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RADIOTRACER STUDIES OF HIDEOUT

AT

HIGH TEMPERATURE AND PRESSURE

MASTER

June, 1963

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ABSTRACT

Local concentration or hideout of solutes at clean and fouled heat transfer surfaces were studied by means of a radiotracer hideout test facility. The study was directed at the elucidation of the factors affecting hideout from boric acid solutions on surfaces fouled with transport corrosion products of stainless steel (called crud), for application to the problem of boron hideout in closed-cycle water reactors with chemical control by boric acid shim.

SUMMARY AND CONCLUSIONS

Utilizing Na^{22} tracer, a technique has been developed which permits the measurement of the concentration of the tracer at heat transfer surfaces under conditions of temperature, pressure and heat flux closely simulating that of closed-cycle water reactors. Techniques have also been developed for forming deposits of magnetite on the test heaters which simulate crud deposits on reactor heat transfer surfaces. Tests were run with Na_3PO_4 and $\text{NaOH} - \text{H}_3\text{BO}_3$ systems to investigate the significance of the solubility temperature relations of the solute on hideout. The results of the investigation are briefly summarized as follows:

1. In the absence of nucleate boiling, concentration of solute does not occur.
2. On clean surfaces, with boiling, concentration occurs for a solute with retrograde solubility (Na_3PO_4) but does not occur in the $\text{NaOH} - \text{H}_3\text{BO}_3$ system where the solubility is very high at the surface temperatures employed.
3. On fouled surfaces, with sub-cooled or bulk boiling, concentration can occur in the high solubility system, $\text{NaOH} - \text{H}_3\text{BO}_3$. For the conditions studied, there appears to be a minimum thickness of deposit required for concentration, of the order of 0.3 to 0.4 mil.
4. Where concentration occurs, it appears to be proportional to the rate of evaporation at the surface.

NOMENCLATURE

- A = system area at which heat is being transferred to the liquid
 $\hat{b}$ = refers to the unheated section of the annulus (background)
 C = solute concentration in a bulk phase liquid, mass solute/volume solution
 C_B = activity concentration of bulk solution, counts/#
 C_f = boundary layer activity, counts/ft² of heater
 C_P = specific heat of solution, Btu/# °F
 D = detector count rate, counts/time
 D' = boundary layer - bulk diffusion coefficient, hr⁻¹
 D_i = inner diameter of an annular region
 D_o = outer diameter of an annular region
 E = boundary layer - bulk mixing coefficient, hr⁻¹
 h = forced convection heat transfer coefficient, Btu/hr-ft² °F
 $\hat{h}$ = refers to the heated section of the annulus
 h_{fg} = heat of vaporization, Btu/#
 k = a calibration constant
 K_i = integration constant
 $\dot{M}$ = mass steaming rate at heater surface, #/hr-ft²
 m = solute concentration in a boundary layer, mass solute/mass solvent
 m^o = solute concentration in bulk phase liquid, mass solute/mass solvent
 N_B = count rate of background, counts per minute (cpm)

NOMENCLATURE (continued)

- N_S = count rate of sample, counts per minute (cpm)
 P = system pressure, psia
 q_{NB}'' = nucleate boiling heat transfer rate, Btu/hr-ft²
 q_T'' = total heat transfer rate, Btu/hr-ft²
 R = hideout ratio, m/m⁰
 S = solute hideout concentration expressed as a surface concentration mass/area
 t_B = time of background count, minutes
 t_f = an effective boundary layer thickness, length
 t_s = time of sample count, minutes
 T_B = bulk coolant temperature, °F
 T_{Sat} = saturation temperature for system pressure, °F
 T_W = heater surface temperature, °F
 V = system volume
 v_s = specific volume of steam, ft³/#
 w_f = mass of solution in film per heater area, #/ft²
 y = nine-tenths error of a counting determination, counts per minute (cpm)
 ΔT_{JL} = Jens-Lottes correction for boiling heat transfer, °F
 μc = micro-curies of radioactivity. 1 μc corresponds to 3.7×10^4 disintegrations/sec.
 ρ_D = density of solution in deposit, gm/cc

1. INTRODUCTION

With the establishment of the more basic concepts and designs for water-cooled and moderated reactors, the next logical steps are toward the improvement of the nuclear reactor economics. The concept of chemical shim for pressurized water reactors falls into this category.

Chemical shim can be defined as the control of that portion of the core reactivity allowing for burn-up during life by varying the concentration of a neutron absorbing chemical, dissolved in the primary coolant. All studies to date indicate that boron as boric acid, homogeneously distributed in the coolant is the most promising chemical for this purpose in water reactors.

Extensive testing has been carried out by Westinghouse Atomic Power Division, indicating the general acceptability of boric acid for shim control. One of the remaining questions on the feasibility of chemical control concerns hideout. Hideout may be defined as the tendency of a solute to concentrate and/or precipitate on or at a heat transfer (fuel rods) surface. A potential reactor hazard would develop since the hideout of course is uncontrolled. A sudden release of the concentrated solute could cause a power excursion as the boron is swept out of the core by the main coolant.

Potential mechanisms for hideout which have been identified in principle are:

1. Precipitation of the solute on heated surfaces due to a decrease in solute solubility with increased temperature (retrograde solubility).
2. The formation of insoluble compounds due to chemical interaction between the solute and the materials of construction of the reactor system.
3. The physical or chemi-sorption of the solute by the system surfaces.
4. The concentration of solute at the boundary layer of the heat transfer surface; for example, the fuel rod, and the liquid coolant. Included in this fourth mechanism is concentration in the interstices of corrosion product (crud) deposits on the heat transfer surfaces.

The first three phenomena have been studied in isothermal systems, the size and other system parameters of which were varied as required to increase the detectability of the effect being studied. The results of these studies indicate that hideout by the second and third mechanism do

not of themselves pose a threat to reactor safety. Hideout from the first mechanism is not possible with boric acid alone and unlikely with NaOH - H_3BO_3 since at the highest temperature reported sodium borate was found to be quite soluble (~ 59 wt % NaBO_2) 1/.

This present report describes the extensive study made to determine both the qualitative and quantitative aspects of the fourth phenomena. Some tests were performed also to verify the lack of retrograde solubility in sodium borate.

It was realized from the start of the program that the experimental detection of the concentration of solute at the heat transfer surface by the analysis of the bulk liquid phase would require either extreme accuracy or gross hideout, for, in any system, the fraction of solute inventory hiding out is given by $[1 + VC/AS]^{-1}$. For the hideout facility as constructed V/A is about 16.5 decimeters and in general C/S is given by $(Rt_f)^{-1}$. Assuming an effective boundary layer thickness of 0.2 mil (the effective boundary layer might correspond, for example, to about one-half the thickness of a porous corrosion product deposit on the surface), about 0.31% of the solute inventory would be hiding out if the concentration ratio were 1000.

Furthermore, since the hideout phenomena of interest may be reversible, i.e., the concentration gradient disappears when the heat transfer stops, post experimental examination of the surfaces is considered of limited value.

It was obvious, therefore, that only in situ measurements of hideout at simulated reactor operating conditions of temperature, pressure and heat flux, would be meaningful. Hence the radiotracer hideout test facility was designed and constructed.

2. GENERAL SYSTEM INFORMATION

2.1. Purpose and Principle of Operation of the Radiotracer Facility

The radiotracer test facility measures quantitatively the concentration of a given solute in water at a heat transfer surface during operation at high temperature, pressure, and heat flux, thereby eliminating much of the uncertainty experienced by post-experimental examination of the surfaces and increasing the sensitivity of hideout detection over straight chemical analysis and material balance techniques. The principle of the operation is, briefly, to compare the gamma energy emission from two geometrically identical sections of the test apparatus, in one of which hideout is suspected to be occurring. The source of the gamma energy is a radioactive nuclide of one of the elements of the compound which is suspected to be hiding out. From the excess gamma emission at the test section a quantitative measure of the extent of hideout is obtained.

Sodium-22 was chosen as the tracer for these hideout experiments for the following reasons:

1. It is anticipated that alkali will be used together with boric acid for chemical shim operation.
2. Na²² has good nuclear properties; i.e., long half-life and high gamma emission energy.
3. No suitable radioactive nuclide of boron exists.

2.2. Facilities Descriptions

2.2.1. Main Loop Components and Cooling System

The radiotracer hideout test facility (Figure 1) consists of a 6" I.D. x 72" inside depth Autoclave Engineers autoclave fitted with a Westinghouse canned motor pump, Type A-11. Solution is pumped from the bottom of the 6" autoclave vertically upward through the test section, the main loop cooler, through an orifice flow meter, a flow control valve and back into the top of the autoclave. All high pressure system components and piping are 304 stainless steel material. A 5" I.D. x 14" inside depth Autoclave Engineers autoclave serves as the system pressurizer during the sub-cooled boiling hideout experiments. A slow, continuous flow from the main circulating line through the pressurizer maintains chemical homogeneity throughout the system.

FIGURE 1

RADIOTRACER CHEMICAL HIDEOUT TEST LOOP

The heart of the facility, the test section, consists of a 0.62-inch diameter Type 304 stainless steel sheathed, electrical resistance heater with a 19 KW rating, fitted concentrically in the vertical leg of the main loop piping which is 1" Schedule 80, Type 304 stainless steel. The overall length of the heater is about 82" with a 12-inch heated section in the middle. The maximum heat flux is about 400,000 Btu/hr-ft². The heaters used in these experiments were fabricated by the Watlow Corporation of St. Louis, Missouri. Figure 2 shows an overall view of one of the heaters. The pressure seals for the heater consist of a modified 1" high pressure Hancock valve machined to allow the 0.62" diameter heater to pass through the valve stem packing gland.

The purpose of the main loop cooler is to remove the heat added to the coolant by the Watlow heater, thus maintaining steady-state conditions. The cooler is of the evaporative type and contains a low pressure secondary cooling water system to minimize the possibility of the radiochemicals leaking into the house drain system in the event of a failure of the high pressure piping. A standard double jacket cooling coil supplied on one side with city water removes the heat from the secondary loop.

2.2.2. Counting Equipment and Traversing Rig

Two separate sets of counting equipment provide the radioactivity hideout data; one unit is stationary and mounted below the heated zone at the bottom of the test section, the second unit is movable, being mounted on a traversing rig equipped with a position indicator. The stationary unit determines system background activity while the movable unit, which can scan the entire heated zone as well as regions above and below, determines activity build-up on the heater and provides additional background activity data.

Each unit consists of a lead collimating block weighing about 500 pounds which contains a 2" x 2" cylindrical NaI crystal and a photo-multiplier tube. The crystal is shielded from all activity beyond the collimated beam by a minimum of 4" of lead which is ~ two 1/10 value layers for the 1.28 mev gamma emitted by the Na²² radiotracer used for this experiment. A preamplifier, amplifier and a high voltage supply are provided for each unit. Pickup from either unit can be read out on a RIDL Model #49-10 six decade scaler while both pickups and their differential are being indicated on a Victoreen dual differential count rate meter. Also, the pickup from either unit or the differential rate can be continuously recorded on a Honeywell strip chart recorder.

OVERALL VIEW OF A WATLOW HEATER

FIGURE 2

2.2.3. Synthetic Corrosion Products Deposition Facility

One phase of the radiotracer hideout experiments, which will be described in detail later, was the study of heat flux induced hideout in the interstices of corrosion product deposits (crud). The purpose of this phase of experimentation was to simulate the condition of "fouled" fuel rods.

A facility was constructed and a technique was developed for the deposition of Fe_3O_4 on test heaters. The facility (see Figure 3) consists of an air-operated piston pump, a high pressure chamber in which the Watlow heater to be prepared is installed, a cooler, a pressure regulator and a flow meter in series. A variable power transformer enables control of the Watlow heater power.

Briefly, the deposit is formed on the heater as follows: A slurry of ferrous hydroxide is recirculated past an energized Watlow heater. Conversion of the hydroxide to Fe_3O_4 , with some small amounts of Fe_2O_3 , and deposition of the oxides occurs on the hot surface of the heater. The heater wall temperature was established by adjusting the heater power, flow rate and system pressure to the values required as determined from heat transfer equations 6, 7, and 8 in Section 4 of this report. Appendix II describes the details of the slurry preparations and deposition.

2.3. Laboratory Calibration

The enhanced sensitivity of the radiotracer facility for the measurement of hideout can perhaps best be understood when it is recognized that it is, in essence, giving a quantitative measure of a very localized inventory and comparing it with the expected local inventory. The localized system volume to surface ratio is made as small as practicable, which increases the hideout contribution, relative to the total observed activity. Assuming as a first approximation that the gamma detector output is proportional to the total activity contained in a small, fixed length of the heater test section the V/A of the localized system is $(D_0^c - D_1^c)/4D_1$, or about 0.0571 dm in our case, and the fraction of the observed activity which is due to hideout becomes $(1 + 225/Rt_F)^{-1}$, with t_F in mils. (With $Rt_F = 200$ as before, the fraction of the local inventory hiding out is 47.1%.) Since in our system, the overall V/A is about 16.5 dm, the total hideout is a negligible fraction of the entire system inventory, and the chemistry does not change during a test.

The difference between the count rate observed at the heater and the background count rate below the heater, corrected for the slightly higher fluid density (hence volumetric activity) due to the lower temperature, is directly proportional to the total hideout per unit length of the heater. Symbolically, we have

CRUD DEPOSITION FACILITY

FIGURE 3

ED. SK. 286117 - B

$$\begin{aligned} D_h &= k(VC + AS)_h \\ D_b &= k(VC)_b \end{aligned} \quad (1)$$

from which,

$$S = \left(\frac{D_h}{D_b} - 1 \right) VC/A \quad (2)$$

It can be seen that no calibration (determination of the absolute value of k) is required except to confirm the assumed equal response of the detector to equal quantities of activity on the heater surface and in the heater annulus.

In order to establish that this was a reasonable approximation, a mock-up of the heater section was fabricated as follows: a 9" length of Schedule 80, 1" stainless steel pipe, the main loop pipe size, was sealed at one end on a supporting base. A 12" length of a used heater was fitted with a thin stainless steel sheath, also sealed at one end, yielding an annulus of about 0.030" with the heater. The sheath and heater were then inserted concentrically by means of top and bottom spacers into the 1" pipe.

Using the actual detector and collimating shield, positioned with respect to the simulated heater section as in the main loop design, the detector response was measured for various combinations of activity concentrations in the inner and outer annuli. The calibration data are summarized in Table I and are plotted in Figure 4 as log (counts per minute) versus log (total activity per unit length, $\mu\text{C}/\text{cm}$). A close look at the data indicates that the detector is slightly more sensitive to activity in the inner annulus than to activity in the outer annulus; however, the fit of the line of unit slope in Figure 2 indicates that the basic assumption is sufficiently accurate to justify the use of Equation 2 as a first approximation in interpreting the data. Thus the surface concentration hideout of any material which is traced by -- i.e., behaves like -- the radioactive nuclide is given in this system by

$$S(\text{mg}/\text{dm}^2) = \left(\frac{D_h}{D_b} - 1 \right) (0.0571) C(\text{mg}/\text{dm}^3) \quad (3)$$

where S and C are the surface and bulk phase volume concentrations of the material of interest.

TABLE I

COUNT RATE IN CPM FOR ANNULI SOLUTION COMBINATION*

a_i , Solution Activity in Inner Annulus, $\mu\text{c Na}^{22}/\text{ml}$	a_o , Activity of Solution in Outer Annulus $\mu\text{c Na}^{22}/\text{ml}$			
	0	0.0386	0.0771	0.1543
0	0	299	585	1193
0.1080	83	377	667	1295
0.0540	46	328	614	1233
0.0054	0	290	610	1208

NOTES:

* Count rates are arithmetical averages of several determinations.

Cross-sectional areas of the annuli: Inner, 0.193 cm^2

Outer, 2.297 cm^2

Correlation (see Figure 3), $D(\text{cpm}) = k(0.193 a_i + 2.297 a_o)$

GAMMA DETECTOR CALIBRATION

FIGURE 4

3. DATA PRESENTATION

3.1. General Description of Tests

The radiotracer hideout experiments included three series of tests:

1. "Clean" surface hideout measurements with $\text{NaOH} - \text{H}_3\text{BO}_3$ solution.
2. "Clean" surface hideout measurements with $\text{NaOH} - \text{Na}_3\text{PO}_4$ solution.
3. "Fouled" surface hideout measurements with
 - a. $\text{NaOH} - \text{H}_3\text{BO}_3$ solution
 - b. NaOH solutions

The "clean" surface experiments were conducted on "as-received" heaters which, of course, developed a tight but extremely thin corrosion film during the high temperature testing. The "fouled" surface experiments were conducted with heaters on which synthetic corrosion products had been deposited.

Extensive testing was performed on fouled heaters to determine the extent and conditions required for heat flux induced hideout in the interstices of the deposits. A total of eight (8) heaters with deposit thicknesses ranging from 0.3 mil to 5.5 mil (radius) was tested. Table II reports the deposit thicknesses at various locations along the heaters tested. These measurements were recorded prior to the start of testing. The crud on fouled heaters 1 through 7 was deposited from a "low pH" ferrous hydroxide media while the crud on heater 8 was deposited from a "high pH" media. (See Appendix II.) Figure 5 shows a typical fouled heater surface prior to testing.

Tables III and IV present summaries of all the tests performed. Included in the tables are the system operating conditions and the loop chemistry. The maximum net detector responses are also shown in Table III. For the "fouled" heater tests the exact counting location is given since the hideout varies with deposit thickness and continuity.

More detailed descriptions of the test conditions and the results are reported in Sections 3.2 through 3.9. Section 4 presents a discussion of the overall results. Section 5 describes the procedure to be followed for calculating surface concentration of the solute from the count rate data.

TABLE II
DEPOSIT THICKNESSES OF FOULED HEATERS

POSITION, INCHES FROM BOTTOM OF HEATER	DEPOSIT THICKNESS ON HEATER *							
	1	2	3	4	5	6	7	8
0					.3	.3	.4	.4
.5	.5	.2	.1	.1				
1.0					.4	.4	.3	.7
1.5	6.5	.7	.1	.3				
2.0					.4	.5	.3	.8
2.5	5.6	.9	.4	.3				
3.0					.6	.7	.3	.7
3.5	5.0	1.2	.2	.2				
4.0					.7	1.0	.3	.6
4.5	Deposit Flaked	1.2	.3	.3				
5.0	"				.7	.8	.3	.5
5.5	"	1.2	.4	.2				
6.0					.5	1.0	.3	.3
6.5	5.6	1.1	.1	.3				
7.0					.5	1.0	.4	.6
7.5	6.4	1.1	.1	.4				
8.0					.6	1.0	.4	.5
8.5	5.6	1.0	0	.2				
9.0					.5	1.1	.3	.6
9.5	4.4	1.4	0	.2				
10.0					.5	1.1	.2	.6
10.5	5.0	1.0	0	.3				
11.0					.5	1.0	.2	.6
11.5	4.2	1.3	0	.3	.5	.8		
12.0					.5	.8	.2	.3

* Measurements taken with standard micrometer.

TYPICAL FOULED HEATER SURFACE PRIOR
TO TESTING

FIGURE 5

TABLE III
SUMMARY OF MAJOR HIDEOUT EXPERIMENTS ON CLEAN AND FOULED HEATERS

HEATER TESTED	AVERAGE CORROSION PRODUCT DEPOSIT THICKNESS	BULK TEMPERATURE AT COUNTING LOCATION	SYSTEM PRESSURE	TOTAL HEAT FLUX q_T	NUCLEATE BOILING ^{3/} HEAT FLUX q_{NBW}	HEATER WALL TEMPERATURE	CORROSION DEPOSIT THICKNESS AT COUNTING LOCATION	COUNTING LOCATION FROM BOTTOM OF HEATER	TIME AT POWER PRIOR TO COUNT	MAXIMUM NET DETECTOR RESPONSE $[D_h - D_b]$	LOOP CHEMISTRY				DATA PRESENTATION
											Na	Na ²²	BORON	PO ₄	
#	mil (Radius)	°F	psig	Btu/hr-ft ²	Btu/hr-ft ²	°F	mil	inches	min	cpm	ppm	uc/ml	ppm	ppm	
Clean 1	0	600	1800	292,000	150,000	626	0	0-12	6360	0	2.5	.068	1800	0	Table V
"	0	600	1800	329,000	192,000	626	0	0-12	2880	0	2.5	.066	1800	0	Table V
"	0	600	1620	206,000	184,000	613	0	0-12	2304	0	2.5	.064	1775	0	Table V
"	0	620	1820	200,000	183,000	628	0	11	180	~ 500	505	.065	< 3	530	Figure 6
Fouled 1	~ 5	470	1790	211,000	30,000 ^{1/}	626	5	7.0	1656	~ 325	2.3	.082	1080	3	Table VII
Fouled 2	1.1	560	1775	210,000	71,400	626	1.1	7.2	0-170	900	2.41	.082	1095	0	Figure 8
"	1.1	563	1775	310,000	177,700	626	1.1	7.2	0-140	1300	2.41	.082	1095	0	Figure 8
Fouled 3	0.2	575 ^{2/}	1800	210,000	103,000 ^{2/}	626	0.2	0-12	180	0	5.1	.082	120	0	Table XI
"	0.2	575 ^{2/}	1800	210,000	103,000 ^{2/}	626	0.2	0-12	120	0	5.1	.082	1340	0	Table XI
"	0.2	600 ^{2/}	1800	308,000	253,000 ^{2/}	626	0.2	0-12	120	0	5.1	.082	1340	0	Table XI
Fouled 4	0.25	550 ^{2/}	1800	210,000	50,000 ^{2/}	626	0.25	0-12	120	0	3.4	.082	1390	0	Table XI
Fouled 5	0.5	550 ^{2/}	1780	210,000	54,600 ^{2/}	624	0.5	0-12	300	44	2.6	0.049	1201	0	Tables XII - XIII
"	0.5	450 ^{2/}	645	210,000	94,500 ^{2/}	505	0.5	0-12	60	0	2.6	.049	1201	0	Table XII
Fouled 6	0.9	(Test conditions presented in Table IV.)													
Fouled 7	0.3	596	1800	252,500	189,500	626	0.5	0-12	2.2	2600			950 to < .1	0	Table XVII
Fouled 8	0.6	573	1780	252,500	143,300	625	0.6	0-12	1245	0	2.7		.4	0	Table XVIII
"	0.6	566	1800	252,500	124,400	627	0.6	0-12	1220	0	3.4		1153	0	Table XVIII
"	0.6	583	1350	252,500	248,000	585	0.6	0-12	420	0	3.4		1153	0	Table XVIII

^{1/} Considers temperature drop through crud deposit.

^{2/} Inlet condition.

^{3/} Calculated from equation 6.

TABLE IV

SUMMARY OF FOULED HEATER 6 TESTING

OPERATING TEST CONDITION	FOULED HEATER 6 TEST NUMBER							
	1	2	3	4	5	6	7	8
System, Pressure, psig	630 - 1800	1800	650-735	685-1510	1420-1820	1800	945-1795	970-1800
Heater Wall Temperature, °F	512 - 627	626	514-528	520- 559	598- 630	628	554- 626	542- 626
Bulk Temperature at Counting Location, °F	466 - 589	566	400-500	466	566	566	528- 539	556- 620
q _{NBW} Nucleate Boiling Heat Transfer, Btu/hr-ft ²	78,000 to 175,000	11,700 to 176,000	8,000 to 193,000	137,000 to 53,000	181,000 to 115,000	120,000	108,000 to 60,000	189,500 to 145,200
Counting Location, inches from Heater Bottom	11.0 - 11.5	11.5	11.0	11.0	11.0	11.0	11.0	11.0
Data Presentation	Figure 10	Table XIV Figure 11	Figure 12	Table XV	Figure 13	Figure 14	Figure 15	Table XVI Figure 16
Test Date	3-6-62 3-8-62 3-9-62	3-7-62	3-10-62	3-14-62	3-15-62	3-16-62	3-23-62	3-28-62
LOOP CHEMISTRY								
Na, ppm	3.17 -2.99*	3.17	2.99	2.64	2.64	2.64	2.64	2.64
Na ²² , µc/ml	.105- .089	.105	.089	.076	.076	.076	.076	.076
Boron, ppm	1494 - 1347	1494	1343	1246	1246	1246	1246	1246

* Demineralized water added to the loop on March 8, 1962, for the 466°F test.

For this report the nine-tenths error of a counting determination was chosen as the level of significance for hideout. The nine-tenths error (y) of a counting determination $N_S - N_B$ is given by the relationship: 2/

$$y = 1.645 \left[\frac{N_S}{t_S} + \frac{N_B}{t_B} \right]^{1/2} \quad (4)$$

In nearly every test, however, when hideout was observed, the amount was well above the (y) value.

3.2. Clean Heater 1 Testing

3.2.1. NaOH - H₃BO₃ Hideout Tests

The first series of tests to determine the extent of hideout from a NaOH - H₃BO₃ system at high temperature in the presence of heat flux was performed on a clean heater surface. Test conditions for the clean heater 1 series are reported in Table V together with the loop chemistry.

No hideout was observed at any position along the heater for any of the conditions tested. Periods 1 and 2 were at sub-cooled nucleate boiling conditions while period 3 was at bulk boiling conditions. (See Section 4 for definitions of boiling heat transfer conditions.)

3.2.2. NaOH - Na₃PO₄ Hideout Tests

After the completion of the bulk boiling period the borate was ion exchanged from the system and solutions of tri-sodium phosphate, a material which was known to hide out, were added stepwise to determine the onset of gross deposition. Gross deposition of the sodium phosphate was observed when the PO₄ concentration was raised to about 500 ppm.

Table VI reports the loop chemistry for the entire phosphate test and the steady-state loop operating conditions for the first 25.2 hours of the test. Included with the operating conditions are the test section count rates.

Figure 6 graphically presents the remainder of the test. The temperature during this period was $615 \pm 5^\circ\text{F}$ and the system pressure was 1850 ± 50 psig. The count rates shown are total detector responses. The notes on the figure indicate operating changes which caused the hideout change.

TABLE V

CLEAN HEATER 1 TEST CONDITIONS AND LOOP CHEMISTRY FOR NaOH - H₃BO₃ TESTSLOOP WATER CHEMISTRY

Time, Hours After Injection of Tracer	Na ²² μc/ml	Na ppm	BORON ppm	pH Unit	RESISTIVITY ohm-cm	Cl ppm
1.5	0.074	2.25	1800	4.87	49,000	1.04
98.5	0.067	2.60	1820	5.70	60,000	.67
249	.065	2.75	1735	5.30	53,000	.78
414 *	.064	2.48	1694	5.70	72,000	.10
512	.061	2.48	1774	6.00	76,000	.29

* Bulk boiling was begun.

LOOP STEADY-STATE OPERATING CONDITIONS

	PERIOD 1	PERIOD 2	PERIOD 3
Pressurizer Temperature	621 ± 2°F	621 ± 2°F	600°F
Loop Temperature	600 ± 5°F	600 ± 5°F	600 ± 2°F
System Pressure	1800 ± 20 psig	1800 ± 20 psig	1620 ± 20 psig
Fluid Velocity Past Heater	11.5 ft/sec	11.5 fps	3.8 fps
Watlow Heater Power	14 Kw	15.7 Kw	9.8 Kw
Dittus Boelter Heat Transfer (inlet)	142,000 Btu/hr-ft ²	137,000 Btu/hr-ft ²	~ 22,000 Btu/hr-ft ²
Boiling Heat Transfer (inlet)	150,000 Btu/hr-ft ²	192,000 Btu/hr-ft ²	184,000 Btu/hr-ft ²
Duration of Period	265 hours	120 hours	96 hours

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TABLE VI
CLEAN HEATER 1 LOOP CHEMISTRY AND TEST CONDITIONS
FOR THE NaOH - Na₃PO₄ TESTS
LOOP WATER CHEMISTRY

TIME AFTER START OF BOILING	ANALYZED FROM LOOP		pH	Na ²²	INJECTED IN LOOP	
	Na	PO ₄			Na	PO ₄
Hours	ppm	ppm	Units	μc/ml	ppm	ppm
0	-	0	9.92	-	2.5 ^{3/}	0
20	-	58		.0564	221	300
22.5	-	300		.0544	940	594
25.8	455	290	11.6	.0671	440	594
26.3	505	532	11.5	.0677	864	1187
28.3 ^{1/}	752	755	11.6	.0655	864	1187
<u>2/</u>	752	830	11.7	.0652	864	1187

^{1/} Taken just prior to shutdown.

^{2/} Taken ~ 4 days after shutdown.

^{3/} Residual Na from borate test.

TABLE VI (continued)

LOOP STEADY-STATE OPERATING CONDITIONS

TIME AFTER START OF BOILING	TEMPERATURE OF WATER INTO WATFLOW	SYSTEM PRESSURE	FLOW RATE	AVERAGE COUNT RATE	WATFLOW ^{1/} POWER	BOILING REGIME
Hours	°F	psig	gpm	cpm	Kw	-
.2	600	1775	15	275	6.4	Local Boiling
1.0	600	1700	15	275	6.4	Local Boiling
2.0	600	1820	15	275	6.4	Local Boiling
3.0	600	1830	15	275	6.4	Local Boiling
3.5	600	1830	15	275	6.4	Local Boiling
3.7	600	1830	15	-	8.3	Local Boiling
4.2	600	1850	15	275	8.3	Local Boiling
5.2	600	1575	5	240 ^{2/}	8.3	Bulk Boiling
6.7	618	1800	5	240	8.6	Bulk Boiling
10	618	1800	5	240	8.6	Bulk Boiling
20	620	1835	5	260	8.6	Bulk Boiling
21	620	1820	5	260	9.5	Bulk Boiling
21.7	620	1820	5	260	9.5	Bulk Boiling
25.2	620	1825	5	280	9.5	Bulk Boiling

^{1/} The element between 3 and 6" from bottom of heater zone was not heated.

^{2/} Drop in count rate is due to void fraction increase.

COUNT RATE DURING PHOSPHATE HIDEOUT TEST

FIGURE 6

E. D. SK. 285694 B

The onset of gross hideout and the fact that it is readily reversed by changing the thermal and hydraulic conditions to suppress boiling heat transfer are quite apparent.

The maximum observed hideout was calculated to be 28.4 mg Na/dm^2 from equation 3 with $D_h = 485 \text{ cpm}$, $D_b = 240 \text{ cpm}$ and $C = 486 \text{ mg Na/dm}^3$. It should be pointed out that this value was not the maximum hideout which would have occurred since the hideout was still increasing at the time of this count rate. The calculated rate of sodium hideout, after the rapid initial increase, was $15.8 \text{ mg Na/dm}^2\text{-hr}$.

A comparison of the injected and analyzed PO_4 and Na concentration in Table VI indicates that deposition was occurring elsewhere in the system. Also after cooling the system to room temperature, a PO_4 to Na ratio of only 1.10 was found instead of the compound ratio of 1.37. This indicates that some of the phosphate was irreversibly deposited throughout the system. The deposition of phosphate of metals other than sodium would not, of course, be detected, since sodium-22 is the radiochemical tracer.

Inspection of the heater at the conclusion of the tests revealed a tight, bluish-black oxide film, typical of high temperature water exposure.

3.3. Fouled Heater 1 Testing

Fouled heater 1 had a synthetic corrosion product deposit of about 5.5 mils (radius). This deposit was formed from the "low pH" media as described in Appendix II.

Hideout was first observed at a heat flux of $211,000 \text{ Btu/hr-ft}^2$ with the system pressure of about 1800 psig when the coolant inlet temperature was raised to about 460°F . No hideout had been observed after three hours of operation at 250°F inlet temperature.

Table VII reports the loop chemistry for the entire testing of fouled heater 1 together with the operating conditions during the 460°F coolant test. Included in Table VII is the hideout profile of the heater after 69 hours of operation at the conditions reported. The maximum hideout accumulated during this period was about 0.06 mg Na/dm^2 which was located at seven (7) inches from the bottom of the heater. Again, as in the phosphate test, the hideout was still increasing when the count rates were taken.

Table VIII shows the build-up and release of hideout at two locations along the heater. The hideout was seen to be reversible when the heater power was lowered below a value necessary to maintain nucleate boiling. The release of activity was initially rapid, then followed by a slow decrease to background condition.

TABLE VII

FOULED HEATER 1 LOOP CHEMISTRY AND TEST CONDITIONS

L O O P C H E M I S T R Y	
Na	2.3 ppm
Na-22	.082 μ c/ml
Boron	1080 ppm
Chloride	.06 ppm
pH	6.0 units
Resistivity	78,000 ohm/cm
O P E R A T I N G C O N D I T I O N S	
Bulk Temperature inlet	460 $\pm$ 5°F
System Pressure	1790 $\pm$ 10 psig
q" _{NBW} Boiling Heat Flux at 7.0"	~ 30,000 Btu/hr-ft ²
Total Heat Flux	211,000 Btu/hr-ft ²
Time at Condition Prior to Scan	69 hours
HIDEOUT ALONG FOULED HEATER 1	
POSITION, INCHES FROM BOTTOM OF HEATER	TOTAL DETECTOR RESPONSE AFTER 69 HOURS cpm
0	589 ^{1/}
.5	559
1.0	588
2.0	599
3.0	624
4.0	674
5.0	635
6.0	813
7.0	915
8.0	784
9.0	609
10.0	613
11.0	637
12.0	609
13.0 ^{2/}	589 ^{1/}

^{1/} This is the average value for the counts in the unheated sections (D_B).

^{2/} 1" above the top of the heater.

TABLE VIII

BUILD-UP AND RELEASE OF HIDEOUT FROM FOULED HEATER 1

HEATER POWER	TIME AT POWER	POSITION, INCHES FROM BOTTOM OF HEATER	
Btu/hr-ft ²	Hours	6 inches	7 inches
		COUNT RATE cpm	
0	0	589	589
211,000	71.5	813	915
211,000	73	871	No Reading
211,000	88.5	893	No Reading
211,000	90	No Reading	No Reading
59,100 *	0.2	794	No Reading
59,100	1.75	751	No Reading
59,100	2.75	No Reading	899
59,100	4.75	740	No Reading
59,100	23	629	712

* Heater power lowered to 59,100 Btu/hr-ft² to observe the reversibility of hideout.

Inspection of the heater after the tests were completed showed the following:

1. A considerable amount of the crud had flaked off unevenly from various locations along the heater. This can be seen on Figure 7 which shows the heater after testing.
2. The maximum thickness of the residual deposit in these flaked locations was about 0.4 mil (radius).
3. Thick crud deposits remained at least on some portion of the circumference, on each section of the heater where hideout was observed.

It should be noted that a minimum deposit thickness of 1.2 mils (radius) was needed to obtain a wall temperature high enough to cause nucleate boiling at the conditions of this test; namely, 1800 psig pressure and 460°F coolant temperature. Therefore, no nucleate boiling was occurring in the flaked regions since the deposit thicknesses at these locations was only 0.4 mil.

3.4. Fouled Heater 2 Testing

The second fouled heater tested had a synthetic corrosion product deposit of about 1.1 mils (radius) along the heated length. The crud was deposited on the heater from a "low pH" media as with fouled heater 1.

Figure 8 presents a plot of hideout vs. time at heater fluxes of 310,000 and 210,000 Btu/hr-ft² for fouled heater 2. Table IX reports the loop chemistry and test conditions during these runs.

Table X shows the hideout profile along the heater after two hours of operation at 210,000 Btu/hr-ft² total heat flux and after 0.5 hours of operation at 310,000 Btu/hr-ft² total heat flux. The other test conditions are those reported in Table IX.

Figure 9 graphically shows the mass transfer of the radiotracer from the heater to the bulk coolant after the heater power was turned off. The power was reduced somewhat slowly over an eight-minute period to avoid thermally shocking the heater. However, about three minutes after starting the power reduction, the heat flux was below that needed for nucleate boiling.

This reversibility test was run after the data on the hideout profile at 210,000 Btu/hr-ft² had been obtained.

FOULED HEATER 1 AT THE COMPLETION OF TESTING

FIGURE 7

FOULED HEATER 2 HIDEOUT RATES AT VARIOUS HEAT FLUXES

FIGURE 8

E. D. SK. 301784-B

TABLE IX

LOOP TEST CONDITIONS FOR HIDEOUT RATES ON FOULED HEATER 2

LOOP CHEMISTRY	HIDEOUT RATE TEST	
	1	2
Na, ppm	2.41	2.41
Na ²² , μ c/ml	.082	.082
Boron, ppm	1095	1095
OPERATING CONDITIONS		
Total Heat Flux, Btu/hr-ft ²	310,000	210,000
Nucleate Boiling Heat Flux At 7-1/4" From Heater Bottom, Btu/hr-ft ² *	177,700	71,400
System Pressure, psig	1775 $\pm$ 25	1775 $\pm$ 25
Bulk Temperature at Counting Location, °F	563	560
Bulk Temperature at Inlet, °F	550	550
Heater Wall Temperature, °F	626 $\pm$ 3	626 $\pm$ 3

* Calculated from $q_{NB}'' = q_T'' - h(T_W - T_B)$.

TABLE X

HIDEOUT PROFILE OF FOULED HEATER 2 AT VARIOUS HEAT FLUXES

POSITION, INCHES FROM BOTTOM OF HEATER	TOTAL DETECTOR RESPONSE AT 210,000 Btu/hr-ft ²	TOTAL DETECTOR RESPONSE AT 310,000 Btu/hr-ft ²
	SCAN STARTED AFTER 2.0 HOURS AT POWER	SCAN STARTED AFTER 0.5 HOURS AT POWER
	cpm	cpm
- 1 *	527	509
0	510	--
.5	--	--
1.0	615	630
2.0	--	731
3.0	--	734
4.0	845	1010
5.0	--	1391
6.0	1562	1722
6.75	1579	--
7.50	1896	2095
8	--	2025
9	--	1360
10	1093	1193
13 *	527	509

* Average of 2 or 3 background count.

FIGURE 9

E. D. SK. 301783-B

The heater failed during another series of tests, contaminating the loop with MgO (the heater's electrical insulating material). A series of acetic acid and demineralized water rinses removed most of the MgO from the system. The concentration of Mg in the loop was less than 2 ppm prior to the start of the fouled heater 3 test series.

3.5. Fouled Heaters 3 and 4 Testing

The third and fourth fouled heaters tested had initial corrosion product deposit thicknesses of about 0.2 and 0.25 mil (radius), respectively. These deposits were formed using the identical procedures as for fouled heaters 1 and 2. No hideout was observed on either heater during any of the tests.

Table XI presents the loop chemistry and operating conditions for the tests on fouled heaters 3 and 4. Test 1 on fouled heater 3 was run with a solution of NaOH alone in an attempt to ascertain whether or not Na hideout can occur from a boron free solution. Fouled heater 3, tests 2 and 3 were with NaOH - H_3BO_3 solutions.

Inspection of the heater at the conclusion of testing revealed that the corrosion products deposit had been removed during the operations. High pH solutions have long been known to effect crud release from system surfaces.

Inspection of fouled heater 4 after four hours of operation revealed a white material on the surface of the deposit. This white substance analyzed to be predominantly magnesium. The magnesium was probably from residual contamination in the loop from the heater 2 failure.

The lack of hideout on heater 4 was due to either the magnesium present in or on the corrosion products deposit or the thickness of the deposit itself. Since no other tests were conducted on a 0.2 mil crud deposit which was formed from a "low pH" media, it is not possible to determine the exact reason for no hideout.

3.6. Fouled Heater 5 Testing

The fifth fouled heater tested had a synthetic corrosion product deposit averaging about 0.5 mil (radius) along the heated length. The deposit was again formed from the "low pH" ferrous hydroxide slurry.

TABLE XI

FOULED HEATERS 3 AND 4 LOOP CHEMISTRY AND TEST CONDITIONS

LOOP CHEMISTRY	HEATER 3			HEATER 4
	TEST 1	TEST 2	TEST 3	TEST 1
Na, ppm	5.1	5.1	5.1	3.4
Na ²² , $\mu\text{c/ml}$	.082	.082	.082	.082
Boron, ppm	120 ^{1/}	1340	1340	1390
pH	9.6	~ 5.5 ^{2/}	~ 5.5 ^{2/}	~ 5.5 ^{2/}
Resistivity, ohm-cm	40,000	-	-	-
OPERATING CONDITIONS				
Bulk Temperature, °F	575	575	600	550
System Pressure, psig	1800	1800	1800	1800
Total Heat Flux, Btu/hr-ft ²	210,000	210,000	308,000	210,000
q _{NBW} Boiling Heat Flux At Inlet	103,000	103,000	253,000	50,000

^{1/} Residual boron from heater 2 test. It is believed to be erroneously high since the loop was given at least eight demineralized water and acetic acid rinses.

^{2/} Calculated value.

Hideout measurements were obtained at the two test conditions outlined in Table XII. The hideout profiles during test 1 after steady-state operation for about 1 hour and 6.5 hours are reported in Table XIII. No hideout was observed during test 2 after a total of about one hour operation time.

The amount of hideout observed during test 1 and reported in Table XIII is itself near the detectable limit. From the maximum count rate observed in Table XIII, namely, 365 cpm at 5.2 inches from the bottom of the heater and the background count rate of 321 cpm, we can calculate the nine-tenths error value (y),

$$y = 1.645 \left[\frac{365}{5} + \frac{321}{5} \right]^{1/2}$$

$$= \pm 19$$

Therefore, the net hideout $[D_h - D_b]$ observed should be written $D_h - D_b = 44 \pm 19$ cpm.

3.7. Fouled Heater 6 Testing

An extensive series of tests was performed on fouled heater 6 in an effort to determine the operating conditions required for hideout and the relative effects of these conditions. This heater had a synthetic corrosion products deposit of about 0.9 mil (radius) which was formed by the same technique used on the first five fouled heaters.

Table IV presents a summary of the operating conditions for each test performed on fouled heater 6. Included in Table IV is the loop chemistry for each test.

Data obtained during this test series are presented in Tables XIV through XVI and Figures 10 through 16. The test conditions for each test are included in the tables and figures for ease of reference.

TABLE XII

FOULED HEATER 5 LOOP CHEMISTRY AND TEST CONDITIONS

LOOP CHEMISTRY	TEST NUMBER	
	1	2
Na, ppm	2.60	2.60
Na ²² , μ c/ml	.049	.049
Boron, ppm	1201	1201
OPERATING CONDITIONS		
Total Heat Flux, Btu/hr-ft ²	210,000	210,000
q" _{NBW} Nucleate Boiling Flux, Btu/hr-ft ²	54,600	94,500
Heater Wall Temperature, °F	624	505
System Pressure, psig	1780 $\pm$ 10	645 $\pm$ 5
Inlet Bulk Temperature, °F	550	450

TABLE XIII

HIDEOUT PROFILE ON FOULED HEATER 5 TEST 1

550°F = Bulk Temperature

P = 1800 psig

 $q_{m}'' = 210,000 \text{ Btu/hr-ft}^2$

POSITION, INCHES FROM BOTTOM OF HEATER	HIDEOUT AFTER ~ 1 HOUR OPERATION	HIDEOUT AFTER 6.5 HOURS OPERATION
- 1	320	347 *
1	338	-
2	332	-
4	347	-
5.2	365	396
7	347	
8	332	
10	347	
11.2	332	
13	347	

* Background change due to instrument drift.

TABLE XIV

EFFECT OF VARYING HEAT FLUX AT CONSTANT WALL TEMPERATURE

(626 $\pm$ 1°F) AT 11.5 INCHES FROM BOTTOM FOR FOULED HEATER 6

TOTAL HEAT FLUX	q''_{NBW} NUCLEATE BOILING HEAT TRANSFER	TIME AT SPECIFIC ^{1/} POWER	TOTAL ^{2/} DETECTOR RESPONSE
Btu/hr-ft ²	Btu/hr-ft ²	min	cpm
0 ^{3/}	0	0	759 ^{4/}
109,600	0	5	754
109,600	0	10	779
147,500	11,700	5	810
147,500	11,700	10	810
168,600	36,900	5	861
168,600	36,900	10	860
189,700	58,600	5	930
189,700	58,600	10	935
210,700	80,100	5	1066
210,700	80,100	10	1080
210,700	80,100	20	1100
210,700	80,100	30	1120
210,700	80,100	90	1230
231,800	103,900	5	1470
231,800	103,900	10	1500
231,800	103,900	20	1540
231,800	103,900	30	1550
252,900	133,200	5	1770
252,900	133,200	10	1850
252,900	133,200	20	1890
252,900	133,200	30	1920
252,900	133,200	40	1920
295,000	176,600	5	2450
295,000	176,600	10	2550
295,000	176,600	20	2630
295,000	176,600	30	2700
295,000	176,600	75	2780

^{1/} Heater was on continually during entire test.^{2/} Counts are the accumulative values which include all hideout at the lower powers.^{3/} Background at temperature and pressure prior to turning on the heater.^{4/} Some residual hideout was present at the start of this test.

TABLE XV

FOULED HEATER 6

EFFECT OF WALL TEMPERATURE VARIATION AT CONSTANT BULK TEMPERATURE
AND CONSTANT TOTAL FLUX 252,500 Btu/hr-ft²

ACCUMULATIVE TIME AT FULL POWER	BULK TEMPERATURE AT LOCATION	HEATER ^{1/} WALL TEMPERATURE	NUCLEATE BOILING q''_{NBW}	TOTAL DETECTOR RESPONSE
min	°F	°F	Btu/hr-ft ²	cpm
0	466	466	0	709 ^{2/}
20	466	525	126,000	1221
60	466	519	137,000	1238
90	466	536	103,000	1265
130	466	559	53,000	1239
175	466	584	0	1064
200	466	607	0	971
305	466	525	126,000	1080
325	466	525	126,000	1062
375	466	550	73,000	1043

^{1/} Calculated value $T_W = T_{Sat} + \Delta T_{JL}$

^{2/} Background count rate.

TABLE XVI

HIDEOUT AT VARIOUS WALL TEMPERATURES DURING
CONSTANT MASS STEAMING FOR FOULED HEATER 6

WALL TEMPERATURE	TOTAL HEATER FLUX	MASS STEAMING RATE AT 11"	NET * DETECTOR RESPONSE	VOLUMETRIC STEAMING RATE
°F	Btu/hr-ft ²	#/hr-ft ²	cpm	ft ³ /hr-ft ²
557	189,000	291	360	129
576	180,600	293	332	108
592	170,100	293	440	90
608	155,400	289	528	73
626	144,900	289	752	63

* Counting location 11.0" from bottom of the heater.

HIDEOUT RATES ON FOULED HEATER 6

E.D. SK.285151-C

Figure 10

Figure 11

EFFECT OF BULK TEMPERATURE AND NUCLEATE BOILING VARIATION
AT CONSTANT WALL TEMPERATURE FOR FOULED HEATER 6

FIGURE 12

E. D. SK. 301785-B

WCAP-3731

EFFECT OF WALL TEMPERATURE CHANGE VARIATION AT CONSTANT BULK TEMPERATURE AND CONSTANT TOTAL FLUX FOR FOULED HEATER 6

Figure 13

E.D. SK. 285153-C

HIDEOUT AND RELEASE RATE ON FOULED HEATER 6 AT 11.0 INCHES FROM BOTTOM OF HEATER

FIGURE 14

E. D. SK. 301789-B

WCAP-3731

HIDEOUT AT VARIOUS WALL TEMPERATURES AT CONSTANT NUCLEATE BOILING
AND CONSTANT BULK TEMPERATURE FOR FOULED HEATER 6

E. D. SK. 301790-B

FIGURE 15

EFFECT OF WALL TEMPERATURE VARIATION AT CONSTANT MASS STEAMING RATE FOR FOULED HEATER 6

Figure 16

E.O. SK. 285156-C

3.8. Fouled Heater 7 Testing

Tests were conducted on fouled heater 7 to determine the effect of the removal of borate from a $\text{NaOH} - \text{H}_3\text{BO}_3$ system in which hideout was being observed. This heater had a corrosion product deposit formed by the same procedure as for the previous six heaters. The average thickness of the deposit was 0.3 mil (radius).

Table XVII reports the count rates observed at various heater positions at several stages of the boron removal and injection test. The boron was removed on an anion form resin leaving the sodium concentration in the coolant unchanged. Included in Table XVII are the test conditions during this experiment.

After the completion of Scan 6, boric acid was injected into the loop. Scan 7 of Table XVII was started after about three hours of full power heater operation at the high boron concentration.

3.9. Fouled Heater 8 Testing

The boron removal and injection tests on fouled heater 7 indicated that the change in solution pH during the test, due to the change in boron concentration, may have affected either the thickness of the deposit or its morphological characteristics.

There was, however, no measurable deposit thickness change observed after the testing. The fact then that there was a significant decrease in the hideout level on fouled 7 after the boric acid was returned to the system indicates that a morphological change occurred in the crud during the high pH, low boron operation.

To confirm this conclusion, synthetic corrosion products were deposited on fouled heater 8 from a "high pH" media. See Appendix II.

The average deposit thickness was about 0.6 mil (radius). No hideout was observed on fouled heater 8 during any of the test conditions reported in Table XVIII.

TABLE XVII

BORON REMOVAL AND INJECTION TEST ON FOULED HEATER 7

COUNTING POSITION INCHES FROM BOTTOM OF HEATER	TOTAL DETECTOR RESPONSE AT POSITION						
	SCAN 1	SCAN 2	SCAN 3 ^{1/}	SCAN 4	SCAN 5	SCAN 6	SCAN 7 ^{1/}
	cpm	cpm	cpm	cpm	cpm	cpm	cpm
- 1.0 ^{2/}	472	457	472	476	437	448	422
2.2	2600 ^{3/}	520	566	559	504	491	645
2.7			647	-	-	-	628
3.2			-	-	-	-	640
4.0			-	-	-	-	734
4.7			920	830	611	545	699
6.0			849	752	561	-	581
7.0			849	-	-	-	-
8.0			878	905	672	-	731
9.0			840	-	-	-	-
10.0			737	-	-	-	566
11.0			661	-	-	-	-
11.7			759	679	549	-	662
12.0			755	-	-	-	-
12.5			680	-	-	-	-
12.7 ^{2/}			-	-	-	-	522
13.7			472	484	437	448	422
TEST CONDITIONS							
Bulk Temperature at Counting Location, °F	596	596	596	596	596	596	596
System Pressure, psig	1800	1800	1775	1800	1760-1635	1800	1800
Total Heat Flux, Btu/hr-ft ²	252,500	252,500	252,500	252,500	252,500	252,500	252,500
q _{NBW} "	189,500	189,500	191,600	189,500	189,500	189,500	189,500
pH	7.8	9.5	8.2	9.5	10.3	10.8	7.8
Boron, ppm	~ 160	~ 10	94	~ 8	4	< .1	950

^{1/} Added boron to system after Scan 2 and then again after Scan 6.

^{2/} These locations are considered background points.

^{3/} This rate dropped to ~ 1200 cpm after the boron was reduced to 143 ppm pH = 7.8.

TABLE XVIII

FOULED HEATER 8 LOOP CHEMISTRY AND TEST CONDITIONS

LOOP CHEMISTRY	TEST NUMBER		
	1	2	3
Na, ppm	2.7	3.4	3.4
Boron, ppm	~ 0.4	1153	1153
pH	10.45	-	-
OPERATING CONDITIONS *			
Bulk Temperature, °F	573	566	583
System Pressure, psig	1780	1800	1350
Total Heat Flux, Btu/hr-ft ²	252,500	252,500	252,500
q _{NBW} Boiling Heat Flux, Btu/hr-ft ²	143,300	124,400	248,000
Temperature Wall, °F	625	627	585

* Operating conditions at 12" from heater bottom.

4. DISCUSSION

The most fundamental requirement for hideout from the NaOH - H₃BO₃ system appears to be the presence of boiling heat transfer. For this discussion nucleate boiling will be used to describe the general condition of boiling heat transfer.

Nucleate boiling can be classified into two types:

1. Local or sub-cooled boiling wherein the bulk coolant temperature is below the system saturation temperature. Steam bubbles would form on the heat transfer surface and collapse near the surface or in the coolant stream. There is no net steam generation.
2. Bulk boiling, wherein the bulk coolant is at saturation temperature. Steam bubbles forming at the heat transfer surface would be stable in the coolant stream. There is net steam generation.

As pointed out by Griffith, Clark and Rohsenow ^{3/}, there are generally two acting modes of heat transfer from a boiling surface. The first is evident in that region of boiling wherein bubbles are forming on only a small portion of the surface. The bare portions of the surface, then, are most likely transferring heat as if no boiling were occurring at all along the heater. The second mode of heat transfer would be wherein the surface is virtually all covered with bubbles. In this case the forced convection heat transfer would be small, the boiling heat transfer predominant.

Based on the concept of partial surface boiling, the amount or degree of nucleate boiling q''_{NB} can be defined by the expressions: ^{3,4/}

$$q''_{NB \text{ Sat}} = q''_T - h [T_{\text{Sat}} - T_B] \quad (5)$$

or

$$q''_{NBW} = q''_T - h [T_W - T_B] \quad (6)$$

The heater wall temperature (T_W) is given by the expression:

$$T_W = T_{\text{Sat}} + \Delta T_{JL} \quad (7)$$

ΔT_{JL} is the Jens and Lottes correction for the wall temperature needed for the start of nucleate boiling. It is defined by the expression 4/:

$$\Delta T_{JL} = \frac{(q''_T)^{1/4}}{0.527 e^{\frac{P}{900}}} \quad (8)$$

The differences in the degrees of nucleate boiling for given systems as calculated from equations 5 and 6 decrease at the higher pressures since the Jens and Lottes correction decreases with increasing pressure. For example, at a total flux of 252,500 Btu/hr-ft², ΔT_{JL} would vary with pressure as follows:

$\Delta T_{JL} (^{\circ}F)$	SYSTEM PRESSURE (psi)
5.8	1800
8.3	1500
14.0	1000
19.5	700

The forced convection heat transfer coefficient (h) used in equations 5 and 6 was calculated on a clean rod basis. It is not possible at present to determine the effect of the crud deposits of the fouled heater series, therefore, the "clean surface" heat transfer coefficient was used throughout in defining the nucleate boiling.

The significance of defining the amount of nucleate boiling can be seen when considering the concept of a mass steaming rate at the heater surface. The mass steaming rate is defined as the mass of solution evaporated at the heater surface per unit time and unit area of heat transfer.

It can be seen, therefore, that the mass steaming rate would be proportional to the boiling heat transfer:

$$\dot{M} = \frac{q''_{NB}}{h_{fg} + C_p \Delta T} \quad (9)$$

where

$$\Delta T = T_{Sat} - T_B$$

The mass steaming rate can be calculated with confidence only during bulk boiling conditions, wherein all the heat transfer is by boiling. For other conditions the heat flux used in calculating the mass steaming rate is indicated as either $q''_{NB(Sat)}$ (equation 5) or $q''_{NB(W)}$ (equation 6). The degree of nucleate boiling is also specified thusly.

Two potential mechanisms can be postulated to describe the hideout observed during the course of the experimentation:

1. The precipitation of the solute on the heated surface due to a decrease in solute solubility with increased temperature. This solute property is known as retrograde solubility.
2. The concentration of the solute in solution at the boundary layer of the liquid and the heated surface.

The "clean" surface tests showed no hideout of Na^{22} from the $NaOH - H_3BO_3$ system (see Section 3.2.1.). Hideout was observed from the $NaOH - Na_3PO_4$ system after the phosphate concentration was raised above 500 ppm. The high loop phosphate concentration needed before hideout could be observed is an indication of the effective mixing of the boundary layer and the bulk coolant. Tri-sodium phosphate has long been known as a "hideout material" from experience in power plant boilers. The solubility of $NaOH$ is known to increase with increasing temperature and sodium borate has been shown to be highly soluble (e.g., $\frac{1}{59.5\%}$ $NaBO_2$ by weight) in water at $275^\circ C$. Later tests on fouled heaters showed significant hideout of Na^{22} from the $NaOH - H_3BO_3$ system at test conditions similar to the "no hideout" clean heater ³¹ test. This indicates that the chemical concentration of the solute in the bulk coolant was not the limiting condition for hideout from $NaOH - H_3BO_3$ solutions during the clean surface tests.

The tests on fouled heaters 7 and 8 (Sections 3.8 and 3.9) were performed in an effort to establish whether sodium borate was precipitating out on the heater surfaces or sodium hydroxide was merely concentrating in the interstices of the deposits.

The corrosion products on fouled heater 7 were deposited in a "low pH" media (see Appendix II). A significant amount of hideout was observed during the initial test run (see Table XVII, Scan 1). As the boric acid was ion exchanged from the system the net hideout decreased significantly. After a period of high pH operation (Scan 4, Table XVII), boric acid was again added to the system. The hideout, however, did not return to the level observed prior to the high pH operation indicating that the deposit was changed in some way. The decrease in hideout during the boron removal, then, was probably due to the high pH effect on the deposit.

Fouled heater 8 was prepared from a "high pH" media and then operated for a time in a high pH, low boron system. No hideout was observed during the high pH operation or after the boron concentration was raised to 1150 ppm (see Table XVIII).

The results of the fouled heaters 7 and 8 tests are inconclusive since it is apparent that the structure of the deposit and/or its thickness changes during high pH operation. The data from Scans 4 and 5 of Table XVIII, however, show hideout at several locations while the boron concentration was very low.

From this fact, together with the solubility measurements of sodium borate, at various temperatures 1, it is felt that chemical precipitation, if it occurred, was a small fraction of the gross hideout observed in the other fouled heater tests.

The major mechanism for hideout then would be the concentration of solute in solution at the thermal boundary layer of the heater surface. All tests have shown that boiling heat transfer is a requisite for hideout and further, that the amount of hideout varies as the nucleate boiling.

We can therefore postulate that the amount of activity transferred into the thermal boundary layer is proportional to the mass steaming rate as defined by equation 9. The amount transferred from the boundary layer to the bulk coolant is proportional to the layer-bulk mixing rate and diffusion rate.

We can write the differential expression:

$$\frac{dC_f}{dt} = C_B \dot{M} - EC_f - D'C_f \quad (10)$$

Integrating equation 10

$$\ln \left[C_f - \frac{C_B \dot{M}}{(E + D')} \right] = \log K - (E + D')t \quad (11)$$

at $t = 0$, $C_f = C_B w_f$, therefore,

$$\ln K = \ln C_B \left(w_f - \frac{\dot{M}}{E + D'} \right)$$

and

$$C_f = \frac{C_B \dot{M}}{E + D'} + e^{-(E + D')t} \left(C_B \left(w_f - \frac{\dot{M}}{E + D'} \right) \right) \quad (12)$$

Since w_f is negligibly small equation 12 can be simplified for times $t > 0$,

$$C_f = \frac{C_B^M}{(E + D)} [1 - e^{-(E + D)t}] \quad (13)$$

It was pointed out previously that the actual mass steaming rate cannot be known with certainty for conditions other than bulk boiling. The uncertainty of the steaming rate increases the difficulty in defining the mixing and diffusion coefficients.

One possible theoretical approach to the mixing coefficient is a mass transfer analogy with the "vapor-liquid exchange action" mechanism used by Forster and Greif ⁵ to describe heat transfer in the boiling regime. The "vapor-liquid exchange" may be described briefly as follows: A bubble forms in the thermal boundary layer, on the heater transfer surface and in forming, displaces a volume of liquid, which is equal to the bubble volume, out of the boundary layer. The bubble itself moves out of the layer or collapses and an equal volume of bulk coolant enters the boundary layer. As this mass of bulk coolant expands, it displaces more concentrated solution out of the boundary layer.

It can be shown from this mechanism that the amount of material transferred from the boundary layer is proportional to the specific volume of the steam formed and the density of the bulk liquid.

This, of course, is a first approximation of a complex action. Actually as the bubble moves out of the boundary layer it would drag a shell of concentrated solution with it increasing the mass transfer from the boundary. However, as the bulk solution moves past the bubble, toward the boundary layer, diffusion of solute from the bubble shell to the bulk coolant would occur increasing the concentration of the solution entering the boundary layer. This would have the net effect of decreasing the mass transfer from the boundary layer.

It is not possible at present to quantitatively define the amount of hideout which occurs in a given system. Additional testing will be required to define the effects of all the various operating conditions and solution properties.

The following qualitative statements, however, can be made based on the experimental results:

<u>STATEMENT</u>	<u>PROOF</u>
1. No hideout occurs on clean heat transfer surfaces during sub-cooled or bulk boiling conditions from NaOH - H_3BO_3 systems for wall temperatures as high as 628°F.	Section 3.2
2. For compounds which exhibit retrograde solubility (Na_3PO_4 , for example) hideout can occur on clean surfaces during boiling heat transfer. The hideout of Na_3PO_4 is reversible.	Figure 6
3. Hideout from NaOH - H_3BO_3 systems occurs on fouled surfaces during boiling heat transfer. The hideout is reversible.	Table VIII Table XVII Figures 8 - 16
4. The hideout increases as nucleate boiling heat transfer increases at constant heater wall temperature and constant bulk temperature.	Table XIV Figure 11
5. Hideout increases as the heater wall temperature increases at constant nucleate boiling and constant bulk temperature.	Figure 15
6. Hideout can occur at wall temperatures as low as 515 to 528°F during boiling heat transfer.	Figure 12
7. Small deposit thickness differences effect significant hideout differences.	Figure 10 (Test 3)
8. There is probably a minimum thickness of deposit required for hideout to occur. For the conditions studied in this investigation, this thickness appears to be of the order of 0.3 to 0.4 mil.	Table XIII Section 3.5
9. After high pH, low boric acid operation, the hideout level on fouled heaters decreases significantly.	Table XVII
10. The environment from which the corrosion products are deposited on the heat transfer surfaces may affect the hideout character of the deposit.	Section 3.9

Table XIX presents a tabulation of some of the system-operating parameters for several of the fouled heater tests for reference. This tabulation is by no means considered to include all the variables which will effect the hideout.

TABLE XIX
TABULATION OF SYSTEM PARAMETERS FOR SEVERAL FOULED HEATER TESTS

HEATER NUMBER	DATA PRESENTATION	SYSTEM PRESSURE psig	BULK TEMPERATURE AT INLET, °F	SATURATION TEMPERATURE, °F	WALL TEMPERATURE °F	TOTAL HEAT FLUX Btu/hr-ft ²	NUCLEATE BOILING HEAT FLUX		SPECIFIC VOLUME OF STEAM (v _g) ft ³ /#	TOTAL DETECTOR RESPONSE FOR TEST SECTION			BACKGROUND COUNT RATE cpm	MAXIMUM NET DETECTOR RESPONSE, cpm	MASS STEAMING (Ṁ) RATE (#/hr-ft ²)			VOLUMETRIC STEAMING (ṽ) RATE (ft ³ /hr-ft ²)			COUNTING LOCATION INCHES FROM HEATER BOTTOM	T _w - T _B °F	T _{sat} - T _B °F
							1/ q _{NB Sat} Btu/hr-ft ²	2/ q _{NB} Btu/hr-ft ²		AFTER 0.5 hr. cpm	AFTER 1.0 hr. cpm	AFTER 2.0 hrs. cpm			FROM q _T	FROM 1/ q _{NB Sat}	FROM 2/ q _{NB}	FROM q _T	FROM 1/ q _{NB Sat}	FROM 2/ q _{NB}			
Fouled 2	Table IX Figure 8	1775 1775	563 560	620 620	626 626	310,000 210,000	190,300 84,000	177,700 71,400	.220 .220	1800 1070	1960 1200	2060 1370	750 470	1310 900	447 300	274 120	256 102	98 66	60 26	56 22	7.25 7.25	63 66	57 60
Fouled 6	Table XVI " " " "	970 1160 1335 1560 1800	543 565 583 601 621	543 565 583 601 621	557 576 592 608 626	189,000 180,600 170,100 155,400 144,900	BULK BOILING HEAT TRANSFER		.442 .370 .307 .257 .218	-- -- -- -- --	-- -- -- -- --	-- -- -- -- --	-- -- -- -- --	360 332 440 528 752	291 293 293 285 289	-- -- -- -- --	129 108 90 73 63	-- -- -- -- --	-- -- -- -- --	-- -- -- -- --	11.0 11.0 11.0 11.0 11.0	14 11 9 7 5	0 0 0 0 0
Fouled 6	Figure 14	1800	566	621	628	252,500	137,000	122,300	.218	8100	8800	9500	600	8900	445	241	215	97	52	47	11.0	69	62
Fouled 6	Figure 10	1800 630 1800	562 465 589	622 494 622	626 512 627	210,000 210,000 252,500	84,000 149,200 183,200	75,600 111,300 172,700	.218 .707 .218	1000 790 3750	1020 795 4050	1070 805 4700	630 750 650	440 55 4050	358 279 459	143 198 333	129 148 314	78 197 100	31 140 73	28 105 68	11.5 11.5 11.5	64 47 38	60 29 33
Fouled 6	Figure 15 " " " "	945 1060 530 1135 1230 1375 1430 1550 1800	528 530 551 561 569 583 593 588 600 539	540 551 565 574 580 593 597 608 620	554 565 574 580 593 597 608 626	126,300 147,300 103,200 168,300 189,400 210,000 231,500 252,500 294,600	101,100 103,200 105,300 111,700 111,700 107,100 120,200 118,100 124,500	71,700 73,800 78,000 88,600 86,100 86,100 101,300 101,300 112,000	.465 .420 .385 .360 .313 .298 .267 .220	775 900 1100 1300 1625 2075 2950 5900	-- -- -- -- -- -- -- --	-- -- -- -- -- -- -- --	650 650 650 650 650 650 650 650	125 250 221 253 289 975 1425 2300 5250	188 221 155 158 170 324 165 359 398 477	151 111 117 135 133 107 157 186 201	107 93 97 104 101 107 106 106 105	87 65 61 61 52 56 50 44	70 47 45 49 42 47 43 40	11.0 11.0 11.0 11.0 11.0 11.0 11.0 11.0	26 35 43 48 59 62 72 87	12 21 30 37 49 53 64 81	
Fouled 6	Figure 13	1420	566	590	599	252,500	202,400	183,000	.293	--	--	4100	750	3350	422	338	306	124	99	90	11.0	33	24

- 1/ From equation 5 in text.
 2/ From equation 6 in text.
 3/ Volumetric steaming rate $\dot{V} = \dot{M} v_g$
 4/ h_{fg} taken at saturation temperature.

It is understood that each of the solution properties, such as viscosity, thermal conductivity, boiling point, etc. will have an ultimate effect on the hideout level. It should be kept in mind, also, that these solution properties are changing as the hideout level changes. It is our point in presenting the data from this somewhat pioneer investigation, to lay a foundation for the interpretation of the results and for future study of this highly complex phenomena.

Figure 17 presents a plot of the net detector response vs. the mass steaming rate divided by the specific volume of steam for the data in Table XIX. The mass steaming rate ($\dot{M}$) was calculated from the nucleate boiling heat transfer as defined by equation 5. The specific volumes of the steam are taken at saturation conditions.

It can be said, in general, that the amount of hideout varies directly with the mass steaming rate and inversely with the specific volume of the steam formed. This can be readily seen from the constant mass steaming rate test. The test data was presented in Figure 16.

The hideout increased by a factor of 3.0 while the specific volume of the steam decreased by a factor of 2.1.

It is of interest to note the significantly lower hideout level of the constant mass steaming rate test (Table XVI and Figure 16) as compared to the Figure 15 tests. The constant steaming rate test was at bulk boiling conditions while the "Figure 15" test was at sub-cooled boiling conditions. The only significant difference between comparable sub-cooled and bulk boiling tests would be the bubble life and travel.

In sub-cooled boiling conditions the bubble formed at the heater wall would begin to decrease in size immediately on leaving the thermal boundary layer and would collapse some distance out from the layer. In the bulk boiling condition the steam bubble formed would remain stable both in the thermal boundary layer and in the bulk coolant.

A possible explanation for the larger hideout under sub-cooled boiling conditions than bulk boiling conditions may be obtained from a consideration of the previously described diffusion process from the concentrated solution (bubble shell) being dragged from the boundary layer by the steam bubble.

For either boiling condition the following flow schematic would represent the steam bubble travel:

Let the shaded areas around the circles represent the bubble shell and the coiled arrows represent the bulk coolant moving toward the heater wall. The steam bubbles are moving out from the heater. In both boiling conditions diffusion of solute would occur from the higher concentration solution of the bubble shell to the bulk solution moving in the opposite direction.

The diffusion process in the sub-cooled tests, however, is accompanied by heat transfer from the bubble to the liquid stream. This probably causes an increase of the diffusion coefficient, thereby causing more of the solute to transfer to the inward moving bulk coolant. The diffusion process in the bulk boiling tests is not aided by heat transfer; therefore, more of the concentrated solution being dragged by the steam bubble will escape the deposit.

Figure 17
HIDEOUT vs. $\dot{M}/v_s$ FOR VARIOUS FOULED HEATER TESTS

FOULED HEATER 6

FIGURE 12 DATA

[•]	T_W	554 - 626°F
	T_B	528 - 539°F
	P	945 - 1800 psig
	q''_T	126,000 - 294,600 Btu/hr-ft ²
	$q''_{NB \text{ Sat}}$	101,000 - 124,500 Btu/hr-ft ²

LOCATION OF COUNTS 11.0" FROM BOTTOM OF HEATER

FIGURE 7 DATA

[x]	T_W	494 - 622°F
	T_B	465 - 589°F
	P	630 - 1800 psig
	q''_T	210,000 - 252,500 Btu/hr-ft ²
	$q''_{NB \text{ Sat}}$	84,000 - 183,000 Btu/hr-ft ²

LOCATION OF COUNTS 11.5" FROM BOTTOM OF HEATER

FIGURE 13 DATA

CONSTANT MASS STEAMING RATE TEST

[o]	T_W	557 - 626°F
	T_B	543 - 621°F
	P	970 - 1800 psig
	q''_T	189,000 - 144,900 Btu/hr-ft ²
	$q''_{NB \text{ Sat}}$	189,000 - 144,900 Btu/hr-ft ²

LOCATION OF COUNTS 11.0" FROM BOTTOM OF HEATER

FIGURE 11 DATA

(1 POINT)

[+]	T_W	628°F
	T_B	566°F
	P	1800 psig
	q''_T	252,500 Btu/hr-ft ²
	$q''_{NB \text{ Sat}}$	137,000 Btu/hr-ft ²

LOCATION OF COUNTS 11.0" FROM BOTTOM OF HEATER

FOULED HEATER 2

FIGURE 5 DATA

[+]	T_W	626°F
	T_B	560°F
	P	1775 psig
	q''_T	310,000 - 210,000 Btu/hr-ft ²
	$q''_{NB \text{ Sat}}$	190,000 - 34,000 Btu/hr-ft ²

LOCATION OF COUNTS 7.25" FROM BOTTOM OF HEATER

5. CALCULATION OF SURFACE CONCENTRATIONS FROM THE COUNT RATE DATA

Throughout the data presentation and the discussion the amount of hideout has been given in terms of detector responses in counts per minute for ease of presentation. The actual surface concentrations of the solute can be readily calculated from equation 3 and the loop chemistry data. Equation 3 is:

$$S(\text{mg/dm}^2) = \left(\frac{D_h}{D_b} - 1 \right) (0.0571) C(\text{mg/dm}^3)$$

The bulk coolant concentration (C) is given for each test in the loop chemistry tables in units of ppm:

$$C(\text{mg/dm}^3) = C(\text{ppm}) \times \text{specific gravity of the solution at test conditions}$$

EXAMPLE 1 (Maximum Hideout During Phosphate Test)

From Table VI the bulk coolant sodium concentration during the test was 752 ppm. From Figure 6 the maximum detector count rate D_h was 485 cpm and the background count rate D_b was 240 cpm. The specific gravity of the solution was 0.6474 at 620°F. Therefore, using equation 3 and the concentration conversion:

$$S(\text{mg/dm}^2) = \left[\frac{485}{240} - 1 \right] (0.0571) [752] (.6474)$$

$$S = 28.4 \text{ mg Na/dm}^2$$

EXAMPLE 2 (Maximum Hideout Observed on Fouled Heater 6)

From Table IV the bulk coolant sodium concentration during the Figure 14 test was 2.64 ppm. From Figure 14 the maximum detector count rate D_h was 13,000 cpm and the background count rate D_b was 600 cpm. The specific gravity of the solution was 0.7211 at 566°F. Therefore, using equation 3 and the concentration conversion as above:

$$S(\text{mg/dm}^2) = \left[\frac{13,000}{600} - 1 \right] (0.0571) [2.64] (0.7211)$$

$$= 2.2 \text{ mg Na/dm}^2$$

The boron surface concentration can be calculated from equation 3 as was the sodium surface concentration. However, since the boric acid is volatile, the actual surface concentration will be lower than calculated, by an indeterminate amount, depending on the efficiency of the "distillation".

Concentration ratios of the solution in the boundary layer to the bulk solution can be calculated as follows:

EXAMPLE (Maximum Concentration Ratio on Fouled Heater 6)

From page 59, the maximum surface concentration for the Figure 14 test was found to be 2.2 mg Na/dm². The deposit thickness on fouled heater 6 was about 0.9 mil (radius).

The interstitial volume of the deposit, assuming 70% voids, is,

$$V_i = 0.1603 \text{ cc/dm}^2$$

If we consider that concentration is occurring over the entire thickness of the deposit, then for the sodium surface concentration of 2.2 mg/dm² we calculate the solution concentration (C) as follows:

$$(C) = \frac{S}{V_i \rho_D}$$

$$\begin{aligned} (C) &= 2.2 \text{ mg Na/dm}^2 \times \text{dm}^2 / 0.1603 \text{ cc} \times 1 \text{ cc} / .6474 \text{ gms} \\ &= 21.2 \text{ mg Na/gm solution} = 21,200 \text{ ppm Na.} \end{aligned}$$

Therefore, the concentration ratio of sodium in the deposit to sodium in the bulk coolant is about 8000.

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APPENDIX IDETERMINATION OF VOID FRACTION AND
SLIP RATIO FROM THE RADIOTRACER APPARATUSNOMENCLATURE

D_b = detector response at unheated zone

D_h = detector response at heated (boiling) zone

C_i = tracer concentration at unheated region

C_o = tracer concentration at boiling region

k = constant of proportionality

$\dot{M}_T$ = total mass coolant flow

X = steam quality, mass steam flow/total mass flow

α = void fraction (steam)

ρ = slip ratio, ratio of vapor to liquid linear velocity

A_T = area of the annulus

Assuming the detector response is proportional to the activity per unit length in the annulus and that there is no activity in the steam (non-volatile tracer),

$$D_b = k C_i A_T \quad (1)$$

$$D_h = k C_o A_T (1 - \alpha) \quad (2)$$

and from a mass balance on the tracer

$$(1 - X) \dot{M}_T C_o = \dot{M}_T C_i \quad (3)$$

Hence,

$$\frac{D_H}{D_b} = \frac{(1 - \alpha)}{(1 - X)} \quad (4)$$

Thus, from a thermal balance, X is calculated and α is then calculated from 4. The slip ratio can then be calculated from

$$\frac{\alpha \rho}{1 - \alpha} = \frac{\rho_l X}{\rho_v (1 - X)} \quad (5)$$

APPENDIX IIVARIOUS METHODS FOR DEPOSITION OF MAGNETITE ON
WATLOW HEATERS USED IN HIDEOUT TESTS

Several methods for depositing magnetite on stainless steel surfaces were investigated prior to selection of the methods used in these tests. These included:

1. Passing a dilute solution of ferrous sulfate through an anion resin in the hydroxide form to obtain ferrous hydroxide. The resulting ferrous hydroxide solution was then circulated past a heated surface where the hydroxide was converted to magnetite and deposited on the surface.
2. Heating the surface for deposition to about 400°F and hot dipping in a slurry of ferrous hydroxide.

Neither of the above procedures produced an acceptable deposit of magnetite (0.5 mil) which would not wash off.

Two procedures were selected for depositing magnetite on the 304 stainless steel clad "Watlow" heaters used in these tests. These will be designated as "low pH" and "high pH" methods. The "low pH" procedure was used to deposit magnetite on the first seven Watlow heaters while the "high pH" procedure was used to deposit magnetite on the eighth Watlow heater. Both procedures are described below:

A. Low pH Method

A slurry of ferrous hydroxide was prepared by adding 0.98 mole of ferrous sulfate and 1.96 moles of ammonium hydroxide to 20 liters of deoxygenated, demineralized water. The slurry was permitted to settle until the supernate volume was 16 liters. The supernate was removed by decanting and replaced with 16 liters of deoxygenated, demineralized water. The washing step was repeated and a sample of the mixture taken for pH measurements. The measured room temperature pH of the solution was 8.5 while the calculated pH from solubility data is 9.5. The difference is probably due to hydrolysis of the ferrous ion but could possibly be due to impurities present in the ferrous sulfate. The washed ferrous hydroxide slurry was circulated past the energized Watlow heater where nucleate boiling was maintained. The average nucleate boiling heat flux as calculated from equation 6 in Section 4 varied from $10,400 \pm 1200$ Btu/hr-ft² at the upstream end of the heated section to $23,300 \pm 1200$ Btu/hr-ft² at the downstream end

of the heated section. The system pressure was maintained at 450 ± 50 psig resulting in a clad temperature of $477 \pm 11^\circ\text{F}$. The deposition time varied from 1.5 hours to 10 hours although the deposit thickness apparently was not time dependent as a heater exposed for 1.5 hours had a 1 mil deposit while a heater exposed for 10 hours had only a 0.5 mil deposit. Typical magnetite deposit profiles are shown in Table II in the body of this report. Chemical and spectrometric analysis of the deposit proved it to be composed of $76 \pm 4\%$ iron of which 70% was present as Fe^{+++} and 30% as Fe^{++} indicating the deposit composition to be about 90% magnetite.

B. High pH Method

In this procedure the ferrous hydroxide slurry was prepared by adding 0.98 mole of ferrous sulfate and 1.96 moles of sodium hydroxide to 20 liters of deoxygenated, demineralized water. After washing as in the "low pH" method the room temperature pH was adjusted to 10 by addition of sodium hydroxide to the ferrous hydroxide slurry. This slurry was then circulated past the energized Watlow heater and deposited as in the "low pH" procedure. The amount of deposition was small with only 0.75 mil deposited after 30 hours exposure.