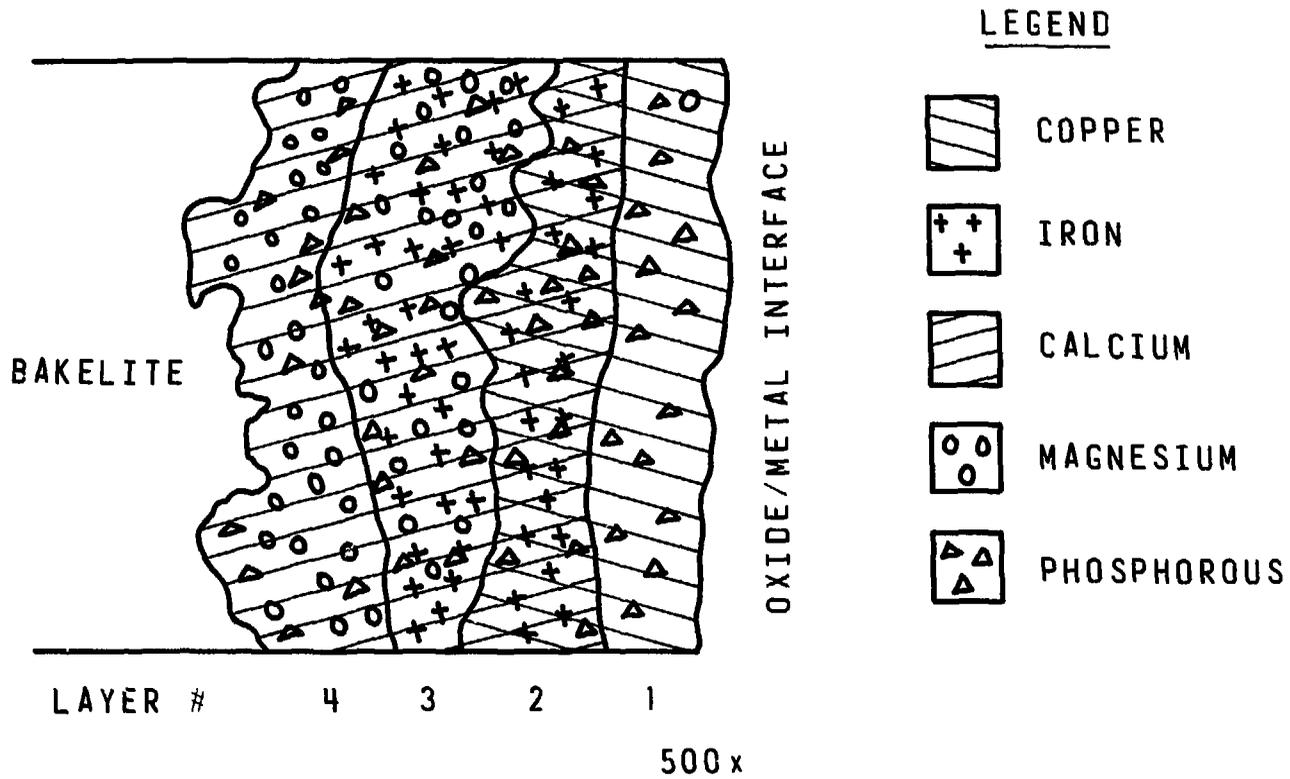
FIGURE 6 COMPOSITE ELEMENTAL X-RAY MAP OF DEPOSIT

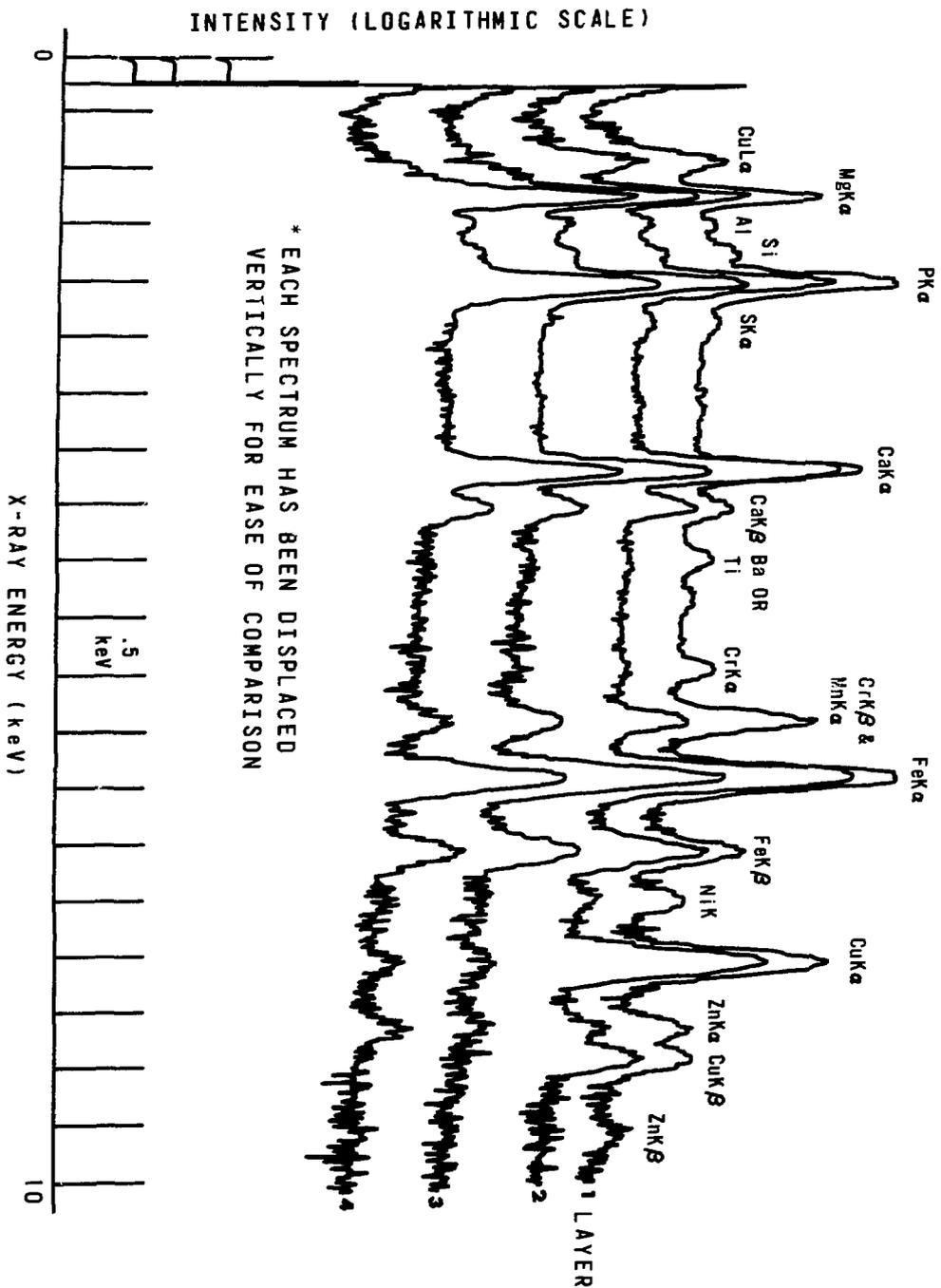FIGURE 7 TYPICAL X-RAY SPECTRA* COLLECTED FROM EACH LAYER

* EACH SPECTRUM HAS BEEN DISPLACED VERTICALLY FOR EASE OF COMPARISON

FIGURE 8   The carbon steel umbrella after Phase 3
            (AVT with sea-water injection)

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