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J. Jo
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7. Abstract

Aging waste has been stored in tanks at Hanford since the early 1950's. The first record of a tank bump occurring was reported in the mid-1950's. Some of these tank bumps have led to undesirable discharges of radioactive contaminants. The last recorded tank bump event occurred in 1965.

The purpose of this document is to compile all the existing significant information and evaluations on past tank bumps to aid in determining the position(s) which Westinghouse Hanford Company (WHC) will adopt in the tank bump scenario.

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THE HISTORY AND EXISTING EVALUATIONS OF THE TANK BUMP

J. Jo
B. L. Jones

Tank Farm Process Technology Section

January 1990

TABLE OF CONTENTS

1.0 INTRODUCTION 4

2.0 SUMMARY 5

3.0 WASTE TANK OPERATIONS HISTORY 9
- 3.1 Past Waste Tank Operations 9
- 3.2 Conjectures on Tank Bumps 11

4.0 AGING WASTE TANK BUMP SCENARIO CALCULATIONS 13
- 4.1 Methodology and Assumptions of Aging Waste Tank Bump Scenario Calculations 13
- 4.2 Methods of Heat Transfer Problem Analysis 18
  - 4.2.1 Two-Dimensional HEATING5 Computer Conduction Code . 18
  - 4.2.2 One-Dimensional Heat Transfer Analysis Derived From Fouriers Second Law of Heat Conduction 19
  - 4.2.3 Comparison of Results 19

5.0 UNRESOLVED ASSUMPTIONS AND RECOMMENDATIONS 21
- 5.1 Liquid Temperature Stratification 21
- 5.2 Heat Transfer During Solids Settling 22
- 5.3 Heat Transfer During Solids Resuspension 23
- 5.4 Process Test 23

6.0 CONCLUSIONS 24

7.0 REFERENCES 25

LIST OF TABLES

TABLE 1 Design and Administrative Changes to Prevent Tank Bumps . . . 7

TABLE 2 Comparison of Past and Present Aging Waste Tank Operating Limits 23

LIST OF FIGURES

FIGURE 1: Vapor Flow Rates Versus Tank Pressure 14

FIGURE 2: Vapor Generation Over an Eight-Hour Tank Bump Event 17

1.0 INTRODUCTION

Since 1944, the U.S. Department of Energy (DOE) and its predecessors have stored high-level waste (HLW) in underground storage tanks at Hanford. In the 1950s, operations of the REDOX and PUREX process were initiated. The HLW from these processes contained radioactive fission products in higher concentrations than the waste from the earlier Bismuth Phosphate ($BiPO_4$) process. The higher concentration of radionuclides caused these wastes to self-boil until a sufficient period of radioactive decay had elapsed. These wastes were stored in "aging waste" tanks during the period of self-boiling.

In an attempt to conserve tank space, the aging waste was allowed to concentrate in-tank by removing the condensate from the self-boiling. The waste in some tanks was concentrated to the point where high temperature excursions in the solids occurred. The temperature excursions periodically lead to a phenomena known as "tank bump". A tank bump is a sudden release of vapor (steam) from the waste, which causes a tank pressurization and resultant release through unfiltered pathways. This document compiles the existing significant information on past tank bumps in support of determining a Westinghouse Hanford Company (WHC) position for future evaluations.

Since the first tank bump experience (mid-1950's) there have been modifications in the design and operation of aging waste tanks in an attempt to prevent tank bumps from occurring. Although past tank bump events occurred for various reasons, the following scenario or any series of the following which lead to the Release to the Environment is accepted as the only credible tank bump scenario that could occur under the current aging waste tank operations:

Initiating Event - Equipment failure which allows the solids to settle or cooling mechanism failure (e.g. solids percolation paths plug).

Heat Build-Up - A temperature rise in the solid and/or liquid phase from radio-isotopic decay.

Heat Released - The superheated solids and/or liquid is agitated (e.g. Airlift Circulators (ALCs) or mixer pumps) which allows the heat stored to be released.

Vapor Generation - The pressurized and superheated liquid raising the temperature of the surrounding supernatant to its boiling point and thus the rapid vapor generation.

Release to the Environment - The vapor generation is great enough to overwhelm the ventilation system causing a tank pressurization and a resultant vapor release to the environment through unfiltered tank pathways (e.g. cover blocks, tank risers and sidefill lines).

The first tank bump scenario calculation involved a great deal of research and data gathering (Jones, 1987). The documents and letters generated over the years pertaining to tank bumps will be included in this document to assist in any future refinements of tank bump calculations (Appendix A).

2.0 SUMMARY

Aging waste has been stored in tanks at Hanford since the early-1950's. The first record of a tank bump occurring was reported in the mid-1950's. The tank bumps over the years are believed to be caused by one of three methods:

* A possible organic crust forms over the surface of the liquid which results in the supernatant superheating and pressurizing, which raises the local boiling point of the supernatant at the liquid surface until the pressure is great enough to crack the organic crust. Upon cracking, the superheated supernatant depressurizes and the local boiling point returns to normal resulting in a rapid generation of vapor (Harmon, 1955).

* The most publicized tank bump was Tank 105-A which was attributed to the evaporation of water entrapped in concrete between the metal liner and concrete wall and floor. A sludge temperature would have to be sufficiently high to produce a vapor pressure exceeding the hydrostatic head of liquid in the tank thus causing the liner to lift (Beard, 1967). This type of tank bump scenario was known prior to the accident of Tank 105-A and the instability of single-shell tank bottoms is best described in Brownwell, 1958.

* A single ALC was placed in-tank and it was noticed that when the circulator was off for a period of time and restarted abruptly, a rapid generation of vapor occurred from heat being released from the superheated solids and/or liquid (Hanson, 1955).

Only the last of the above methods could occur under current aging waste tank operations. Design and administrative changes have been implemented in aging waste tank farm management over the 40 years of operation to help prevent tank bumps from occurring. Since Tank 105-A (1965) there has not been another recorded tank bump. The changes in tank design and operations are outlined in Table 1. As a result of these changes to the tank design and operations, the only tank bump scenario that is credible is the one in which the solids and/or supernatant superheats and the heat is released in an uncontrolled fashion upon solids and/or supernatant agitation.

The "superheated solids/supernatant agitation" tank bump scenario has been characterized by utilizing the two-dimensional HEATING5 computer conduction code (Jones, 1988) and verified by a one-dimensional derivation of Fouriers second law of heat conduction (Kuhn, 1988). The results of the two heat transfer analyses were within 2% difference. The comparison of tank bump heat transfer methodologies was made on the current projected worst case aging waste tank conditions (no N Reactor case, Mihalik, 1988).

The tank bump scenario methodology has three assumptions that the conservatism cannot be quantified. Although the assumptions in question have been agreed upon as being conservative for the current worst case conditions, a quantifiable conservatism could not be derived. The three questionable assumptions are: thermal stratification of the supernatant, instantaneous solids settling upon loss of the tank agitation equipment, and the solids resuspend in a negative exponential fashion over an 8-hour time period. The current worst case tank bump scenario (Mihalik, 1988) has acceptable recovery times to prevent a tank bump event from occurring. Therefore, it is recommended that no additional modelling work be performed to refine the questionable assumptions unless an aging waste tank condition arises or is projected to exceed the current worst case conditions.

TABLE 1 Design and Administrative Changes to Prevent Tank Bumps

Design or Operation Change	Results or Benefits
Double-Shell Tanks	A second ventilated shell (annulus) was added to the single-shell tanks to safely contain a primary tank leak and reduce the possibility of the water vapor pressurizing from the lack of space and high temperatures such as were seen in Tank 105-A. The aging waste tank annulus ventilation systems provide limited heat and vapor removal and containment in the event a small leak develops.
In-Tank Agitation	22 - ALCs have been symmetrically spaced throughout the tank to provide liquid agitation and solids suspension as well as transferring heat from both phases.
Temperature Limits	Temperature limits are placed on the aging waste tanks to prevent degradation of the tank materials, uneven surge boiling, or other conditions which could endanger containment of the waste. If temperature limits are exceeded, all aging waste transfers to that tank would cease until the problem could be corrected.
Sodium Limits	The sodium limit of 5 and 5.5M has been implemented to minimize the amount of precipitated solids in the tank. Aluminum Hydroxide (Gibbsite) is suspected to precipitate when the tank contents are allowed to concentrate to sodium levels above 5.5M.

OUTPUT FROM CP.FOR GENERATED AS OF 19-APR-1988 11:26:30 PAGE 55 OF 26

Table 5. Results of Conduction Calculations: Case 5

hrs	Temperature Rise, °F Tctr	Tsurf	Heat Conducted BTU	Fract
5	20.83	8.94	3.200e+05	0.105
10	35.68	17.63	8.970e+05	0.147
15	46.19	25.60	1.610e+06	0.176
20	53.99	32.72	2.410e+06	0.198
25	60.04	39.02	3.260e+06	0.214
30	64.89	44.62	4.130e+06	0.226
35	68.89	49.61	5.020e+06	0.235
40	72.27	54.10	5.910e+06	0.242
45	75.19	58.17	6.800e+06	0.248
50	77.74	61.87	7.680e+06	0.252
55	80.01	65.27	8.560e+06	0.255
60	82.05	68.40	9.440e+06	0.258
65	83.90	71.30	1.030e+07	0.260
70	85.59	74.00	1.120e+07	0.261
75	87.15	76.53	1.200e+07	0.262
80	88.59	78.89	1.280e+07	0.263
85	89.94	81.12	1.370e+07	0.264
90	91.19	83.23	1.450e+07	0.264
95	92.38	85.22	1.530e+07	0.264
100	93.49	87.11	1.610e+07	0.264
105	94.55	88.91	1.690e+07	0.264
110	95.55	90.63	1.770e+07	0.264
115	96.50	92.27	1.850e+07	0.264
120	97.40	93.84	1.930e+07	0.263
125	98.27	95.34	2.000e+07	0.263
130	99.10	96.78	2.080e+07	0.262
135	99.89	98.17	2.150e+07	0.262
140	100.65	99.50	2.230e+07	0.261
145	101.38	100.78	2.300e+07	0.260
150	102.09	102.02	2.370e+07	0.260
155	102.77	103.22	2.450e+07	0.259
160	103.43	104.38	2.520e+07	0.258
165	104.06	105.50	2.590e+07	0.257
170	104.68	106.59	2.660e+07	0.257
175	105.27	107.64	2.730e+07	0.256
180	105.85	108.66	2.800e+07	0.255
185	106.41	109.65	2.870e+07	0.254
190	106.95	110.61	2.940e+07	0.253
195	107.48	111.55	3.010e+07	0.253
200	108.00	112.46	3.070e+07	0.252
205	108.50	113.35	3.140e+07	0.251
210	108.99	114.21	3.210e+07	0.250
215	109.46	115.06	3.270e+07	0.249
220	109.93	115.88	3.340e+07	0.249

225	110.38	116.68	3.400e+07	0.248
230	110.82	117.46	3.470e+07	0.247
235	111.25	118.23	3.530e+07	0.246
240	111.67	118.98	3.590e+07	0.245
245	112.09	119.71	3.660e+07	0.245
250	112.49	120.42	3.720e+07	0.244
255	112.89	121.12	3.780e+07	0.243
260	113.27	121.81	3.840e+07	0.242
265	113.65	122.48	3.910e+07	0.242
270	114.03	123.14	3.970e+07	0.241
275	114.39	123.78	4.030e+07	0.240
280	114.75	124.41	4.090e+07	0.239
285	115.10	125.03	4.150e+07	0.239
290	115.45	125.64	4.210e+07	0.238
295	115.79	126.24	4.270e+07	0.237
300	116.12	126.82	4.330e+07	0.236

Table 6. Results of Conduction Calculations: Case 6

hrs	Temperature Rise, °F Tctr	Tsurf	Heat Conducted BTU	Fract
5	2.24	1.53	5.320e+04	0.017
10	4.47	3.06	1.500e+05	0.025
15	6.70	4.59	2.760e+05	0.030
20	8.91	6.13	4.250e+05	0.035
25	11.08	7.66	5.940e+05	0.039
30	13.20	9.19	7.810e+05	0.043
35	15.27	10.72	9.850e+05	0.046
40	17.28	12.25	1.200e+06	0.049
45	19.23	13.78	1.440e+06	0.052
50	21.13	15.30	1.680e+06	0.055
55	22.97	16.83	1.940e+06	0.058
60	24.76	18.35	2.210e+06	0.060
65	26.49	19.86	2.490e+06	0.063
70	28.18	21.36	2.780e+06	0.065
75	29.82	22.86	3.080e+06	0.067
80	31.42	24.35	3.390e+06	0.069
85	32.98	25.83	3.710e+06	0.072
90	34.49	27.30	4.040e+06	0.074
95	35.97	28.75	4.370e+06	0.075
100	37.41	30.20	4.720e+06	0.077
105	38.82	31.63	5.070e+06	0.079
110	40.19	33.05	5.420e+06	0.081
115	41.53	34.46	5.790e+06	0.082
120	42.84	35.85	6.160e+06	0.084
125	44.12	37.23	6.530e+06	0.086
130	45.38	38.59	6.910e+06	0.087
135	46.60	39.94	7.300e+06	0.089
140	47.80	41.28	7.690e+06	0.090
145	48.98	42.60	8.080e+06	0.091
150	50.13	43.91	8.480e+06	0.093
155	51.26	45.20	8.890e+06	0.094
160	52.37	46.47	9.300e+06	0.095
165	53.45	47.74	9.710e+06	0.096
170	54.52	48.99	1.010e+07	0.098
175	55.56	50.22	1.050e+07	0.099
180	56.59	51.44	1.100e+07	0.100
185	57.60	52.64	1.140e+07	0.101
190	58.58	53.83	1.180e+07	0.102
195	59.56	55.01	1.220e+07	0.103
200	60.51	56.17	1.270e+07	0.104
205	61.45	57.32	1.310e+07	0.105
210	62.37	58.46	1.360e+07	0.106
215	63.27	59.58	1.400e+07	0.107
220	64.17	60.69	1.440e+07	0.108

225	65.04	61.78	1.490e+07	0.108
230	65.90	62.86	1.530e+07	0.109
235	66.75	63.93	1.580e+07	0.110
240	67.59	64.99	1.620e+07	0.111
245	68.41	66.03	1.670e+07	0.112
250	69.22	67.06	1.710e+07	0.112
255	70.01	68.08	1.760e+07	0.113
260	70.80	69.09	1.800e+07	0.114
265	71.57	70.09	1.850e+07	0.114
270	72.33	71.07	1.890e+07	0.115
275	73.08	72.04	1.940e+07	0.116
280	73.82	73.00	1.990e+07	0.116
285	74.54	73.95	2.030e+07	0.117
290	75.26	74.89	2.080e+07	0.117
295	75.97	75.82	2.120e+07	0.118
300	76.66	76.74	2.170e+07	0.119

Table 7. Results of Settling Calculations, zones
(See text for explanation of headings)

Zone	Maximum Size, Microns	Solids volume fraction	Zone Velocity, ft/sec	Fraction Settled %	Elapsed Time hrs	Heat Deposited BTU
1	1.000	0.0036	5.26e-06	100.0	1427.00	3.89e+07
2	1.259	0.0055	8.23e-06	98.8	912.10	3.71e+07
3	1.585	0.0081	1.29e-05	97.5	584.40	3.33e+07
4	1.995	0.0117	2.00e-05	95.7	376.50	2.90e+07
5	2.512	0.0162	3.10e-05	93.5	244.00	2.47e+07
6	3.162	0.0217	4.76e-05	90.6	159.10	2.05e+07
7	3.981	0.0281	7.29e-05	87.0	104.40	1.68e+07
8	5.012	0.0352	1.11e-04	82.6	68.82	1.35e+07
9	6.310	0.0428	1.69e-04	77.4	45.54	1.07e+07
10	7.943	0.0507	2.56e-04	71.4	30.20	8.26e+06
11	10.000	0.0584	3.89e-04	64.9	20.02	6.28e+06
12	12.590	0.0657	5.92e-04	57.9	13.25	4.69e+06
13	15.850	0.0724	9.05e-04	50.7	8.74	3.43e+06
14	19.950	0.0784	1.39e-03	43.5	5.74	2.46e+06
15	25.120	0.0835	2.14e-03	36.6	3.75	1.73e+06
16	31.620	0.0877	3.32e-03	30.1	2.44	1.20e+06
17	39.810	0.0912	5.17e-03	24.2	1.57	8.14e+05
18	50.120	0.0938	8.11e-03	19.0	1.01	5.44e+05
19	63.100	0.0958	1.28e-02	14.6	0.64	3.59e+05
20	79.430	0.0973	2.03e-02	10.9	0.41	2.33e+05
21	100.000	0.1000	3.21e-02	8.0	0.26	1.51e+05

Table 8. Results of Settling Calculations, particles
(See text for explanation of headings)

Size, Microns	Initial Conc., %	Fraction of total volume	Slip Velocity, ft/sec
1.000	0.313	0.031	3.39e-06
1.259	0.166	0.048	5.53e-06
1.585	0.229	0.071	8.75e-06
1.995	0.306	0.101	1.37e-05
2.512	0.392	0.141	2.18e-05
3.162	0.484	0.189	3.43e-05
3.981	0.575	0.247	5.39e-05
5.012	0.657	0.312	8.50e-05
6.310	0.723	0.385	1.34e-04
7.943	0.766	0.461	2.10e-04
10.000	0.781	0.539	3.31e-04
12.590	0.766	0.616	5.20e-04
15.850	0.723	0.688	8.18e-04
19.950	0.657	0.754	1.29e-03
25.120	0.575	0.811	2.03e-03
31.620	0.484	0.860	3.19e-03
39.810	0.392	0.899	5.04e-03
50.120	0.306	0.930	7.98e-03
63.100	0.229	0.952	1.27e-02
79.430	0.166	0.969	2.02e-02
100.000	0.313	1.000	3.24e-02

TABLE 1 (cont.)

Design or Operation Change	Results or Benefits
Organic Limits	Separable organic compounds used in the PUREX process are recovered and not allowed to be transferred to aging waste tank farms. This process eliminated possibility of organic crust built up on top of the supernate (RHO-MA-116).
Heat Load Limit	A limit on the heat load has been imposed on each aging waste tank. The heat load cannot exceed 4 million Btu/hr. If the limit is reached the tank will be considered full to prevent excessive heat loading (Bergmann, 1989).
Ventilation Systems	The ventilation systems today are capable of handling higher flow rates and larger vapor loading due to the larger piping, deentrainers, and surface condensers. The original aging waste tanks in S and SX Tank Farms that bumped had no ventilation system.

3.0 WASTE TANK OPERATIONS HISTORY

3.1 Past Waste Tank Operations

The first plutonium separations process began operating at Hanford in 1944. Since that time, there have been three different plutonium separations processes housed in four operating facilities which are: T Plant (1944-1956), B Plant (1945-1952), REDOX (1952-1966) and PUREX (1956-1972; 1983-present). The three plutonium separations processes used at Hanford all produce HLW. The first processing rates and conditions from the $BiPO_4$ process at B Plant and T plant were such that the stored HLW could dissipate the heat from radioactive decay to the ground without attaining a temperature high enough to boil the waste solution. However, with technological development, a method to reduce volume of chemical waste per unit of uranium processed was developed which produced a higher rate of heat evolution per waste volume and caused some of the waste to boil. The waste is allowed to sit in the tanks until the heat load eventually decreases from radioactive decay to a point where further processing can take place and eventually final disposal. The time required for the heat load to decrease to manageable levels is the reasoning for the waste to be termed "aging waste." Currently only Tanks 101- and 102-AZ are used as aging waste tanks.

Prior to August of 1952, heat from the radioactive decay was dissipated to the surrounding soil without boiling any of the tanks. In addition to conductive cooling, air cooled heat exchangers were installed above ground on the S tanks. During August of 1952, Tank 110-S reached boiling temperature and water was sprayed on the air condenser which provided sufficient heat exchange capacity to contain the vapors. In 1953, Tank 107-S boiled at a rate exceeding the capacity of the water sprayed air condenser. A water jacket was installed on the air condenser to provide additional capability. In both cases of boiling, contamination was not found.

In August of 1953, an auxiliary water cooled condenser was installed on Tanks 104-S and 101-S to avert boiling. Without the auxiliary condenser, the water jacketed air condenser was not sufficient to remove heat generation. However, occasional increases in evaporation rates and contamination in the condensate were discovered. The increasing evaporation rates for these tanks were preceded by a mild eruption, which was introduced by a disturbance of the sludge layer, and in some cases no observed causes. In January of 1954, a different type of eruption was first observed in 101-S Tank. This type of eruption, called "bumping," took the form of a series of five to twenty-five abrupt pressure surges at about 100-second intervals. The initiation of this "bumping" was coincidental with the attainment of above 240 ^{o}F at the bottom of the tank.

In the spring of 1954, Tank 110-U contained a 5-foot layer of concentrate from the operation of the $BiPO_4$ first-cycle waste concentrator before adding the REDOX wastes. Tank 110-U evaporated water uniformly for twelve months, reducing volume 55% without evidence of non-uniform boiling or contamination spread.

From May, 1954 to February, 1955, REDOX wastes were routed to the 101-102-103-SX cascade through Tank 101-SX. In October of 1954, Tank 101-SX reached boiling. Non-uniform boiling as in the S farm was observed in December, 1954. During December and January, the "normal" condensate flow rate was 2 to 3 gal/min., falling to zero upon the addition of fresh waste and rising abruptly to a peak rate of up to 8 gal/min. about six hours later and subsiding to the "normal" rate during the next few hours.

In February of 1955, a series of five to twenty-five abrupt pressure surges at intervals of about 30 seconds were observed in Tank 101-SX. Instantaneous condensate flow rates up to eighteen times the "normal" condensate flow rates were observed during these periods of bumping. These pressure surges occurred about once per day when self-initiated, but could be initiated two to three times daily by manually turning a specially built auger installed in the tank. During a two month period of self evaporation with no additions of waste, the intensity of pressure surges increased from about 20 to 50 inches of water, and the heat released per series increased from about 400,000 to 4,000,000 Btu as the liquid level was reduced by evaporation from 30 feet to about 25 feet in the tank. After about six weeks of intermittent bumping, the auger was motorized and operated continuously. No bumping occurred during two and three-week intervals of auger operation, although bumping did recur when the auger was not operated (Tomlinson, 1955).

The possible organic crust-type tank bump resulted in short-lived pressure surges of 35 inches water gauge (WG) and an instantaneous boiling rate of 8.5 gallons per minute (Harmon, 1955). This particular example was of Tank 101-SX which was possibly induced by agitating the crust with an auger. The auger was implemented in the procedure and would be turned several times a day to possibly prevent pressure build-up under the crust.

In June of 1955, Tank 104-SX was boiling but had produced no bump. In order to keep the tank from bumping, an air lift circulator (ALC) was installed. When the ALC was activated, the rate of condensate flow increased from 3 to 7 gal/min, returning to normal in about six hours. About 5.5 million Btu of stored heat was removed and the temperature differential from top to bottom of the tank fell from about 4 ^{o}F to 0 ^{o}F (Tomlinson, 1955). On July 14, 1955, the ALC became inoperative in Tank 104-SX. When the ALC restarted, a bump occurred, increasing the condensate flow from 0.8 gal/min to 17.2 gal/min almost instantaneously. The temperature of the primary condenser cooling water increased from 74 ^{o}F to 148 ^{o}F over a 20-minute period, the vapor header pressure increased to 3 inches and the vent header pressure to 3.3 inches. The duration of the bump was about 70 minutes with heat evolution of 4,700,000 Btu/hr (Hanson, 1955).

During August of 1958, a temperature increase in the 114-SX tank was observed even with the four ALCs operating at 10 cfm each. On Friday, August 22, 1958, the temperature in the tank solid was 357 ^{o}F thus, the air to the ALCs was shut off and water was introduced at 15 gal/min through each ALC. Over the weekend the tank bumped three times and steam escaping through the risers was observed (Harmon, 1958).

The Tank 105-A bump occurred in January of 1965 (Smiset, 1965). This particular tank bump was postulated to be caused by liquid being trapped between the concrete floor and the carbon steel liner (Brownwell, 1958). The liquid was believed to have come from water entrapped in the concrete. During startup of the tanks in the AX Tank Farm in 1965, several hundred gallons of water from the concrete were collected from TK-103-AX and TK-104-AX. Then, the water vaporized and began to build pressure which exceeded hydrostatic head of the liquid in the tank thus causing the liner to lift (Beard, 1967).

According to an internal memo (Bendixsen, 1989), Tank 101-AX bumped once between 1968 and 1969. This information was discovered through a phone conversation between R. B. Bendixsen and F. E. Boyd. Due to lack of finding any contamination in the vicinity of the tank, the event was never recorded. The sludge temperature at the time of the bump was estimated to be at 260 °F and the initiating event for the bump was attributed to ALC shutdown and restart.

On November 5, 1986, the air lift circulators for 101-AZ and 102-AZ tanks were turned off for 15 hours and 25 minutes without any tank bumps (Off-Normal Condition/Event Report, #86-49). During this time, the average daily supernate temperature showed no significant change.

3.2 Conjectures on Tank Bumps

The past tank bumps are speculated to have occurred from one of three methods. The first two of the three methods are believed to be improbable to achieve in a current double-shell aging waste tank. The methods are as follows:

1) A possible organic crust forms over the surface of the liquid which results in the supernatant superheating and pressurizing, which raises the local boiling point at the liquid surface, until the pressure is great enough to crack the crust. Upon cracking the superheated supernatant depressurizes and the supernatant boiling point returns to normal, resulting in a rapid generation of vapor (Harmon, 1955).

2) The most publicized tank bump was Tank 105-A which was attributed to the evaporation of water entrapped in concrete between the metal liner and concrete wall and floor. A sludge temperature would have to be sufficiently high to produce a vapor pressure exceeding the hydrostatic head of liquid in the tank thus causing the liner to lift (Beard, 1967). This type of tank bump scenario was known prior to the accident of Tank 105-A and the instability of single-shell tank bottoms is best described in Brownwell, 1958.

3) A single ALC was placed in-tank and it was noticed that when the circulator was off for a period of time and restarted abruptly that a rapid generation of vapor occurred from heat being released from the superheated solids and/or liquid (Hanson, 1955).

A possible organic crust-type tank bump resulted in short-lived pressure surges of 35 inches water gauge (WG) and an instantaneous boiling rate of 8.5 gallons per minute (Harmon, 1955). This particular example was of Tank 101-SX which was induced by possibly agitating the organic crust with an auger. The auger was implemented in the procedure and would be turned several times a day to prevent a potential pressure build-up under the organic crust.

In order to limit the amount of organics in the aging waste tanks, separable organic compounds used in the PUREX process are recovered and not allowed to be transferred to aging waste tank farms (RHO-MA-116). Furthermore, in order to have the crust build up on the top of the supernate, the specific gravity of the supernate has to exceed the specific gravity of the crust material which is not probable in the current aging waste tanks. Therefore, in the current aging waste tanks, a tank bump due to the pressure build up under an organic crust is considered improbable.

The Tank 105-A bump occurred in January of 1965 (Smiset, 1965). This particular tank bump was postulated to be caused by liquid being trapped between the concrete floor and the carbon steel liner (Brownwell, 1958). The liquid was believed to have come from a possible leak or water entrapped in the concrete. The water vaporized and began to build pressure which exceeded hydrostatic head of the liquid in the tank thus causing the liner to lift (Beard, 1967).

For the current aging double-shell waste tanks, the annulus is ventilated to provide gas removal up to 2,200 SCFM. This ventilation system will aid in preventing pressure build up between the liners, thus eliminating tank bumps such as the 105-A tank bump event.

The ALC-induced tank bump occurred in Tank 104-SX (Hanson, 1955). The tank bump accident occurred on July 14, 1955 when the single ALC became inoperative due to a failed air compressor gasket. The ALC was repaired and resumed operation approximately 13 hours later. The restart of the ALC generated a tank bump which increased the condensate flow from .8 gallons per minute to 17.2 gallons per minute almost instantaneously. The temperature of the primary condenser cooling water increased from 74 ^{o}F to 148 ^{o}F over a 20-minute period. The vapor header pressure increased from 3 inches WG to 3.3 inches WG. The duration of the tank bump was 70 minutes with an estimated heat evolution of 4,7000,000 Btu/hr. The tank pressure increase was not reported or the data was not available.

4.0 AGING WASTE TANK BUMP SCENARIO CALCULATIONS

4.1 Methodology and Assumptions of Aging Waste Tank Bump Scenario Calculations

The tank bump scenario calculation was developed to identify critical operating parameters that would lead to a possible tank bump event. The tank bump calculation was first developed to characterize a worst case aging waste tank (Jones, 1987). Since the initial calculation, the same methodology for calculating tank bumps has been applied to a number of storage tanks with a wide variation in heat and solids loading. The tank bump calculation is broken down into four sections. The four sections will be discussed in detail including key assumptions:

1. An assessment of the available tank pathways for unfiltered release of steam to the environment and system air flow balance involving the ventilation system, tank inleakage and ALC air flows.

2. The heat transfer problem was analyzed to determine the total heat stored in the settled solids as a function of time.

3. Heat released as the solids are resuspended and the resulting volumes of vapor generated were calculated.

4. Tank pressures and resulting flow rates through the ventilation system and the environmental pathway were calculated.

Tank Farm Process Engineering (TFPE) has determined the major physical pathways available for vapor to escape during a tank pressurization in the AY and/or AZ tank farms (Hanson, 1987). The pathways consist of three one-inch breather holes located in the process pits and the tank sidefill transfer lines which originate at the 152-AX diversion box. The flow through each pathway is characterized by the Blasius equation for compressible flow. The ventilation system and ALC flows were characterized by the Darcy flow equation for non-compressible flow. In this particular case the results from the two equations do not vary significantly due to the relatively low line-pressure differentials. The flow for the complete system was balanced by integrating the two flows for each pathway (Figure 1). The total vapor flow in Figure 1 represents the addition of the ventilation and unfiltered flow rates. There are no key assumptions made in developing the flow characteristics of the tank since the calculation is derived from basic fluid dynamics.

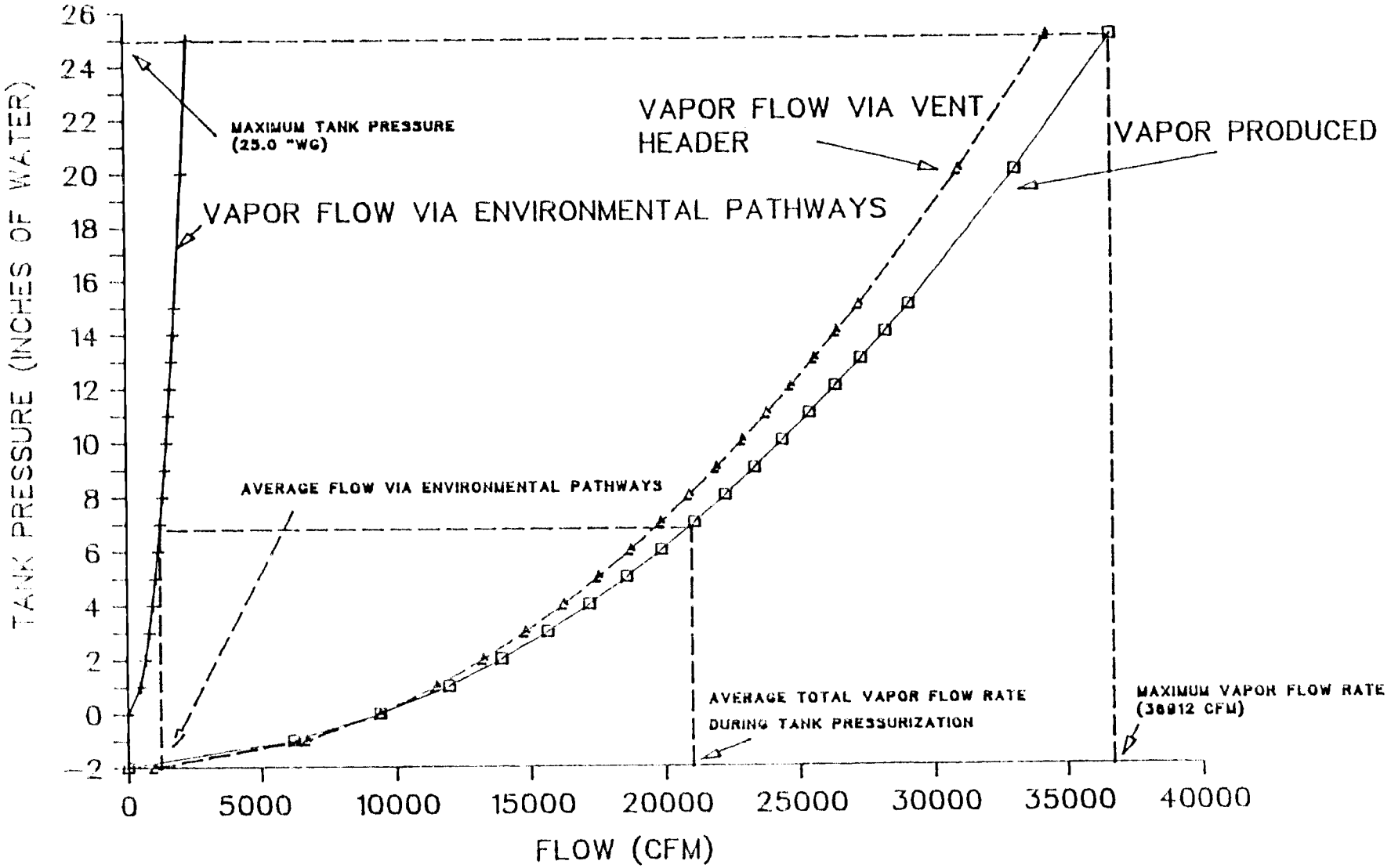

FIGURE 1. VAPOR FLOW RATES VS TANK PRESSURE

The heat accumulation stored in the solids layer as a function of time was generated using the two-dimensional HEATING5 computer conduction code. The waste is assumed to be from a worst case boiling waste tank which has a maximum heat generation rate of 4 million Btu/hr and 20% solids by volume. However, boiling waste conditions of this magnitude have not occurred since the operation of AX tank farm in the 1960s and are not expected to occur as long as N Reactor remains in cold standby (Mihalik, 1988). The key assumptions for developing the heat accumulation in the solids layer are described below.

1. Thermal stratification does not occur in the supernatant.

2. The thermal physical properties of the supernatant and sludge are as follows:

Material	Thermal Conductivity (Btu/hr.ft.F)	Specific Heat (Btu/lb.F)	Density (lb/ft^3)
Concrete	0.54	0.21	144.0
Hot Solids	1.00	0.20	103.0
Cold Solids	1.00	0.20	103.0
Soil	0.25	0.22	113.0
Insulating Concrete	0.11	0.24	62.0
Supernatant	0.39	1.00	62.4
Air	0.016	0.24	0.071

3. The HEATING5 inputs on boundary conditions are as follows:

   * A 70 ^{o}F forced convection at ground level.

   * A 55 ^{o}F isothermal boundary at a depth of 200 feet due to the water table which runs at a constant 55 ^{o}F.

   * A 70 ^{o}F adiabatic boundary at 60 feet radially. This simulates a tank in the middle of a large array of tanks, all generating the same amount of heat.

   * The liquid-solids interface is at the liquid boiling point and remains constant.

The solids begin to heat when the ALCs are interrupted for times of up to 72 hours. After 72 hours the superheated solids are resuspended abruptly over 8 hours (one shift) to initiate the tank bump event. The heat stored in the solids is instantaneously transferred to the supernatant where it produces vapor until the solids and liquid temperature equilibrate. The key assumptions are described on the next page.

1. The solids settle instantaneously and no heat transfer takes place during this time.

2. All the new settled solids are resuspended when the ALCs are restarted. The ALCs are not expected to resuspend any more solids than were suspended prior to the interruption in operation.

3. The solids are resuspended in a negative exponential fashion over 8 hours (one shift). The negative exponential was chosen solely for its characteristic initial peak that quickly diminishes which simulates past tank pressurization of this type of tank bump event.

4. Heat transfer during resuspension is assumed to be instantaneous.

5. ALCs will be down no longer than 72 hours.

The vapor is generated in a negative exponential curve by definition of the solids resuspension and assuming the heat transfer between the resuspended solids and supernatant is instantaneous (Figure 2). The vapor generation is assumed large enough to overwhelm the ventilation system resulting in a tank pressurization. The excess vapor is relieved from the tank by escaping through the unfiltered pathways until the tank pressure is returned to below atmospheric pressure. The maximum tank pressure is obtained by determining at which point the maximum vapor flow rate occurs during the tank bump. The maximum vapor flow rate is determined by integrating the negative exponential curve as time approaches zero. By plotting the maximum vapor flow rate point on the total vapor flow curve in Figure 1, the maximum tank pressure can be obtained from the y-axis (as shown). The environmental release is obtained by determining the average vapor flow rate during the time the tank is pressurized. The average vapor flow rate is obtained by integrating the negative exponential curve over the time the tank is pressurized (as shown in Figure 2) and dividing by the time the tank is pressurized. By plotting the average vapor flow rate point on the total vapor flow rate curve in Figure 1, the average environmental flow rate can be obtained as shown in Figure 1. The average flowrate is then multiplied by the time the tank is pressurized to obtain the total volume of vapor released to the environment. The released vapor volume is then multiplied by the measured aerosol partition factor (Ruecker, 1987) to obtain the total amount of liquid waste released to the environment. The key assumptions in this calculation are listed below:

1. The negative exponential curve describes the vapor generation rate.

2. The heat transfer between the resuspended solids and the supernatant occurs instantaneously.

3. The vapor removed by the ventilation system is completely contained (no release to the environment).

4. The aerosol partition factor is 10^{-7}.

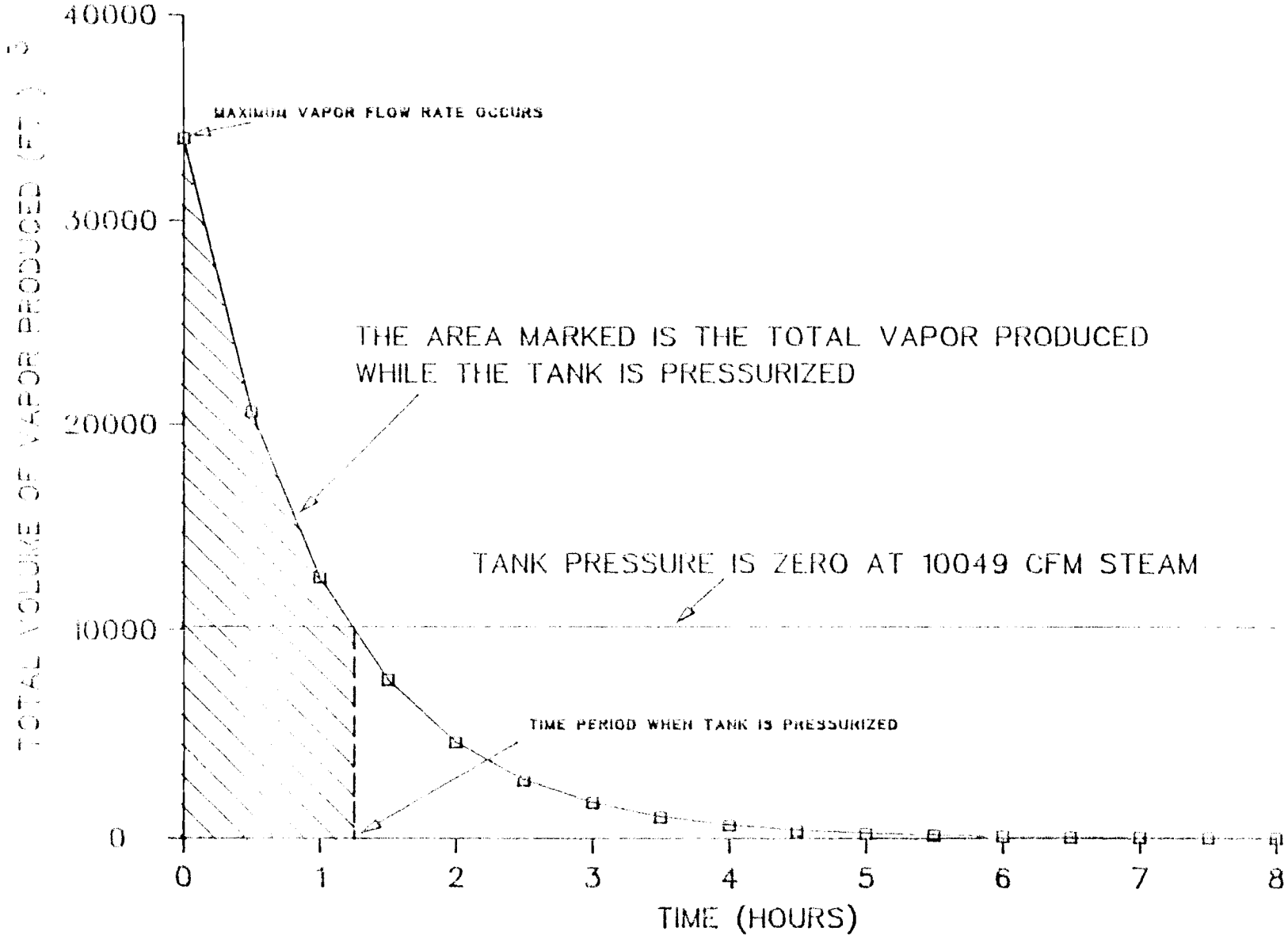

FIGURE 2. VAPOR GENRATION OVER AN EIGHT HOUR TANK BUMP EVENT

4.2 Methods of Heat Transfer Problem Analysis

The current tank bump calculation assumed that the solids would superheat upon settling and the heat would be released when the solids are resuspended. The worst case aging waste tank is assumed to be Tank 102-AZ assuming N Reactor does not restart (Mihalik, 1988). The tank bump scenario for Tank 102-AZ was modelled by WHC personnel using the HEATING5 heat transfer computer code (Jones, 1988) and confirmed by Pacific Northwest Laboratories (PNL) personnel who calculated the solids temperatures by utilizing a one-dimensional heat transfer analysis derived from Fouriers second law of heat conduction (Kuhn, 1988).

4.2.1 Two-Dimensional HEATING5 Computer Conduction Code

HEATING5 is a generalized heat conduction code designed to solve steady-state and/or transient heat conduction problems in one- two- or three-dimensional Cartesian or cylindrical coordinates. The thermal conductivity, density and specific heat may be both spatially and temperature dependent. The thermal conductivity can be anisotropic. Materials may undergo a change of phase. Heat generation rates may be dependent on time, temperature and position and boundary temperatures may be time dependent. The boundary conditions, which may be surface-to-surface or surface-to-boundary, may be fixed temperatures or any combination of a prescribed heat flux, forced convection, natural convection and radiation. The boundary condition parameters may be time- and/or temperature-dependent.

The point successive over-relaxation iterative method and a modification of "Aitken^2 extrapolation process" are used to solve the finite differential equations which approximate the partial differential equations for a steady state problem. The transient problem may be solved using any one of several finite differential schemes. These include an implicit technique which can range from Crank-Nicolson to the Classical Explicit Procedure, an explicit method which is stable for a time step of any size, and Classical Implicit Procedure, which involves the first forward time differential. The solution of the system of equations arising from the implicit technique is accomplished by the point successive over-relaxation iteration, and includes procedures to estimate the optimum acceleration parameter. The time step size for implicit transient calculations may be varied as a function of the maximum temperature change at a node. Transient problems involving materials with change-of-phase capabilities cannot be solved using the implicit technique with this version of HEATING5.

4.2.2 One-Dimensional Heat Transfer Analysis Derived From Fouriers Second Law of Heat Conduction

The two-dimensional HEATING5 computer conduction code solids and supernatant temperature predictions were verified by PNL's staff, using a one-dimensional heat transfer analysis method derived from Fouriers second law of heat conduction. Fouriers second law of heat conduction can be modelled for one-, two-, or three-dimensional heat transfer problems. The one-dimensional analysis was chosen because the ratio of height of solids to tank diameter

is small (0.04) which allows the assumption of little or no heat transfer occurring in the radial direction. The one-dimensional heat transfer assumption simplified the calculations considerably. The assumption of no heat transfer in the radial direction was supported by the HEATING5 results.

Fouriers second law of heat conduction is a differential heat transfer equation which can be applied to this particular problem by correctly choosing the appropriate boundary conditions. The boundary conditions are chosen in this case to configure the problem to an existing solved derivation of Fouriers second law available in literature (Carslaw, 1959). The solved problem is in the form of an infinite series which is solved for heat conducted to the supernatant as a function of time. The solution to the infinite series and temperature calculations can be found in Kuhn, 1988.

4.2.3 Comparison of Results

The results of the two heat transfer calculation methodologies were compared by analyzing the midplane solids temperature data for similar aging waste tank conditions. The conditions of the heat transfer problem used for comparison are described as follows:

* The settled solids volume is 36 inches at the bottom of the tank.
* The total heat generation rate is 690,000 Btu/hr with 610,000 Btu/hr generated by the solids.
* The density, heat capacity and thermal conductivity of the solids are 103 lb/ft^3, 0.3 Btu/lb^oF and 1.0 $Btu/hr.ft.^oF$, respectively.
* The density, heat capacity and thermal conductivity of the supernatant are 62.4 lb/ft^3, 1.0 Btu/lb^oF and 0.3 $Btu/hr.ft.^oF$, respectively.

There are two differences in the assumptions of the heat transfer methods. First, the two-dimensional HEATING5 computer conduction code includes heat transfer in the radial direction and the one-dimensional analysis neglects heat transfer in the radial direction. Second, the HEATING5 conduction code assumes that turbulent convection exists in the supernatant and any heat transferred to the supernatant is evenly distributed throughout the liquid layer or removed through evaporation. The one-dimensional method allows the supernatant to thermally stratify. The two differences would lead you to expect the HEATING5 results to be lower in temperature since both assumptions improve the heat removal from the solids layer.

The difference in assumptions between the two heat transfer analyses were insignificant. The HEATING5 computer conduction code results showed that an insignificant amount of heat transfer took place in the radial direction within the solids layer. The PNL evaluation determined that only 2% to 20%

of the total heat can be stored in the supernatant as opposed to 88% in the solids. The results are listed below for a 300-hour heat-up time. The results are listed as differentials, therefore, to obtain the midplane solids temperature. The initial solids temperature is added to the results.

TIME (HRS)	ONE-DIMENSIONAL (^{o}F)	HEATING5 (^{o}F)
0	0	0
50	52	51
100	74	72
150	86	84
200	96	95
250	104	104
300	111	112

The results indicate that the HEATING5 computer code did in fact predict the midplane solids temperature 1 to 2% below the one-dimensional analysis but this percent difference is well within acceptable limits.

5.0 UNRESOLVED ASSUMPTIONS AND RECOMMENDATIONS

5.1 Liquid Temperature Stratification

Past tank bumps where ALCs are believed to be the initiating event have been postulated to occur from the supernatant being thermally stratified. Because of the increased hydrostatic pressure at the tank bottom, the supernatant temperatures can locally increase above the boiling temperature existing at the top of the supernatant. The stratified supernatant could "roll over" carrying the superheated supernatant to the surface where the temperature of the supernatant is above the local boiling point and the supernatant flashes to vapor. This theory has been disputed since the conditions in the tanks do not support liquid thermal stratification. The HEATING5 computer conduction code work performed by WHC staff assumes that turbulent convection exists that results in even heating of the supernatant layer. The review of this assumption is addressed in the PNL final report (Kuhn, 1988) which is summarized below.

The tendency for natural convection to occur depends on the length scale of the system. The outbreak and intensity of natural convection depends on the Grashof Number. Correlations for steady-state laminar natural convection occurring from horizontal surfaces have been developed for Grashof Numbers in the range of 10^4 to 10^7. PNL's staff calculated the Grashof Number for a full tank to be on the order of 10^{12}. This result is five orders of magnitude above the range for which laminar natural convection is expected at a horizontal surface. Therefore, even for the assumed 1 ^{o}F temperature difference, initially thermal stratified tank contents would lapse into turbulent natural convection. Moreover, since the ALCs would cause the tank contents to be in motion initially, the large Grashof Number suggests that the contents would never become stratified. However, in June of 1955, Tank 104-SX had a temperature differential from top to bottom in the tank of approximately 4 ^{o}F. This can be explained by the fact that the boundary layer between the sludge and the supernate could have higher temperature than the bulk supernate temperature.

Although detailed arguments against supernatant thermal stratification have been presented, PNL's staff investigated the effects on the tank bump calculation as if thermal stratification was present. The results from the temperature calculations suggest that 2% to 23% of the heat stored could be stored in a thermally stratified supernatant, depending on the thermal and physical properties of the solids. This amount was considered insignificant as compared to the 88% of the heat stored in the solids layer.

It is recommended that if further work is needed on tank bumps or analyzing of the heat transfer problem as described in the tank bump scenario, an experiment should be developed to determine if the Grashof Number adequately defines aging waste supernatant in a double-shell tank and if conditions can be created to thermally stratify the supernatant.

5.2 Heat Transfer During Solids Settling

The current tank bump scenario assumes that once the ALC operation is disrupted, the solids settle instantaneously and begin to store heat. Past aging waste samples and theoretical analysis have indicated that suspended aging waste solids are primarily flocculent in nature and may take several hundreds of hours for settling to occur (Peterson, 1989). During the settling period only the fraction of solids that is settled will undergo heat storage. The fraction of solids suspended will give heat to the supernatant which is used to increase the supernatant temperature or will be removed from the tank completely if the supernatant is already at its boiling point. The ALC downtime required to achieve a tank bump potential is prolonged when the solids settling heat transfer is incorporated into the tank bump prediction calculation. When the supernatant is not at its boiling point, the fraction of heat generation from the suspended solids is not removed from the system due to its being used to raise the supernatant temperature. The results of this type of calculation would be identical to the calculations done assuming instantaneous solids settling since no additional heat is removed from the tank.

PNL has developed a theoretical method for evaluating the heat transfer during solids settling. The method assumes the following:

* The suspended solids are of uniform concentration throughout the supernatant ranging in size from 1 to 100 microns.

* The solids settling is described by multi-sized particle sedimentation equation developed by Selim et al. utilizing a simple successive substitution rather than the Newton-Raphson method.

* The heatload in the solids is distributed equally.

* The settled solids store heat and the suspended solids heat is transferred into the supernatant.

This method was used to analyze the solids settling and resultant heat transfer for the worst case aging waste tank conditions projected to be present in Tank 102-AZ (Kuhn, 1988). The results indicated that the particle slip velocities are on the order of 0.01 ft/sec. A particle falling at 0.01 ft/sec. would need 300 hours to fall 30 feet from the top of the slurry to the bottom of the tank. Because of the size distribution and the initial proximity of some particles to the bottom of the slurry, about 50% of the solids are settled after 10 hours and 90% solids settling occurs at 160 hours. The complete calculation is given in Kuhn, 1988.

It is recommended that the solids settling heat transfer analysis be taken in consideration when further tank bump potential calculations are performed. This will eliminate the conservatism and give a more realistic answer. A laboratory analysis of aging waste solids settling and heat transfer should be considered to verify the theoretical method developed by PNL.

5.3 Heat Transfer During Solids Resuspension

The current tank bump scenario assumes that the solids resuspend in a negative exponential fashion over an 8-hour period and the heat transfer occurs instantly upon solids resuspension. The negative exponential resuspension characteristic was chosen for its abrupt high tank pressurization that quickly diminishes in a relatively short amount of time. The assumption of a negative exponential suspension over eight hours is considered conservative although the conservatism can not be quantified.

It is recommended that if further work is performed on the tank bump prediction calculation, a laboratory experiment be developed to analyze the resuspension characteristics of ALCs and any other agitating equipment which may be present in an aging waste receiver tank. This information can be used to verify the current tank bump calculation as well as give a more quantifiable answer.

5.4 Process Test

All the documented tank bumps occurred prior to 1969. Since then the tank conditions have changed due to the modifications in the operation specifications (Table 2). The current aging waste tanks are not as hot as the aging waste tanks of the past. The supernate temperatures of the current aging tanks are around 140 ^{o}F, well below the estimated boiling point of 220 ^{o}F.

In order to resolve the unresolved assumptions above, it is recommended that feasibility of safe process testing be carefully studied. In the light of the off-normal event in November of 1986 (Off-Normal Condition/Event Report, #86-49), the process test can be safely performed for 15 hours and 25 minutes and probably longer.

TABLE 2 Comparison of Past and Present Aging Waste Tank Operating Limits

Operating Parameter	Past Observed Max/Min Level	Present Operating Specifications
Sodium Molarity	9.5 Molar	5 & 5.5 Molar
Fuel Age	50 days	180 days
Solids Temperature	534 ^{o}F	400 ^{o}F
Heat Load	10 Million Btu/hr	4 Million Btu/hr

6.0 CONCLUSIONS

The aging waste tank bump scenario calculation was developed in support of the aging waste SAR and its objective was to identify the critical ALC downtime that could possibly initiate a tank bump event. The methodology for evaluating an aging waste tank bump was developed and applied to the projected worst case aging waste tank condition (Jones, 1987). The assumptions in the tank bump calculation are considered very conservative although the conservatism is not quantifiable. To obtain a more realistic answer and to quantify the conservatism in the results, extensive experimentation would be required to evaluate the aging waste thermal and physical behavior. These experiments have yet to be initiated and there is no longer a need due to the worst case aging waste tank conditions being reduced in light of the N Reactor shutdown (Mihalik, 1988).

The revised worst case aging waste tank bump was evaluated using the identical tank bump scenario methodology (Jones, 1988) and was verified by PNL (Kuhn, 1988). The results showed a tank bump potential did not exist until 320 hours of ALC downtime. The conservatism in the tank bump calculation results are still unqualifiable due to the fact that there was a possible temperature stratification in Tank 104-SX (possibly due to high boundary layer temperature). No further work on refining the tank bump calculations or assumptions is recommended unless the aging waste tank conditions are projected to exceed the current worst case tank. Also, a safe process test to evaluate waste temperature behavior without ALC operation should be considered.

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APPENDIX A: PAST AGING WASTE TANK BUMP EVENT DOCUMENTATION

1100

February 3, 1965

MEETING MINUTES
Single-Shell Tank
"BUMPING" OF TK 241-A-105

This was not a bump as we now view them - + appears that waste leaked between the liner & concrete, vaporized, & bulged up the liner. Liner now observed to be severely corr at wall/bottom interface.

A meeting was held among representatives of Purex Operation, Research & Engineering and Facilities Engineering to discuss the "bump" that occurred in A Farm. The "bump" was unusual because of its severity and because it is the first time a "bump" occurred with the air lift circulators apparently in operation. Those attending the meeting were:

S. J. Beard	J. B. Fecht	L. R. Michels
J. M. Blackburn	W. H. Koontz	J. J. Shefcik
M. O. Clement	J. H. Mathis	O. V. Smiset
G. E. Cunningham		

At 2:50 PM on January 28, 1965, a severe "bump" occurred in Tk-241-A-105. Four Purex Operation personnel were in the immediate vicinity of 105-A at the time. They noticed a decided shaking of the ground and steam emission out of the A Farm tanks. An 8-inch nozzle on Tank 103-A contains a light bar used for internal tank inspection and was covered with a 16-inch square lead sheet 1/16 inch thick. The lead sheet was blown off the riser. The steaming on the 105-A Tank lasted about ½ hour before subsiding to a point where the ventilation system could handle it. At the same time, Jones Minor Construction forces were preparing to make the final weld in a line to tie 105-A to the 151-AX diverter station. The line was observed to shake and liquid spilled out on to the ground. Radiation reading of 400 R at one foot was observed. One Purex Operation radiation monitor was slightly contaminated.

During the subsequent inspection of A Farm, the electrode tape in 105-A was found to be broken and the weight factor enclosure for 105-A was contaminated to 500 R/hr. The water levels in the seal pots were found to be normal with the exception of the 103-A overflow. This was blown sounding the alarm in the control room. No wastes were added to 105-A from Purex that day with the only addition being tank farm condensate. A sample of condensate taken the following day from the 417 tank had a radiation level of 8,000 counts per minute vice a normal reading of 200 counts per minute. The air to the circulators was on and at the recommended flows of 8 cfm. This is the first "bump" known to occur with the air lift circulators in operation.

Prior to the "bump" the electrode reading indicated a level of 317 inches in 105-A. A new electrode installed on January 29 indicated a level of 303 inches. This latter level was confirmed by a radiation profile reading. The radiation probe for the leak detection laterals gave indications of malfunction prior to the 28th and was undergoing repair at the time of the "bump". Readings taken on February 2 indicated no abnormal radiation levels.

Measurements to check the operation of the circulators were made on the evening of January 29. The circulators are equipped with dip tubes to measure the pressure differential between its inside and outside.

A dp of 3 to 7 inches would indicate normal operation but a 20 inch dp would indicate a plugged circulator. This instrumentation, designed to record in the control room, has not been in service for several years. The valves on the air purged dip tubes in 105-A were closed. The dp's and the static pressure on the circulator dip tubes were measured with a manometer. Meaningful results were obtained only on one circulator and these results indicated normal operation. The static pressures measured on the other circulators indicated air leaks, improper connection or partial pluggage. Here, no conclusions concerning circulator operation could be reached. On two circulators, the back pressure of the motive air was measured and found to be normal.

Thermocouples were inserted into the 8-inch dry well and into the thermowell containing the bulb for the dial thermometer. Both thermocouples indicated normal temperatures. The temperature recorder for the profile thermocouples has been out of service for more than a month awaiting replacement parts. The thermocouples have been read with a portable potentiometer but the temperatures noted are suspect. Temperatures of less than 100°C are frequently noted.

Since the "bump" the air rates to the circulators have been increased from 8 to 10 cfm. Additional items for action were discussed during the meeting. The following list summarizes these items:

1. Put the instrumentation in 105-A into service and do whatever is necessary to place the contact condensers on automatic stand-by.

2. Recheck circulators for operation.

3. Add air through dp dip tubes on circulators whose operation is questionable.

4. Define and procure

   a. A seismograph
   b. A fast response pressure recorder for Tank 105-A pressure and vapor header pressure.
   c. A radiation probe to be used for sludge and liquid level measurement.

5. Investigate the radiation levels in the 105-A pump pit.

6. Investigate the cost of a new pump pit.

7. Investigate and determine the best way to install emergency recirculators. This investigation would consider possible use of a modified existing spare recirculator. After mutual concurrence on the best approach, recirculators would be made available for emergency installation.

8. Make necessary preparations for the possible pumping out of 105-A.

9. Add an air sparger through the available 2-inch riser on 105-A Tank.

The above enumeration does not necessarily represent the order of priority or order of work. Purex Operation assumed responsibility for Items 1, 2, 3, 5, 8 and 9. Facilities Engineering assumed responsibility for Items 4, 6 and 7. Research & Engineering will provide assistance when possible.

In addition to the above items the following two problems were discussed and agreement reached that engineering attention should be directed to:

1. Providing an air sampling system so that stack air could be reliably sampled.

2. Providing an emergency back-up on the vent system since both fans are running and both could conceivably fail at the same time.

The next meeting will be scheduled when some meaningful data has been accumulated.

O V Smiset

O. V. Smiset, Manager
Fission Products Processing
Purex Operation

OVS:de

273

GENERAL ELECTRIC COMPANY

[illegible]

February 24, 1955

D. F. Beaulieu
Redox Process Engineering Unit
Separations Section

OPERATION OF THE AUGER-TYPE AGITATOR - 101 HX TANK

Ref.: Letter, M. E. Hanthorn to G. H. Pilley, "C.S. 539 Additional Waste Storage for Redox Change of Scope", Dec. 23, 1954

Records have been obtained of the tank pressures and temperatures during the first period outlined in the reference letter (i.e., pressure surges observed during the time the auger was not used).

On February 17, the operation of the auger in Waste Storage Tank 241-HX-101 resulted in a short-lived but intense pressure surge, the peak reaching 35 inches of water, and an instantaneous boil-up rate of 8.5 gal./min. This indicates that this may be a fairly efficient method of agitating the contents of the tank and that frequent or continuous operation of this device may eliminate bumping by preventing the build-up of superheat in the tank.

Since bumping has been occurring frequently of late, it is recommended that, in conformity with the reference letter, the auger be operated once every eight hours by giving the handle at least 25 turns each time. It should be noted whether this results in any changes in tank pressure, temperature or condensate flow rate. If bumping results within 10 minutes, operation of the agitator should be resumed until the tank pressure returns to zero gauge.

The time of auger operation should be indicated on the condensate flow recorder chart.

M. E. Harmon, Head
Redox Plant Processes
Separations Technology Section

by KEL
K. L. Adler

MEH:KLA/mob

cc: G. F. Hill
B. D. Wilson
C. A. Bohrmann
E. E. Hanthorn
M. E. Harmon
EPPU File

March 2, 1955

A. P. Boston
Plant Services Unit
202-S, 200 West Area

101-SX TANK "AGITATOR"

Operation of the auger-type agitator in the 101-SX tank on February 17, 1955 resulted in a short-lived pressure surge measured at 35" H_2O with an instantaneous boiling rate of 8.5 gal/min.

In view of this reaction, we have been asked to operate the auger once each shift by giving it 25 turns. This may eliminate bumping or at least provide some measure of control over the severity of surges. Results from operation of the auger should be observed for approximately ten minutes and, if positive evidence is seen to indicate increased activity, operation of the agitator should be resumed until the tank pressure returns to zero gauge.

The time of auger operation should be recorded on the condensate flow recorder chart.

If the above recommendation meets with your approval, will you please put it into effect as soon as possible.

O. F. Beaulieu
Redox Process Engineering

OFB:ag

cc: MK Harmon
Letterbook
File (2)

RADIATION OCCURRENCE

TO:

M. I. Harmon

RADIATION OCCURRENCE FACTS

DATE	TIME
8-25-58	0900

LOCATION: 241-SX Tank Farm

TYPE OF RADIATION OCCURRENCE:

NO. 7 (b)

Spread of contamination from a radiation zone.

— ⇒ Dick - FYI Bill Powell

RECEIVED JUL 5 1989

COMPLETE DESCRIPTION:

During the week of August 18, temperature in the 114-SX tank gradually increased in spite of the fact that four air lifts were operating at 10 cubic feet each. On Friday, August 22, Redox Technology instructed the WH&DO to shut off the air and run 2 cubic feet per minute of water through each of the air lifts. Temperature in the 114-SX tank at this time was 357°.

Over the weekend the 114-SX tank "bumped" three times. Personnel from Redox increased water flow through the air lifts to 3 cubic feet per minute and valved the condensate water to reflux to 114. On August 25, shortly after 9:00 a.m., 114-SX tank bumped again and showed pressure to 71" of water. Steam was observed to escape from the risers of all the tanks in the immediate area. Two of the risers in the 113-SX tank pump pit were not sealed. A pump was installed in the 12" riser and a prototype air circulator in the 4" riser. Redox Technology was contacted concerning the high pressure and the decision was made to leave the condensate refluxing to the 114-SX tank and turn the air back on the air lifts at 10 cubic feet per minute. The bumps in the 114-SX tank forced contaminated vapors out of the 113-SX pump pit. Contamination was deposited on the ground around the 113-SX tank and was spread outside the tank farm by the high wind on the afternoon of August 25. Contamination inside the tank farm covered about 15,000 square feet and showed a maximum level of 5 rads/hour. An area of about 2 acres east of the tank farm was contaminated generally to 40,000 c/m with spots to 100 mrads/hour. This included a 200 foot stretch of Camden Avenue.

CAUSES:

It is believed that turning off the air to the air lifts in 114-SX tank could have reduced circulation in the tank and caused the tank to bump.

CC:

CT Groswith
JC Glover(2) ←
HF Coule

IMMEDIATE ACTION TAKEN BY RADIATION MONITORING:

Camden Avenue was roped off and posted as a radiation zone.

INVESTIGATED FOR R.M.O. BY	SUPERVISOR INVOLVED	DATE OF INVESTIGATION
J. C. Loud		8-29-58

EXPOSED EMPLOYEES:

NONE

A-5840-002 (2-58)

273

July 21, 1955

O. F. Beaulieu, Unit Head
Redox Process Engineering

241-SX OPERATION

10: PM

At @ 2200 on 7-14-55 the air lift became inoperative because of a failed gasket in the air compressor. The air compressor was repaired on 7-15-55 and operation of the air lift resumed at @ 1050 7-15-55. When the air lift was started, a "bump" occurred which increased the condensate flow from 0.8 gal/min to 17.2 gal/min almost instantaneously. The temperature of the primary condenser cooling water increased from 74°F to 148°F over a 20 minute period; the vapor header pressure increased to 3 inches and the vent header pressure to 3.3 inches. The duration of the "bump" was @ 70 minutes with heat evolution of 4,700,000 Btu/hr.

At @ 1900 on 7-16-55 the air valve to the air lift vibrated shut. The air was turned back on at @ 1330 on 7-17-55 and a "bump" occurred, (the air had been off @ 18 hrs.) which increased the condensate flow from 0.5 gal/min to 12.0 gal/min. One hour later the condensate flow, which had fallen to 3.6 gal/min again rose rapidly to 8.0 gal/min and leveled off at 5 gal/min for 3 hours; thereafter the condensate flow returned to normal. Heat evolution during this bump was at 3,000,000 Btu/hr. The air flow to the air lift was decreased from 13.15 CFM to 6-8 CFM on 7-19-55 in an attempt to decrease the aerosol problem.

It is apparent that "bumping" can occur when air circulation of the 104-SX is interrupted. Every effort should be made to insure uninterrupted operation of the air lift.

G. L. Hanson
G. L. Hanson
Process Engineer

GLH:ss

cc: AP Boston
EA Foskett
MK Harmon
RT Jessen
GL Hanson - File

PLANT OPERATIONS	OFF-NORMAL CONDITION / EVENT REPORT	
Department: Tank Farm Surveillance & Operations	Facility: 241-AZ Tank Farm	Work Area: 200 East
Report No.: 86-49	Initial ☒ Final ☐	Date: November 7, 1986 / Time: 0900 hours

Subject: Violation of Operating Specification Document (OSD-T-151-00017) Limiting Conditions for Airlift Circulator Operation

1. DESCRIPTION OF APPARENT CAUSE

☐ DESIGN ☐ MATERIAL ☒ PERSONNEL ☐ PROCEDURE ☐ OTHER

On November 5, 1986, at 0905 hours the airlift circulators were turned off to perform a routine operability test on the 4000 CFM portable backup exhauster and crane crew activities in the AZ-02-B sluice pit. Upon completing the routine operability test on the 4000 CFM portable backup exhauster, problems were encountered while attempting to restart the 702-A ventilation system. While attempting to correct the problem, the airlift circulators were inadvertantly allowed to exceed the fifteen hour maximum down time limit specified in the Operating Specification Document (OSD-T-151-00017). On November 6, 1986, at 0030 hours the airlift circulators were turned back on as specified under Operation Safety Requirements (OSR-11.3.2.4) recovery plan.

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2. OPERATING CONDITIONS OF THE FACILITY AT TIME OF EVENT/SITUATION

1. Routine operability test was being conducted on the 4000 CFM portable backup exhauster.
2. Flushing and alternating surface condensors.

3. IMMEDIATE EVALUATION, CORRECTIVE ACTION TAKEN AND RESULTS

1. Initiated recovery plan per OSR requirements.
2. Appropriate personnel were immediately notified.
3. Airlift circulators were turned back on at 0030 hours.

4. RECOMMENDATIONS AND CORRECTIVE ACTION TAKEN

1. All Tank Farm Processing Operations Managers will review and document Airlift Circulator Operation (OSD-T-151-00017) by 11/12/86. (Action F. E. Boyd)
2. Procedural changes will be made on all applicable standard operating procedures identifying the fifteen hour airlift circulator maximum downtime limit. (Action T. G. Hanson, ECD: 11/10/86)
3. Off-Normal to be reviewed by all Tank Farm Processing Operations personnel and documented by 11/14/86. (Action P. Hinojosa)

Is Further Evaluation Necessary? ☐ Yes ☒ No	If Yes, By Whom	When
Permanent Corrective Action To Be Implemented By:	Name P. Hinojosa	Date 11/15/86
Originated By D. R. Nunamaker	Title Shift Manager, A-Shift	Date 11-7-86
Reviewed By F. E. Boyd	Title Manager, TFPO	Date 11/7/86
W. H. Trott	Plant Manager, TFS&O	11/7/86
T. G. Hanson	Engineer, WMPE	11/7/86
G. L. Dunford	Manager, WMPE	11/7/86
P. Hinojosa	Manager, Days Processing	11-7-86

APPENDIX B: PAST AGING WASTE TANK OPERATION DOCUMENTATION

CG-539 ADDITIONAL WASTE STORAGE FOR REDOX
CHANGE OF SCOPE

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File (2)

Richland, Washington
December 23, 1954

O. H. Pilkey
Design Engineering
761 Building

CG-539 ADDITIONAL WASTE STORAGE FOR REDOX
CHANGE OF SCOPE

Summary: The scope of subject project is changed as follows:

1. The vapor manifold is to be increased in size to 24" pipe throughout.

2. A water seal and stack are to be mounted in place of the air condenser on tank 106.

3. An additional condenser building, substantially the same as the existing condenser building, is to be erected.

A meeting was held December 21, 1954, to determine the views of the various interested departments on a proposed change of scope for this project. Those present were:

B. D. Wilson	Manufacturing
K. R. Bidgway	"
E. T. Merrill	Separations Technology
C. A. Rohrmann	Process Engineering
M. W. Cook	"
H. E. Hanthorn	Projects

M. W. Cook presented computations, based on several possible assumptions, which indicated that surges may be expected in the operation of 241-SX tank farm with sustained (10-40 min.) rates ranging from a possible low value of 10,000 - 15,000 lb steam per hour to a possible high value in the range of 200,000 lb steam per hour. We are still ignorant of the actual mechanism of heat storage in the tanks which leads to the surges.

It was further pointed out that under the proposed method of operation of the farm with high energy wastes, all of this steam could be expected to be released from one tank. Thus the logic of a vapor manifold design with 14" branches feeding 24" headers is not apparent.

Design Engineering has computed that partial failure of a filled 241-SX design tank by cracking of the tank walls may be expected at a pressure of 5.2 psig and that catastrophic failure may occur at a pressure of approximately 16 psig. Mr. Cook's computations indicate that pressures close to this latter value may be expected with the release of steam at the rate of 100,000 lb/hr in a tank connected to a 14" branch of the vapor manifold.

E. T. Merrill questioned the assumptions and particularly the application of more than one scale-up factor to the magnitude of the surges. In his opinion, the increased rate of heat release will be manifest in increased frequency, rather than magnitude of the surges.

It was agreed to consider proposed solutions to the problem. Two alternatives were discussed, the first, to increase the size of the vapor manifold and branches to 24" throughout, and the second, to require operation of the farm in such manner as to divide the heat load among three tanks, until further data on surges in 101-SX tank become available. B. D. Wilson stated that the second course is unacceptable to Manufacturing.

Thus it is proposed, with the dissent of Separations Technology Section, to revise the design scope given you for the vapor manifold. This manifold will now be 24" pipe throughout including the entries to all tanks and all valving. It is recognized that this change will entail a delay of about three weeks in the design schedule because of the studies for flexibility which must be made. Manufacturing Dept. has agreed to accept this delay in the project schedule, with a beneficial use date of June 7, instead of May 15 as presently scheduled.

It was recognized that the existing bank of six condensers is inadequate for surges in the maximum range discussed. It was further recognized that the proposed addition of an identical bank might still be insufficient. In order to avoid any possibility of a pressure build-up in the system sufficient to rupture a tank, Process Engineering recommended provision of a safety water seal. This recommendation was accepted. The proposal of Design Engineering, that the seal be designed as a unit for installation on tank 106 in place of the air condenser, was adopted.

Proposals for increased condenser capacity were discussed. The following facts were adduced in support of a waiting period before a decision to install additional condensers:

1. The possibility, however remote, of a catastrophic failure of any 241-SX tank has been averted by the provision of the larger manifold and the safety seal. (Wastes to be stored in tanks 101-105 inclusive are considerably less energetic than those scheduled for 107-115, so no danger is anticipated from these tanks.)

2. Data presently available are insufficient to serve as a basis for rational design of condenser capacity.

3. Added condenser capacity cannot be provided in time to receive the first surges anticipated from 241-SX-101.

4. The only data presently available are from 241-S-101 having a steam emission rate of about 1000 lb/hr. Tank 241-SX-101 is believed to have a steam emission rate about three times as great. Comparison of surge data from these tanks should enable conclusions to be drawn as to whether surges will be larger in magnitude or more frequent in occurrence with greater heat release.

5. To date, no contamination has reached the condenser bank from tank 106, even though condensate is being collected at the rate of about 2000 gal/day. Thus the 106 tank appears to be an effective de-entrainment device. Some further de-entrainment by the water seal may be anticipated. It therefore appears that vapor blowing past the water seal would carry very little contamination.

For these reasons, the consensus of the group was to postpone action on the added condensers and to request Separations Technology and Manufacturing to obtain data from the initial surges in tank 106 in accordance with the following program.

Records of tank pressures and temperatures are to be obtained for three periods:

1. No operation of the "crust breaker". This period will continue until one or more surges have been observed.

2. Daily manual operation of the "crust breaker" at a specified hour for a specified period of time. This period will continue until a trend of surge intensity is observed.

3. Motorized operation of the "crust breaker". This period will continue until a trend of surge intensity is observed.

I am informed that by a management decision, subsequent to the meeting above, Design Section has decided to recommend the immediate addition of a bank of condensers. This decision has the concurrence of the Manufacturing representative at the meeting, but not that of the Process Engineering, Project, or Separations Technology representatives. It should be emphasized that the non-concurrence of the persons listed is solely on the timing and method of performing work for the condenser house. In our opinion, advantage should be taken of the opportunity for delay to accumulate further data. If these data indicate the need for additional condensers, they could be installed quickly by Minor Construction. A delay of no more than one month in completion date is involved.

By a management decision in Project Section, this recommendation is accepted. You are therefore requested to proceed to include the additional condensers installation in the bid package substantially as you now have it designed. Please continue to segregate this portion of the bid package as item 2 (item 1 being the vapor manifold system). In view of the fact that it will not be possible to complete the condenser installation before surges from tank 101-SX are observed, the possibility of a cancellation of some portion of this item should be allowed for.

A project proposal revision incorporating these changes is being prepared by this office.

H. E. Hanthorn
Project Engineer, Redox

HEH:de

Rex

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Rockwell Hanford Operations
Richland, WA 99352

TITLE AND AUTHOR

BOILING WASTE TANK FARM OPERATIONAL HISTORY

W.L. Godfrey and W.C. Schmidt

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BOILING WASTE TANK FARM SUMMARY

Tank No.	First Waste	Tank Pre-Heated	Pre-Heat Start	Liquid Heel Used	First Waste Rec'd From	Tank Failed	Inspected For Bulge	Bulge Present	Did Tank Boil on 1st Loading	Tank Started Boiling	Tank Emptied & Reused*	$NaNO_3$ Leached from Sludge
101-SX	19 May 54	No	-	No	Redox	No	No	-	Yes	Nov 54	No	No
102-SX	Sep 54	No	-	No	101-SX, Cascade	No	No	-	No	-	No	No
103-SX	Nov 54	No	-	No	102-SX, Cascade	No	No	-	No	-	No	No
104-SX	2 Feb 55	No	-	No	Redox	No	No	-	Yes	Jun 55	No	No
105-SX	11 May 55	No	-	No	104-SX, Cascade	No	No	-	No	-	Yes	No
106-SX	Jun 54	No	-	No	Tank Farm Condensate	No	No	-	No	-	-	-
107-SX	3 Mar 55	No	-	Yes	Redox	Yes, 1964	Yes	Yes	Yes	Jun 56	Yes	Yes
108-SX	8 Nov 55	No	-	No	Redox	Yes, 1962	Yes	Yes	Yes	Jun 56	Yes	Yes
109-SX	20 Sep 55	No	-	Yes	Redox	Yes, 1965	Yes	No	Yes	Dec 55	Yes	No
110-SX	Nov 60	Yes	Apr 60	No	Redox	-	No	-	No	Between 1/01-6/61	Yes	No
111-SX	9 Jan 56	No	-	No	Redox	-	No	-	Yes	Nov 56	Yes	No
112-SX	13 Feb 56	No	-	No	Redox	Yes, 1969	Yes	Yes	Yes	Mar 56	Yes	No
113-SX	20 Feb 58	No	-	No	Redox	Yes, 1958	Yes	Yes	Yes	Apr 58	No	No
114-SX	Nov 56	No	-	No	Redox	-	No	-	Yes	Jun 57	Yes	Yes
115-SX	4 Nov 59	Yes	Sep 58	Yes	Redox	Yes, 1965	No	-	Yes	Nov 59	No	Yes
101-A	20 Jan 56	No	-	6" H_2O	Purex	No	Yes	No	Yes	Jul 57	Yes	No
102-A	20 Mar 56	No	-	6" H_2O	Purex	No	No	-	Yes	Jul 58	Yes	No
103-A	15 May 56	No	-	6" H_2O	Purex	No	No	-	Yes	Jul 56	Yes	No
104-A	30 Jun 59	No	-	6" H_2O	Purex	No	Yes	No	Yes	Aug 59	Yes	No
105-A	31 Jan 63	Yes	Jan 63	Yes	Purex	Yes, 1963	Yes	Yes	No***	Mar 63	No	No
106-A	31 Dec 60**	Yes	23 Feb 61	Yes	Purex	No	No	-	Yes	Aug 61	Yes	No
101-AX	1 Jun 65**	Yes	23 Nov 66	Yes	TK-103-A and TK-112-B	No	No	-	No***	Dec 66	Yes	No
102-AX	30 Sep 65**	Yes	2 Mar 69	Yes	TK-101-AX and TK-103-A	No	No	-	No***	Apr 69	No	No
103-AX	10 Feb 65	Yes	Nov 64	Yes	Purex	No	No	-	Yes	Apr 65	No	No
104-AX	9 Sep 66	Yes	Jun 66	Yes	Purex	No	No	-	Yes	Oct 66	No	No

* Emptied indicates supernatant was pumped out but sludge remained.

** Tanks used for temporary waste storage prior to the receipt of IWW or HLW.

*** Did not boil until IWW was routed to the tank.

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Battelle
Pacific Northwest Laboratory
Richland, Washington 99352

DATE 7-8-55

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STORAGE OF HIGH ACTIVITY WASTES.

R. E. TOMLINSON

CONTRACT PROJECT NO.
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STORAGE OF HIGH ACTIVITY WASTES

By

R. E. Tomlinson

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July 8, 1955

Process Planning Unit
Separations Technology Section
ENGINEERING DEPARTMENT

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STORAGE OF HIGH ACTIVITY WASTES

INTRODUCTION

The fission of uranium in the Hanford piles releases large quantities of energy. While most of this energy is removed immediately as heat in the pile cooling water, a small fraction of the total energy of fission is released at an ever decreasing rate for hundreds of years. This slow energy release is in the form of beta and gamma emissions from the decay of fission products, and ultimately appears as heat as the beta and gamma emissions are absorbed in the mass containing and surrounding the fission products.

In the separations processes utilized at H.A.P.O., the fission products are separated from the products uranium and plutonium and are stored as a chemical "waste" for which there is no immediate use. Until recently, the processing rates and conditions were such that the stored wastes could dissipate the heat from radioactive decay to the ground without attaining a temperature high enough to boil the waste solutions. Recently, however, technological advances have been made which permit the attainment of higher levels of uranium irradiation in the piles, higher processing rates in the pile and separations facilities, and reduced volume of chemical waste per unit of uranium processed. These changes produce a higher rate of heat evolution per unit of chemical waste volume and, in August of 1952, caused some stored waste solution to boil for a few weeks. Subsequent to that time, other stored wastes have boiled, producing condensate at average rates up to 4 gal./min. It is currently predicted that an increasing percentage of the stored wastes will boil at still higher rates, potentially reaching 40 gal./min. condensate rates (the equivalent of up to 10% volume reduction per day) from individual tanks in the next two years.

The economic incentive of reducing the volume of the stored wastes through self concentration is recognized, and the more recent tank farms were designed to exploit this potential. The phenomenon of a million-gallon tank of radioactive solution slowly boiling from its own heat, however, is new in practice and little practical experience in this field exists upon which operating plans may be based. To provide a maximum assurance that present and planned waste storage practices and conditions are safe, a cooperative study was undertaken by the Engineering and Manufacturing Departments. These studies were conducted by E. F. Smith and M. W. Cook (Design Section) and R. E. Tomlinson (Separations Technology Section) of the Engineering Department, and O. F. Beaulieu and C. R. Anderson representing the Redox and Purex Sub-Sections of the Manufacturing Department, respectively. This document presents the results of these studies; it appraises current waste storage practices from engineering and operating viewpoints, evaluates the recognized hazards, and presents an operating plan which realizes maximum economy consistent with safe operational conditions.

SUMMARY AND CONCLUSIONS

The technology and procedures involved in the storage of self-heating aqueous slurries containing "waste" fission products was appraised and found to be sound. Within the operating restrictions described here, permitting the waste solutions to boil and self-concentrate is a safe procedure and offers economic advantages over any other known method of waste disposal. The self-concentration of wastes is currently being realized to a limited extent, and the further exploitation of this economic potential is confidently predicted.

The hazard of storing aqueous wastes in buried tanks lies in the potential released of fission products to the environs in such a form that irradiation of people could ensue. This potential release might be caused by 1) chemical corrosion, 2) chemical reaction, or 3) internal or external mechanical stress. Laboratory data, both at H.A.P.O. and other sites, show that neither chemical corrosion nor chemical reaction poses a safety hazard in the next several decades. Likewise, the threat of external mechanical stress, such as from earthquake or bomb detonation, was evaluated and factored into the design of the tanks. The point of principal concern at the present time is one of potential tank rupture through stresses created by the rapid evaporation of water by stored heat -- commonly called bumping.

As observed in the H.A.P.O. waste storage tanks, bumping takes the form of a series of five to twenty-five abrupt pressure surges, developing up to 1.8 lbs./sq. in. pressure in the tank and releasing up to 4,000,000 Btu. per series of surges. The bumping phenomenon is believed to result from the low rate of energy release within the boiling wastes. This low rate of heat evolution per unit of volume (or per unit of surface area) results in very low rates of convection within the liquid. This in turn allows the development of elevated temperatures in the liquid at the bottom of the tank, with resultant temperature gradients from bottom to top. In addition, the formation and deposition of precipitates concentrates some of the fission products, thereby increasing the rate of heat generation at the bottom of the tank. The unstable energy system which thus develops in the stored wastes can be disturbed by liquid movement or agitation, with the sudden release of stored heat in the form of steam.

Analysis has shown, however, that regardless of the amount of stored heat in the tank, any liquid layer at the base of the tank, if suddenly transported to the top, cannot produce a vapor pressure on flashing into steam that will exceed the hydrostatic head to which it was subjected prior to turnover. This fact, together with a knowledge of the allowable tank stress, permits the hazard of rupture-producing bumping to be completely eliminated by limiting the loading of each tank to a predetermined safe level. This safe loading, termed the "hydrostatic head limitation", is the 10 lbs./sq.in. stress limit of the tank dome. In order that this hydrostatic head limitation apply in the strictest sense, the entire contents of the tank must remain free-flowing. While some flocculent precipitates are present, their nature is such that they ~~can probably be~~ kept suspended by the operation of a gas-lift recirculator, ~~currently being demonstrated~~. The quantity of dense precipitates present in fresh wastes is so small that their presence does not significantly alter the heat storage phenomenon.

Based on the above considerations, it is planned to store wastes at both Redox and Purex in accordance with limitations listed below until such time as plant operating experience and development data demonstrate that these limits may be relaxed. Plant test programs as discussed later will require some deviation from these limits under carefully controlled "Production Test"-type conditions.

1. The hydrostatic head limitation will be observed in the storage of fresh extraction wastes. Observance of this precaution will result in filling extraction waste tanks only 1/3 to 2/3 full initially at both Redox and Purex.

2. Self-concentration will be permitted within the limitations of hydrostatic head as noted above. The crystallization of the bulk solids (sodium aluminate or sodium nitrate in Redox, sodium nitrate in Purex) at the boiling point will be avoided by water addition if necessary. Small amounts of hydrated oxides will precipitate but it is believed these can be mixed fairly well.

3. At Redox, coating wastes may be added to non-boiling tanks in excess of the hydrostatic head limitation if required by space considerations. When added to a boiling tank, the hydrostatic head limitation will be observed. At Purex, it is planned to store coating wastes separately in C Farm.

4. Recently devised gas-lift recirculators of the type which are proving successful in preventing bumping in 104-SX will be installed in each tank (Redox and Purex) to provide further safety factor under conditions of self-concentration. Failure of the recirculators cannot result in an unsafe condition so long as the hydrostatic head limitation is being observed.

While the above 4-point operating plan is one that is assuredly safe, there is considerable evidence accumulated to date that such limits may be relaxed and further economic gain realized through greater tank utilization. This evidence also supports the fact that the proposed plant test program itself can be conducted under conditions that can be considered safe. Notable items in this evidence are as follows:

1. The almost insignificant agitation supplied by the mechanical auger in Tank 101-SX has been sufficient to minimize, if not prevent, bumping.

2. The initial operation of the gas-lift recirculator in 104-SX removed about 5.5 million Btu. of stored heat and has, subsequently, prevented bumping and the development of a top-to-bottom temperature gradient. Other tanks not so equipped have developed a temperature gradient.

3. The maximum bump thus far observed has been less than 2 lbs./sq.in. compared with the 10 lbs./sq.in. dome limitation which is controlling when a tank is loaded to safe conditions.

4. Based on tank bottom temperatures, no bump has ever removed all the stored heat present.

Based on these observations, an in-plant development program will be conducted under "Production Test" conditions with a two-fold objective:

1. The feasibility of utilizing agitation to prevent bumping will be more firmly established in tanks where the hydrostatic head limit may be exceeded.

2. The bumping characteristics of stored wastes will be developed over appropriate ranges of evaporation rates and salt concentrations within the hydrostatic head limitation.

During the execution of this test program, supporting development work will continue on laboratory and semi-works scales. While this program has a long-range objective of developing an alternate disposal method which is simultaneously cheaper and more permanent than present methods, the primary effort has been placed on the definition of safe operating conditions for the immediate future. For example, a fail-safe type of recirculation equipment will be developed. A program to understand better the limits imposed by the presence of solids will also be undertaken. In the Hot Semiworks, an experimental tank is being filled with Purex wastes to study their characteristics during self-concentration. This study is expected to pilot the operation of the Purex waste farm. In addition to the above, the Design Section plans to study the design requirements for new tanks which would permit maximum tank economy while remaining completely safe from a stress-rupture standpoint.

DISCUSSION

A. The Characteristics of Stored Chemical Wastes

1. Chemical Composition

The chemical wastes from the Redox and Purex separations facilities are essentially alkaline solutions of sodium aluminate ($NaAlO_2$) and sodium nitrate ($NaNO_3$) with small quantities of insoluble salts of uranium, iron, chromium, and aluminum. Redox wastes currently contain manganese also, but process changes are planned which will eliminate this ion. The volumes and compositions of the wastes vary, depending on the processing conditions which produced them. Typical waste volumes and compositions are given in Table I for the processes currently in use or scheduled for the near future. The "metal wastes" from the $BiPO_4$ process are also included, although this process is to be abandoned and the metal wastes recovered in the near future so the storage of these wastes constitutes no future problem.

The quantity of precipitated salts in the stored waste is variable, depending on the process which produced them and the temperature of storage. In the $BiPO_4$ metal wastes, uranium forms a bulky precipitate, the solubility of which is decreased by an increase of temperature. In the Redox and Purex wastes, uranium forms a dense precipitate which occupies little volume and is probably fast-settling. Iron, and chromium ~~in the Redox wastes~~ form flocculent, slow-settling precipitates which carry up to half of the radioactivity by adsorption. These precipitates may be ~~predicted to form an easily churned "sludge" layer of indeterminate depth near the base of the storage tanks~~, and most of the heat is evolved in the vicinity of these precipitates. While the sodium aluminate in Redox wastes is very soluble at high temperatures, the salt slowly decomposes into sodium hydroxide and a hydrated aluminum oxide of indefinite composition. Once precipitated, this gelatinous oxide is slowly dehydrated to form a dense, granular material which is insoluble in acid or alkali. This action produces a sludge layer which slowly grows in density and depth with time; the action is largely beyond operator control although laboratory data indicate that the rate of precipitation is slower at elevated temperatures. It is expected that on the order of a foot or less of dense precipitate will be formed in the first few years of storage.

2. Heat Generation

The decay of the fission products associated with the chemical wastes produces heat at a rate determined by the extent and intensity of the irradiation of uranium in the pile and by the length of time the fission products have "cooled" since pile discharge, as indicated in Table I. During the time that the chemical wastes from a separations plant are added to a given tank, the rate of heat generation in that tank increases, depending on the rate of uranium processing and its irradiation and cooling history. When the addition of fission products to the tank ceases, the rate of heat generation starts decreasing as the fission products decay. During the first year of utilization of a given tank for waste storage, the rate of heat generation is governed by the decay of fission products with a short half-life; e.g., 60 days or less, and the heat generation rate changes quite rapidly; within a few years after the last addition of fission products, however, the rate of heat generation has fallen to a small fraction of the peak rate and further decreases are gradual, as controlled by the longer-lived fission products.

The calculated heat generation rates are presented graphically in Figures 1, 2, and 3 for three operating conditions which bracket the anticipated range of operating conditions at H.A.P.O., on the assumption that the waste tanks will be filled and possibly self-concentrated without interruption.* It will be noted that little self-concentration appears possible (see Heat Dissipation, below) under the conditions of the limited irradiation depicted in Figure 1. In the cases of higher irradiation, however, more heat is available than would be required to evaporate the solutions to dryness.

3. Heat Dissipation

The heat generated in the stored wastes is absorbed in the containing media (waste solution, tank, and surrounding soil) until a temperature gradient has been established in the soil in steady-state with the waste temperature and the earth. This steady-state heat flow requires up to two years to attain, at which time approximately 4 billion Btu. has been absorbed in the solution, tank, and surrounding soil and approximately 250,000 to 500,000 Btu./hr. of heat is being lost to the soil. These rates of heat loss to the soil were calculated from the performance of boiling waste solutions in existing tank farms, and no doubt vary somewhat with time and from tank to tank. Any heat generated above that lost to the ground is utilized to evaporate water which escapes from the tank as water vapor. The recently constructed tank farms (S, SX, A, and SY, being designed) are designed to conduct this vapor to a condenser facility, thereby effecting self-concentration unless water is returned to the tank.

4. Boiling Characteristics

Prior to August of 1952, the heat generated in the buried waste storage tanks was dissipated to the ground without creating a boiling temperature in any tank. At that time, the operating conditions were such that Tank 110-S attained a boiling temperature and the heat-exchange capacity of the air-cooled reflux condenser was exceeded. Water was sprayed on the air condenser and provided sufficient heat exchange capacity to contain the vapors. This condition existed for a few weeks and subsided. In February of 1953, the contents of Tank 107-S started boiling at such a rate that the water-sprayed air condenser was inadequate and a water jacket was installed on the air condenser. This expedient proved adequate and boiling subsided after a few months. In both cases, the water evaporation rates were low (although not measured) and in neither case was any contamination spread observed.

In July, 1953, Tank 104-S was filled and its contents started boiling at a rate which exceeded the heat exchange capacity of the water-jacketed air condenser. In August, 1953, an auxiliary water-cooled condenser was installed on Tanks 104-S and 101-S (the next tank predicted to reach a boiling temperature). While the additional condenser proved to have sufficient capacity to condense the vapors at the average rate of formation, a growing contamination was observed at the new condenser. Subsequent investigations revealed occasional changes of evaporation rates and contamination in the condensate. Characteristically, the nominal "average" rate of condensate flow would fall from about

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* For a more fundamental treatment of this subject, see HW-31000, Chapters II and X.[1]

1.3 gal./min. to zero on the addition of fresh waste to the tank (the additions were a slurry of precipitated manganese salts from the Redox head-end scavenging step). A few hours later the rate of condensate flow would rise abruptly to the range of 5 to 7 gal./min. and the radioactivity of the condensate would rise by a factor of about 200. Over the next few hours, the rate of condensate flow would fall off gradually to the average flow rate, and the radioactivity content would fall exponentially to its normal low level. The subsequent operation of Tank 101-S revealed the same type of phenomenon, although the mild eruptions were found to be initiated also by a disturbance of the sludge layer and, in some cases, by no observed external cause. In January, 1954, a different type of eruption was first observed in 101-S. This type of eruption, called "bumping", is now believed to have been responsible for the contamination spread from 101 and 104-S, and took the form of a series of five to twenty-five abrupt pressure surges at about 100-second intervals. In both cases, the initiation of this phenomenon was coincidental with the attainment of above 240°F. temperatures (the limit of the recorder) at the bottom of the tank. While these eruptions were mild, in that instantaneous vapor pressures within the tanks were never observed to exceed forty-five inches of water pressure, some radioactive materials were ejected from the tank and contaminated the area. Tanks 104-S and 101-S were boiled down to approximately half-volume and refilled. They continued to boil and erupt periodically for eight months, then subsided to a gentle simmer, and have nearly stopped producing condensate.

In the spring of 1954, Redox wastes were routed to U Farm Tanks 110, 111, and 112 through 110. Tank 110-U contained a 5-foot layer of concentrate from the operation of the $BiPO_4$ first-cycle waste concentrator before adding the Redox wastes. After these tanks were filled, Tank 110-U evaporated water uniformly for twelve months, effecting a volume reduction of 55%, based on the Redox wastes in that tank. No evidence of non-uniform boiling rates or contamination spread was observed during this period.

From May, 1954 to February, 1955, Redox wastes (except coating wastes) were routed to, and nearly filled, the 101-102-103SX cascade through Tank 101-SX. In October, 1954, Tank 101-SX reached a boiling temperature, at which time Tank 102-SX was being filled through 101-SX. In November, 1954, the Redox process was modified to include a single-stage backcycle and reuse of wastes, thereby reducing the volume of stored wastes per ton of uranium processed by about 30%. Measurable condensate flow was first observed in December, 1954, at which time the same type of non-uniform boiling experienced in the S Farm was observed. During December and January, the "normal" condensate flow rate was 2 to 3 gal./min., falling to zero upon the addition of fresh waste and rising abruptly to a peak rate up to 8 gal./min. five or six hours later and subsiding to the "normal" rate during the next few hours. During a three-week period in January, no fresh wastes were added to the tank and the boiling rate was uniform during this period.

In February, 1955, bumping was observed in 101-SX.(2) As observed here, bumping consisted of a series of five to twenty-five abrupt pressure surges at intervals of about 30 seconds, the maximum pressures of twenty to fifty inches of water apparently being developed in one to twelve seconds during each surge. Instantaneous condensate flow rates up to eighteen times the "normal" condensate flow rates were observed during periods of bumping.

These pressure surges occurred about once per day when self-initiated, but could be initiated two to three times daily by manually turning a specially built auger installed in the tank. During a two-month period of self-evaporation with no additions of waste, the intensity of pressure surges increased from about 20 to 50 inches of water, and the energy release per series increased from about 400,000 to 4,000,000 Btu. as the liquid level was reduced by evaporation from 30 feet to about 25 feet in the tank. After about six weeks of intermittent bumping, the auger was motorized and operated continuously. No bumping occurred during two and three-week intervals of auger operation, although bumping did recur after two weeks of continuous agitation, and later when the auger was not operated. In an effort to prevent bumping, a gas-lift recirculation device was installed in Tank 104-SX in June, 1955, at which time the tank was boiling but had produced no bumps. When the gas-lift was activated, the rate of condensate flow increased from 3 to 7 gal./min., returning to normal in about six hours. About 5.5 million Btu. of stored heat was removed, and the temperature differential from top to bottom of the tank fell from about 4° to 0°F.

Bumping is theorized to result from the alternate gradual storage of sensible heat in the waste solution under high hydrostatic head deep in the tank, followed by the rapid release of this heat as a current raises the hot solution to a point of lower pressure, thereby permitting the solution to boil. Such an upflow of solution might be caused by any disturbance of a dense sludge layer which would suddenly expose a surface with a higher temperature than the general area, a random eddy current which would elevate some waste solution (and possibly some flocculent precipitates) to a point where it would boil under the reduced pressure, or a mechanical turbulence (auger operation) which would effect the same result. Whatever the cause, the energy release would tend to be self-perpetuating since the local release of vapors below the surface would decrease the apparent weight of the column of liquid containing the gas and the mixture would then be displaced upward by the heavier liquid surrounding it. This upward displacement would cause additional boiling of solution, thereby accelerating the upward current and vapor release. The accelerating flow of water vapor from the tank would create an increasing pressure drop in the vapor header and condenser, thereby increasing the pressure at all points within the tank. Assuming the rate of pressure rise within the tank exceeds the rate of pressure decrease on the upflowing liquid, then a pressure might be reached at which vapor formation would cease and the liquid upflow would decelerate. The rate of vapor flow from the tank would then exceed the rate of vapor formation and the pressure within the tank would fall. As the tank returns toward ambient pressures, however, some of the liquid which has been displaced upwards might again start to vaporize (after a certain degree of super-heat had been established), and the entire cycle could be repeated. These cycles of self-quenching pressure surges could recur until the rising liquid no longer vaporizes sufficiently under the reducing pressure to continue the gas-lift which is propagated by the upflow of liquid.

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5. Gas Evolution

Water is decomposed by irradiation to the extent that a molecule is broken down into elemental hydrogen and oxygen for every 200 electron volts of absorbed energy.(3) This indicates that approximately 40 standard cubic feet per hour (scfh) of hydrogen and 20 scfh of oxygen is released for each million Btu./hr. of heat energy released. This rate of hydrogen evolution is highly suspect, however, in that it is computed from laboratory data based on irradiation from cobalt-60 with a 1.33 Mev gamma. The existence of a threshold energy below which water decomposition does not occur is probable, and represents a degree of conservatism not factored into this calculation. Samples of air removed from Tank 101-T containing $BiPO_4$ metal waste generating on the order of 200,000 Btu./hr. at about 160°F. analyzed less than 0.1% hydrogen on a water-free basis. Sodium nitrate is also decomposed into oxygen and sodium nitrite by irradiation.(4) The implications of this gas release are discussed later.

B. Alternate Methods of Waste Disposal

Several proposals for alternate methods of waste disposal have been made, but a simple method which combines operating economy with permanent disposal has yet to be developed. Some of these alternate methods are discussed briefly below.

1. Semipermanent Storage as Aqueous Salt Solutions

The method of waste disposal so far employed at H.A.P.O. has as its object the semipermanent storage of the long-lived fission products in buried tanks. The short-lived fission products are also stored but decay to innocuous concentrations in a few years. The advancing technology of irradiation and chemical separations has resulted in the storage of fission products at ever-increasing concentrations and rates. These increases have resulted in increasing heat generation rates such that current wastes boil themselves, and future wastes are predicted to self-boil for many years. This heat generation may be utilized to remove water from the stored wastes, thereby effecting a two to five-fold reduction in the volume to be stored. Whether or not this economic advantage is taken, the facilities must be provided and operated to remove the heat. Alternate methods of heat removal are discussed below.

During the self-concentration of wastes, the stored wastes are permitted to self-boil, and water is removed (and cribbed) until the supernatant solution approaches saturation with respect to the bulk salt present (sodium aluminate and/or sodium nitrate). Water is added as required to prevent over-concentration, and additional waste from any source desired is added until the desired quantity of waste has been stored in that vessel. A concentration factor of two is readily obtainable for Redox wastes, and factor of five for Purex wastes excluding coating wastes. These available concentration factors are variable, depending on the actual processing conditions employed in the production plant. After the rate of heat generation falls to a value less than that which can be dissipated to the ground, the solution stops boiling and the temperature of the stored waste gradually declines. The bulk salts then partially crystallize, increasing the fraction of solid phase present as the temperature falls. In fifty years, such a tank could contain up to 60 to 70 per cent precipitated solids, thereby limiting sharply the volume of wastes which could be drained to the soil if the tank should spring a leak.

The prevention of boiling within storage tanks by the operation of cooling coils is a feasible though expensive operation, and the inclusion of cooling coils in the H.A.P.O. storage tanks was rejected as an unnecessary expense. For example, a storage tank for Purex wastes would require on the order of 20,000 feet of 2-inch pipe (possibly arranged as vertical pipes on 40-inch triangular centers) for heat exchange surface to be cooled by a peak water flow in excess of 300 gal./min. Suitable precautions would also have to be provided against the possibility of loss of cooling water supply or a leak in the cooling coils. For this additional expense, no advantage is gained provided the tank contents can safely be permitted to boil. Since no undue hazards were predicted in permitting wastes to boil themselves, the tanks were designed on this basis.

Another potential method of preventing boiling in a waste storage tank embraces the limitation of the quantity of fission products placed in a given tank, or the rate at which they are added. For example, on the assumption that 500,000 Btu./hr. is lost from a given buried tank, then the wastes from a Purex plant processing 5 MW/T uranium at 20 tons per day could be placed in that tank for eight to ten days before the heat generating capacity of the stored wastes would equal the capacity of the tank and soil to dissipate the heat. At 410 gallons of waste per ton, this waste would form a pool two to three-feet deep. These same fission products, however, stored at 3900 gallons per ton as $BiPO_4$ metal waste, would more than fill one of the 500,000-gallon tanks of the old tank farms. Assuming these Purex wastes were diverted to successive tanks, filling each tank to this degree and then permitting to cool until another increment of waste could be added without causing boiling, then a minimum of sixty tanks would be required to be in various stages of filling simultaneously. All of these tanks would constantly be at near-boiling temperatures, and each day's waste would be routed to a different tank to prevent boiling. Similarly, a Redox plant processing daily 10 tons uranium irradiated to 5 MW/T would require thirty tanks in simultaneous operation. Should the more realistic heat dissipation rate of 250,000 Btu./hr. per tank be assumed, then Purex would require 120 tanks and Redox would require 60 tanks in simultaneous operation.

An independent study(5) of the storage problem resulted in the proposal that the wastes be stored in large pits lined with an impervious material (possibly asphaltic), filled with coarse gravel or rubble, and topped with a graded sand covering. In this proposal, the storage facility would be operated essentially as the self-concentrating tanks above, except that the water vapors would be dissipated through the sand cover to the atmosphere rather than being condensed and routed to the ground. While this type of facility could probably be constructed for perhaps 10 to 15¢ per gallon of storage space, the long-term integrity of known impervious materials in the temperature range of 50° to 350°F. observed in storage tanks is less certain than that of a concrete-jacketed steel tank, and the concept of an area discharging water vapor and potentially entrained radioactivity to the atmosphere in the vicinity of operating plants would require considerable development demonstration prior to adoption.

2. Semipermanent Storage as Solids

Development personnel at other sites have proposed methods of stabilizing the aqueous wastes in a solid form before disposal. In one method, following storage as solution a few years, a calciner would dry and possibly calcine the salts present and discharge them directly to a buried tank similar to those currently in use at H.A.P.O. At K.A.P.L., development work on this approach was discontinued in 1952 because of numerous troubles encountered with the dryers, the lack of any appreciable reduction of volume of the concentrated evaporator slurry by drum drying, and the additional expense.(6) The cost of drying (exclusive of the cost of evaporation or storage of solids), based on processing 3,000,000 gallons of raw waste per year, is estimated at 4 cents/gallon of raw waste. Development work is proceeding at Brookhaven National Laboratory(7)(8)(9) on a calciner designed to produce a melt of $NaNO_3$ above its melting point of 585°F. Development work to date has been directed toward establishing the operating characteristics of the equipment with "cold" feeds. No data on the radiation and thermal stability of the stored melt have yet been published.

In another method, the wastes would be stored a few years to minimize the heat dissipation and radiation problems, then they would be dried and incorporated in concrete blocks(10) for burial in a desert or at sea.

3. Chemical Removal of Fission Products

A potential operating technique which would obviate the storage of self-heating wastes involves the chemical removal of most of the fission products for disposal elsewhere and the discharge of residual wastes to the ground, possibly after an interim storage period to permit additional decay. This technique may prove attractive if a market develops for irradiation sources, whereby the responsibility for future containment of the fission products may be transferred to another organization. This approach will receive further study by technical organizations. Another alternative lies in the chemical concentration of the fission products into a much reduced volume for storage in smaller vessels especially designed for the removal of heat from a relatively intense source for an extended period of time, e.g., 20 to 100 years. A cursory review of this approach indicates that the smaller, more complicated storage tanks required would probably not save enough in capital investment to offset the amortization and operational costs of the fission-product concentration facility.

C. Evaluation of Potential Hazards

The hazard of storing aqueous wastes in buried tanks lies in the potential release of fission products to the environs in such a form that irradiation of people could ensue. In the more serious case, a tank might be ruptured by internal or external cause, releasing the tank contents to the ground and potentially contaminating the subterranean waters, or the tank dome might be lifted from the tank and collapse the dome and overburden into the tank. In the less serious case, a portion of the tank's contents might be ejected from the tank as foam or mists and spread over the surface of the ground. While the latter mechanism could cause serious operating problems, it is believed that any contamination spread by this mechanism, which did not rupture the tank, would probably be confined to the Hanford reservation and could be contained without undue personnel hazard. Specific

design features to minimize this type of contamination spread include knock-out tanks and filters to remove any entrained materials from the vapors escaping the tank. These precautions are believed adequate to protect the environs from contamination by particulate matter, and the subsequent discussion will deal primarily with an evaluation of the tank integrity.

The storage tanks currently available for the storage of radioactive aqueous wastes at H.A.P.O. are reinforced concrete structures with mild steel liners. These 75-ft.-diameter tanks were constructed in a series of "farms", with the tanks in each farm of similar design but differing somewhat from farm to farm as indicated in Table II. The potential causes of tank failure are: external - bomb or earthquake damage; or internal - corrosion, mechanical stress, or chemical reaction.

1. External Hazards

External forces which might cause the failure of a storage vessel include earthquake and bomb detonation. The vessels were designed in accordance with the Uniform Building Code for utilization in a Class II earthquake zone.(11) While no effort was made to make the vessels bomb-proof, they are buried under seven or more feet of earth and a direct hit would probably be required to jeopardize the tank structure. The risk so taken was considered justified to reduce the capital investment involved.

2. Corrosion

The probability of a tank failure by corrosion in the next century is very small. Laboratory data indicate that corrosion rates of the order of 5×10^{-5} inches per month are experienced with mild steel in contact with concentrated Purex waste systems at temperatures up to 250°F., and the increase of corrosion rates with increasing temperature indicates still higher temperatures are permissible from a corrosion viewpoint.(12)(13) A cursory examination of the tank liners in which $BiPO_4$ metal waste was stored for ten years revealed that the primer coat of paint was still intact on the mild steel in many cases. The point of worst corrosion was observed over a band about four inches wide at the liquid-air interface.(14) These data predict that a submerged tank liner will probably remain intact more than 200 years. The portion of tank liner in contact with condensing vapors corrodes up to ten time more rapidly than the submerged portion,(12) and that portion of the liner above liquid level may be predicted to fail much sooner. In the event that a tank should spring a leak to the soil, the leak could be detected by an active program of liquid-level measurement or by radiation monitoring wells in the proximity, and the bulk of the tank contents could be pumped to another tank. If the leak were detected in time, the liquid which thus escaped the tank would be held in the soil below the tank on a "specific retention"* basis.

3. Mechanical Stress

The ability of a given tank to withstand hydrostatic head and transient gas pressure surges (bumping) is limited by the structural strength of the reinforcing steel in the tank walls resisting rupture of the walls, and by the resistance of the dome and soil above the tank to the lifting of the tank dome off the walls. The limitations for each different tank design have been calculated by the Design Engineering Sub-Section(11) on two bases.

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* The soil beneath the waste tanks is dry and will retain on the order of 100 to 150 gallons per square foot of cross section by capillarity before a percolating liquid reaches the ground water.

In the first case, the reinforcing steel was assumed capable of withstanding a tensile stress of 20,000 lbs./sq.in. for long-term liquid pressures. This stress is about 45% greater than that employed in normal design calculations; it is justified on two bases. First, it is recognized practice in certain structural fields to assume higher unit stresses in rating the capacity of existing structures. Second, coupled with the above item is the real, though indeterminate, effect of external soil pressure. Its use to resist internal pressure is not good practice; nevertheless, it exists to some degree except, perhaps, after a tank has been expanded by elevated temperatures and is shrinking away from the earth while cooling. In view of the above items, it is felt that the increased allowable stress is reasonably safe for long-term loads from the liquid within the tank.

In the second case, a stress of 27,000 lbs./sq.in. was assumed permissible for short-term loads such as those encountered during the bumping action which accompanies the boiling of stored wastes. This stress assumption is analogous to that employed in the standard evaluation of a structure's resistance to transient pressures such as wind loads or earthquake and is recognized by all building codes, including the Uniform Building Code to which Hanford designs conform. Since this is very close to the approximately 30,000 lbs./sq.in. yield point of the steel, it might be argued that this will open many cracks in the tank wall. The actual stresses encountered are less than calculated, as part of the forces causing stress are offset by the external soil pressure. This is particularly true because when bumping takes place the tank has undergone thermal expansion and is pressing against the surrounding soil. The net result is a stress which is believed reasonable for temporary loading conditions.

In the tables below, the maximum permissible liquid loadings and transient gaseous pressures are presented as limited by the structural strength of the tank wall. Since the most vulnerable point in the tank wall is a small distance up from the base-to-side junction in each case, interpolation between the values quoted should not be attempted without a detailed study.

Permissible Liquid Loading
and Transient Pressures in Waste Tanks

Basis: Tank filled with solution having indicated specific gravity. Vulnerable point is steel in tank wall.

Tank Farms	Sp.Gr.	Simultaneous Vapor Pressure, Lbs./Sq.In.
T, U, B, C, BX	1.9	2.5
S, BY, TX, TY	1.2	1.8
SX	1.5	4.8
A	2.2	6.9

Permissible Depth of Solution
with Sp.Gr. of 2.2

Farm	Feet of Liquid	Simultaneous Vapor Pressure, Psig.
T, U, B, C, BX	15	3.0
S, BY, TX, TY	16.5	3.0
SX	21.5	5.5

By loading a given tank to a lower hydrostatic head (by reduced liquid level or specific gravity), a correspondingly greater pressure may be tolerated up to a limit of 10 lbs./sq.in., at which pressure the tank dome is jeopardized. These stress relationships are presented graphically in Figure 4.

The hydrostatic head and transient gas pressures actually developed within a tank can be held to safe levels. Hydrostatic head is controlled by the degree of filling and self-concentration permitted and is entirely under operational control. Transient gas pressures can be limited either by preventing the accumulation of heat which energizes the bumps, or by controlling conditions such that the maximum possible bump cannot exceed the safe operating limits of the tank.

The accumulation of heat in a simmering liquid pool is minimized by agitation (either convection or mechanical) and is augmented by any mechanism (such as a dense or flocculent layer of solids) which interferes with free liquid movement. The rate of energy release determines the maximum pressure developed in a given system and is controlled by the rate of liquid displacement during transient conditions. These relationships cannot yet be defined in mathematical terms, more information being required before the intensity, magnitude, or frequency of bumps can be predicted for operating conditions beyond those already experienced.

The maximum pressure which can potentially be developed in a given fluid system can be computed with certainty. The vapor pressure, above atmospheric, which can be produced by a layer of liquid is no greater than the hydrostatic head which exists on that liquid since at this point the solution would boil in its present position. This means, then, that regardless of the quantity of heat stored in a given system, and regardless of the peak rate of transient liquid movement in that system, a vapor pressure cannot be produced above the liquid which exceeds the hydrostatic head existing at the base of the tank. This "hydrostatic head limitation" may be utilized to assure that with any fluid system under any condition of heat generation rate or turbulence the safe working conditions of the tank will not be exceeded. These assured safe working limits are noted below for tanks to be utilized for the storage of boiling wastes and are based on a maximum permissible pressure of 10 lbs./sq.in. in the vapor space above the liquid.

Working Depth of SX or A Farm Tanks vs. Specific Gravity of Stored Solution for Assured Safe Storage

Sp.Gr.	Guaranteed Safe Depth of Solution
1.0	23 ft.
1.1	21
1.3	17.5
1.5	15.3
1.7	13.5
1.8	12.7

It should be noted that the above storage conditions do not rely on agitation to minimize heat storage but do assume that solids will either remain relatively fluid as a flocculent precipitate or remain static as a thin layer of dense solids on the bottom of the tank. The known characteristics of the small mass of solids present in the storage tanks are such that the conditions noted above are predicted. As the mechanisms controlling the magnitude, intensity, and frequency of the bumps in unagitated boiling systems become better understood, the assured safe limits noted above may well be increased.

4. Chemical Reactions

Three types of potentially hazardous chemical reactions can be postulated for the stored wastes. These reactions include: (a) the autocatalytic uranium-nitrate-organic reaction associated with "red oil" potentially present in Purex wastes, (b) the high temperature combustion of organic materials in the presence of decomposing nitrate salts, and (c) the simple combustion of hydrogen or solvent with oxygen from the air or the decomposition of water or sodium nitrate.

a. Autocatalytic reactions

The potential for the uranium-nitrate-organic reaction in alkaline systems has been determined to be negligible by investigations at the Savannah River site.(15) No evidence of such a reaction was found in neutral or alkaline systems simulating Purex wastes when evaporated at atmospheric pressure to a temperature of 285°F. and then heated in a closed vessel to 390°F.

b. Nitrate instability

The potential for nitrate-organic combustion under stored waste conditions is considered small since the temperatures required to decompose nitrates are not likely to be encountered. Combustion of this type is initiated at temperatures about 500°F. or higher(16) as compared with a maximum temperature of about 350°F. observed to date (at the bottom of Tank 101-SX). The quantity of organic materials in Redox stored wastes is negligible since the solvent is steam stripped from the wastes during the concentration step in the Redox Plant. While appreciable quantities of Purex solvent will be present in the Purex wastes routed to the farm, virtually all of the diluent and a large fraction of the TBP will be

removed by steam distillation while boiling, and the remaining quantities of organic material will be either accumulated as a separate layer at the top of the mass at a relatively low temperature or diffused through the mass in very low concentrations. In either case, a nitrate-organic reaction is very improbable. While this hazard should be constantly evaluated in the formulation of operating plans, the potential hazard under planned operating conditions is considered negligible.

c. Simple combustion

The combustion of solvent above stored waste is considered unlikely. The Redox solvent is kept from entering the storage tanks by the normal waste concentration procedures, and the Purex solvent has a flashpoint so high that the water vaporized at this temperature will have displaced over half of the oxygen in the atmosphere. Combustion under these conditions is very unlikely.

The evolution of hydrogen and oxygen by the decomposition of water creates a potential hazard of hydrogen combustion during those times that the vapor pressure of water over the stored wastes is insufficient to establish an effective inert blanket. The presence of less than 0.1% hydrogen in the Tank 101-T atmosphere at about 160°F., however, reveals that this hazard is not serious. The greater than forty-fold increase of hydrogen concentration required to approach the lower explosive limit is much greater than the two-fold increase of heat release required to boil the solution, and, hence, the system is safe from hydrogen combustion.

The production of oxygen by radiation decomposition of sodium nitrate is of negligible concern. In an aqueous solution of sodium nitrate, an equilibrium always exists between sodium nitrate and its decomposition products oxygen and sodium nitrite. While irradiation no doubt increases the rate of chemical decomposition of sodium nitrate, the increased concentration of sodium nitrite and oxygen serves to increase the rate of recombination to form sodium nitrate. Thus, while it is theoretically possible to produce oxygen by this mechanism in aqueous solutions, the net increase of oxygen production is negligible.

D. Evaluation of Current Conditions

Three conditions have existed which exceed the assured safe operating conditions noted above. On the basis of the current stress calculations, Tanks 101 and 104-S were unknowingly loaded to a higher hydrostatic head than is recommended under the operating conditions employed. The current status of these tanks has been appraised by Technical and Design personnel and is believed to be satisfactory.(11a Tanks 101 and 104-SX were filled and are being permitted to boil with a hydrostatic head exceeding the 10 lbs./sq.in. pressure (at the base of the tank) assured to be safe under any condition of agitation. In the incremental approach to our current position, however, these tanks have at no time approached within 0.15 specific gravity units or 4.5 lbs./sq.in. simultaneous vapor pressure of the allowable simultaneous loadings presented. In addition, the agitation being supplied is now preventing bumping. On the basis of the data at hand, no reason is now seen to reduce the liquid level of these tanks below current levels. In the light of current data, the S and U Farm tanks were permitted to boil without adequate emergency pressure relief in event of condenser failure. The SX and A Farms are adequately protected, and the S and U Farm tanks have virtually stopped boiling without incident.

E. Operating Plan

It is the intention of Engineering and Manufacturing personnel to develop and utilize operational procedures which will exploit the economic potential of the self-concentration of stored wastes while maintaining a maximum degree of assurance that the radioactive fission products will be safely retained within the control of H.A.P.O. personnel. To this end, the storage conditions will generally be controlled such that the maximum possible bump would not endanger the integrity of any storage tank. Exceptions to this condition will be made only under carefully controlled experimental conditions. No tank will be permitted to boil without adequate emergency pressure relief facilities.

1. Redox

Storage facilities available on June 30, 1955 for the storage of Redox wastes, based on single-stage backcycle of wastes are as follows:

Cascade	Volume Available, Gals.	Equivalent Tons of Coating Waste		Equivalent Tons of Extraction Waste
110-U	220,000	880		
101-S	30,000	120		
104-S	260,000	1040		
101-SX	540,000	2080	or	300
104-SX	700,000*			390

* Includes 300,000 made available by self-concentration: two months at about 4 gal./min. condensate removal.

About September 1, 1955, Tanks 107 through 115-SX will be completed and available for use. Until that time, the utilization of storage space will be essentially as indicated in the above table. Solvent extraction wastes will go first to 104-105SX then to 101-SX if necessary; coating wastes will go first to 104-S, then to 110-U. By utilizing the available storage facilities as outlined below, the Redox Plant can process more than 7500 tons of uranium (with two-stage backcycle, self-concentration factor of two) after September, 1955 before additional waste storage is required.

a. Standard plan

The following operational plan is regarded as the standard and deviations from this plan will be made only under controlled test conditions.

1. A gas-lift recirculator about ten feet tall and one about twenty-two feet tall will be installed in each of Tanks 241-107 through 115-SX. These recirculators will be instrumented with fail-safe instruments to indicate continuously that the recirculator is in operation.

2. Extraction wastes will be stored in a given vessel of the SX Farm until the hydrostatic head at the base of the tank approaches but does not exceed 10 lbs./sq.in. The hydrostatic head will be determined by the operating records of the wastes added to the tank in conjunction with a measured liquid level.

3. Self-concentration will be permitted as experienced, within the limitations of hydrostatic head as noted above and of preventing the crystallization of the bulk salts at the boiling point. Water will be added as required to prevent over-concentration.

4. Coating wastes will be added to non-boiling tanks in excess of the hydrostatic head limitations noted above. If necessary to add coating wastes to a boiling tank, the hydrostatic head limitations will be observed.

b. Experimental program

Observations have been made thus far which indicate that the above operating plan may be unduly restrictive and that operating limits noted above can probably be relaxed without undue hazard. For example, the almost insignificant agitation supplied by the auger was sufficient to minimize, if not prevent, bumping in 101-SX. The initial operation of the gas-lift recirculator in 104-SX removed about 5.5 million Btu. of stored heat. Subsequent operation of this recirculator has prevented bumping, and a temperature gradient has not again developed in the tank; all other tanks filled without agitation as the first in cascade have developed a temperature gradient from top to bottom. The maximum bump thus far observed has been less than 2 lbs./sq.in., compared with the 10 lbs./sq.in. dome limit controlling when loaded to assured safe conditions. The bumps observed in 101-S, 104-S, and 101-SX did not release all of the stored heat present since the temperature at the bottom of the tank remained high with respect to that at the top of the tank.

TEMP. GRADIENT.

The above observations show that an experimental in-plant program can be safely executed with a two-fold objective. First, the feasibility of utilizing agitation to prevent bumping will be more firmly established. Second, the bumping characteristics of stored wastes will be developed through all operable ranges of evaporation rates and salt concentrations within the limitations of hydrostatic head for "assured" safe operation. When these characteristics are understood, the hydrostatic head limitations will be relaxed incrementally as indicated by the data obtained above.

A tentative experimental program is presented below, subject to later agreement as to operating details.

1. Tank 104-SX and 105-SX will continue to receive extraction wastes (single-stage backcycle, low MWD/T) as at present, receiving the wastes from about 350 tons of uranium. The specific gravity of 104-SX when 105-SX is filled will be about 1.39. A maximum boil-off rate of about 5 gal./min. is predicted for 104-SX, and the vessel will probably continue to boil for one to two years. Coating wastes will be routed to 104-SX for about six months after 105-SX is filled. During this time, the boil-off rate will decrease from about 5 to 2 gal./min., the liquid level will fall from 30 feet to about 22 feet, and the specific gravity will rise from about 1.39 to 1.58. Continued use of this tank for coating waste storage for another six months will refill the tank at a specific gravity of 1.48. The gas-lift recirculator will be kept in continuous operation until the tank stops boiling. If necessary, before proceeding to Step 2, a gas-lift recirculator will be installed in 101-SX and extraction wastes stored there.

[redacted]

2. With the attainment of two-stage backcycle of waste and the processing of low MWD/T wastes, a second demonstration of self-concentration of wastes with agitation will be conducted in Tank 113-SX. This tank will be filled to a 30-foot liquid level with agitation and permitted to self-concentrate. It is anticipated that about 1450 ton-equivalents of waste will be stored here, a maximum boil-off rate of about 5 gal./min. will be attained, and the tank will continue to boil for about two years.

3. With the return to high MWD/T feed stock, Tank 109-SX will be filled, without recirculation, to a maximum hydrostatic head of 10 lbs./sq.in. Self-concentration will be permitted with occasional additions of fresh waste as required to maintain the hydrostatic loading in the 7 to 10 lbs./sq.in. range. The bumping characteristics of this system will be closely observed until the solution has been concentrated to crystallization of salts at the boiling point and then permitted to cool to the non-boiling state. Tank 112-SX will be used to store wastes under recirculation as required to satisfy storage requirements during the test in 109-SX. Tank 109-SX will contain the wastes from about 850 tons of uranium, will attain a peak boil-off rate of about 5 to 7 gal./min., and the wastes will continue to boil for about two to three years.

4. On the basis of data collected on the bumping characteristics in 109-SX, a new "assured" safe liquid loading will be predicted. For example, if the maximum bump observed in 109-SX is 4 lbs./sq.in., the bumps could safely be permitted to double in intensity. On the premise that the bump intensity might increase as the square of the liquid loading (one theory suggests that the intensity may actually decrease with increasing liquid depth), a liquid loading of 13 to 14 lbs./sq.in. at the base would be tested. This test would be conducted in 107-SX.

2. <u>Purex</u>

a. Coating wastes will be stored separately in C Farm pending the development of techniques which will permit their disposal to the ground.

b. Two 10-ft. and two 22-ft. (approximately) gas-lift recirculators will be installed in each tank.

c. Each tank, starting with Tank 101-A, will receive concentrated Purex wastes and be permitted to self-concentrate to the point of incipient precipitation of sodium nitrate. The liquid level will be held at or below that point at which the hydrostatic head at the base of the tank is 10 lbs./sq.in. (about 21 ft. of waste as produced, or about 15 ft. as concentrated waste). Under these conditions, the existing tanks will contain the Purex extraction wastes from about 37,000 tons of uranium, based on the HW No. 4 Flowsheet and a concentration factor of five.

d. Subsequent development data will be used to decide the utilization of the unused portion of the waste storage tanks.

F. Development Agenda

An active laboratory and semiworks scale development program is in progress to define and alleviate the hazards of confining the fission products created as a by-product of plutonium production. While this program has a long-range objective of developing an alternate disposal method which is simultaneously cheaper and more permanent than present methods, the primary effort has been placed on the definition of safe operating conditions for the immediate future. To this end, the following development agenda has been and is being actively pursued.

1. Laboratory

a. Possible mechanisms contributing to bumping in the Redox tanks were studied, together with a study of methods of control.

b. The evolution of hydrogen and oxygen from highly radioactive stored wastes is being evaluated more precisely.

c. A study is being made of the stability of nitrate salts at the elevated temperatures potentially available in waste storage tanks.

d. The solubility of the mixed salts encountered in Redox and Purex wastes is being determined as a function of temperature, together with the volume of solids separating from the hot wastes upon cooling.

e. Additional corrosion data is being obtained in laboratory and field specimens at temperatures up to the maximum observed in the field.

f. Processes are being developed to permit the disposal of coating waste to the ground.

2. Large Scale

a. Since the phenomenon of a self-boiling solution at low specific heat generation rates is a new one, many of the technical observations must be made directly on the full-scale unit. To this end, Engineering personnel are closely observing the boiling tanks and obtaining data from which an understanding of the controlling mechanisms may be deduced. The effects of a settled solid phase on boiling characteristics will be determined.

b. A gas-lift recirculation device is currently being evaluated to determine its efficacy in preventing bumps both in experimental facilities and in boiling waste tanks. This device is believed effective in fluid systems; should sludge be controlling, alternate agitation methods would be required and are currently under consideration. Fail-safe instrumentation to indicate continued operation will be developed and installed.

c. Temperature gradients actually encountered in the soil and concrete shells will be established.

d. An experimental tank, 39 inches in diameter by 35-feet tall, is being filled with Purex-type aqueous wastes. This tank is equipped to study the rate and uniformity of vapor production, heat losses to the ground, tank temperatures as a function of tank height, and the formation and consistency of any sludge formed. It is planned to pilot the self-concentration of wastes to incipient salt formation, corresponding to a self-concentration factor of five to six.

e. The boiling characteristics of large volumes of solution at low heat flux are being studied under test conditions.

f. An experimental crib facility is planned to study the disposal of coating wastes to the ground.

3. Design

The Design Section will study the design of new tanks which will permit maximum tank economy and which will remain completely safe from a stress-rupture viewpoint.

R. E. Tomlinson

Head, Process Planning
Separations Technology Section
ENGINEERING DEPARTMENT

RE Tomlinson:mj

[redacted]

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TABLE I

FLOWSHEET COMPOSITION OF RADIOACTIVE CHEMICAL WASTES

Waste Waste Backcycle	Coating* Waste	$BiPO_4$ Metal Waste	Redox Backcycled Wastes, Single-Stage	Redox Backcycled Wastes, Double-Stage	Purex HW #4
Composition, M					
$Na_2U_2O_7$			0.002	0.003	0.006
Na_2CO_3					0.1
$NaNO_3$			4.23	4.2	2.1
$Fe(OH)_3$			Trace	Trace	0.04
Na_2SO_4			Trace	Trace	0.07
Na_2CrO_4			0.06	0.15	
$NaAlO_2$	1.16		1.4	1.4	
NaOH	1.09		0.18	0.1	
$NaNO_2$	0.81				
$NaSiO_3$	0.04				
U		0.26			
NO_3^-		0.16			
$SO_4^=$		0.25			
$PO_4^=$		0.27			
Na^+		3.62			
Volumes/Ton U					
As stored, gallons	240	3840	1800	1050	410
Sp.Gr.	1.18	1.25	1.32	1.32	1.10
At saturation of sodium salts (~220°F.) gallons	~120	>3840	~900	~525	~80
Sp.Gr.	1.5	--	1.66	1.66	1.5

* This waste is typical of all plants and may be stored with the other wastes or handled separately as desired.

The activity associated with one ton of uranium after irradiation at 5 MW/T to 600 MWD/T is as follows:

Cooling Time, Days	50	100	1000	10,000
Curies, Beta	6×10^5	4×10^5	1.8×10^4	2600
Gamma	4.6×10^5	2.7×10^5	5000	1000
Watts, Beta	1400	950	60	7
Gamma	1500	900	12	4

TABLE II

CHARACTERISTICS OF STORAGE TANKS

Farm	Construction Date	No. Tanks	Concrete Walls Thickness, In.	Liner Height, Ft.	Liner Thickness, In.	Storage Capacity, Gal.
T	1944	12	12	18	5/16-1/4	530,000
U	1944	12				
B	1944	12		Same as T		
C	1944	12				
BX	1944	12				
BY	1948	12	15	24	3/8-1/4	760,000
TX	1948	18				
TY	1951	6		Same as BY		
S	1950	12				
SX	1955	15	15 Top 24 Bottom	32 1/3	3/8	1,000,000
A	1955	6		Same as SX		

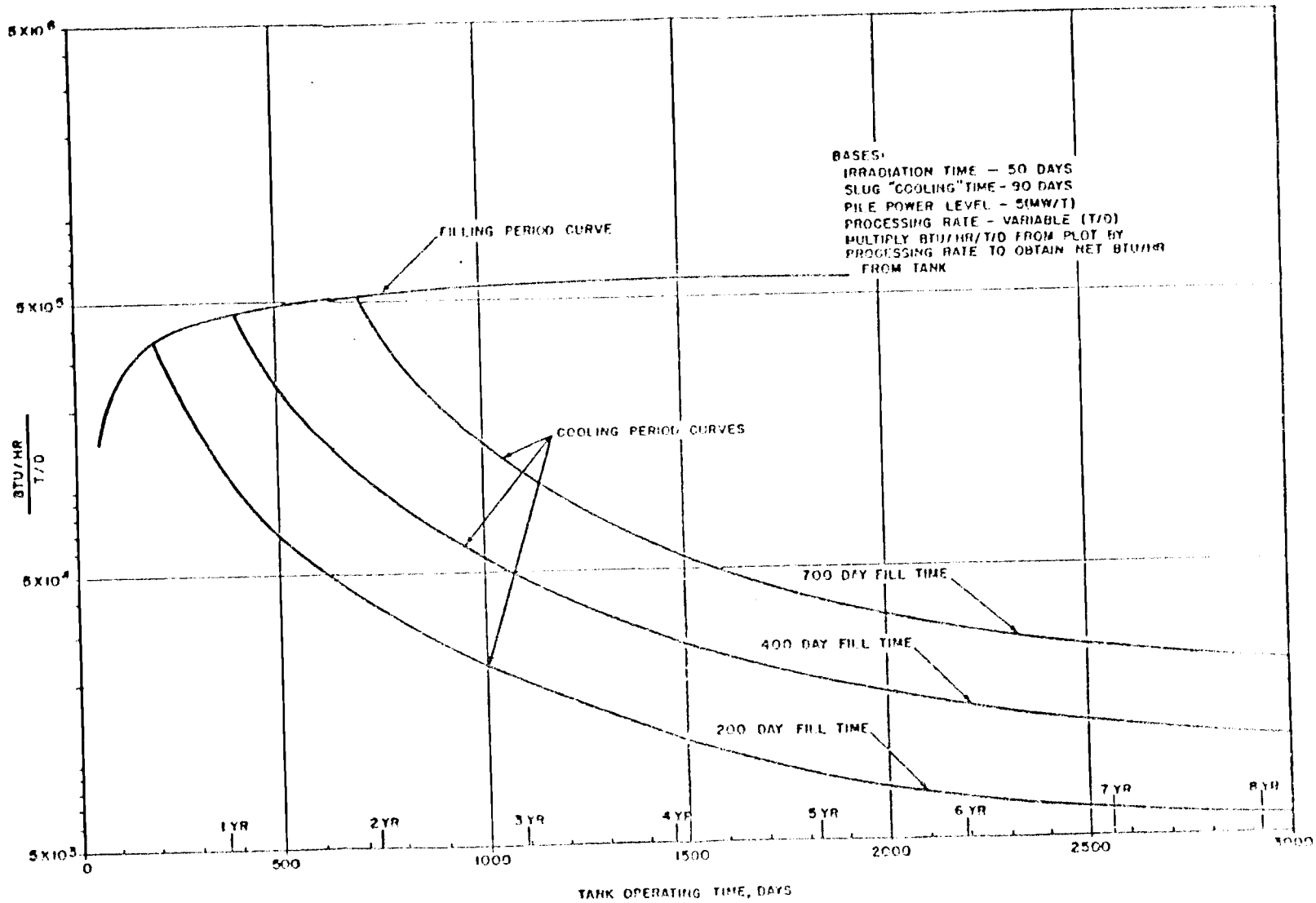


FIGURE 1
HEAT GENERATION IN WASTE STORAGE TANKS
FOR URANIUM IRRADIATED 50 DAYS

DECLASSIFIED

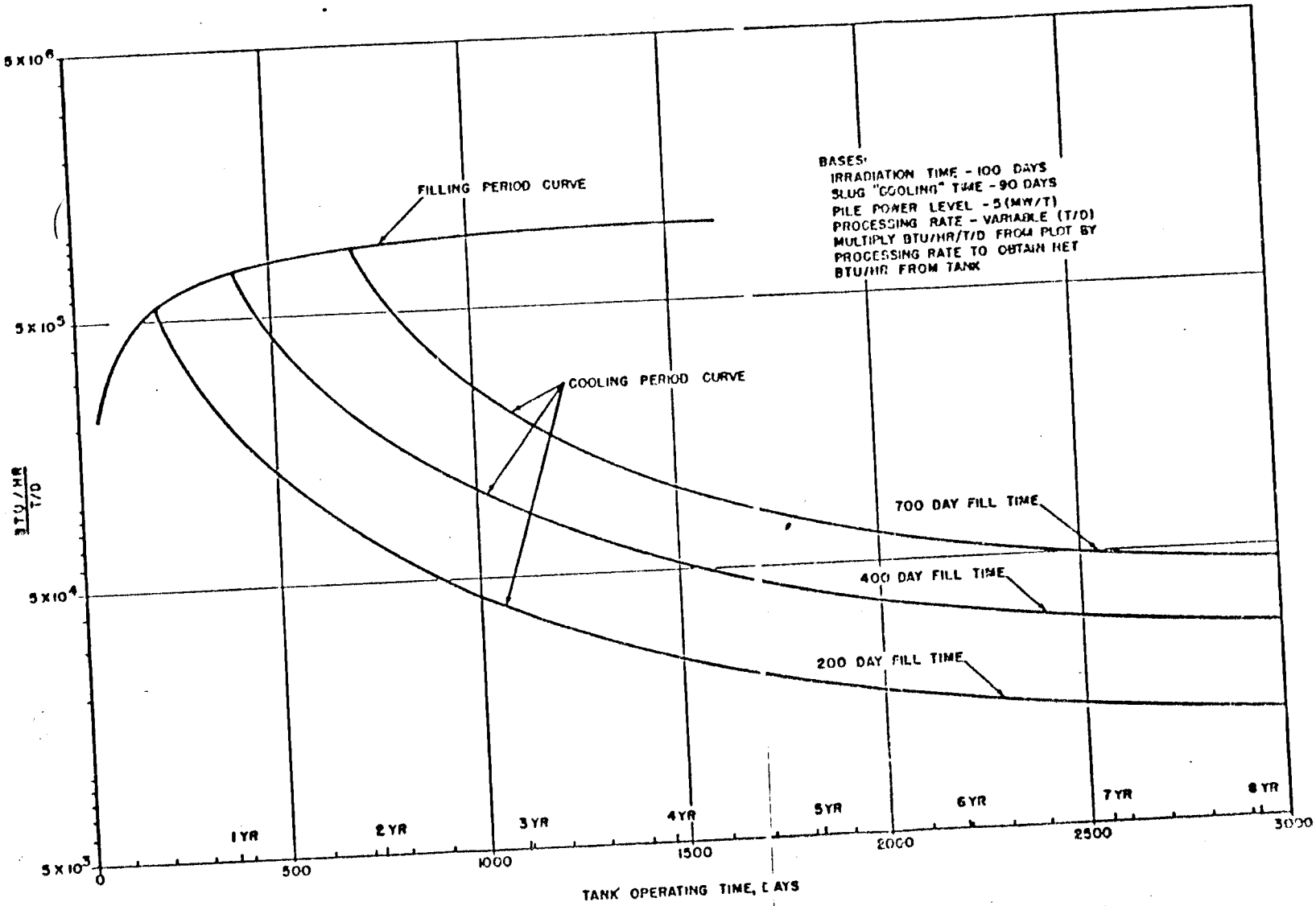


FIGURE 2

HEAT GENERATION IN WASTE STORAGE TANKS
FOR URANIUM IRRADIATED 100 DAYS

DECLASSIFIED

DECLASSIFIED

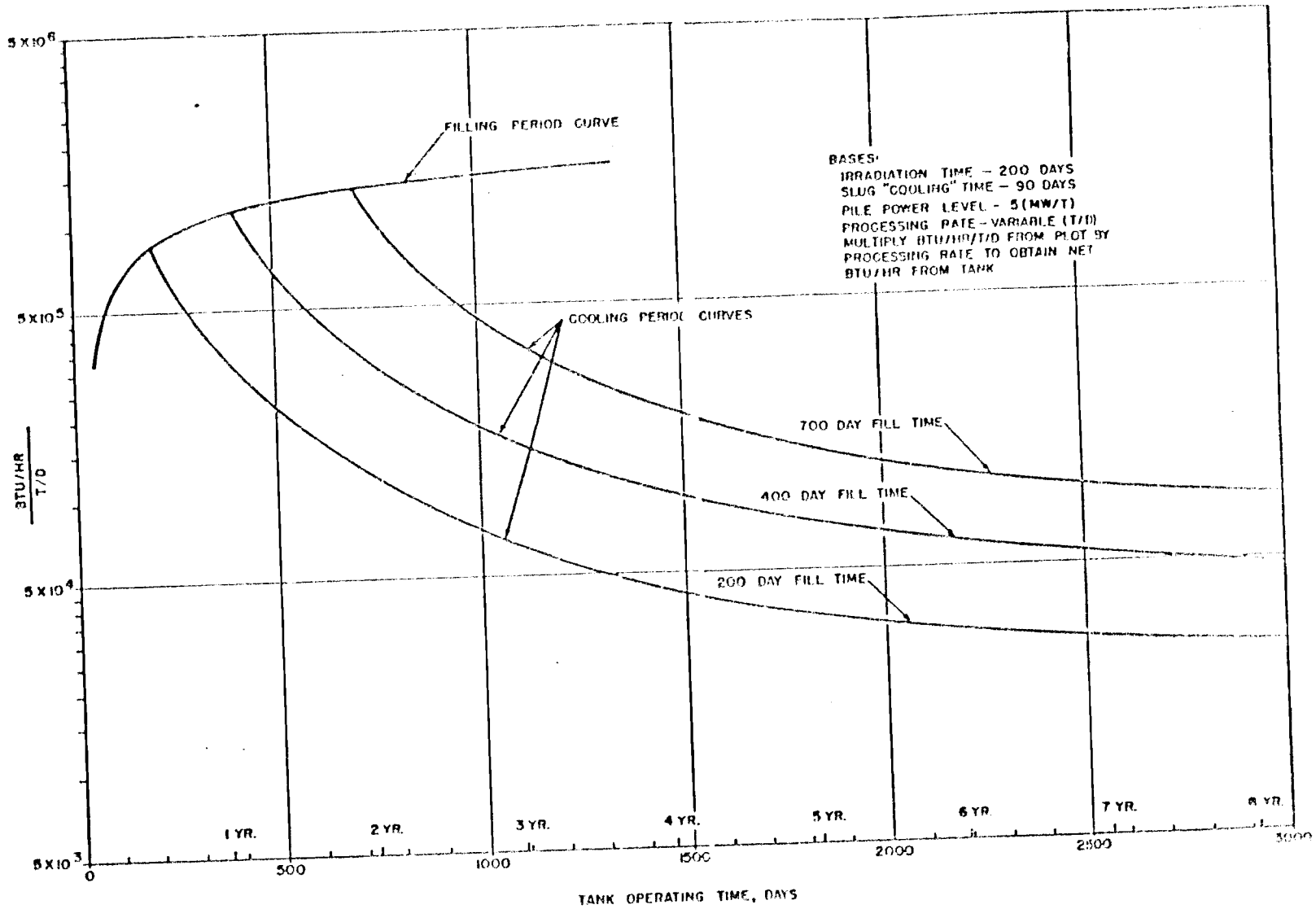


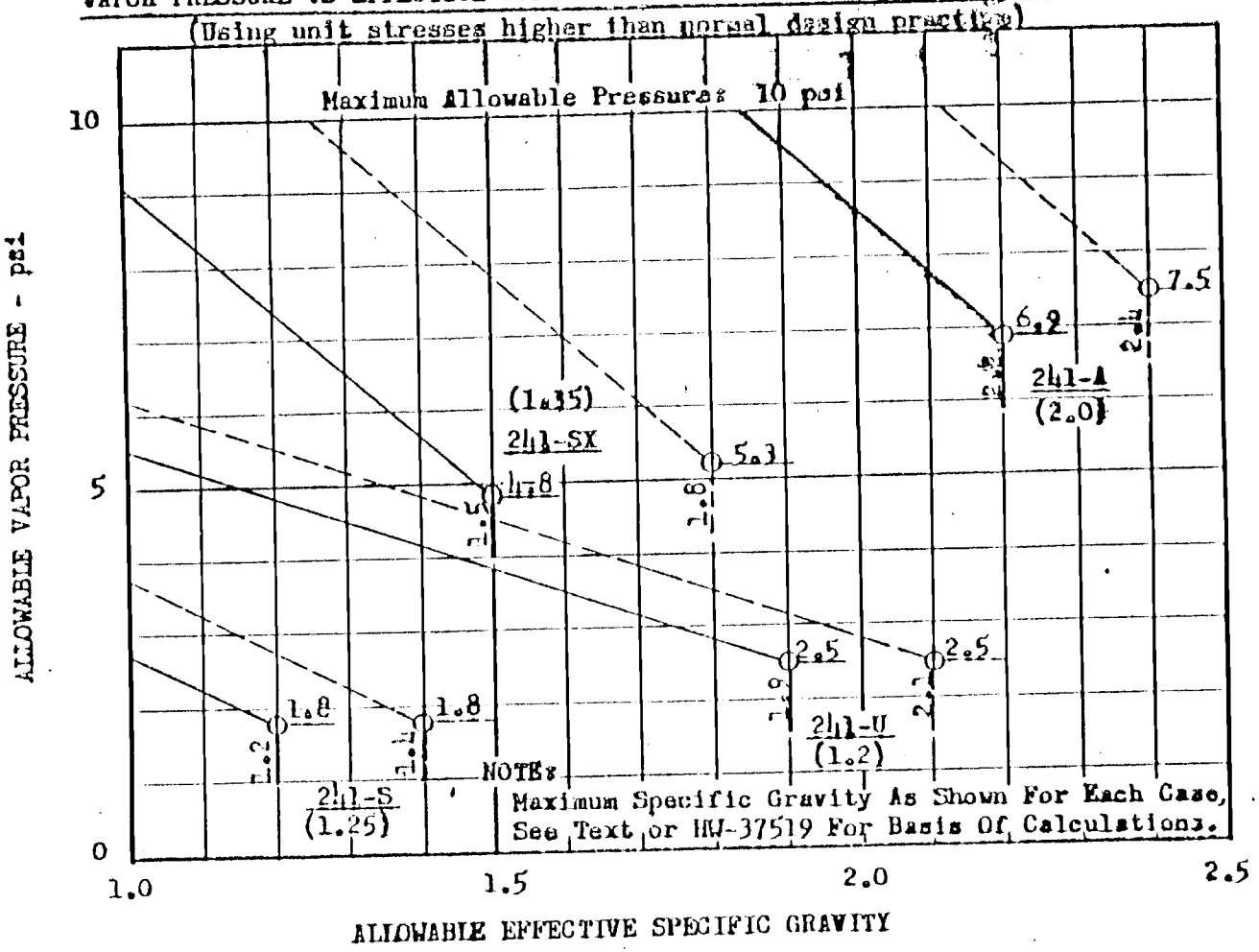
FIGURE 3

HEAT GENERATION IN WASTE STORAGE TANKS
FOR URANIUM IRRADIATED 200 DAYS

DECLASSIFIED

FIGURE 4

VAPOR PRESSURE VS EFFECTIVE SPECIFIC GRAVITY IN FULL WASTE STORAGE TANKS
(Using unit stresses higher than normal design practice)



COMPUTED BY:

Edgar F. Smith

DESIGN ENGINEERING SUB-SECTION
June 15, 1955

LEGEND: Tank contents hot ——— (applies)

Tank contents cold - - - - - (for information only)

Original design Sp.Gr shown in ( ), no allowance for vapor pressure

APPENDIX C: AGING WASTE THERMAL PHYSICAL CHARACTERIZATION

WHC-SD-WM-TI-406 Rev. 0

RHO-LD-171

Informal Report

Heat Transfer Analysis for In Situ Disposal of Nuclear Wastes in Single- and Double-Shell Underground Storage Tanks

G.D. Campbell

Prepared for the United States
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Under Contract DE-AC06-77RL01030

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Engineering Analysis Group
Systems Engineering Department

October 1981

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CONTENTS

Introduction 1
Background 1
Purpose 2

Summary 2

Results 3
General 3
Single-Shell Tanks 9
Double-Shell Tanks 9
Sensitivity Analysis 20

Thermal Parameters and Assumptions 23
Parameters 23
Assumptions 25

References 27

Appendices:
A. Survey of Hanford Tank Heat Loads A-1
B. HEATING5 Code Check Calculations B-1

FIGURES:
1. Single-Shell Tank Heat Transfer Model 4
2. Double-Shell Tank Heat Transfer Model 5
3. Transient Waste Temperatures for a Single-Shell Tank with No Ventilation, a Waste solids depth of 15 ft, and Various Backfill Materials in Air Spaces 8
4. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and No Backfill Material in Air Spaces 10
5. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces 11
6. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and No Backfill Material in Air Spaces 11
7. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and Concrete Backfill in Air Spaces 12
8. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Concrete Backfill in Air Spaces 12
9. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Concrete Backfill in Air Spaces 13
10. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and Sandy Soil Backfill in Air Spaces 13

11. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Sandy Soil Backfill in Air Spaces. 14
12. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Sandy Soil Backfill in Air Spaces. 14
13. Peak Concrete Temperatures of a Single-Shell Tank with 4 m (13.12 ft) of Soil Overburden, a Waste Solids Depth of 15 ft and Sandy Soil Backfill in Air Spaces 15
14. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and No Backfill Material in Air Spaces. 15
15. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces. 16
16. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and No Backfill Material in Air Spaces. 16
17. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and Concrete Backfill in Air Spaces. 17
18. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Concrete Backfill in Air Spaces. 17
19. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Concrete Backfill in Air Spaces. 18
20. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and Sandy Soil Backfill in Air Spaces. 18
21. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Sandy Soil Backfill in Air Spaces. 19
22. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Sandy Soil Backfill in Air Spaces. 19
23. Peak Concrete Temperatures of a Double-Shell Tank with 4 m (13.12 ft) Soil Overburden, a Waste Solids Depth of 15 ft, and Sandy Soil Backfill in Air Spaces. 20
24. Sensitivity to Waste Thermal Conductivity in a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces. 21
25. Sensitivity to Soil Thermal Conductivity in a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces. 22
26. Sensitivity to Adiabatic Radius in a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces. 23

TABLES:

1. Linear Curve Fit Coefficients 6
2. Thermal Properties. 24
3. Interchange Factors and Convection Coefficients 25

INTRODUCTION

BACKGROUND

Radioactive waste resulting from reprocessing nuclear fuel is stored in underground storage (UGS) tanks at the Hanford Site. Based upon limited data on estimates of transuranic isotopes in the waste and emerging criteria for disposal of radioactive waste, it is expected that some in-tank radioactive waste will qualify for near-surface disposal in the existing waste tanks (in situ disposal). Implementation of in situ waste disposal would require drying of the damp salt cake and sludge to an acceptable level, solidification of the residual liquors and slurries, provision of support to the tank dome, and finally, installation of an earth-rock cover over each tank farm.[1]

These operations, if implemented, would affect the heat transfer characteristics of the waste storage tanks. Heat generated by fission product decay is currently transferred to the surrounding soil and to the atmosphere mainly by conduction and in some tanks by forced air ventilation. Under the in situ disposal alternative, tank ventilation would be terminated. Drying or immobilizing the waste would tend to lower its thermal conductivity. Backfilling the tank dome void spaces and building an earth cover over the tank farms would further restrict heat transfer by increasing the resistance to heat transfer between the waste and the atmosphere.

According to the radioactive waste inventory in Reference 2, the total heat loading (decayed to 1995) of all the UGS tanks is about 1.74 million Btu/hr. If evenly distributed among all 169 tanks, the average heat loading per tank would be 10,300 Btu/hr; if evenly distributed among all 75-ft-diameter single-shell tanks, the average heat loading per tank would be 13,100 Btu/hr. A list of tanks with estimated heat loadings is included in Appendix A.

This study was performed as part of the Long-Term High-Level Defense Waste Program (AR-05-15-10).

PURPOSE

A parametric heat transfer analysis was conducted for predicting peak waste and concrete temperatures for long-term, in situ disposal of high-level radioactive waste. Families of maximum temperature versus total radiogenic power graphs were prepared for variable waste depths, backfill materials and tank types, and for tanks with 4 m (13.12 ft) of earth cover added to the tank farms.

SUMMARY

Parametric heat transfer calculations were made for single- and double-shell tanks to predict maximum temperatures possible in the waste and concrete structure during in situ disposal. Transient calculations were carried out until the temperatures of interest reached their peak values with respect to time. Computer runs were made, varying the initial heat generation rate, waste volume, backfill material, and soil overburden. The peak waste and concrete temperatures are plotted as a function of total initial heat loading for the various in situ disposal configurations. Given a tank with a known heat load, the maximum temperature expected under various in situ disposal configurations may be determined. Conversely, given a maximum allowable temperature in the waste or concrete, the maximum heat generation rate may be determined.

For example, if the maximum allowable waste temperature is 350°F, the maximum heat loading in a UGS tank ranges from about 26,000 to 50,000 Btu/hr, depending on tank type and size, waste depth, backfill material, and the presence of overburden material. Similarly, if the temperature in the concrete tank wall is limited to 250°F, then the maximum heat loadings range from about 21,000 to 56,000 Btu/hr.

Further calculations were made to show the dependence of the temperatures on certain input parameters. The thermal conductivity of the waste and soil, the adiabatic boundary radius, and the lower boundary temperature were varied and compared to the "base case" single-shell tank model results. The soil and waste thermal conductivities have the most significant effects on peak temperatures.

This analysis does not consider tanks with layered waste. Tanks with most of the heat generating material concentrated on the bottom would have significantly higher temperatures in the waste, base, and wall. Since several tanks fall into this category, it is recommended that individual tanks be analyzed prior to implementation of the in situ disposal option.

RESULTS

GENERAL

The transient heat transfer calculations were made using the HEATING5[3] computer program, using the Classical Implicit Procedure. The detailed geometric models used to represent a single-shell tank and a double-shell tank are shown in Figures 1 and 2, respectively. The locations of temperatures of interest in this report are the peak waste temperature at the tank centerline, the concrete base temperature at the centerline, the peak concrete wall temperature, and the concrete dome temperature at the centerline. The results of the heat transfer analysis are summerized in Table 1, where the peak temperatures in each configuration are correlated to fit the straight line equation given by:

$$T_{max} = a \cdot \frac{P_o}{1000} + b$$

where:

T_{max} is the maximum temperature (^oF)

a is the slope of the temperature vs. power curve, $^oF/(kBtu/hr)$

$P_o/1000$ is the initial power level converted to kBtu/hr

b is the y-axis intercept at $P_o = 0.0$ (^oF).

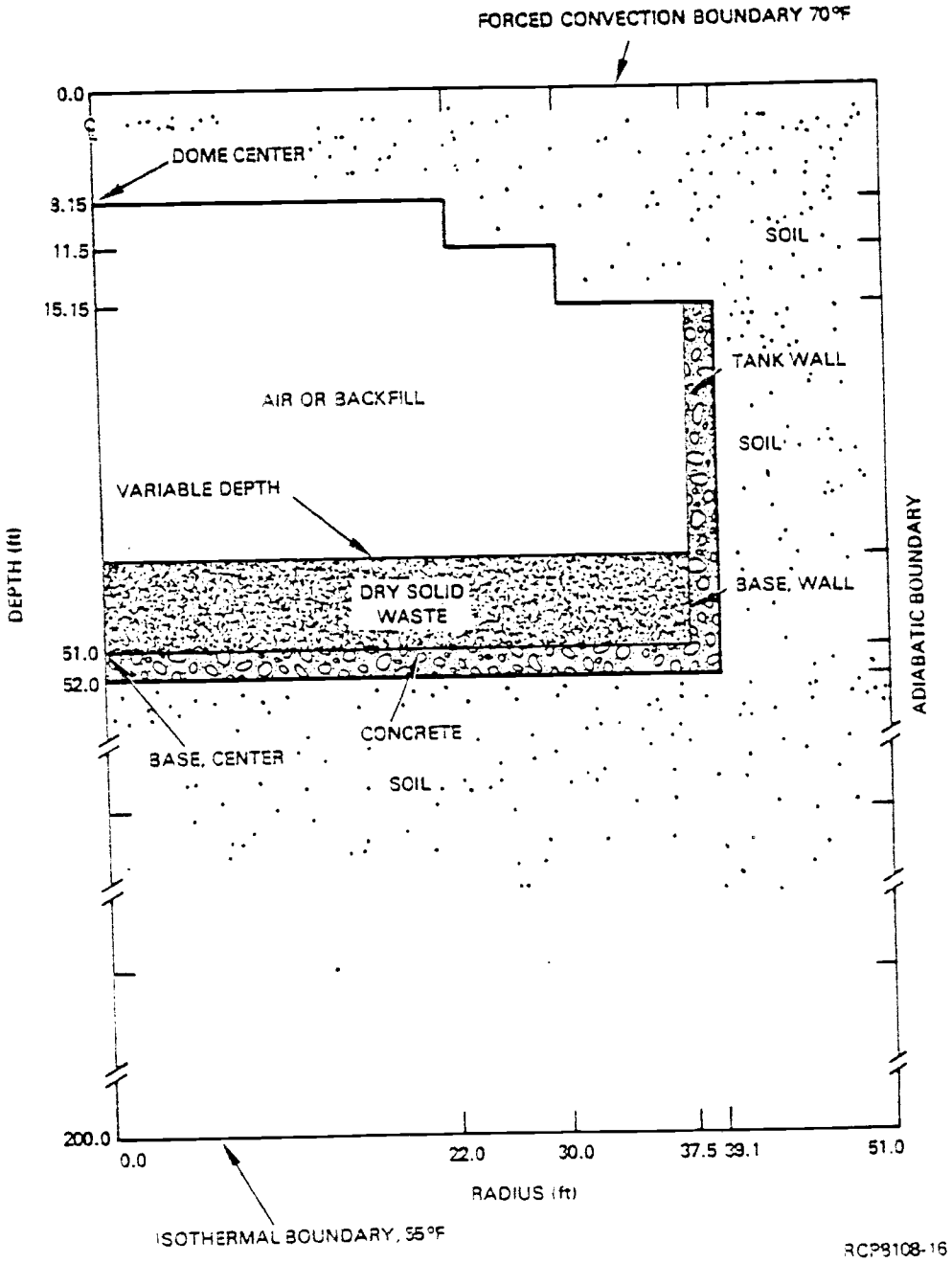

FIGURE 1. Single-Shell Tank Heat Transfer Model.

TABLE 1. Linear Curve Fit Coefficients (Continued).[a]

Tank Type	Backfill Material	Waste Depth (ft)	Peak Waste Temperature		Peak Concrete Temperature					
					Base, Center		Wall		Dome	
			a (^{o}F/kBtu/hr)	b (^{o}F)	a (^{o}F/kBtu/hr)	b (^{o}F)	a (^{o}F/kBtu/hr)	b (^{o}F)	a (^{o}F/kBtu/hr)	b (^{o}F)
Single-Shell (530,000 gal)	None	6	5.48	89	5.34	89	3.91	89	4.31	82
		15	6.09	91	5.71	91	4.45	90	3.73	80
	Concrete	6	7.22	92	7.06	92	5.52	90	2.59	76
		15	7.04	92	6.56	92	5.18	89	2.74	76
	Sandy Soil	6	8.93	93	8.57	94	6.39	90	1.99	74
		15	7.99	93	7.32	93	5.7	89	2.29	75
Double-Shell	None	6	5.50	91	4.99	93	2.74	98	4.46	84
		15	5.92	94	5.07	95	3.36	95	3.82	83
		30	5.98	98	4.79	99	3.78	94	2.99	81
	Concrete	6	6.93	100	6.42	99	4.51	93	1.70	78
		15	6.87	99	5.97	99	4.40	92	1.80	79
		30	6.39	99	5.10	99	3.93	94	2.02	80
	Sandy Soil	6	8.86	101	7.96	105	5.18	92	1.22	75
		15	8.18	100	6.92	100	4.84	93	1.36	75
		30	7.00	99	5.46	99	4.21	93	1.73	77
Double-Shell with 13 ft overburden	Sandy Soil	15	8.39	102	7.14	101	5.30	94	2.50	81

[a] Used in equation: $T_{max} = a \cdot \frac{P_o}{1000} + b$

The variable "b" would be expected to be between 60° and 70°F, but due to minor nonlinearities in the heat transfer system, higher values resulted. The peak temperature of the waste or concrete may be calculated, if the initial power level or heat load and the other configuration parameters are known. The peak temperatures reported occur 8 to 30 years after time "zero" at disposal, depending on the disposal configuration. This thermal response time is illustrated in Figure 3, where the waste temperatures of four configurations are plotted as a function of time from disposal when the vent system is shut down and the waste is dry and backfill is placed in the tank. The peak temperatures are higher and the time required to reach the peak is longer as heat transfer is further restricted by backfill or overburden. In general, temperatures of the waste, the concrete base center, and the concrete wall increase as waste depth increases with no backfill but decrease as waste depth increases with concrete or sandy soil backfill in the air spaces. However, the concrete dome center temperature decreases as waste depth increases with no backfill and increases with backfill.

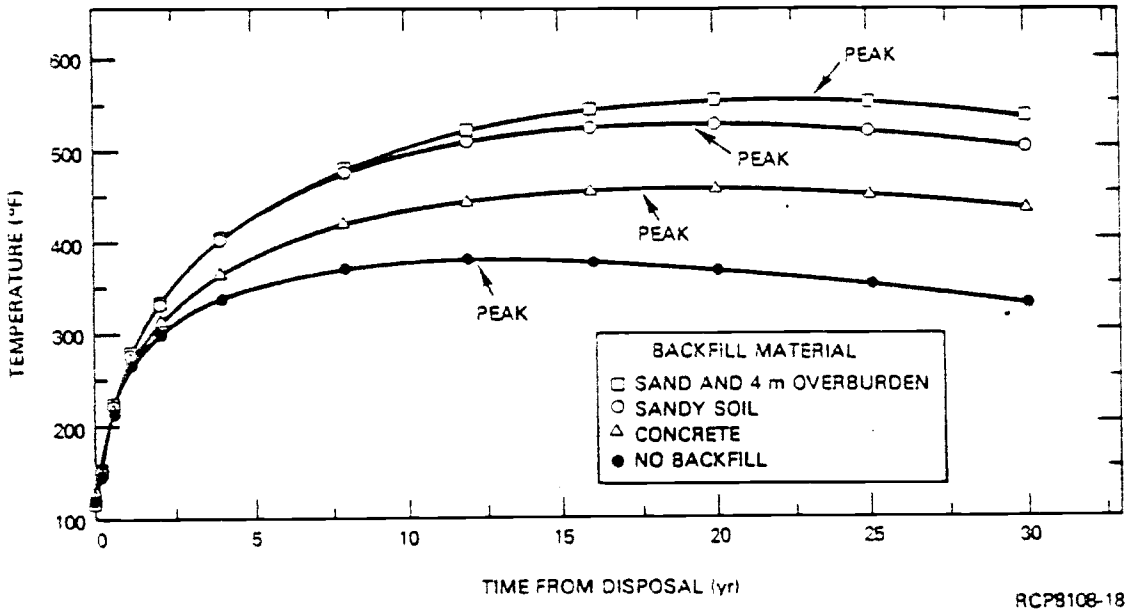

FIGURE 3. Transient Waste Temperatures for a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Various Backfill Materials in Air Spaces (50,000 Btu/hr).

Adding backfill to the air space above the waste and in the annulus in double-shell tanks restricts heat transfer and results in higher temperatures in the waste, concrete base center and concrete wall, but results in lower concrete dome center temperatures. Because the thermal conductivity of the sandy soil is lower than concrete, sandy soil backfill restricts heat transfer more than concrete backfill.

Adding 4 m (13.12 ft) of soil overburden to the existing earth cover resulted in higher temperatures in all locations, because of the increased distance to the upper boundary.

SINGLE-SHELL TANKS

Calculation results for a 1 million gal, single-shell tank are plotted in Figures 4 through 13. Peak waste and concrete temperatures for a tank with no backfill material in the air space and containing dry waste solid depths of 6, 15, and 30 ft are shown in Figures 4, 5, and 6, respectively; the results of adding concrete to the air space for the same three waste depths are shown in Figures 7, 8, and 9, respectively; and the results of substituting sandy soil for concrete as backfill are shown in Figures 10, 11, and 12, respectively.

The results of the calculations for single-shell tanks with 530,000 gal or 750,000 gal nominal capacities are reported in Table 1. Generally, the temperature differences, caused solely by different tank capacities, are less than 10%.

The results of adding 4 m (13.12 ft) of soil overburden to one configuration, that of a 1 million gal, single-shell tank with 15 ft of waste solids and sandy soil backfill, are shown in Figure 13. The largest increase was in the concrete dome temperature while the temperatures in the wall, base, and waste changed little.

DOUBLE-SHELL TANKS

The results for double-shell tanks are plotted in Figures 14 through 23. Peak waste and concrete temperatures for a tank with no backfill and dry waste solid depths of 6, 15, and 30 ft are shown in Figures 14, 15,

and 16, respectively. The results of adding concrete to the air spaces, including the annulus, are shown in Figures 17, 18, and 19, for the same three waste depths; the results of adding sandy solid backfill are shown in Figures 20, 21 and 22.

The results of placing an additional 4 m (13.12 ft) of soil overburden on top of existing soil on a tank with dry waste solids 15 ft deep and sandy solid backfill are shown in Figure 23. The effect on temperatures is similar to that of the single-shell tank.

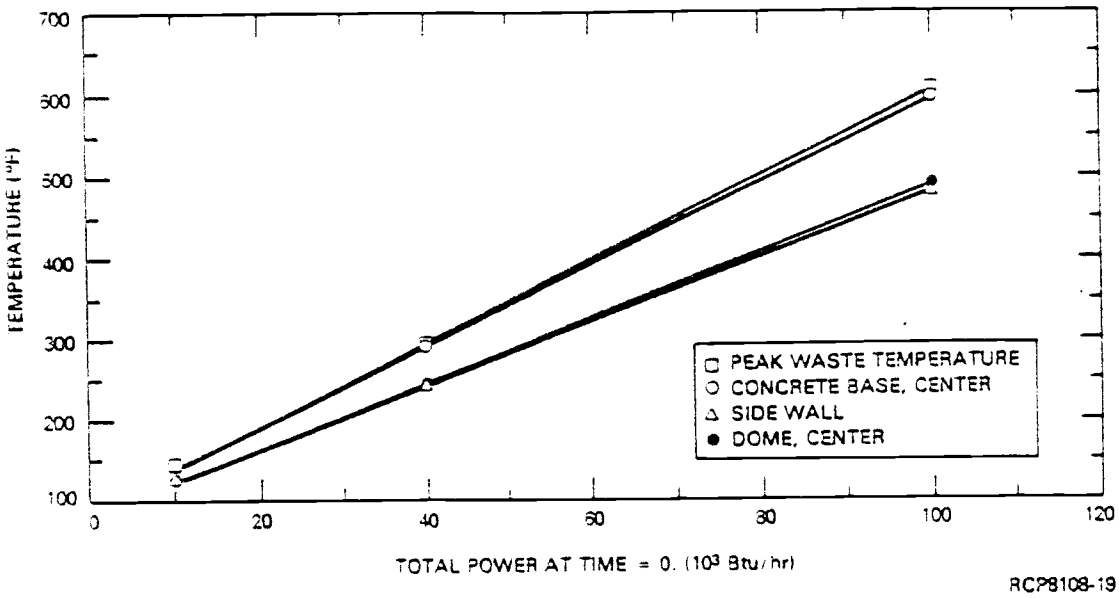

FIGURE 4. Peak Concrete Temperatures for a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and No Backfill Material in Air Spaces.

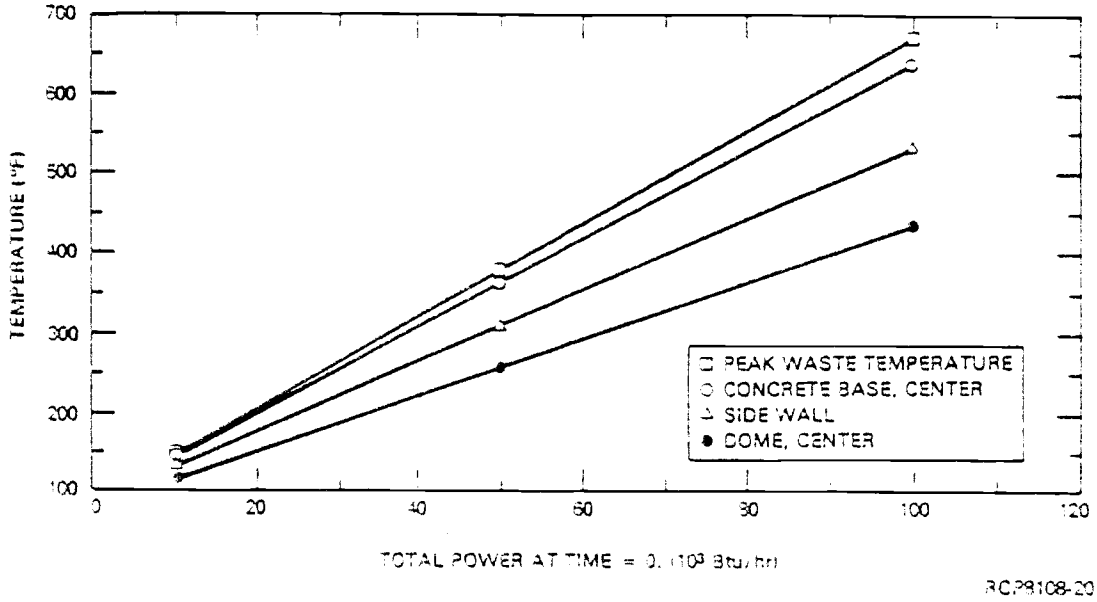

FIGURE 5. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Space.

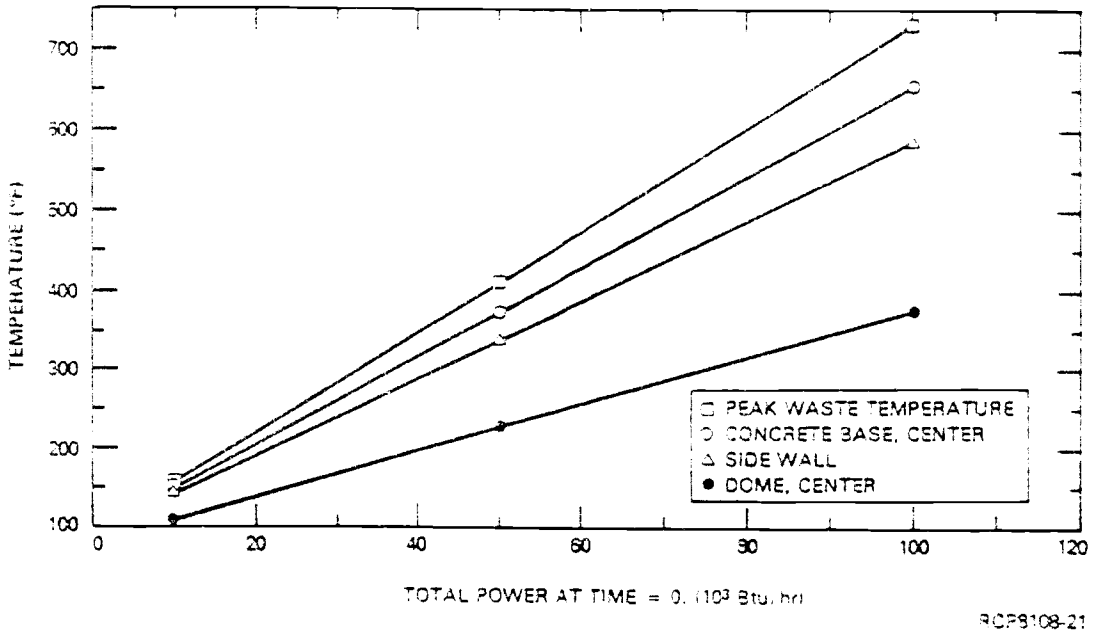

FIGURE 6. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and No Backfill Material in Air Spaces.

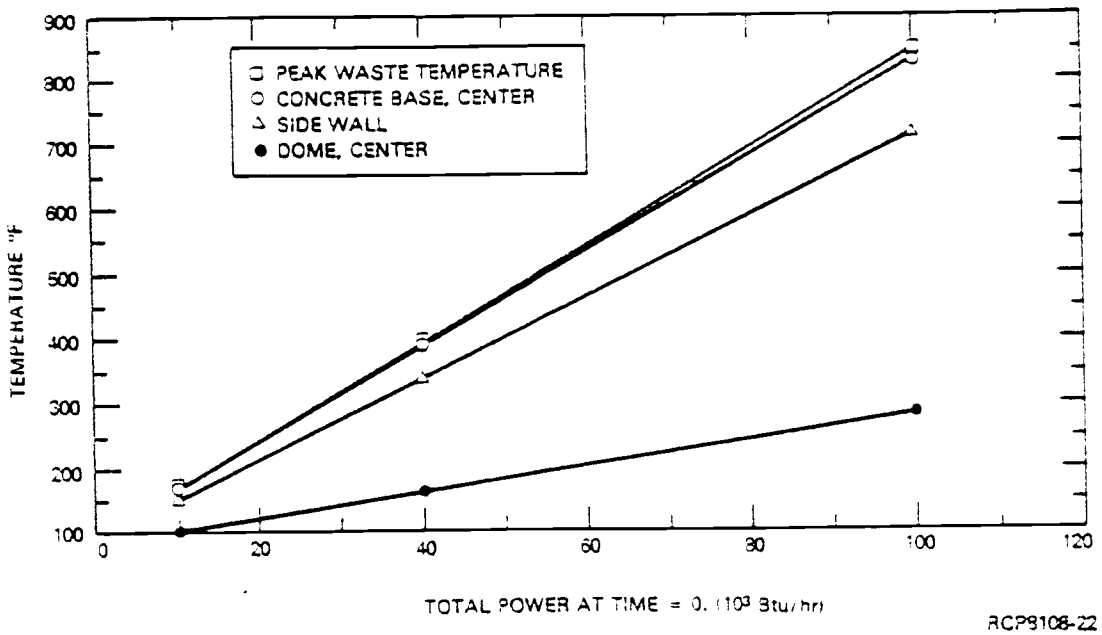

FIGURE 7. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and Concrete Backfill in Air Spaces.

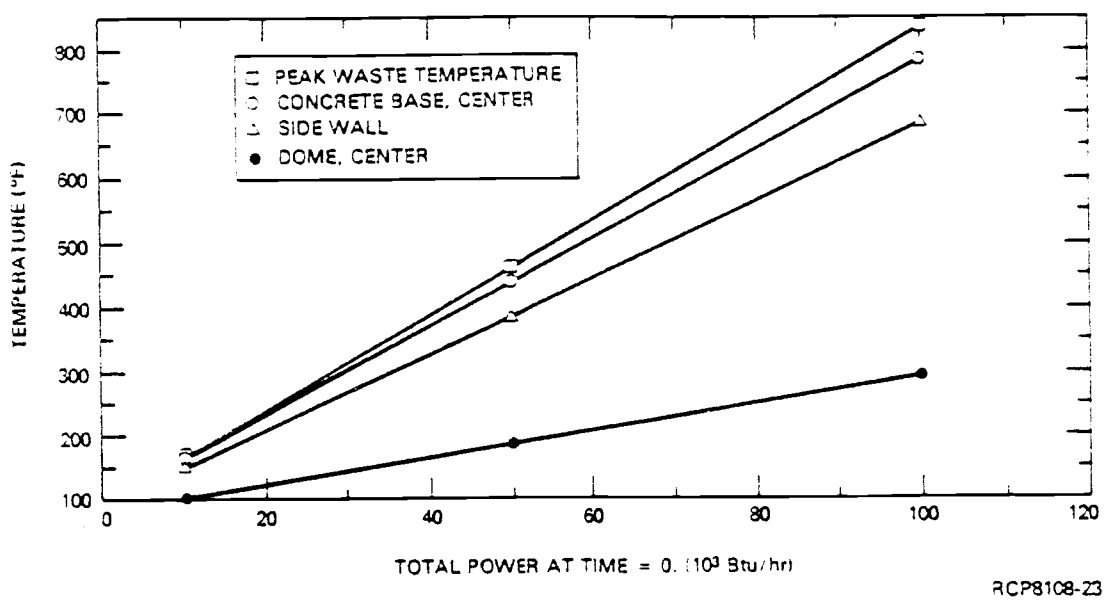

FIGURE 8. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Concrete Backfill in Air Spaces.

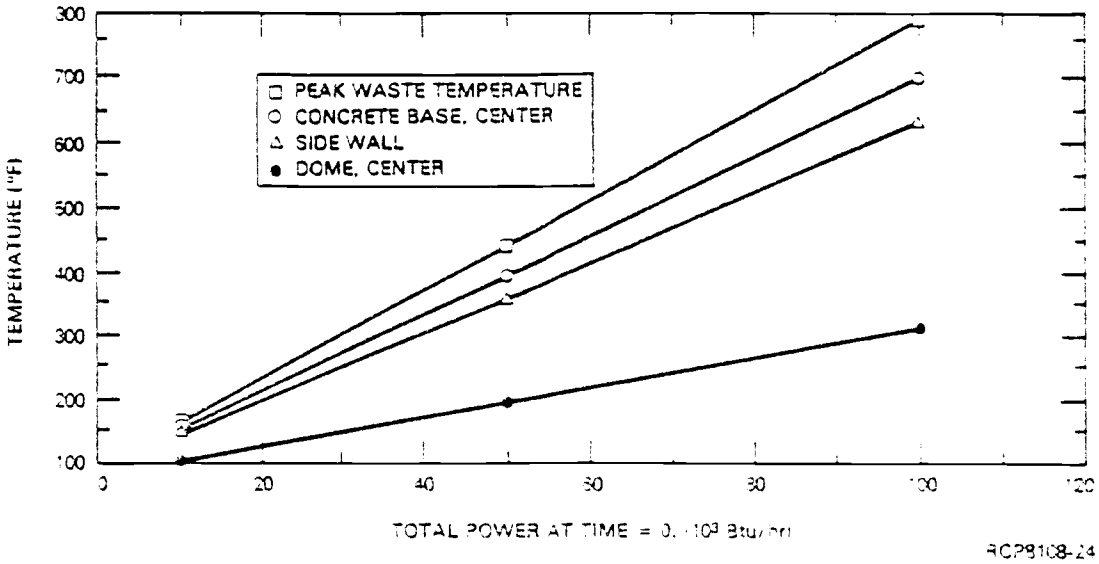

FIGURE 9. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Concrete Backfill in Air Spaces.

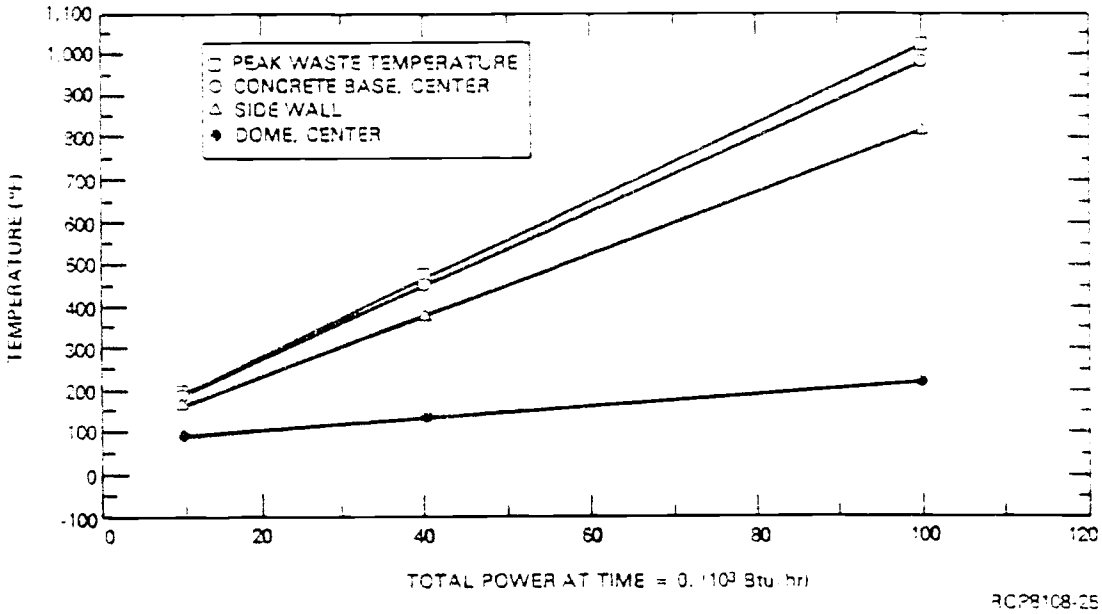

FIGURE 10. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 5 ft, and Sandy Soil Backfill in Air Spaces.

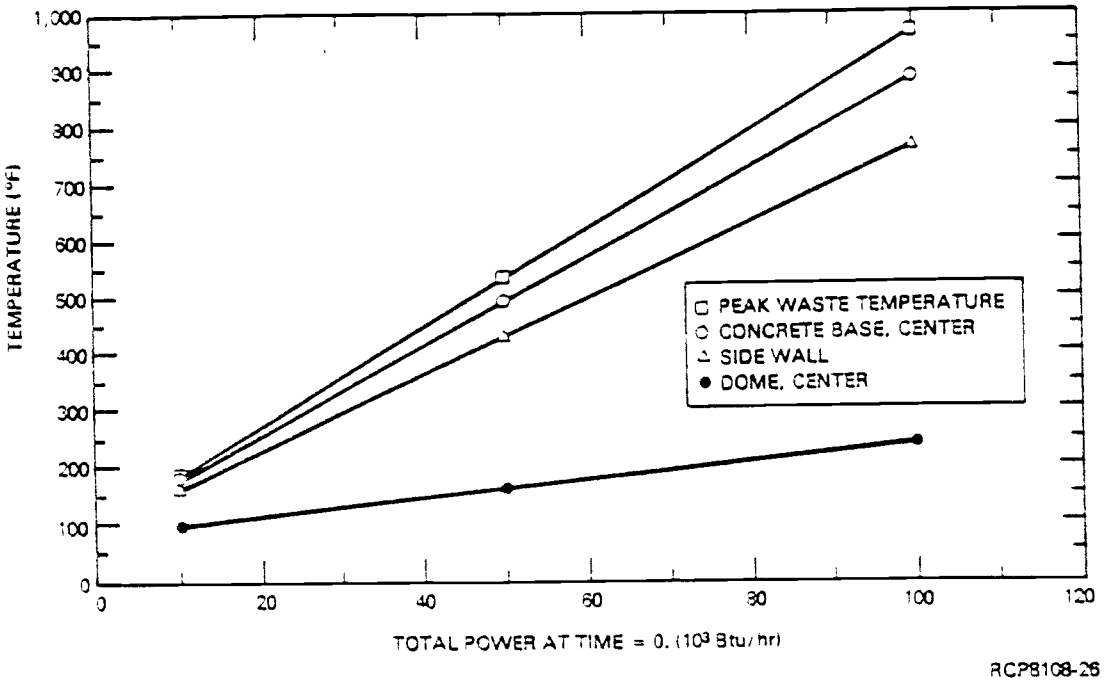

FIGURE 11. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Sandy Soil Backfill in Air Spaces.

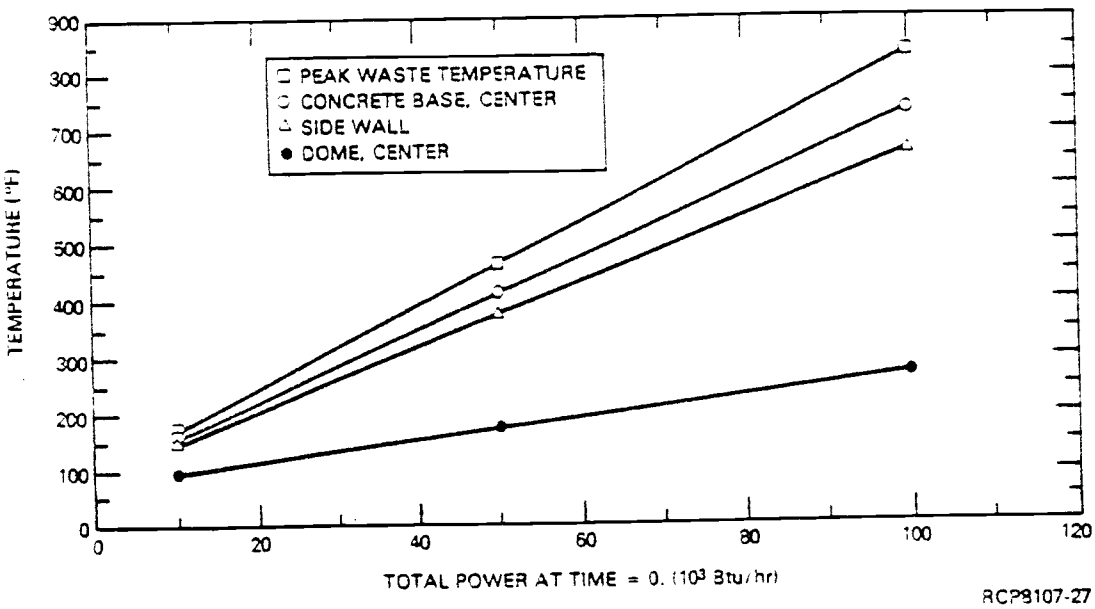

FIGURE 12. Peak Concrete Temperatures of a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Sandy Soil Backfill in Air Spaces.

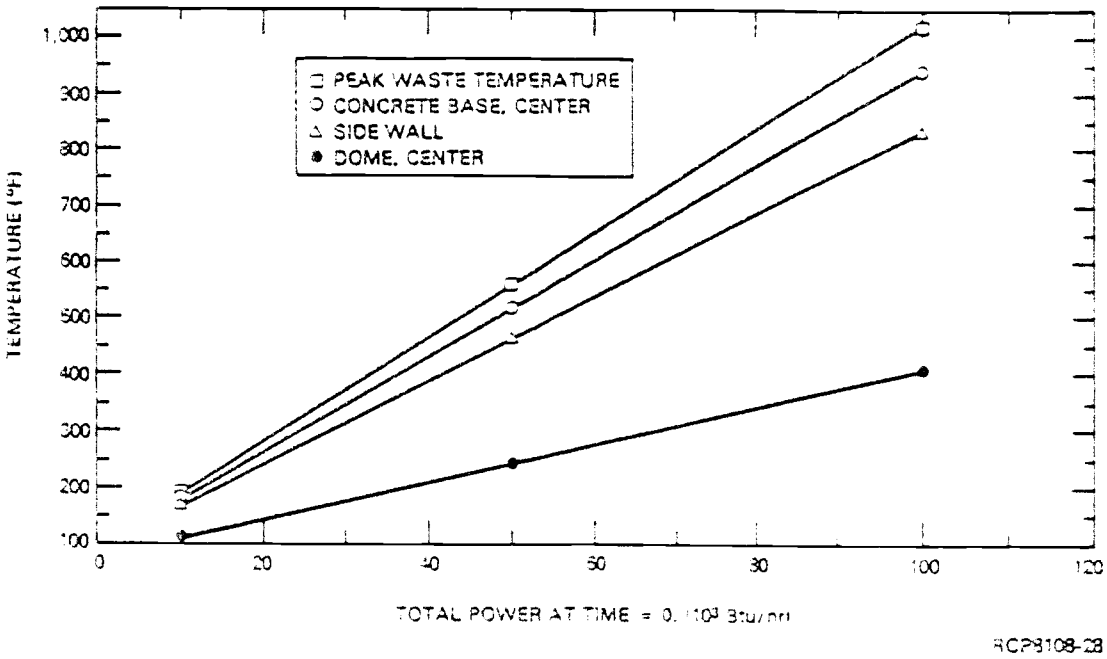

FIGURE 13. Peak Concrete Temperatures of a Single-Shell Tank with 4 m (13.12 ft) of Soil Overburden, a Waste Solids Depth of 15 ft, and Sandy Soil Backfill in Air Spaces.

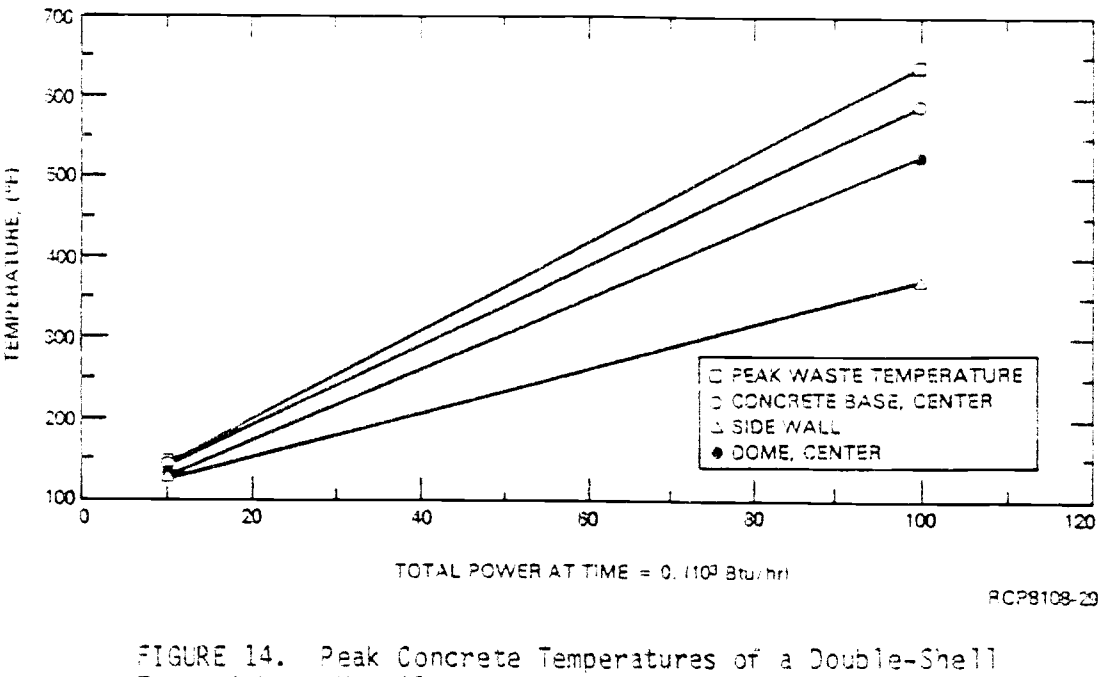

FIGURE 14. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 5 ft, and No Backfill Material in Air Spaces.

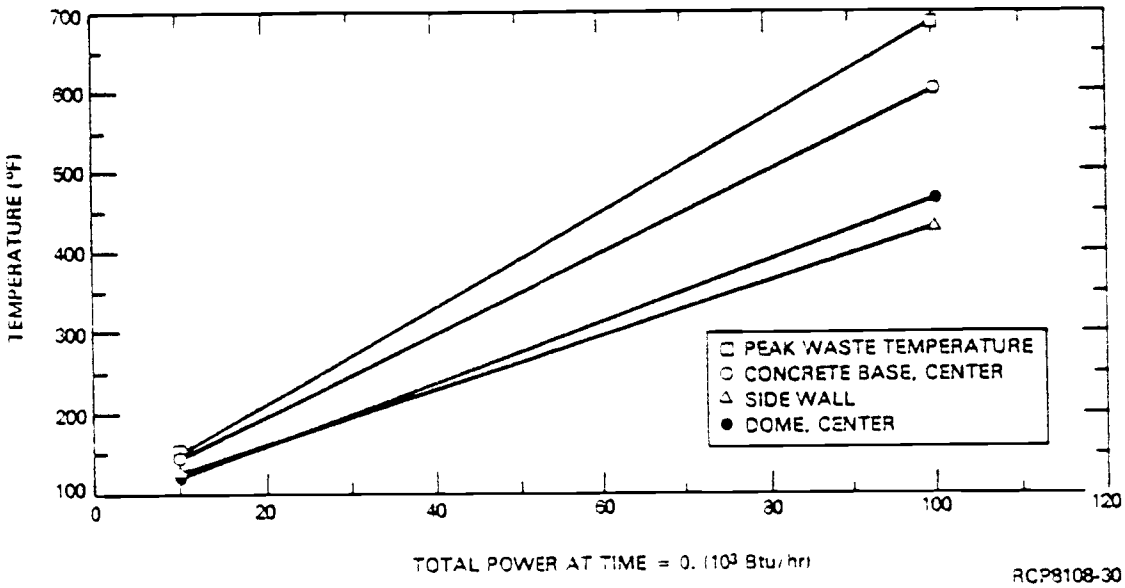

FIGURE 15. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces.

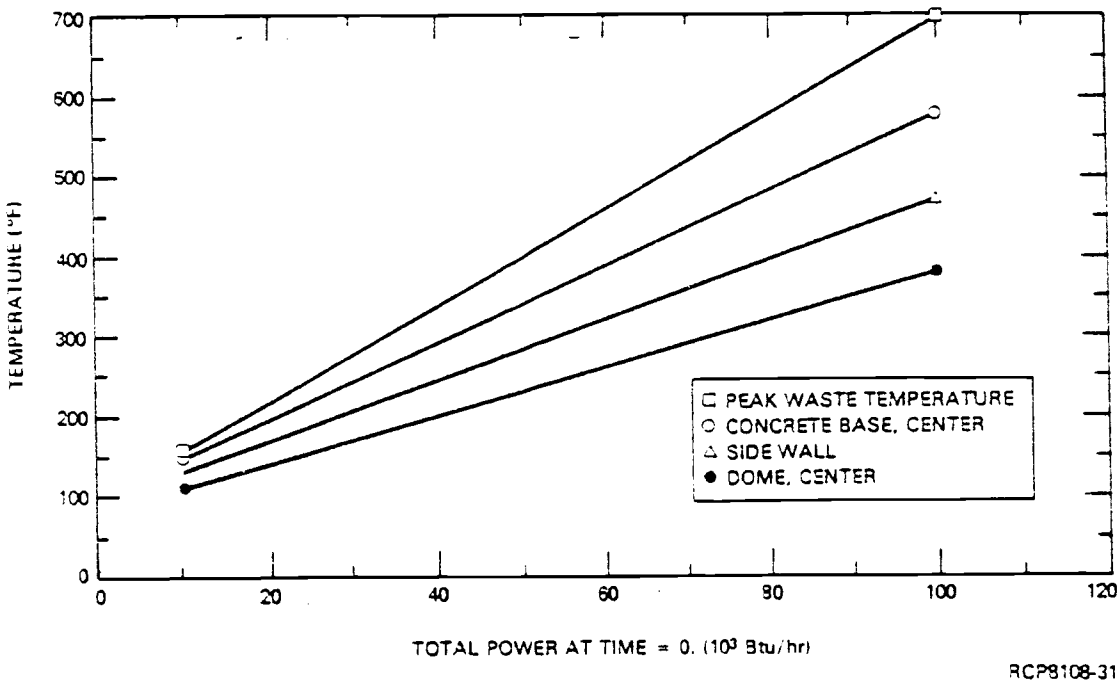

FIGURE 16. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and No Backfill Material in Air Spaces.

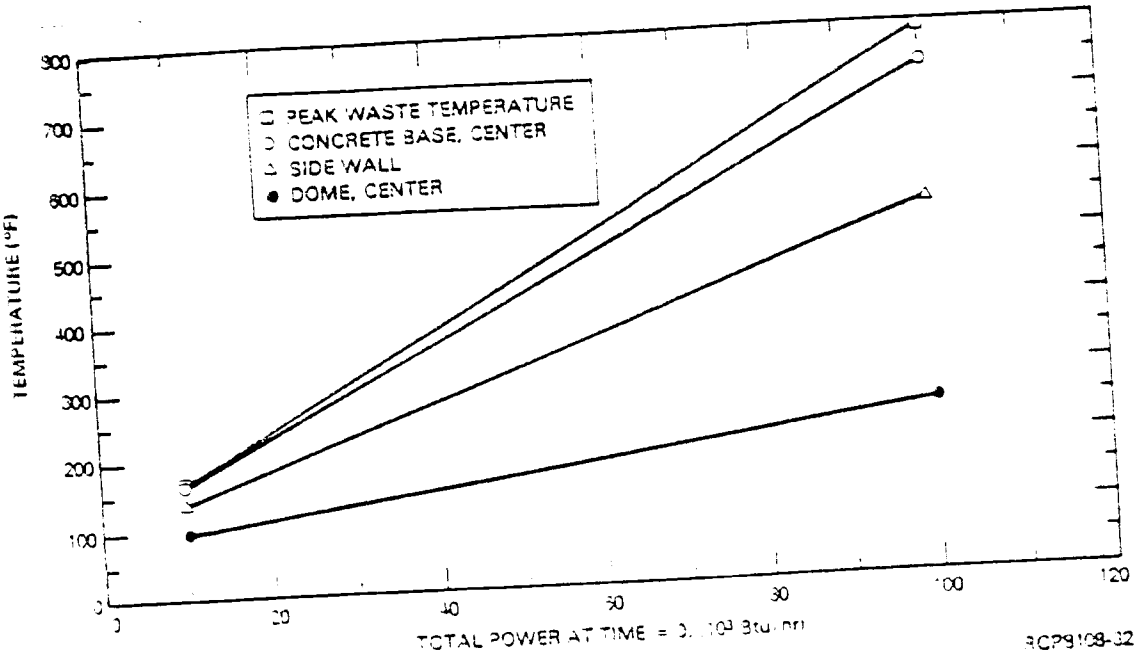

FIGURE 17. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 6 ft, and Concrete Backfill in Air Spaces.

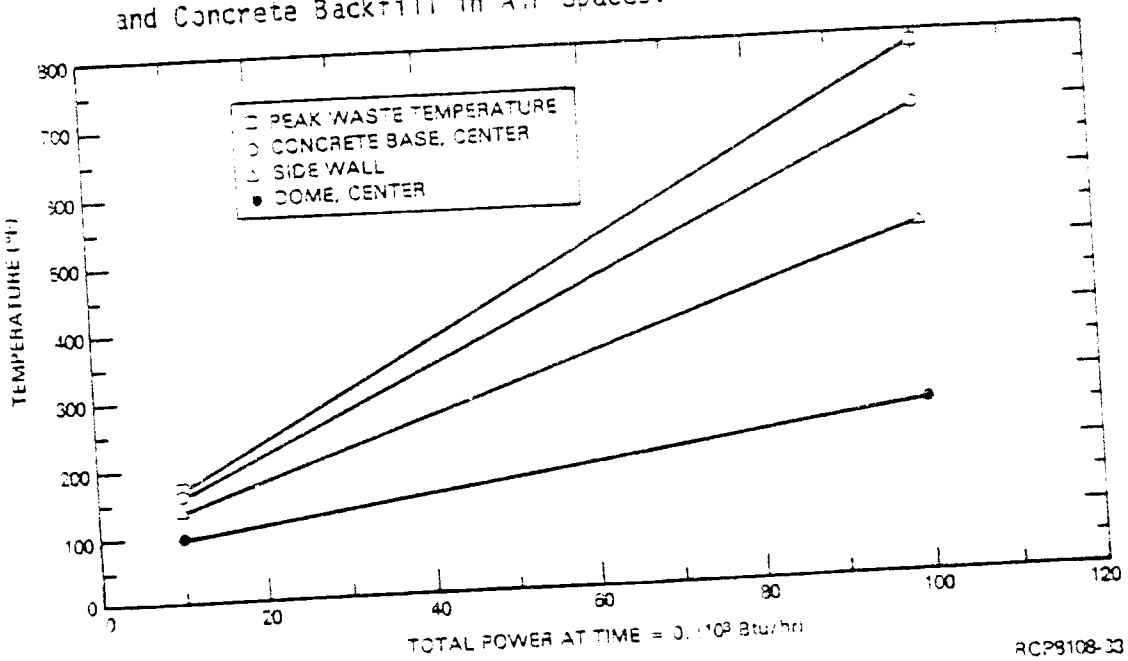

FIGURE 18. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 16 ft, and Concrete Backfill in Air Spaces.

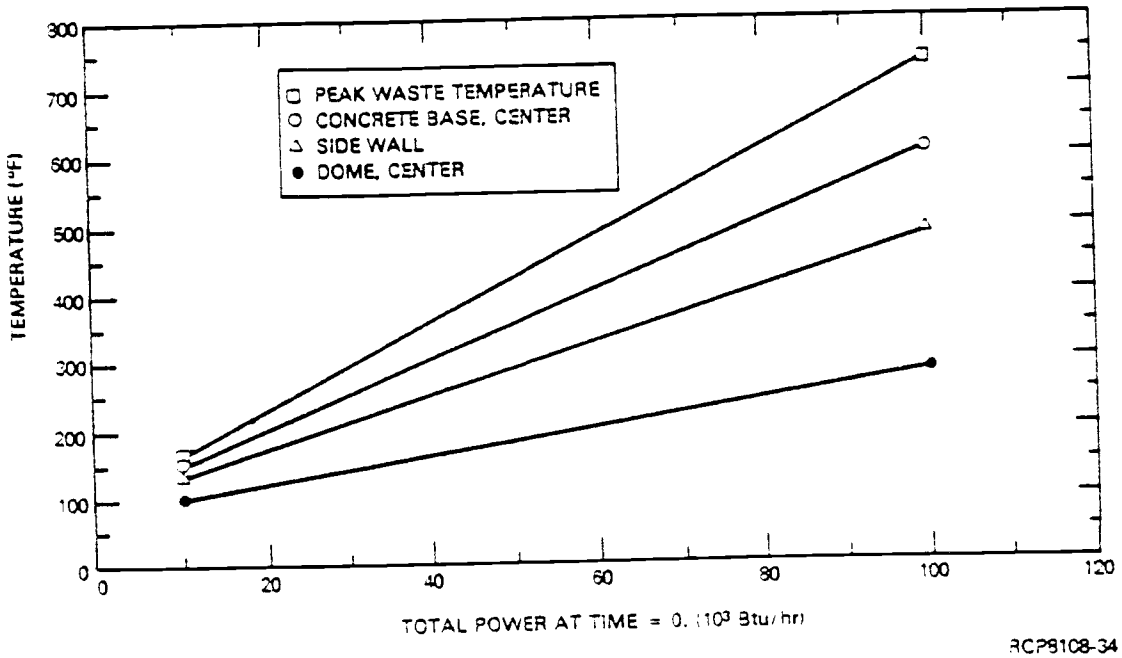

FIGURE 19. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Concrete Backfill in Air Spaces.

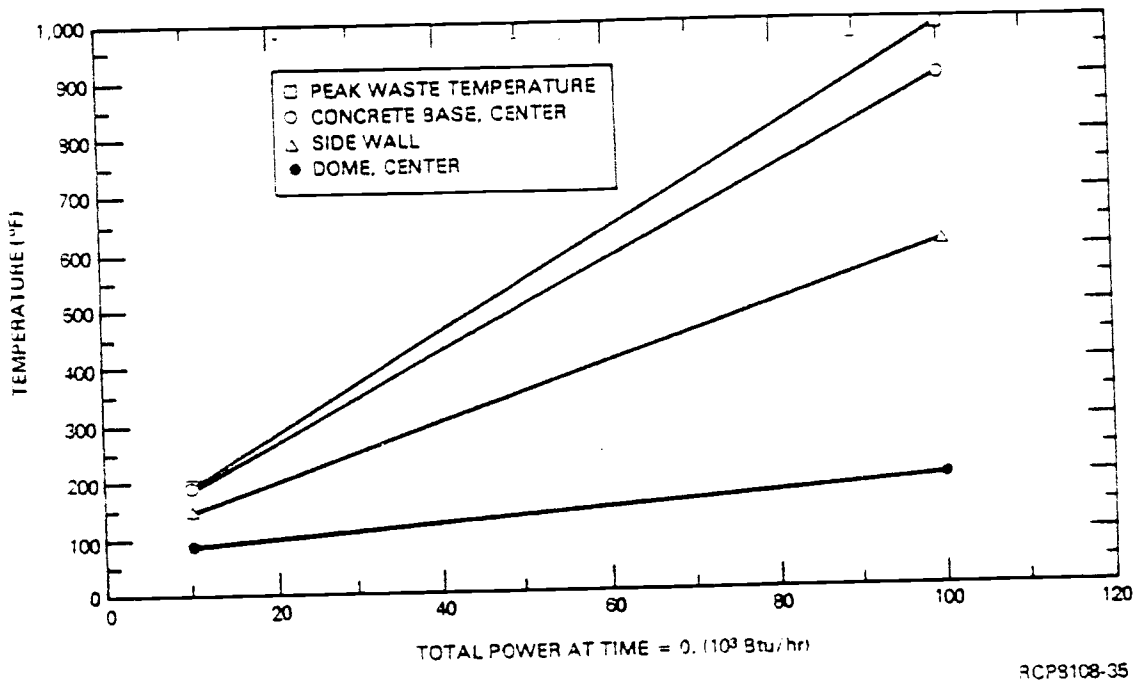

FIGURE 20. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 5 ft, and Sandy Soil Backfill in Air Spaces.

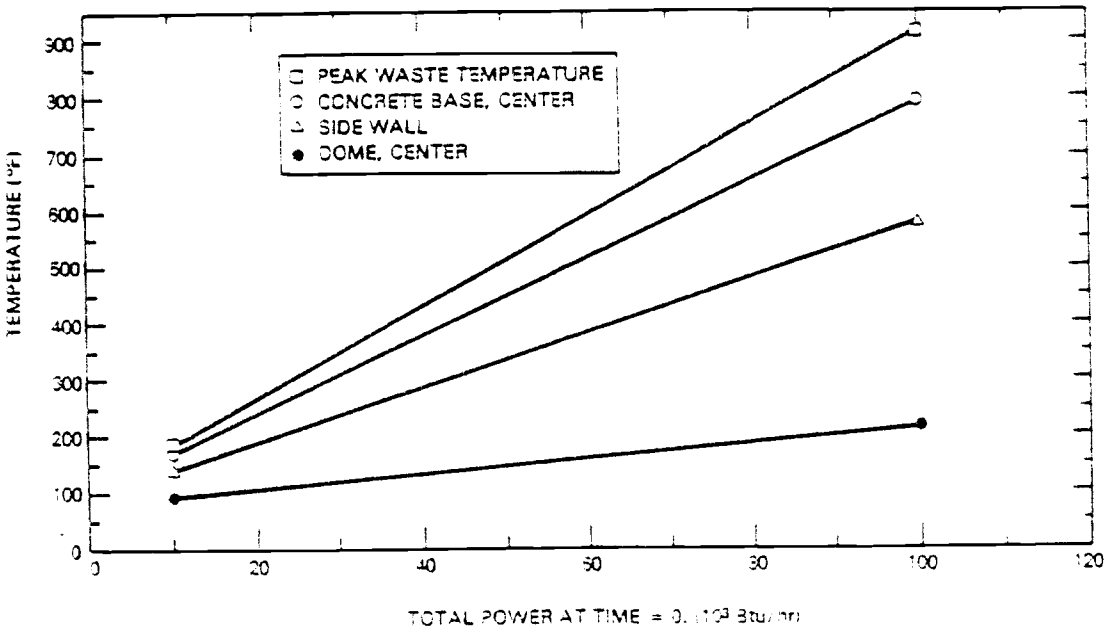

FIGURE 21. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and Sandy Soil Backfill in Air Spaces.

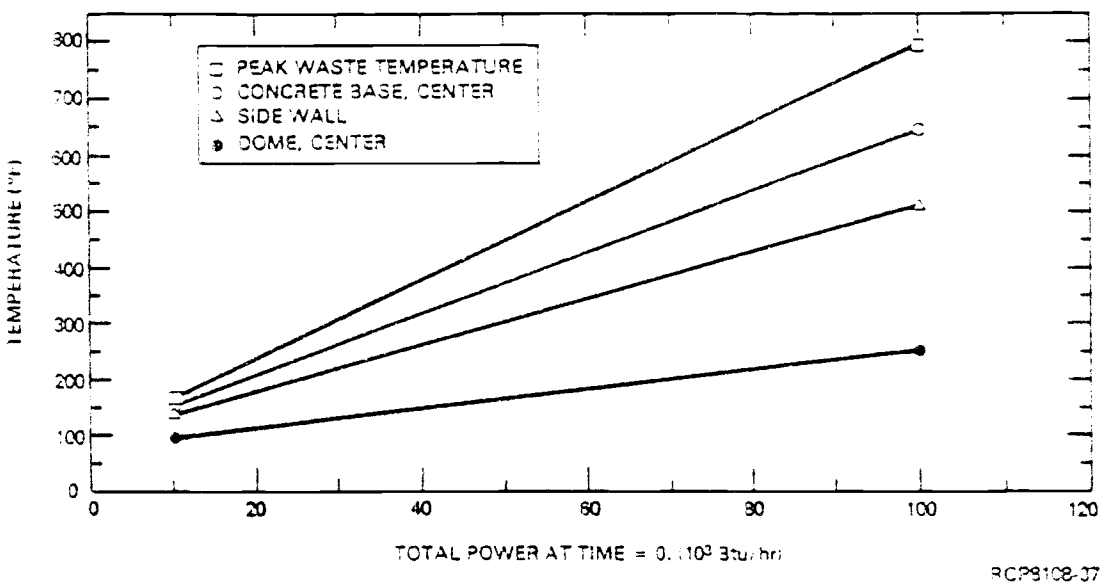

FIGURE 22. Peak Concrete Temperatures of a Double-Shell Tank with No Ventilation, a Waste Solids Depth of 30 ft, and Sandy Soil Backfill in Air Spaces.

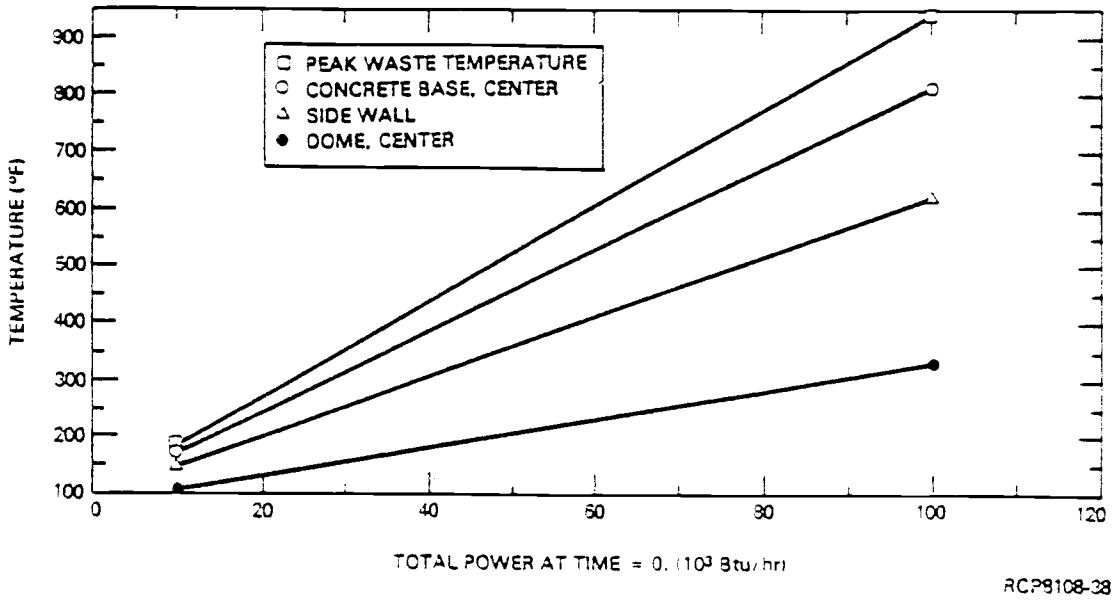

FIGURE 23. Peak Concrete Temperatures of a Double-Shell Tank with 4 m (13.12 ft) Soil Overburden, a Waste Solids Depth of 15 ft, and Sandy Soil Backfill in Air Spaces.

SENSITIVITY ANALYSIS

Due to the variability and uncertainty of the input parameters, calculations were made to show how sensitive the resultant temperatures are to varying certain thermal properties and boundary conditions. The waste thermal conductivity and density, the soil thermal conductivity, the adiabatic boundary radius, and the lower isothermal boundary temperature were each varied, one at a time, to determine their individual effects on peak temperatures. The mathematics of the HEATING5 program was checked on a one-dimensional model and found to be accurate to within 1°F (see Appendix B).

The thermal conductivity of the waste solids is dependent on moisture content, density, and the type of waste it is. As a base case, the value of 0.25 Btu/hr·ft·°F was chosen to represent reasonably dry waste and is based on measurements of dry sludge and saltcake samples. The results of varying the waste thermal conductivity from 0.15 to 1.0 Btu/hr·ft·°F for a single-shell tank with waste 15 ft deep,

generating 50,000 Btu/hr, and no backfill, are shown in Figure 24. Increasing the thermal conductivity decreased the temperatures (except for the dome), but had little effect above 0.5 Btu/hr·ft·°F. Increasing the density of the waste from 65 lb/ft^3 to 103 lb/ft^3 decreased all temperatures less than 3%.

The soil thermal conductivity was varied from 0.15 to 0.50 Btu/hr·ft·°F for the single-shell tank model with waste solids 15 ft deep, generating 50,000 Btu/hr, and no backfill. The temperatures as a function of soil thermal conductivity are shown in Figure 25. Soil thermal conductivity has a large effect on the temperatures. Increasing the thermal conductivity through this range caused a 180°F decrease in temperatures. The base case value, 0.25 Btu/hr·ft·°F, is an average value from measurements on Hanford soil.

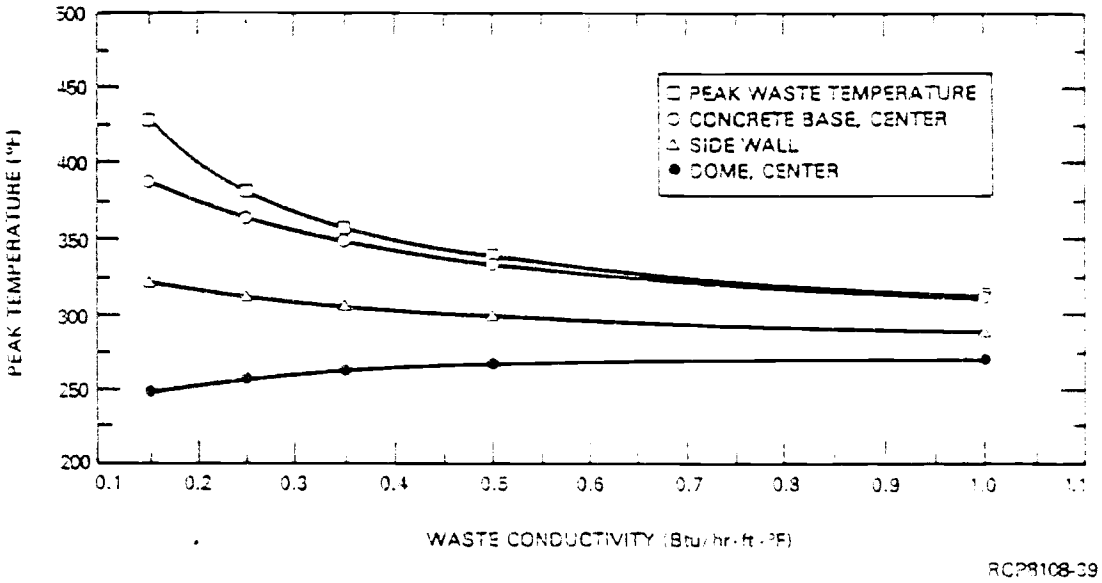

FIGURE 24. Sensitivity to Waste Thermal Conductivity in a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces (50,000 Btu/hr).

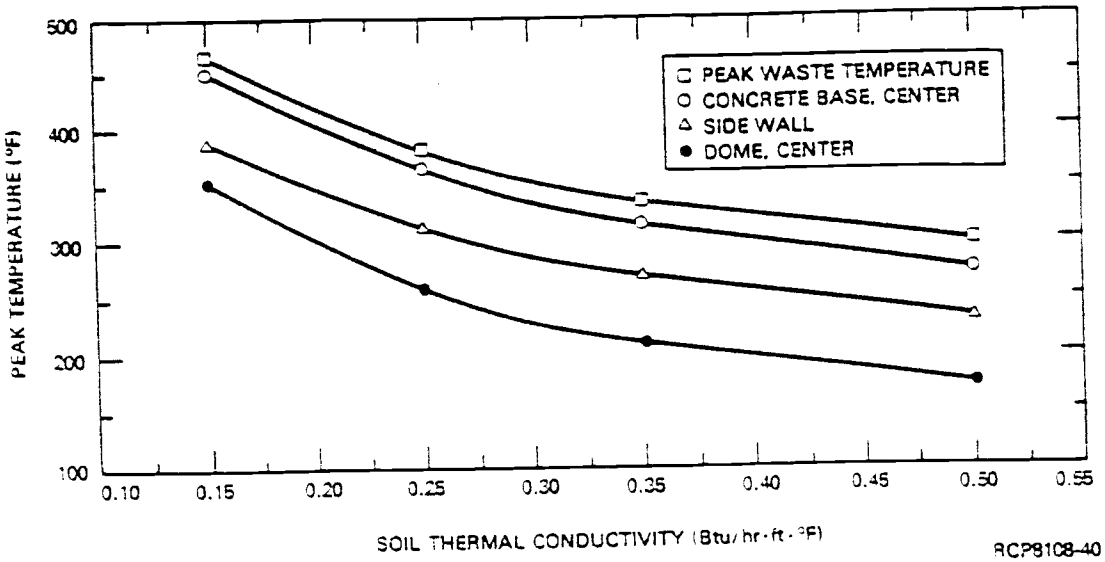

FIGURE 25. Sensitivity to Soil Thermal Conductivity in a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces (50,000 Btu/hr).

The 51-ft adiabatic radius for single-shell tanks is derived from half of the 102-ft, center-to-center tank spacing. Due to the cylindrical coordinate system, this boundary is slightly conservative for a tank in the center of 3 x 3 tank array, and is not as good a model for tanks on the side or corner of a tank farm. The adiabatic radius boundary was varied from 51 ft to 80 ft for a 1 million gal single-shell tank with waste 15 ft deep, generating 50,000 Btu/hr, and having no backfill. The results of these calculations are plotted in Figure 26. The peak waste and concrete base temperatures only dropped about 30°F. The concrete wall temperature dropped about 87°F because it is nearer to the boundary; the dome centerline temperature only dropped 11°F. The 60-ft adiabatic boundary, used for the double-shell tank model, is larger than half of the 107-ft, center-to-center spacing because all double-shell tanks are on an edge or corner of a tank farm (no 3 x 3 tank arrays).

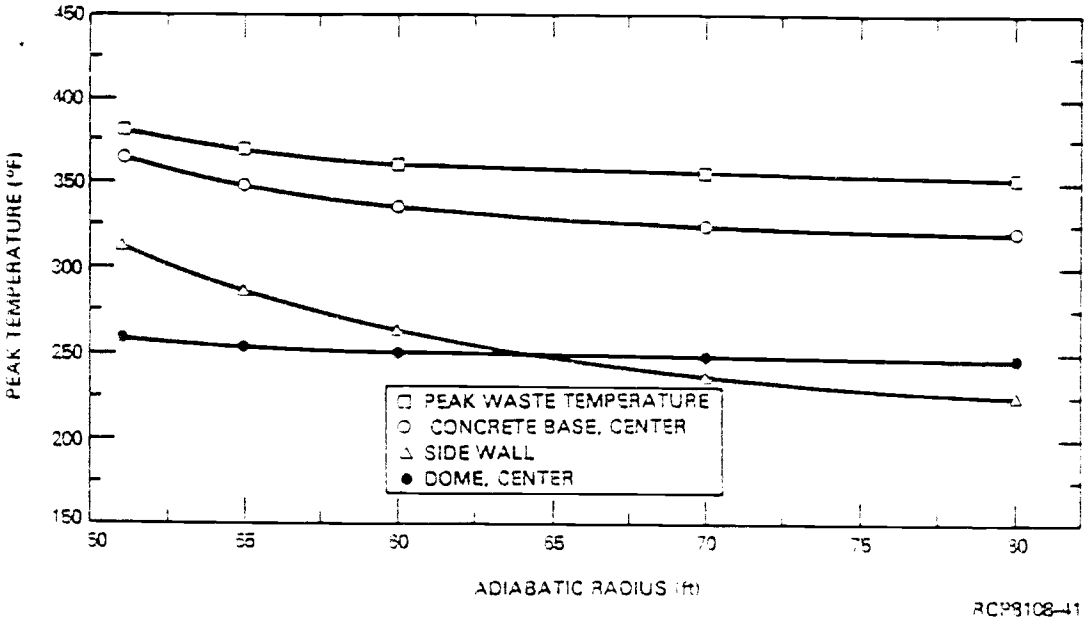

FIGURE 26. Sensitivity to Adiabatic Radius in a Single-Shell Tank with No Ventilation, a Waste Solids Depth of 15 ft, and No Backfill Material in Air Spaces (50,000 Btu/hr).

The isothermal boundary at 200 ft below grade was varied from 55°F to 70°F, resulting in a maximum temperature change of less than 1°F for the four temperatures of interest. This implies that, for practical purposes, an increase or decrease in the average ambient air temperature above the tank would cause an equal change in peak temperatures. However, seasonal fluctations may be neglected, since peak temperatures occurred only after 8 to 30 yrs, depending on the disposal configuration.

THERMAL PARAMETERS AND ASSUMPTIONS

PARAMETERS

The thermal parameters needed to describe heat transfer in UGS tanks are material thermal properties, convection coefficients, boundary conditions, and, in some instances, thermal radiation properties. Heat transfer through waste, structural concrete, soil, and backfill materials is by conduction only. When there is no backfill material, heat transfer

through the tank vapor space and the annulus in double-shell tanks is by conduction, natural convection, and thermal radiation. The boundaries of the heat transfer model are:

- Forced convection to ambient air at the earth surface
- An isothermal or constant temperature boundary at the 200 ft level below the earth's surface
- An adiabatic or insulated boundary at a constant radial distance from the centerline.

The base case material thermal properties used in these calculations are given in Table 2. The thermal property values are for dry materials and are assumed constant with respect to temperature.

TABLE 2. Thermal Properties.

Material	Thermal Conductivity (Btu/hr·ft·°F)	Density (lb/ft^3)	Specific Heat (Btu/lb·°F)
Air (in air space)	0.016	0.071	0.24
Concrete (including backfill)	0.54	144.0	0.21
Insulating concrete (double-shell tank)	0.11	62.0	0.2
Soil (including backfill)	0.25	113.0	0.22
Waste solids (single-shell tanks)	0.25	65.0	0.3
Waste solids (double-shell tanks)	0.25	103.0	0.3

Radiation interchange factors and natural convection coefficients are listed in Table 3. A radiation interchange factor is the "effective" emissivity, and is a function of emissivity and the shape factor.

TABLE 3. Interchange Factors and Convection Coefficients.

Location	Radiation Interchange Factor (Dimensionless)	Natural Convection Coefficient ($Btu/hr \cdot ft^2 \cdot {}^oF$)
Vapor Space (6 ft waste)	0.485	$0.22\Delta T^{.33}$
Vapor Space (15 ft waste)	0.529	$0.22\Delta T^{.33}$
Vapor Space (30 ft waste)	0.592	$0.22\Delta T^{.33}$
Double-Shell Tank Annulus	0.674	$0.5\Delta T^{.33}$

The boundary conditions for the top, outer side, and bottom of the heat transfer model are as follows:

- Adiabatic radius for a single-shell tank is 51.0 ft.
- Adiabatic radius for a double-shell tank is 60.0 ft.
- Isothermal boundary temperature at 200 ft below earth surface is 55°F
- Ambient air temperature is 70°F
- Forced convection coefficient at the earth's surface is 2.0 $Btu/hr \cdot ft^2 \cdot {}^oF$.

ASSUMPTIONS

The assumptions needed to model the single- and double-shell tanks for the HEATING5 computer program are included in the following list:

- Axisymmetric symmetry is assumed. The two-dimensional cylindrical (R, Z coordinates) heat transfer models are defined in Figures 1 and 2. This assumption tends to make the calculations conservative by reducing the surface area through which heat is transferred to the upper and lower boundaries.
- The waste material is assumed to be a cylindrical slab of uniform thickness, thermal conductivity, and power density. Actual tanks have layered solids and varying degrees of nonuniformity

of thermal properties. The resultant temperatures may be somewhat higher or lower, depending on how the heat-generating material is distributed.

- A decay rate half-life of 30 yr is assumed because most of the heat generated is by strontium or cesium decay. This enters into the calcultions, because the peak temperatures reported in Figures 4 through 23 occur from 8 to 30 yr after "zero" time at disposal.
- All air ventilation cooling systems are assumed to be off. Currently, tanks with enough heat generation to be considered a problem are on ventilating systems.
- The concrete in the tank dome of both models is assumed to have the same thermal properties as soil so that the dome curvature could be modeled. Making this conservative and simplifying assumption results in a very slight temperature increase.

REFERENCES

1. U. S. Energy Research and Development Administration, Alternatives for Long-Term Management of Defense High-Level Radioactive Waste, ERDA-77-44, Hanford Site, Richland, Washington (September 1977).

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4. W. L. McCabe, and J. C. Smith, Unit Operations of Chemical Engineering, Second Edition, pp 395-405, McGraw-Hill Company, New York (1967).

RHO-LD-171

APPENDICES

RHO-LD-171

APPENDIX A

SURVEY OF HANFORD TANK HEAT LOADS

A review of readily available data records was made to estimate bulk heat loading in Hanford waste tanks. Since heat generation rates cannot be measured directly, psychrometric data from tank ventilation systems and some solid waste sample analytical data were analyzed to obtain the list of single-shell tanks and estimated heat loads in Table A-1. Psychrometric readings are generally more reliable than solid waste analytical data (due to the number of readings), so most of the estimates listed come from psychrometric data input plus an estimated heat loss by conduction.

This table gives an indication of how many single-shell tanks have more than 20,000 Btu/hr and gives an estimate of their respective heat loads. Psychrometric data is being taken monthly on most of the tanks listed. Heat generation rate estimates may vary from one report to the next because more data is available as time goes on and because of the inherent problems in making this kind of estimate.

Based on results of chemical analysis of double-shell slurry feed and product supernatant samples, the heat generation rate of wastes to be stored in double-shell tanks ranges typically from 40,000 to 90,000 Btu/hr per million gallons of concentrated liquor. When these liquid wastes are solidified (as in preparation for in situ disposal), the heat generation rate would be higher by a factor of 1.2 to 2.0 depending on the method used for drying and solidifying the waste.

RHO-LD-171

TABLE A-1. Hanford Tank Heat Loadings.

Tank	Average Waste Depth (ft)	Estimated Heat Generation Rate (Btu/hr)
101-A	28.2	20,000 ± 10,000*
104-A	0.85	60,000 ± 40,000*
105-A	0.57	60,000 ± 40,000
106-A	2.84	40,000 ± 20,000*
103-AX	3.60	20,000 ± 10,000*
104-AX	0.09	20,000 ± 10,000*
104-BY	18.8	20,000 ± 10,000
105-BY	18.9	30,000 ± 15,000
106-BY	18.9	20,000 ± 10,000
103-C	5.30	20,000 ± 10,000*
105-C	4.54	40,000 ± 20,000
106-C	5.96	180,000 ± 40,000
107-C	10.2	20,000 ± 10,000*
101-S	12.6	25,000 ± 10,000
102-S	16.8	20,000 ± 10,000
103-S	6.99	20,000 ± 10,000
107-S	10.3	15,000 ± 10,000
110-S	20.9	15,000 ± 10,000
101-SX	13.8	30,000 ± 20,000*
102-SX	15.7	30,000 ± 20,000*
103-SX	19.2	30,000 ± 20,000*
104-SX	21.6	30,000 ± 20,000*
105-SX	20.4	30,000 ± 20,000*
107-SX	3.30	45,000 ± 20,000
108-SX	2.63	54,000 ± 20,000
109-SX	7.78	60,000 ± 30,000
110-SX	1.18	50,000 ± 20,000
111-SX	3.78	53,000 ± 20,000
112-SX	3.21	50,000 ± 25,000
114-SX	6.05	70,000 ± 35,000

*No Psychrometric data available.

APPENDIX B

HEATING5 CODE CHECK CALCULATIONS

A one-dimensional heat conduction problem was selected to compare the HEATING5 calculational method to the results of an exact solution. The problem of the uniformly heated, semi-infinite slab was modeled for HEATING5. The slab is 30 ft thick and generates heat according to the equation:

$$Q = Q_0 e^{-\lambda t} \text{ for } t \geq 0.$$

where:

Q_0 is the Initial Power Density (Btu/hr ft^3)

$-\lambda$ is $\ln(0.5)/\tau$; τ = half-life = 30 yr = 2.63E+5 hr

$-\lambda$ is -2.636E-6 hr^{-1}

t is time (hr).

The two surfaces are held constant at 0.0°F and the initial slab temperature is 0.0°F. The transient temperatures were calculated over a 10 yr (87,660 hr) period. Selected results of the HEATING5 calculations are compared in Table B-1 with the results of the exact solution given by the following equation:[1]

$$T = \frac{\kappa Q_0}{\lambda k}\left(\frac{\cos(x\sqrt{\lambda/\kappa})}{\cos(\ell\sqrt{\lambda/\kappa})} - 1\right) e^{-\lambda t} + \frac{4\kappa Q_0}{\pi\lambda k}\sum_{n=0}^{\infty}\frac{(-1)^n\, e^{-\kappa(2n+1)^2\pi^2 t/4\ell^2}\cos((2n+1)\pi x/2\ell)}{(2n+1)\,(1-((2n+1)^2\pi^2\kappa/(4\lambda\ell^2)))}$$

where:

T is the temperature at point x and time t

κ is the thermal diffusivity (ft^2/hr)

k is the thermal conductivity ($Btu/hr \cdot ft \cdot {}^oF$)

x is the distance from slab center (ft)

ℓ is 15 ft, $-\ell \leq x \leq \ell$

e is 2.71828...

π is 3.14159...

The summation on the right side of the equation converges within 40 terms for small values of t and within 4 terms for large values of t. The results in Table B-1 show that the finite differencing method in HEATING5 is accurate to within 1^oF in the test problem.

TABLE B-1. Temperatures at Point x and Time t for HEATING5 and Exact Solution.

t, time (hr)	x, Distance from center of slab (ft)					
	0.0		6.0		12.0	
	HEATING5	EXACT	HEATING5	EXACT	HEATING5	EXACT
1.0	0.08	0.08	0.08	0.08	0.08	0.08
10.0	0.77	0.77	0.77	0.77	0.76	0.77
100.0	7.69	7.69	7.69	7.69	6.97	7.36
1,000.0	76.04	76.34	72.24	72.84	43.08	43.6
8,766.0 (1 year)	370.40	371.39	313.31	314.11	136.91	137.21
35,064.0 (4 years)	415.37	415.32	348.77	348.74	149.30	149.28
87,660.0 (10 years)	361.83	361.81	303.81	303.79	130.05	130.04

REFERENCE

1. H. S. Carslaw, and J. C. Jaeger, Conduction of Heat in Solids, second edition, p 132, Oxford Press, Cambridge (1959).

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INSTABILITY OF STEEL BOTTOMS IN WASTE STORAGE TANKS

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L. E. BROWNELL

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INSTABILITY OF STEEL BOTTOMS IN WASTE STORAGE TANKS

INTRODUCTION

In early June, instability of the steel liner in the bottom of storage tank 113-SX was indicated by column rod readings through the risers in the top of the tank. These measurements showed an upward dishing of the tank bottom to a height of about 4 feet followed by a return of the liner to a horizontal position later in the month. A theory explaining the phenomenon has been developed and is presented herein.

POSTULATE

Either air, vapor or liquid pressure between the steel liner and the concrete bottom may have caused the upward dishing of the liner. The deflection of 4 feet is too great to be explained by expansion of entrapped air. It has been proposed that liquid waste leaked from the charging nozzle between the liner and the wall to cause the dish. However, a tremendous volume and weight of liquid would be required to dish the bottom to a height of 4 feet. The gravity flow of so great a volume of liquid (10,755 ft.^{3}) equal to about 22 per cent of the volume of waste in the tank through a leak in the open nozzle does not seem probable. Also, insufficient activity was found when a swipe of the inlet annulus (see drawing H-2-39517) was made to account for a liquid leak at this point. Furthermore, drawing H-2-39512 shows that the shell and bottom were thoroughly reinforced with steel every few inches and that the shell was tied to the bottom all around the perimeter with reinforcing steel. Thus, although cracks no doubt exist in the concrete (particularly at the junction of the shell and bottom) as a result of tensile stresses, these cracks should be of hairline size and would not provide a rate of leakage of liquid sufficient to account for over 10,000 cu. ft. and permit return of the steel bottom in a few days as observed.

On the other hand, only a small weight of liquid either as water entrapped in the grout (see drawing H-2-39511), or organic solvent from asphalt primer used on concrete bottom or a combination of both could through vaporization dish the bottom of the liner. Therefore, it is suggested that the instability of the steel bottom in Tank 113-SX was caused by vapor.

It is possible that the reason the phenomenon of dishing was not observed previously on other tanks, may be that this was the first tank in which the junction between the concrete shell and steel liner was vapor tight (see drawing H-2-39511). It will be shown that the forces associated with the deformations observed were sufficient to bend the bottom of the steel shell away from concrete shell. The question has been raised as to why this did not permit the vapor to escape? It is proposed that a small amount of asphalt was forced around the bottom outer corner of the steel liner and up to a height of 10 inches or more as shown in Fig. 2 after the tank was partially filled with hot waste and before the vapor

pressure was sufficient to raise the steel bottom. As the bottom raised, it is believed that the steel shell below the first stiffener moved inward, opening the bottom corner to the vapor, but making a still tighter seal near the stiffener as shown in Fig. 3. As the strain on the bottom increased, one of three possible events could have released the vapor quite suddenly, permitting the steel liner to return to rest on the concrete bottom.

One means of vapor escape would be the failure of the weld at the junction of the steel shell and steel bottom as shown in Fig. 8. Bending stresses here would have produced large plastic strains. When asked about the possibility of failure of this joint, F. H. Waldrep, welding inspector, (Bldg. 2723-W) stated that in his opinion some part of the bottom circumferential joint would surely be expected to fail if the bottom liner were raised 4 feet. Such a rupture would permit the vapor to escape into the tank, allow the bottom to return and would show a drop in liquid level as observed. However, if the bulge had been caused by liquid, such a rupture would have made no appreciable change in liquid level in the tank.

Vapor might also have escaped from under the steel liner as a result of a blow-out of the mastic sealing the shell. In this case the vapor might have leaked out over an extended period of time and the steel liner could still be intact.

A third method of vapor release would be the buckling of the lower stiffener, permitting the vapor to escape between the steel and concrete shell above the level of proposed mastic flow. In this case, the liner would be deformed with a bulge inward where the stiffener buckled, but although deformed, the liner could still be intact and free of leaks.

The first six following sketches (Fig. 1-6) summarize the theory proposed for the development of the instability of the steel bottom. Figure 7 shows a sketch of the tank after it was empty and the shell had cooled causing shrinkage and ridging of the bottom. The next three sketches (Fig. 8-10) show the three proposed paths for vapor escape.

DISCUSSION

A. Evidence that the Bottom of Steel Shell Plastically Deformed Inwards Away From Concrete Shell

Various ideas regarding the reason for instability of the steel tank bottom have been proposed. These involve a consideration of whether or not the steel shell plastically deformed inwards away from the concrete shell. The minimum strain inward would occur if the bottom took the shape of a section of a sphere; therefore, this condition will be considered first.

The steel liner of the tank bottom as built has a dish downward with the center 1' 2-7/8" below the junction at shell (see drawing H-2-39511). Vapor pressure underneath could reverse this curvature as a result of "oil-can" action without additional strain, leaving the center 2' 5-3/4" above original position and 1' 2-7/8" above horizontal through corner junction as shown in Figure 11.

With reference to Figure 11:

$$r^2 = (r - 1.2396)^2 + (37.5)^2$$

$$r^2 = r^2 - 2.4792r + 1.537 + 1406.25$$

$$r = \frac{1407.787}{2.4792} = 567.839$$

$$\sin \theta_1 = \frac{37.5}{567.84} = 0.0660397$$

$$\theta_1 = 3.787°$$

$$l_1 = \frac{2\pi(567.839)\ (3.787)}{360}$$

$$= 37.5318 \text{ ft.}$$

Thus an arc length, l_1, of 37.5318 ft. could exist across a tank radium of 37.50 ft. without producing a tensile hoop stress.

At maximum buckling the bottom raised over 4 feet. The minimum strain would be produced if the buckled condition also produced an arc as shown in Figure 12.

With reference to Figure 11:

$$r_2^2 = (r_2 - 3)^2 + (37.5)^2$$

$$r_2^2 = r_2^2 - 6r_2 + 9 + 1406.25$$

$$r_2 = \frac{1415.25}{6} = 235.875'$$

$$\sin \theta_2 = \frac{37.5}{235.875} = 0.15898$$

$$\theta_2 = 9.1476°$$

$$l_2 = \frac{2\pi(235.875)\ (9.1476)}{360} = 37.659 \text{ ft.}$$

$$l_2 - l_1 = 37.659 - 37.532 = 0.127 \text{ ft. or } 1.524 \text{ inches}$$

The strain involved (uncorrected for thermal expansion) in increasing the bottom dish to 4.25 ft. at center is 0.127 ft. or 1.524 inches. Part of this strain will be taken up by thermal expansion as the tank bottom heats up from an ambient temperature of approximately 60°F to the tank bottom temperature of approximately 230°F or

$$37.532\ (12)\ (230 - 60)\ (0.65)\ 10^{-5} = 0.498 \text{ inches}$$

1.524 inches total strain
-0.498 thermal elongation

$$\Delta \ell = 1.026 \text{ inches}$$

Thus a $\Delta \ell$ of 1.026 inches remains to be accounted for by elastic or elastic plus plastic strain. To estimate the magnitude of the stress if the strain were all elastic, consider a diametral strip of 1 inch width across the tank bottom. The unit strain e will be:

$$e = \frac{1.026 \text{ in.}}{37.532\ (12)} = 0.002278 \text{ inches/inch}$$

$$f = 0.002278 \times 30 \times 10^6 = 68{,}340 \text{ psi}$$

Thus, a stress of 68,340 would be produced if the bottom of the vertical shell remained in its original position and if the strain were entirely elastic in the tank bottom. This is impossible since the elastic limit of the bottom is about 30,000 psi for the steel used in the tank. Furthermore, long before the elastic limit in straight tension would have been reached in the bottom, the shell near the junction would have undergone permanent strain as a result of the high bending stresses produced. Since the spherical dish assumed would produce the minimum strain, there is no need to calculate the larger strain which would have been produced if the dish had a shape such as shown in Figure 6. It must be concluded that the bottom of the shell moved radially inward to relieve the strain produced in the steel bottom as it bulged.

B. Calculation of Pressure on Vapor Below Dish

The pressure on the vapor believed to have produced the dish may be calculated. A comparison of this pressure with the vapor pressure corresponding to the temperature at the bottom indicates whether or not vapor could have existed.

By a balance of forces, it is apparent that the pressure on the vapor must be sufficient to equal the sum of the pressure caused by the hydrostatic head of liquid, weight of steel in bottom and the hoop stress in the dished bottom. The column rod measurements showed a 4'1" rise at the south 12" riser where the indicated liquid level was 14.7 ft. and the sp. gr. was found to be 1.32. This actual depth of liquid therefore was 14.7 - 4.08 or 10.62 feet. Other measurements showed a rise of 4'2" at 8 feet radius, 4'1" at 12 feet radius and 36-1/4" to 40-3/4" at 20 feet radius. No measurements were made at a greater radius. It will be assumed that the restraint of the shell prevented any significant rising of the bottom near the shell wall.

Since the hydrostatic head varies across the diameter of the tank, the pressure caused by this head will be calculated by dividing the total weight of supported liquid by the bottom area. As an approximation the height of supported liquid will be taken as 10.7 ft. out to a radius 17.5 ft. The liquid above the bottom at the shell wall will be 1.2 ft. less than 14.7 ft. or 13.5 ft. because of slope of bottom (see drawing H-2-39511). The curvature of the bottom from a 17.5 ft. radius to the shell wall is unknown, therefore an estimated average depth of 11-1/2 ft. will be used for liquid in annulus, or:

Weight of Liquid Waste

$$\left[\pi(17.5)^2 10.7 + \pi(37.5^2 - 17.5^2)11.5\right] \quad 62.4(1.32) =$$

$$(10,300 + 40.400)\ 82.4 = 4,180,000 \text{ lbs.}$$

Weight of Steel Bottom

$$\pi(37.5)^2 \frac{(3/8)\ 460}{12} = \begin{array}{r} 60,000 \text{ lbs.} \\ 4,240,000 \text{ lbs.} \end{array}$$

Pressure from Gravitation Components

$$p_1 = \frac{4,240,000 \text{ lbs.}}{\pi(37.5)^2(144)\text{ in.}^2} = 6.36 \text{ psi or } 6.4 \text{ psi}$$

The pressure, p_2, caused by the hoop tension in the bottom must also be added to the gravitational component. The D/t ratio for the steel shell is so large that restraint to bending as a result of shell curvature will be neglected. Since a 5" x 3-1/2" angle stiffener exists only 9" above the bottom and provides a fulcrum the maximum bending moment (except from discontinuity at the junction) will result from cantilever action over the angle stiffener as shown.

Assuming the yield point (taken as 30,000 psi) of the mild steel over the stiffener has been reached, f = 30,000 psi

$$f = \frac{Mc}{I} = \frac{6\ M}{b\ t^2} \quad \text{or } M = \frac{fbt^2}{6}$$

For a unit strip of shell (b = 1")

$$M = \frac{(30,000 \text{ lb./sq.in.})(1 \text{ in.})(3/8 \text{ in.})^2}{6}$$

Also for cantilever action (l = 9")

$$M = Pl$$

$$P = \frac{(30{,}000 \text{ lb./sq.in.})(1 \text{ in.})(3/8 \text{ in.})^2}{(9 \text{ in.})(6)}$$

$$= 78.1 \text{ lbs. per linear inch}$$

Therefore, hoop tension in bottom is:

$$f = \frac{P}{t} = \frac{78.1 \text{ lb./in.}}{3/8 \text{ in.}} = 217 \text{ psi}$$

The estimate of the pressure on the vapor created by a hoop tension of 217 psi in the dished bottom will be treated as a section of a sphere.

With reference to Figure 12:

$$r = 235.875$$

For section of sphere

$$p_2 = \frac{4(f)(t)}{d} = \frac{4(217 \text{ psi})(3/8 \text{ in.})}{(235.9)\ (24)}$$

$$= 0.0525 \text{ psi}$$

Some additional restraint will be caused by curvature of shell and strain at the junction. Therefore, pressure due to hoop stress will be arbitrarily taken as 0.4 psi.

The total pressure on vapor is $p_1 + p_2 =$

$$6.4 + 0.4 = 6.8 \text{ psi gage}$$

or 21.5 psi abs.

C. Comparison of Measured Temperature with that Required for Production of Vapor Under Liner

The specific volume of steam at 21.5 psi abs. is 18.72 cu. ft./lb. and the saturation temperature is 232°F. This temperature is within expected agreement with the sludge temperature measured to be approximately 230°F. at the maximum dish. Therefore, the vapor will be treated as pure steam. However, it is quite probable that some small amount of organic vapor is present as a result of using on the concrete bottom an asphaltic primer containing a solvent (see specification HW-4957). The effect of the presence of an organic vapor would be to lower the pressure and therefore the temperature of the water vapor as

a result of partial pressure relationships (Dalton's Law). In either case the temperature as measured at the bottom of tank would be adequate to produce saturated vapor with sufficient pressure to dish the steel bottom.

D. Volume, Weight and Source of Water which Might Produce Vapor Causing Dishing

The volume of vapor in the dish is estimated to be equal to that in a cylinder 4 feet high and 17.5 feet radius plus that in an annulus 2 feet high with an O.D. of 37.5 feet and an I.D. of 17.5 feet or

$$\text{Volume} = \pi(17.5)^2\ 4 + \pi(37.5)^2 - 17.5^2)2$$

$$= 3845 + 6910 = 10{,}755 \text{ cu. ft. vapor}$$

$$\text{Wt.} = \frac{10{,}755}{18.72} = 575 \text{ lbs.}$$

$$\text{Vol. liquid water} = \frac{575}{62.4} = 9.2 \text{ cu. ft.}$$

The 2-inch layer of grout (see drawing H-2-39511) would be a possible source of liquid water. The weight of grout under the tank bottom is:

$$\text{Wt. grout} = \frac{\pi\ (75)^2}{4} \times \frac{2}{12} \times \frac{150 \text{ lbs.}}{\text{Cu. Ft.}} = 110{,}500 \text{ lbs.}$$

The weight per cent moisture loss in grout to produce vapor would be:

$$\frac{575 \text{ lbs.}}{110{,}500 \text{ lbs.}} \times 100\% = 0.52\%$$

It appears reasonable that heating of the grout might release 0.52 per cent water since the grout is made with a hydraulic cement and usually an excess of water. If the tank liner was installed and made vapor tight at top seal (see Section 250 of drawing H-2-39511) before the excess moisture had been driven from grout, it would remain trapped. Ripples have been observed in bottoms of empty tanks. Heating of tank bottoms and trapped water to temperatures less than 230°F. might explain such rippling.

E. Questions Raised Against the Vapor Theory of Bottom Instability

In considering the cause of bottom instability a number of questions have been raised against the vapor theory. These are:

1. Why was the vapor retained under the bottom rather than escaping up side between liner and concrete shell?

2. When the steel bottom is raised slightly by vapor, the heat transfer through the bottom would be reduced which should result in condensation of vapor and collapse of bulge. If this is true, how can one account for a bulge 4 feet high in the tank bottom?

3. A material balance was made on solids in tank based upon specific gravity measurements. These calculations indicate a considerable loss of solids from tank. How can one account for this loss without assuming a loss of liquid from tank?

4. Why would vapor produce a bulge as observed in tank 113 on SX farm and not in tanks previously filled?

F. Possible Answers to These Questions

1. It is believed that a possible method of containment of vapor has been described under item 2, and in Figures 1, 2 and 3. The flow (10 inches up shell) of mastic under pressure and heat from initial waste charged would provide sufficient gasket material to make a vapor-tight seal. However, there must have been a gap between the concrete shell and steel liner to permit flow of mastic. Probably such a gap exists since the concrete was poured in successive increments of about 6 feet around the steel shell with the latter completely filled with water. Consider the stress on the lower 10" of the steel liner at the time of pouring the concrete:

Internal hydrostatic pressure from 30 feet of water

$$= \frac{30 \text{ ft.} \times 62.4 \text{ lbs./ft.}^3}{144 \text{ sq. in./ft.}^2} = 12.99 \text{ psi}$$

External pressure from 4 feet of wet concrete:

$$\frac{6 \text{ ft.} \times 150 \text{ lbs./ft.}^3}{144} = 6.24 \text{ psi}$$

Net internal pressure on steel shell at bottom

$$12.99 - 6.24 = 6.75 \text{ psi}$$

Hoop stress in steel shall at bottom

$$f = \frac{pd}{2t} = \frac{6.75\ (75)(12)}{2(3/8)} = 8{,}100 \text{ psi}$$

Unit circumferential strain on steel shell

$$e = \frac{f}{E} = \frac{8{,}100}{30 \times 10^6} = 0.00027 \text{ in./in.}$$

Total radial strain, Δ

$$\Delta = 0.00027\ (37.5)(12) = 0.122 \text{ inches}$$

Thus, the gap between the steel liner and concrete shell probably exceeded 1/8" after water was emptied from the tank. This would be sufficient for mastic flow in a heated tank.

2. The degree of reduction in the heat removal from bottom of the concrete tank as a result of vapor formation between steel and concrete bottoms can be calculated.

From Perry's Handbook the following values for thermal conductivities were obtained:

k for stone aggregate concrete = 0.54 BTU/(hr.)(sq.ft.)(°F/ft.)

k for grout (1:4 portland cement and sand) = 0.44

k for asphalt = 0.43

k for steel = 25.9

The resistances to heat transfer are equal to the thicknesses divided by the respective conductivities, or:

for steel: resist. $= \frac{3/8}{25.9\ (12)} = 0.0012$

grout resist. $= \frac{2}{(0.44)(12)} = 0.378$

asphalt resist. $= \frac{3/8}{0.43\ (12)} = 0.073$

concrete resist. $= \frac{1\ \text{ft.}}{0.54} = \underline{1.852}$

Total resistance to thermal conduction through tank bottom before lifting of steel liner = 2.304

If all of the steel bottom is raised to leave a vapor space between the steel liner and the grout, the resistance of the vapor to heat transfer will be added to the resistances previously present. It is estimated that the combined heat transfer coefficient for the vapor for heat transfer by both radiation and natural convection is about 1.0 BTU/(hr.)(sq.ft.)(°F). This is equivalent to a resistance of 1.0 since the resistance is the reciprocal of the coefficient. Thus, if the entire bottom is raised, the thermal resistances increase from 2.30 to 3.30 and the amount of heat transferred would be reduced by about 1/3. However, the original curvature of the tank bottom would result in reversal of curvature at first (see Figure 5). Then the greater hydraulic head at the annulus as compared to the center of the tank will tend to perpetuate the bubble shape as shown in Figure 6, leaving

the annulus of the steel bottom in contact with the grout. Since the annulus might contain approximately 50% of the bottom area, the average resistance would be increased to approximately 2.80. The percentage of the original heat transfer would be (2.30/2.80)(100%) = 82%. Thus, it is believed that the added resistance of the bubble of vapor is not sufficient to stop the evolution of vapor from the grout.

3. In regard to the material balance, it must be recognized that the distribution of solids in the tank is not uniform because of the accumulation of sludge near the bottom. Therefore, it is not possible to make an accurate material balance based on the specific gravity of a sample taken 3 feet above the tank bottom.

4. There is no single answer as to why vapor may have formed under the bottom of this tank to produce a bulge and did not do likewise under other tanks. It may be that this was the first tank in which a vapor tight mastic seal was produced. However, some other tanks may have dished without detection. A lower temperature during initial fill would prevent dishing. After complete filling the hydrostatic head is so great that there is less probability of vapor formation below the liner provided agitation is sufficient to prevent excessive temperature build-up at the bottom of the sludge.

G. Suggestion for Changes in the Design of Waste Storage Tanks

Whether or not the instability of the bottom of tank 113-SX was caused by vapor, by liquid, by thermal expansion, or by a combination of these, is more or less of academic interest. The important consideration is that this type of failure should be prevented in future tanks by appropriate changes in the design.

If a modification of the present design is to be used in future tanks, it is recommended that a suitable vent be provided to the interfacial zone between the steel liner and the concrete bottom so as to allow for the escape of either vapor or liquid that otherwise might be trapped. Many designs are possible that should provide a satisfactory solution to this problem.

Another change in design should be made so as to provide an allowance for thermal expansion of the bottom of the tank liner. Earlier tanks of BX design (see drawing H-2-602) and TX design (see drawing H-2-802 or see report by E. F. Smith - HW-37519) had two features that allowed for thermal expansion. First a layer of mastic and gunite on the outside of the steel shell permitted some expansion of bottom and shell before being stopped by the restraint of the reinforced concrete shell. Second, the four-foot radius at the lower corner was particularly useful in transfer of compressive stress in the bottom liner around the arc so as to relieve the stress by lifting the shell of the tank. These were good design features which were eliminated in the SX Tanks (see drawing H-2-39511) and the Purex Tanks (see drawing H-2-55911). If either a radius in the lower corner or the mastic had been retained in the later designs there would have been some provision for thermal expansion of the bottom steel liner relative to the concrete tank.

There is nothing wrong with a design of a steel tank with a completely flat bottom and a 90 degree junction at the lower corner, provided the shell and bottom are free to expand and the bottom is vented so as to prevent collection of trapped vapor or liquid. These problems are of special importance when the tank is filled with hot fluid having temperatures above the boiling point of water.

Welded steel tanks with flat bottoms and 90 degree junctions built according to the specifications of API Standard 12C have been used with great success in the oil industry. There is no known report of instability of the bottom of these tanks and the bottoms are usually free of trouble if set on properly prepared pads of sand or gravel over a sound foundation. Such tanks are often charged with hot residual stocks having temperatures higher than those observed in 113-SX. The sand or gravel pad is porous and permits the venting of any vapor that might be produced under the tank. Also, the tanks are free to expand radially.

Gravel might be used as a vent under the bottom liner of future waste storage tanks at Hanford. One possible design is shown in Figure 13. Figure 13 shows a sump in the center of the tank bottom which would collect any liquid which might leak from the tank. If a tank liner developed a leak a suitable monitor probe placed in the sump could be used to warn of the leak and allow emptying of the tank. Either vapor of liquid could pass through the porous bed of gravel (35 to 40 per cent porosity for uniform sized stones). This would prevent a build-up of pressure under the steel liner on the bottom.

Circumferential baffles of expanded metal could be used to prevent radial shifting of the gravel while the steel bottom liner is being laid. Radial sheet metal solid baffles leading to the sump could be used to divide the gravel bed into quadrants. In case of a leak, this might be useful in locating the quadrant of the leak.

It is suggested that the vent from the sump might consist of an eight inch XH pipe resting on a bearing plate on the reinforced concrete. The pipe would be perforated as it passed through the gravel section so as to vent vapor and liquid. Vapor could be vented above grade from the top of the pipe through a low pressure relief valve and collected in a small tank for inspection and monitoring before release to the atmosphere.

A steel liner which fits tightly inside a concrete shell provides no means for differential thermal expansion. Such expansion can result in high compressive stresses in the steel liner which may produce elastic instability. Instability is particularly likely to occur in the flat bottom of the liner resulting in rippling of the bottom. This is more apt to occur in designs in which the junction at the lower corner is 90 degrees as in the SX Tanks than in designs in which a radius is used as in BX and TX Tanks of earlier design. Empty tanks on the SX farm have been observed to have rippled bottom liners before filling.

A hydraulic head would tend to flatten the ripples but filling with hot waste would tend to increase the degree of rippling because of the restraint of the concrete shell. Under certain conditions this might cause rupture of a joint. The severity of the rippling is believed to have been demonstrated by the instability of the bottom of Tank 113-SX after it was emptied. It is suggested that the restraint offered by the concrete shell be reduced by a return to the use of an asphalt expansion joint between the steel shell and the concrete shell.

The suggested design shown in Figure 13 has been given only preliminary consideration and is only one possibility of a means of improving the existing design. Several other designs should also be considered.

One obvious design that would eliminate some of the faults with existing tanks would be to simply set a steel tank similar to one meeting specifications of API Standard 12C inside a concrete tank of present design with a clearance between shells and a porous pad between bottoms. Such a steel tank (of proven design in the petroleum industry) would be capable of holding the hot waste by itself provided it is protected from external pressure of the earth by the concrete tank.

H. Possible Procedure for Preparing Tank 113-SX for Reuse

The bottom of Tank 113-SX has undergone such a series of severe plastic strains that it must be assumed that some of the welds in the bottom or at the junction with the shell have failed. If the tank is refilled with liquid, slow leakage will probably occur through the concrete shell due to small tensile cracks in the concrete. The mastic on the bottom should prevent leakage through the concrete bottom.

The 113-SX tank might be used again for storage of radioactive waste if a new bottom liner could be placed in the tank. Since it probably is neither possible nor practical to decontaminate the tank sufficiently to permit a welding crew to enter the tank, some other method of repairing the bottom must be considered.

It is suggested that a new bottom consisting of concrete and asphalt be installed remotely. The following procedure might be used. The present rippled bottom should be flushed and pumped out as completely as possible. Then it is suggested that a layer of wet "ready mixed" concrete one foot thick be sprayed through hoses as uniformly as possible to cover the bottom. This layer of concrete should be allowed to set so as to hold down all contamination possible before applying a second layer. Successive layers should be applied until the present rippled steel bottom is completely covered and a nearly uniform flat surface has been obtained with a free-flowing cement mix. The concrete should then be allowed to cure and any excess surface water evaporated by blowing hot air into the tank and passing the exhaust air through a filter to collect any solids with contamination that might be blown from the shell walls.

As an alternate to this procedure, about two feet of gravel might first be sprayed around the tank as uniformly as possible to level the bottom. The gravel could then be covered with about a foot of concrete. This would provide some economy in concrete required.

The dry slab of concrete in the bottom will not make a liquid-tight seal with the steel shell and will produce a number of cracks across the bottom as it ages. To seal the junction with the steel shell and also to seal cracks in the concrete, it is suggested that the entire bottom be sprayed with a high melting asphalt cut with a non-combustible solvent. Because of the irregular surface of the unscreeded concrete, an asphalt thickness of one to two inches may be required. Into the asphalt about two inches of pea gravel should be sprayed to provide an aggregate strong in compression. The solvent in the asphalt is removed by blowing hot air through the tank. Then, on top of the asphalt and gravel, another six inch slab of concrete is poured to protect the two inches of asphalt which provides the true seal in the new bottom. The pea gravel in the asphalt prevents the asphalt from being squeezed out by compressive forces. The protective six-inch slab of concrete should be especially prepared with a formula providing maximum resistance to attack by the waste solutions. The above procedure should permit reuse of tank 113-SX with a loss of about ten per cent in capacity. If it is decided that this tank should not be subjected again to hot fresh wastes, it is suggested that it be used for storage of old radioactive sludge. These sludges have a tendency for self-sealing, and therefore would be less likely to leak from the tank if some small cracks developed in concrete and asphalt seal at the bottom.

I. Suggested Procedure for Avoiding Future Difficulty in Filling Existing Tanks In SX and Purex Tank Farms

Excessive rippling in the bottom of these tanks (which have no allowance for thermal expansion) should be avoided by first charging the tank with a "heel" of old waste in the SX tanks and water in the case of the Purex tanks. It is believed that this heel should be at least four feet to hold the tank bottoms down.

To avoid or at least minimize the formation of vapor under the tank bottoms, it is suggested that bottom temperatures be controlled at the lowest possible temperature. Agitation using existing air lift circulators and dilution may be used to control the temperatures in the tank. Effort should also be directed at minimizing sludges which can give rise to high temperatures due to the low heat transfer coefficient of these sludges if allowed to settle into a bottom layer.

J. Suggested Reuse of Empty Tanks Built Before 1949

As a result of recovery of uranium from old bismuth phosphate wastes many of the early tanks are now empty or nearly empty. According to report HW-37519 by E. F. Smith a total of 54 such tanks with a total capacity of 35,500,000 gallons were built between 1943 and the end of 1949. Many millions of gallons

of storage capacity valued at many millions of dollars remain in these tanks. However, this storage capacity is not being used at present partly because these tanks were not designed to handle the boiling wastes of high specific gravity now being produced by the Redox and Purex plants.

From the consideration of bottom design these early tanks are superior to the SX and Purex tanks now being used for this purpose. However, as shown by E. F. Smith (report HW-37519) these early tanks were not designed to withstand internal vapor pressures and should not be used for vapor pressures over 1.8 to 2.5 psig.

Since the storage capacity in these tanks has a replacement value estimated at many millions of dollars, it is proposed that consideration be given to modification of these tanks to permit their use at higher vapor pressures. The following procedure might be used to lower radiation levels.

The heels of waste in the nearly empty tanks should be pumped out and the tanks flushed. Then the tanks should be partially filled with several feet of water to provide additional shielding from residual sludge in the bottoms. It is believed that this will reduce the radiation level on the outside of the concrete to permit reinforcing the tank with steel.

The reinforcing in the concrete shell is the present limitation to the permissible internal vapor pressure. Increase in vapor pressure will have no undesirable effect on the tank bottom since it acts as a compressive load on a bearing surface. In fact, such a pressure on the bottom could be beneficial in preventing rippling of the bottom liner as a result of thermal expansion. Likewise an internal vapor pressure of 10 psi or less will have little or no effect on the concrete dome. This dome carries a dead load of several psi as a result of the fill placed on top of the dome. Thus a force (vapor pressure X area) equal to the dead weight must be reached before there is any reversal of load in the dome. At a vapor pressure of 10 psi there is a possible lifting of the dome and overburden by the vapor.

However, in the case of the shell it is not safe to take credit for the pressure of the fill against the concrete shell in setting the permissible internal pressure. This is because a previous expansion and contraction of the tank may have left a void between the concrete and the fill. Since we cannot depend upon the earth pressure to resist the internal vapor pressure and since there is insufficient hoop reinforcing steel to contain both the hydrostatic pressure and the vapor pressure some means must be provided for strengthening the reinforced concrete shell.

The concrete shell contains both hoop reinforcing steel around the circumference to carry hydrostatic hoop stresses and axial reinforcing running vertically to carry the bending stresses caused by the pressure from backfilling. If the upper corner and lower corner of the concrete shell could be considered fixed the shell could be treated as a uniformly supported beam on end. In this way the existing vertical reinforcing could be used to carry the shell vapor pressure loading not carried by the hoop steel in the shell.

To make use of the vertical reinforcing steel for this purpose it is proposed that steel hoop rings with turnbuckles be placed around the outside of the concrete shell near the top. The turnbuckles could be tightened so as to remove slack and place a slight compressive prestress on the top of the tank. An article on the design of prestressed concrete tanks by Mason of U. S. Navy (reprinted by Portland Cement Assoc.) describes the procedure of attaching and tightening steel hoop rings to the outside of concrete tanks.

The reinforcing ring would be expected to carry half the vapor pressure load on the shell less that which can be carried by existing shell hoop steel if we neglect restraint offered by the dome. The junction between the dome and shell carries very little vertical steel to avoid discontinuity stresses.

This procedure of reinforcement (if considered feasible after further study) could be performed by a small crew of steel workers after excavation to about three feet below the top of the concrete shell. This should permit filling the tank with boiling wastes and operating at vapor pressures up to 10 psi.

Since 12,000,000 to 15,000,000 gallons of storage capacity might be reclaimed in this manner a savings of perhaps $10,000,000 could be realized in new tank construction.

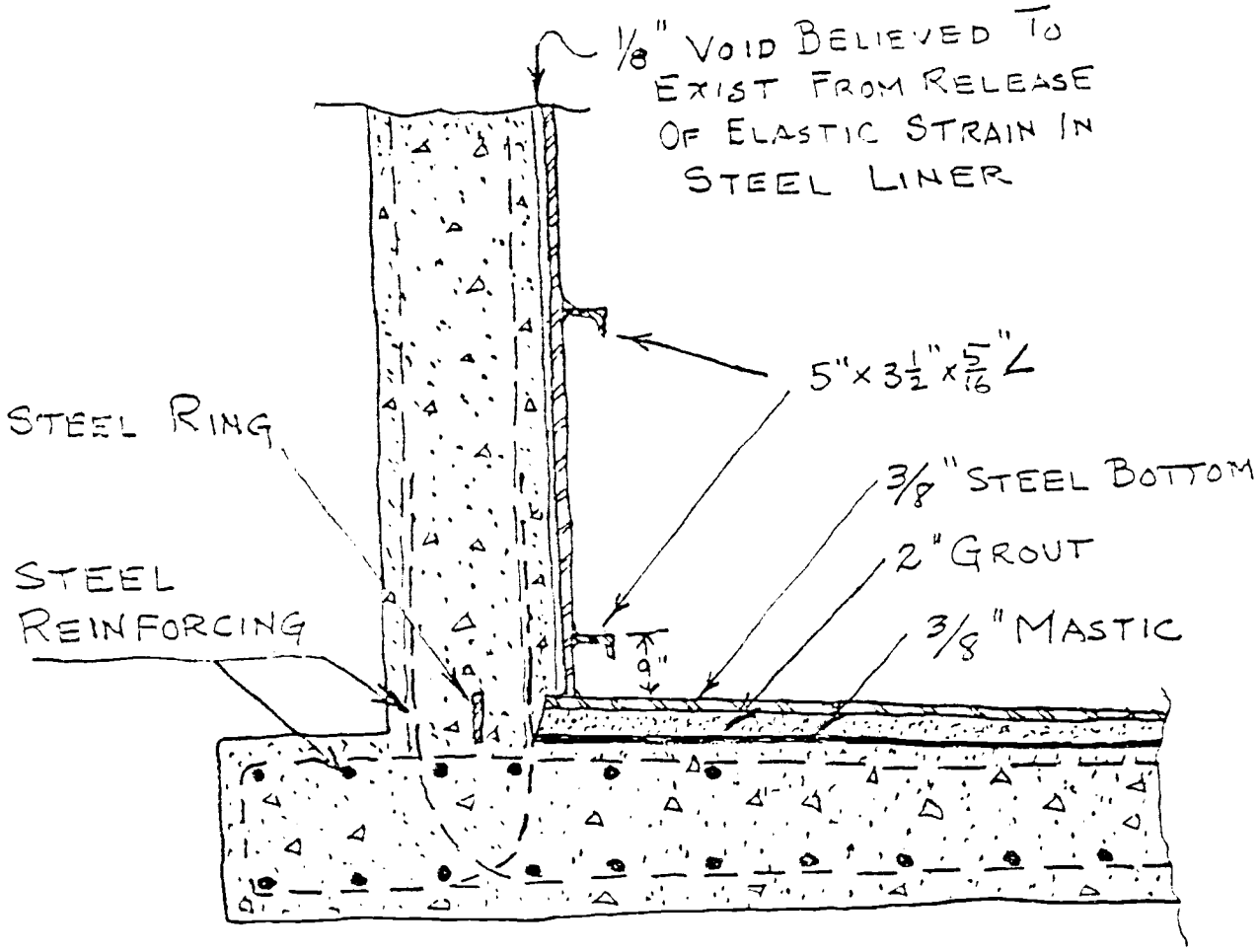

FIG. 1. SKETCH SHOWING SECTION OF LOWER CORNER OF TANK AS BUILT

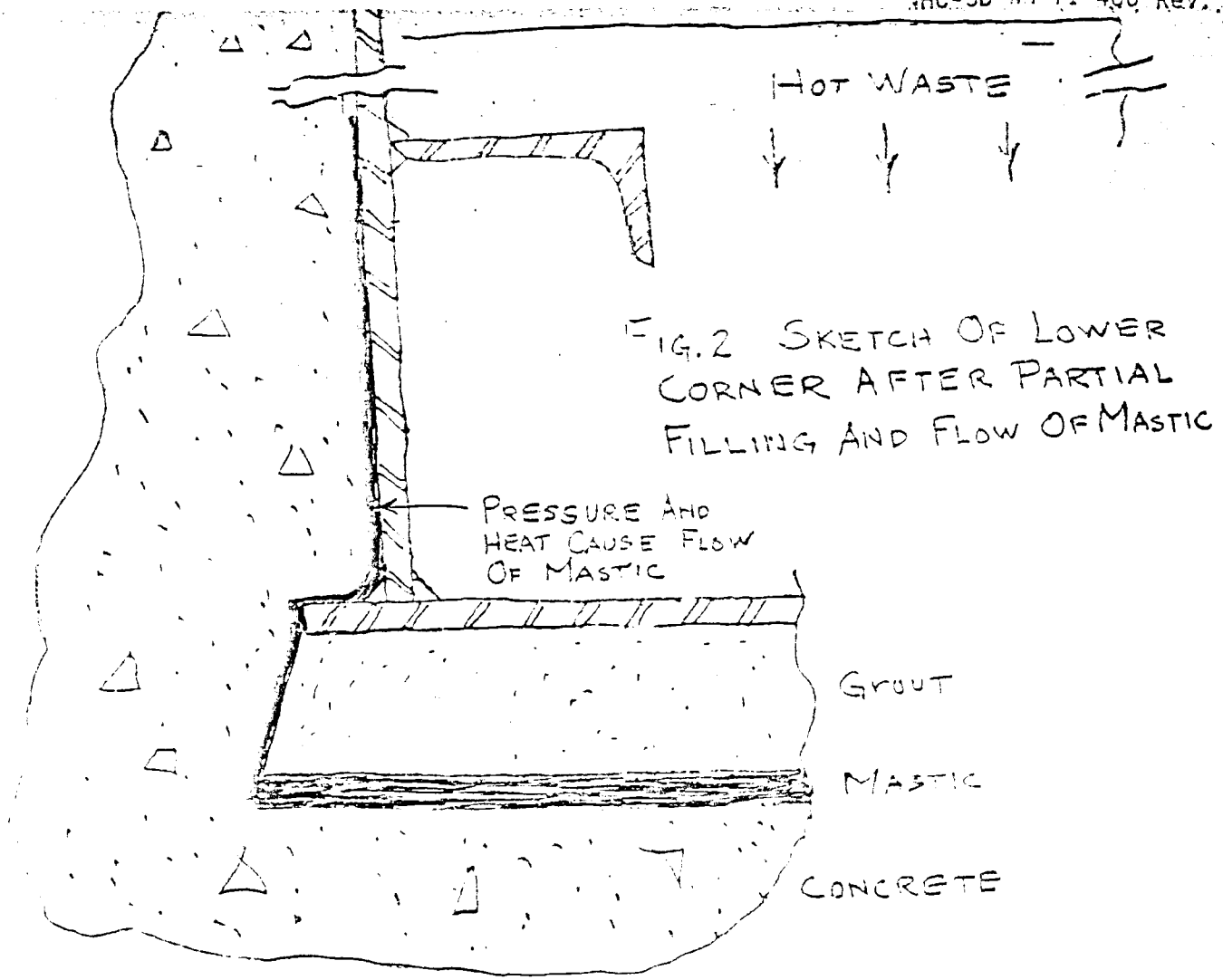

FIG. 2 SKETCH OF LOWER CORNER AFTER PARTIAL FILLING AND FLOW OF MASTIC

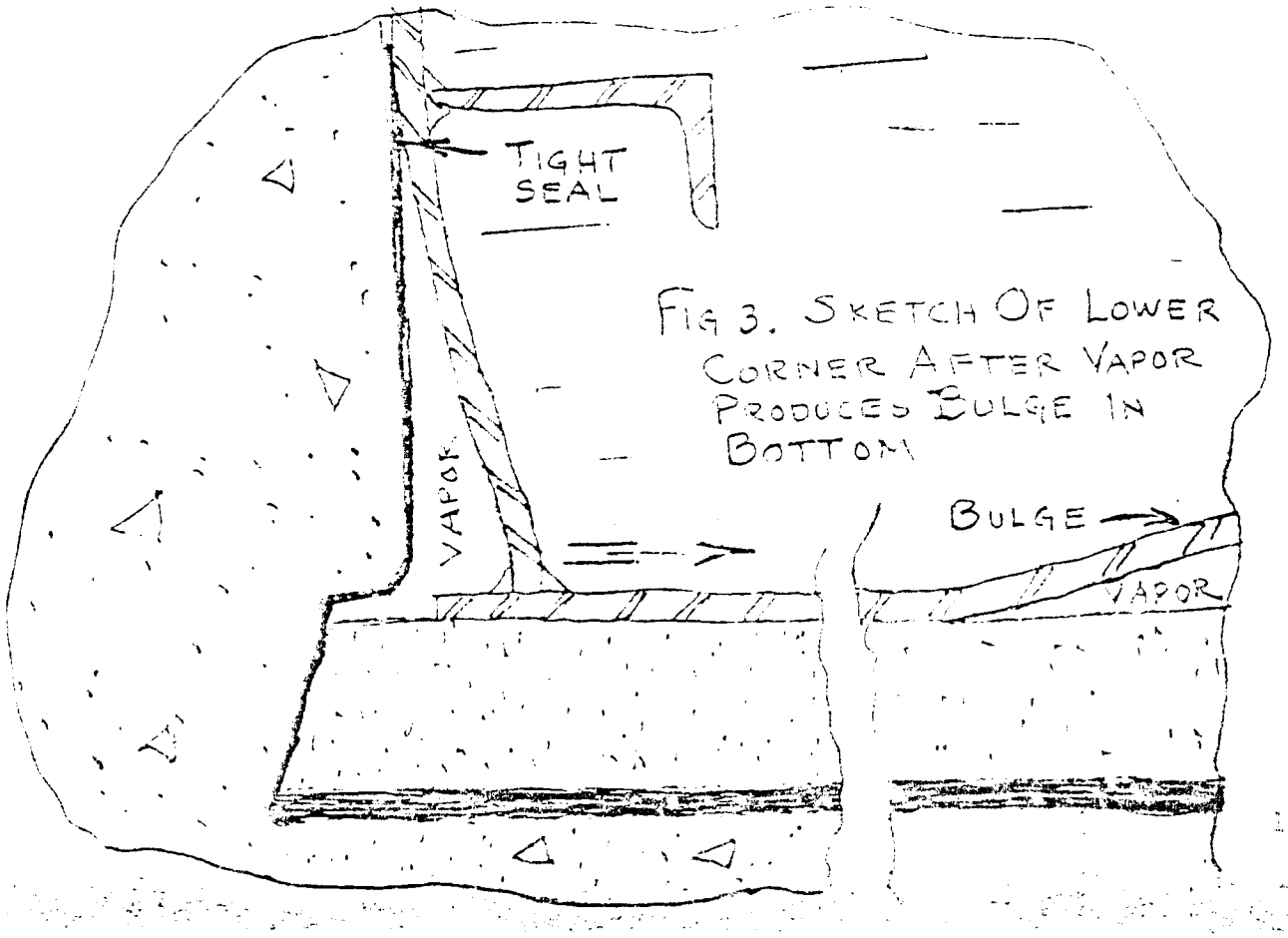

FIG 3. SKETCH OF LOWER CORNER AFTER VAPOR PRODUCES BULGE IN BOTTOM

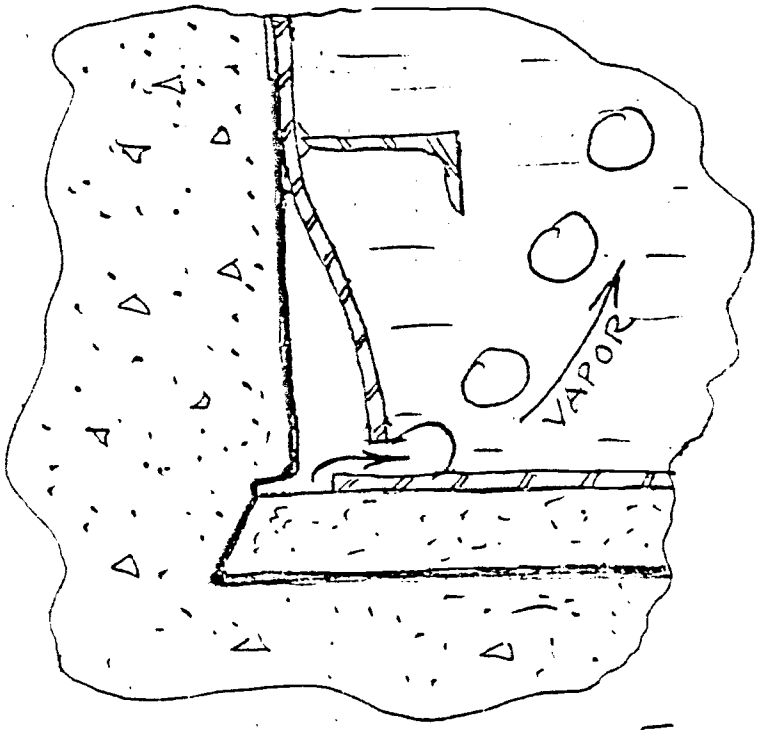

FIG 8. SKETCH OF VAPOR ESCAPE THROUGH RUPTURE AT JOINT

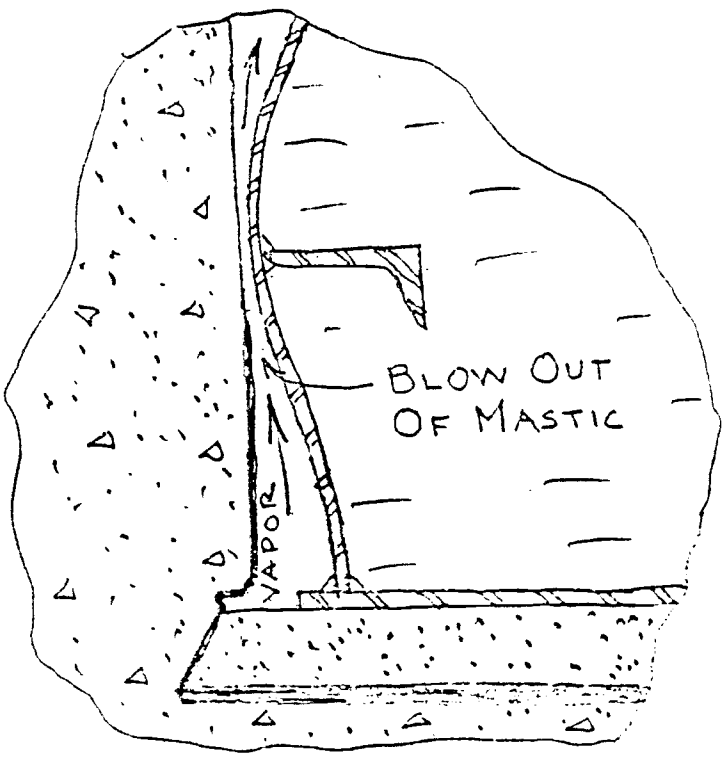

FIG. 9, SKETCH OF VAPOR ESCAPE THROUGH BLOW OUT OF MASTIC

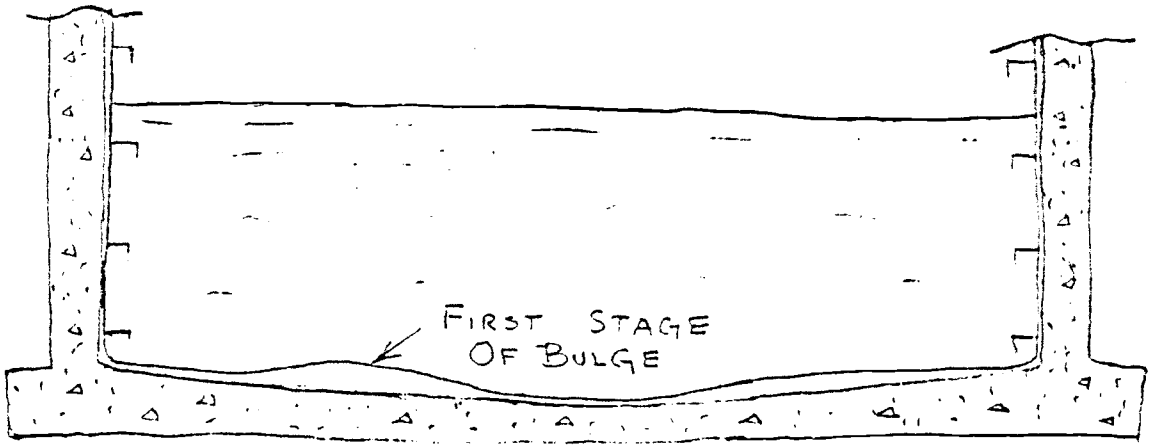

FIG. 4. SKETCH SHOWING POSSIBLE FIRST STAGE OF INSTABILITY OF BOTTOM

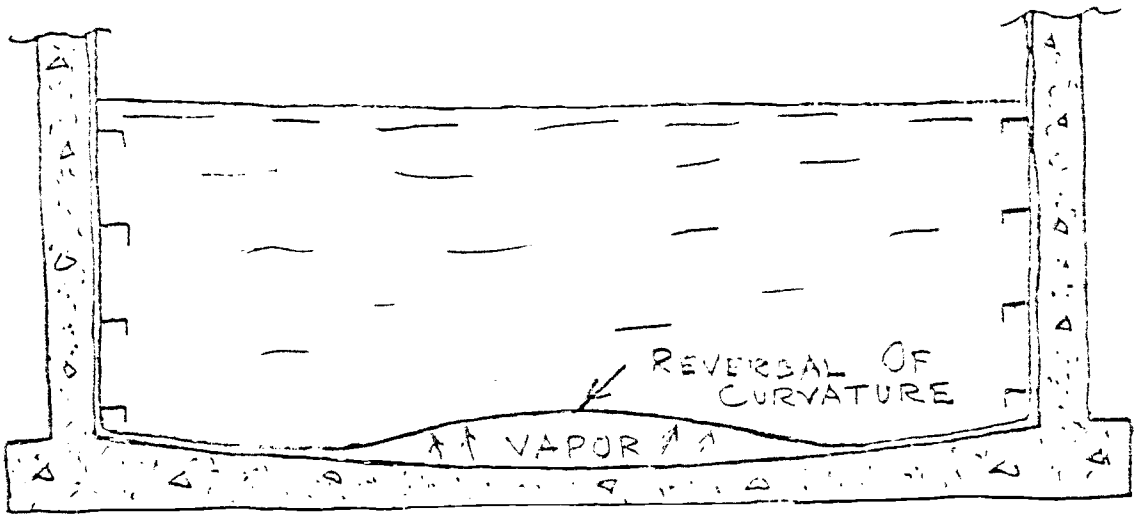

FIG. 5. SKETCH OF SECOND STAGE OF INSTABILITY OF BOTTOM WITH REVERSAL OF CURVATURE

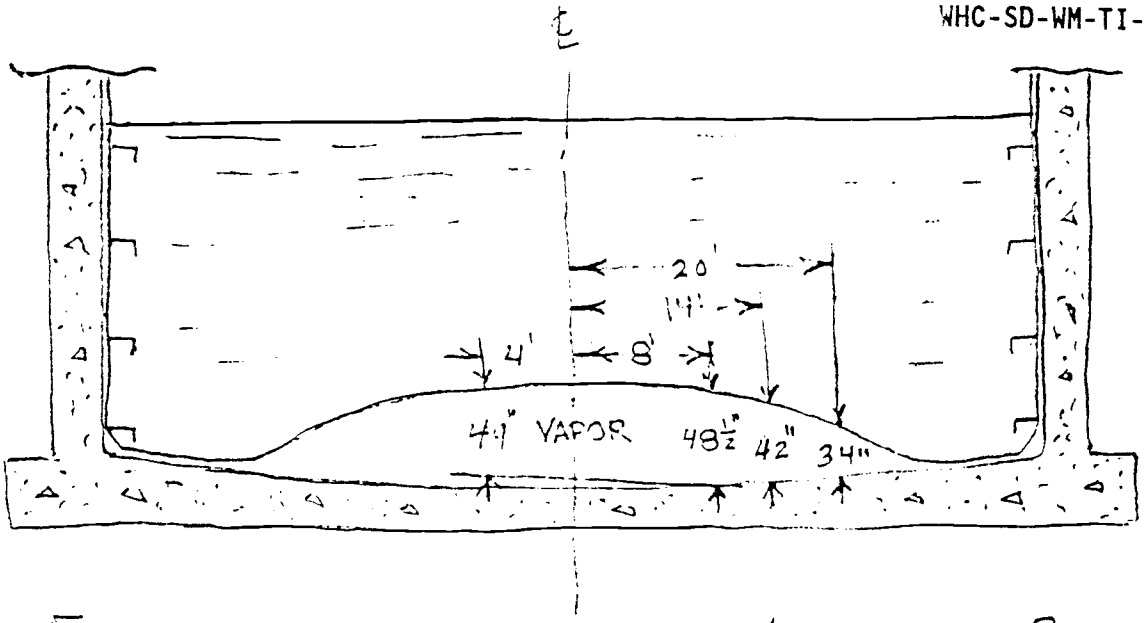

FIG. 6. SKETCH SHOWING MAXIMUM BULGE AND SOME OF THE MEASUREMENTS

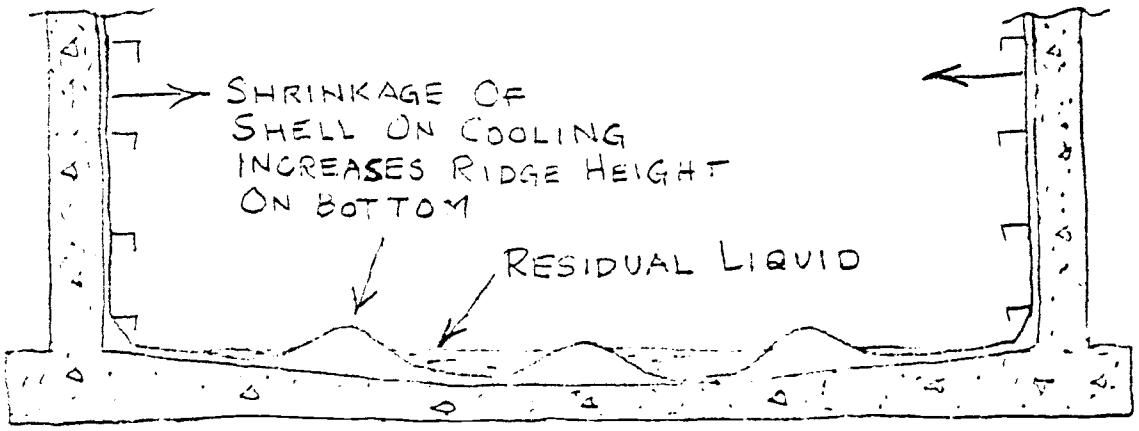

FIG. 7 SKETCH OF FINAL CONDITION OF TANK LINER AFTER THE TANK WAS EMPTY AND SHELL COOLED

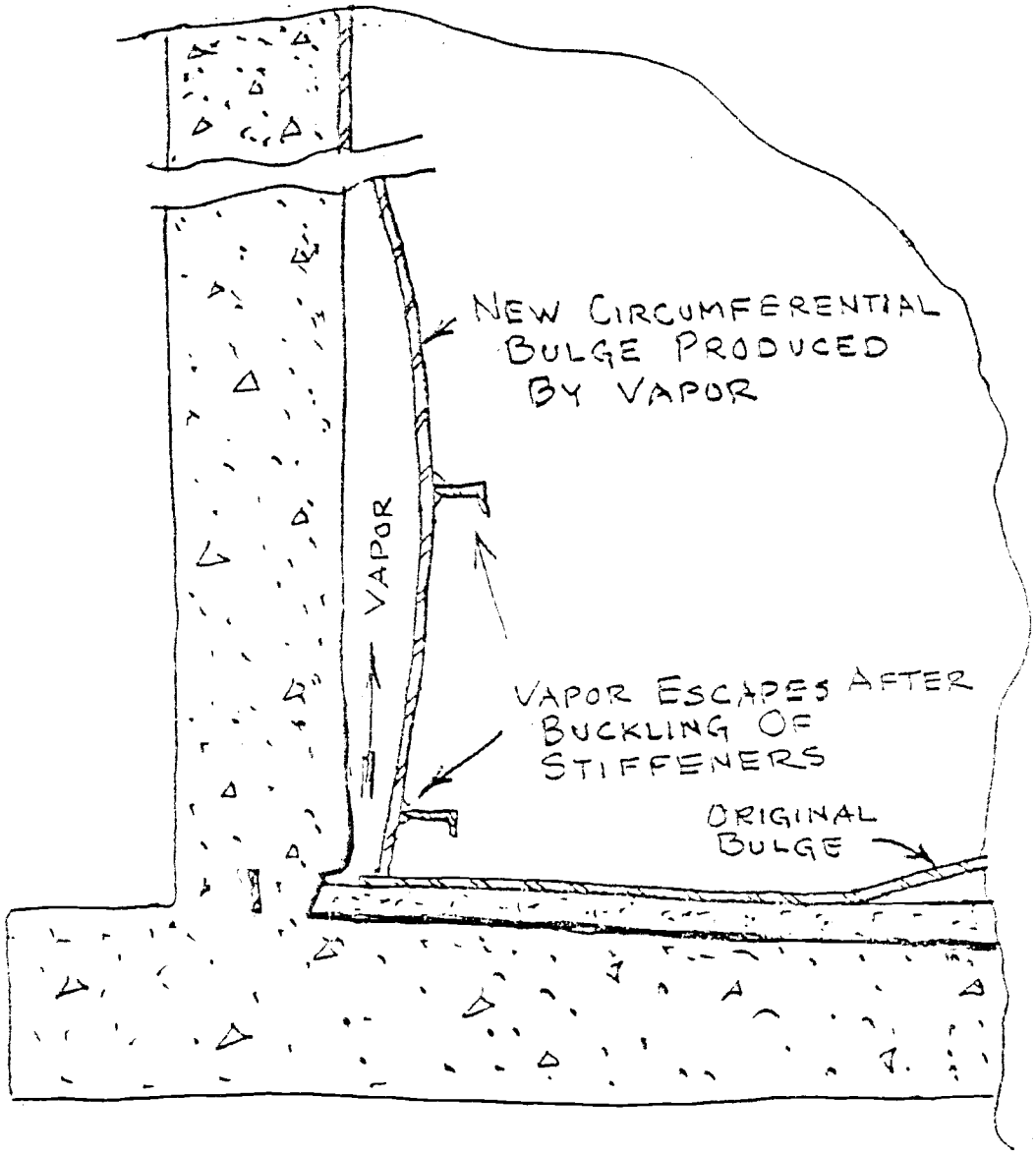

FIG 10. SKETCH OF VAPOR ESCAPE THROUGH OPENING PRODUCED BY BUCKLING OF STIFFENERS

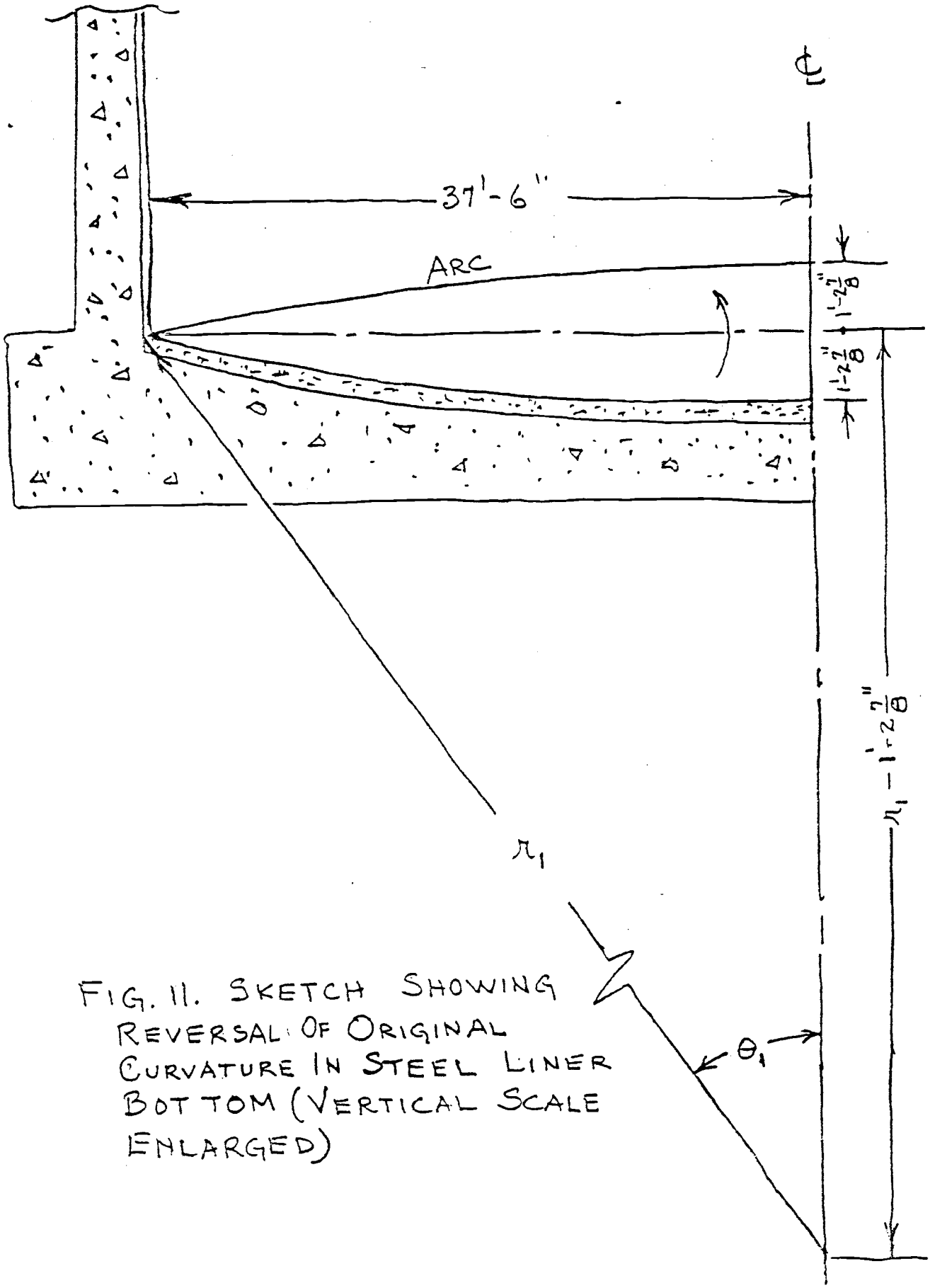

FIG. 11. SKETCH SHOWING REVERSAL OF ORIGINAL CURVATURE IN STEEL LINER BOTTOM (VERTICAL SCALE ENLARGED)

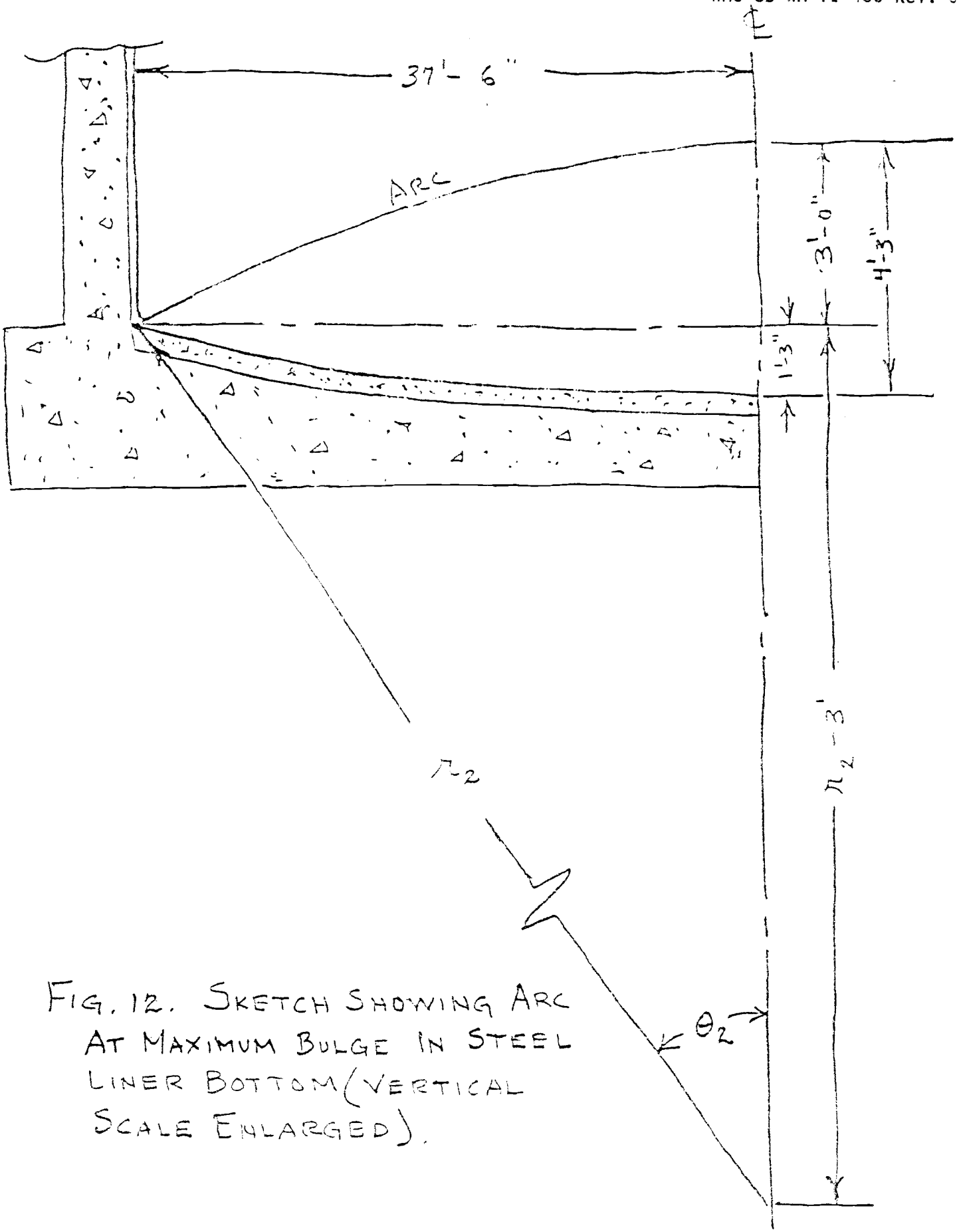

FIG. 12. SKETCH SHOWING ARC AT MAXIMUM BULGE IN STEEL LINER BOTTOM (VERTICAL SCALE ENLARGED).

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Ben Dixson

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PUREX TK-105-A WASTE STORAGE TANK LINER INSTABILITY AND ITS IMPLICATIONS ON WASTE CONTAINMENT AND CONTROL

by

S. J. Beard and P. Hatch
Atlantic Richfield Hanford Company

and

G. Jansen and E. C. Watson, Jr.
Pacific Northwest Laboratory
Battelle Memorial Institute
Richland, Washington

J. Jo's copy

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TABLE OF CONTENTS

		Page
I.	INTRODUCTION	5
II.	SUMMARY	6
III.	TANK FILL HISTORY	8
IV.	STEAM RELEASE INCIDENT	11
V.	ANALYSIS OF TANK CONDITION	12
VI.	POSTULATED LINER INSTABILITY MECHANISMS	17
VII.	THERMAL AND CHEMICAL CONSIDERATIONS	18
VIII.	TANK EVALUATION CONCLUSIONS	20
IX.	OPERATING PLAN	23
X.	CHANGE IN TANK STATUS	25
XI.	REVISED OPERATING PLAN	27
XII.	HAZARDS ANALYSIS	27

LIST OF FIGURES

Figure 1 - TK-105-A Liquid Level & Sludge Temperature History	9
Figure 2 - TK-105-A Plan View	13
Figure 3 - TK-105-A Lateral Temperature History	16
Figure 4 - TK-105-A Fission Product Inventories	19
Figure 5 - Predicted Settled Sludge Temperatures for Uncontrolled Conditions	21
Figure 6 - Rate of Temperature Rise in Dry Sludge	22
Figure 7 - Bulge Venting Tool	24
Figure 8 - Predicted Temperatures Generated in Mixtures of Settled Sludge [illegible] Solidified Supernate Beneath the Bulge	26
Figure 9 - Predicted Groundwater Cor[illegible]ation as a Function of Travel Time	[illegible]

LIST OF TABLES

	Page
Table 1 - Circulator Static Pressure Readings	14
Table 2 - TK-105-A Bottom Probing Measurements	14
Table 3 - TK-105-A Slurry Composition	18
Table 4 - Volatilization Factors - TK-105-A	30
Table 5 - Calculated Total Body Dose - TK-105-A - Condition 1	31
Table 6 - Calculated Total Body Dose - TK-105-A - Condition 3 as of January 1, 1968	35

PUREX TK-105-A WASTE STORAGE TANK LINER INSTABILITY AND ITS IMPLICATIONS ON WASTE CONTAINMENT AND CONTROL

I. INTRODUCTION

Irradiated fuels from the Hanford reactors are processed in the Purex plant for recovery of plutonium, uranium and other useful reactor-produced products. Nearly all of the fission products (>99.99%) and process chemicals are collected in a single small volume aqueous waste stream, neutralized with sodium hydroxide and stored in large underground tanks. Normal practice is to continually add waste to a tank while maintaining the liquid volume relatively constant at 70-80 percent of tank capacity by allowing the waste to self-concentrate from fission product decay heat. As the tank is filled, the waste separates into an insoluble sludge layer and a supernatant liquid. Nearly all of the fission product decay heat is associated with this insoluble sludge. Heat is removed from the sludge by conduction and percolation of supernate through the sludge with the latter being the major mechanism for heat removal. As the sludge layer increases in depth and as the salt concentration in the supernate increases with tank filling, the removal of heat from the sludge becomes more difficult. Experience has shown that sludge temperatures cannot be effectively controlled above a supernate sodium concentration of about 7 or 8 molar. When this supernate salt concentration is reached in a waste volume equal to about 80 percent of the tank volume, the tank is considered full.

Purex Waste Tank 105-A is a typical tank in the original Purex plant tank farm. It was the last tank to be filled (six tank farm) and was filled in a routine manner. However, the TK-105-A performance differed from the other tanks in three important respects:

1) Waste seepage was detected under the tank when the tank had received about 50 percent of the tank's capacity expressed as tons of uranium processed;

2) After the tank was filled a sudden steam release occurred which differed from other steam releases in that the circulators were reported to be in operation during the event; and

3) The bottom liner of the tank was found to be bulged upward about 8.5 feet and remains in this position.

The presence of radioactive contamination beneath the tank and the discovery that the bottom plate was bulged upward provided conclusive evidence that the tank integrity had been compromised. Engineering studies were conducted to provide guidance for controlling the tank under stable boiling conditions and also under assumed conditions of further deterioration.

The purpose of this report is to detail the history of TK-105-A activities including the engineering studies and hazard assessments that have been made.

II. SUMMARY

Purex Waste TK-105-A was built in 1955, and remained in reserve status with a nominal water heel until May of 1962. From May of 1962 until January of 1963 the tank was used to store aged supernate and to provide feed for cesium recovery operations in Purex and later in the C-Farm cesium loadout station. Preparation of the tank for full radiation level Purex waste storage started in January, 1963, and the tank commenced to self-concentrate in March, 1963. Filling of TK-105-A was routine except for the detection of low intensity radiation in one leak detection lateral when the tank was half filled. Since the leak became inactive after one week and since instrumentation indicated the amount leaked to be small, use of the tank was continued. Emptying the tank was not considered because no spare self-boiling tankage was available. In December, 1964, the tank was filled to capacity with waste from the processing of 11,000 tons of uranium.

On January 28, 1965, a sudden steam release occurred in TK-105-A which was believed to be more intense than any previous similar event. The release also appeared to differ from previous releases (commonly called "bumps") in that the event occurred while the airlift circulators were reported to be in operation. Inspection of the tank instrumentation and equipment revealed no major damage, and the normal tank operation was continued with special emphasis on surveillance of tank behavior and operation of tank control instrumentation.

Subsequent investigations at that time by the CPD operating and engineering staffs with technical assistance from Pacific Northwest Laboratory led to the following conclusions being reached in late 1965.

1. The tank had ceased to leak.

2. No evidence was found to indicate that the leakage was sufficient to create significant potential for contaminating the atmosphere or the groundwater.

3. The tank liner was bulged upward at one point to an elevation of 8.5 feet creating a void space of about 80,000 gallons.

4. The void under the bulge might contain vapor or supernate, but it was considered unlikely that it contained any appreciable amount of sludge.

5. The bottom liner was possibly balanced between the steam pressure underneath and the solution hydrostatic head on top. A method for venting the bulged area should be developed to prevent liner movement during removal of solution from the tank.

6. The probability of leaking sludge from the tank into the soil was very low; but if it should occur very high temperatures at the concrete-soil interface would result.

7. Leakage of filtered supernate into the soil would not result in temperatures at the concrete-soil interface that would cause damage to the structure.

8. If solution were removed or lost from the tank and the sludge allowed to dry, temperatures in excess of 10,000 F could result.

9. If the sludge were overheated, it would denitrate and expel NO_2 gas and later release fission products at higher temperatures.

10. Under all emergency conditions a release of radioactivity to the groundwater would be less serious than a release to atmosphere since the sorption capacity of the soil would delay the movement of radioactivity to the edge of the reservation until most of it had decayed.

11. The potential hazard to the environment and the difficulty of emptying the tank would decrease with time as the fission products decay.

Based on the conclusions of the several studies, an operating plan was developed embracing four main objectives:

1) Control the tank sludge temperatures under all possible conditions of tank failure including the release of liquid to the ground;

2) Provide and maintain capability for emergency sluicing and emptying of the tank;

3) Maintain the tank status as static as possible; and

4) Continue intensive surveillance of tank leak detection and control instrumentation.

In the fall of 1965 when all arrangements had been completed for emergency sluicing and emptying TK-105-A, the behavior of the tank during the elapsed time since the steam release incident was reviewed. During the review various potential hazards were considered, particularly the possibility of extreme sludge temperatures. A decision was made to maintain TK-105-A in a static condition until such time as the tank was scheduled for Waste Management processing or until there was some evidence of further tank deterioration.

In April, 1967, a cyclic liquid level variation began to occur. A typical cycle consists of a 9-10 inch drop in liquid level in a matter of minutes followed by a relatively stable period lasting about 20 hours. The liquid level then returns to its original level in about a day. No significant movement of the liner can be detected. A logical explanation for this behavior is that part of the area under the bulge alternates between a vapor and liquid phase.

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Evidence that a hole has developed in the liner is now readily apparent. The concrete vessel is almost certainly cracked, but leakage is not evident - probably because of salt deposition in the concrete cracks or surrounding soil. The possibility for the accumulation of heat-producing solids under the bulge with resulting localized temperatures as high as 1860 F has become a new concern.

A hazard analysis indicated that if the entire tank achieved temperatures limited only by the laws of nature, environmental contamination would create a problem of considerable magnitude. Total body dose in excess of 25 rems, for a 2-hour exposure at 5 miles or 24 hours at 18 miles from the tank could be anticipated if as much as 5 percent of the volatilized radionuclides escape to the atmosphere. A more likely event would be loss of all or part of the tank supernate to the ground with sludge temperature control effected by continual water additions to the tank. Under this condition contamination of atmosphere or ground surface would probably not occur, but serious groundwater contamination would result. However, contamination at the river would not be expected to approach the drinking water limit assuming a continuation of current groundwater flow patterns. Contamination of the ground and groundwater would be sufficient, however, to be a major deterrent and possibly to preclude irrigation activities in the vicinity that could change the groundwater flow pattern under the 200 Area plateau.

III. TANK FILL HISTORY

The detailed account of the waste transfers to and from TK-105-A and the resulting temperatures are summarized here and in Figure 1. The first addition was made prior to tank farm startup in 1955. Six inches of water were added to each tank as protection against possible bottom liner lifting from vacuum generated by the ventilation exhaust blower during equipment testing. The water was added as a supplemental protective measure to the safety afforded by a six-inch water seal in the tank farm vent header. The TK-105-A volume gradually increased from this initial 6 inches of liquid in 1955 to 18 inches of liquid in May of 1962. These 12 inches of liquid were the accumulation of water additions to various vapor seals over a period of 7 years. In May of 1962, 330,000 gallons of supernate were pumped from TK-103-A into TK-105-A over a period of 20 days. TK-105-A temperature increased from 46 to 56 C as a result of this solution transfer. On July 27, 1962, an additional 180,000 gallons of supernate from TK-103-A were transferred to TK-105-A causing an 8 C increase in temperature. During the period from July 27, 1962 to December 12, 1962, about 63,000 gallons of supernate were removed from TK-105-A for cesium recovery in Purex. On December 12, 1962, about 252,000 gallons of TK-101-A supernate were added to TK-105-A with a 14 C temperature increase. This transfer was made to prepare optimum feed for the TK-103-C cesium loadout feed tank. After blending with the airlift circulators in TK-105-A, 490,000 gallons of supernate were transferred to TK-103-C. Following the solution transfer to C Farm, TK-105-A contents were pumped to TK-101 A until only

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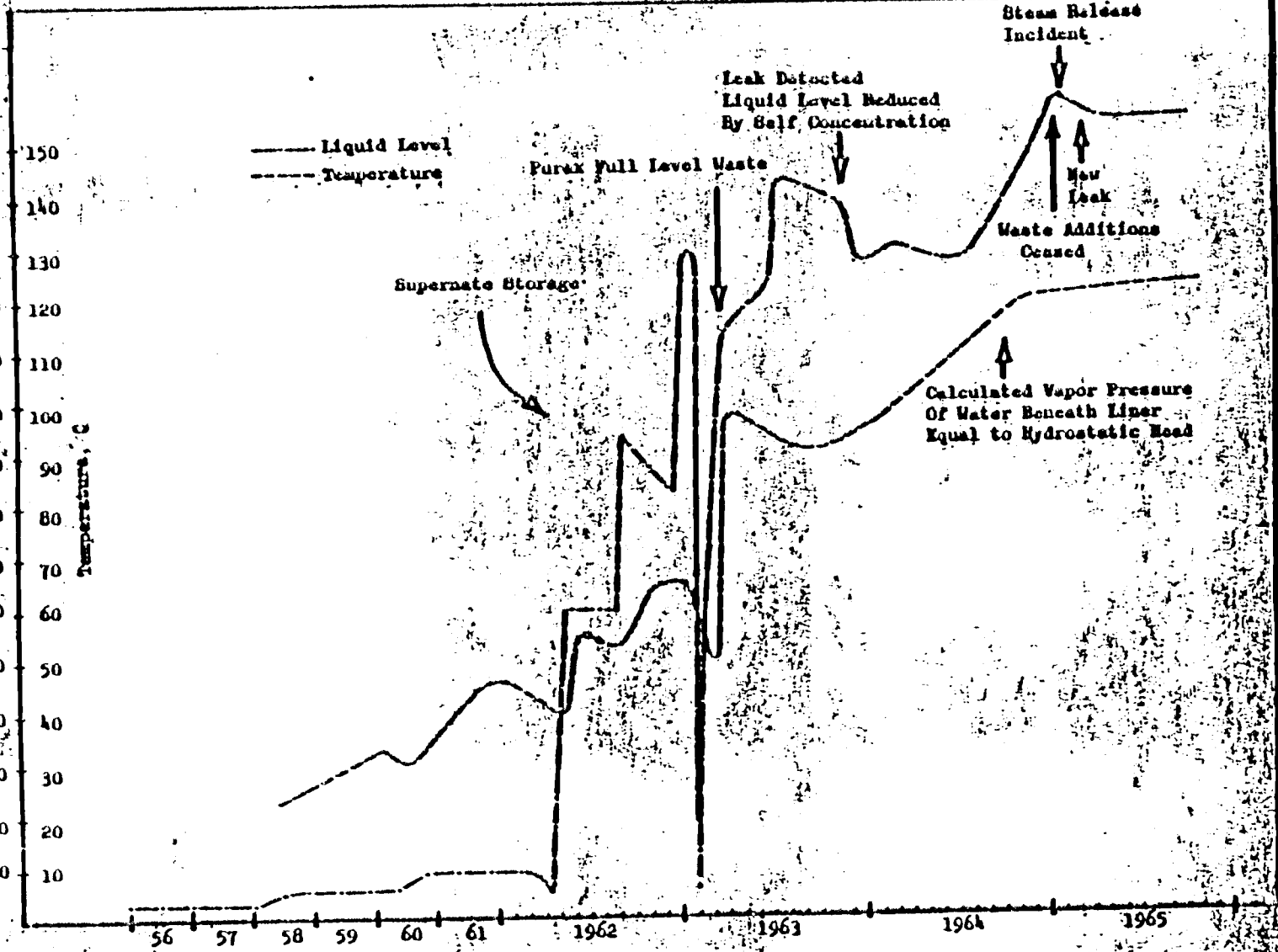

FIGURE 1

TK-105-A Liquid Level and Sludge Temperature History

a 10-inch heel remained. In January, 1963, 330,000 gallons of thermally hot tank farm condensate were added to TK-105-A to heat the tank and partially prepare it for receipt of Purex self-boiling waste. The tank was heated from 50 C to 62 C with 330,000 gallons of tank farm condensate, and then brought up to boiling temperature at a nearly uniform rate with full-level waste, reaching boiling on about March 5, 1963.

The filling of TK-105-A was routine until November 19, 1963, when the tank was about half filled. On this date radiation was noted in one lateral at an intensity of 17,000 c/m increasing to 150,000 c/m seven days later. Accurate conversion from c/m to mR/h is not possible, but 5 mR/h is approximately equal to 150,000 c/m for this instrument. Radiation dose rate as measured from a dry well inside the tank was 40,000 R/h indicating the size of the leak to be very small. Further, the radiation could only be detected over a very short segment of the lateral indicating that a narrow finger of contamination had approached the lateral. The intensity of the radiation in the leak detection lateral was observed to gradually decay until March 6, 1965, when an increase occurred which will be described later. During the period from November, 1963, to March, 1965, the radiation intensity decreased a factor of 3 to approximately 50,000 c/m.

It was noted that the tank liquid level had reached the range of 280 inches in July, 1967, a few months before the leak was detected. A leak in the side wall was postulated as a possibility so the tank liquid level was reduced by self-concentration to 260 inches. A slow decline of the radiation intensity in the lateral indicated the leak had stopped either because of self-sealing or because the liquid level was below the leak point. No spare tanks were available at this time; however on the basis of the available data, it probably would have been considered prudent to continue filling TK-105-A even if spare tankage were available since only 50 percent of its capacity had been used. The current spare, TK-103-A, was not available at the time because it contained 3 feet of settled sludge. Hanford and Savannah River experience had indicated that if filling of a self-heating tank is discontinued for any significant period of time (a few months), excessive temperatures will occur in the settled sludge upon the addition of fresh waste to the tank. Purex TK-101-A and TK-102-A had both experienced temperature excursions as a result of adding fresh waste to a tank containing settled sludge.

The tank appeared to behave normally in all respects while the tank liquid level was maintained at 260 inches and as the salt concentration gradually increased with waste additions to the operating limit of 7.0 M sodium. About September 1, 1964, the salt concentration operating limit was reached, and liquid level increases were permitted at a rate that maintained a salt concentration of 7.0 M sodium. In October, 1964, the postulated leak level was reached with no evidence of any new leakage occurring. In December, 1964, the tank was filled to capacity.(1)

[redacted]

IV. STEAM RELEASE INCIDENT

On January 28, 1965, a sudden steam release occurred in TK-105-A. The earth in the immediate vicinity of the tank was reported to have trembled, and a temporary lead cover on a riser on TK-103-A was dislodged allowing steam to vent from this opening for about 30 minutes. A water seal in the vent system designed to relieve tank pressure at 60 inches of water was not blown. Calculations confirm that the temporary lead cover on a TK-103-A riser should have relieved first at about 3.5 inches of water pressure.

At the time of the bump, Purex personnel were in the farm supporting Jones construction forces who were preparing to make a final weld in a line connecting TK-105-A with the 151-AX diverter station. A few gallons of liquid were ejected onto the ground in the excavation. Radiation dose rates of 400 R/h were measured one foot from the spill. A rapid survey of tank farm instrumentation and equipment stations revealed that the liquid level electrode tape in TK-105-A was broken and that the TK-105-A instrument enclosure at the tank was contaminated to levels that resulted in dose rates of 500 R/h at one foot. The water levels in the various seal loops were found to be normal with the exception of the TK-103-A overflow seal which was blown sounding an alarm in the control room. This seal is of minor importance; its function is to provide a vapor seal in the overflow cascade line between TK-103-A and TK-106-A. No wastes were added to TK-105-A the day of the incident except for tank farm condensate. A sample of tank farm condensate taken the following day had a radiation intensity of 8,000 c/m compared to a normally observed intensity of 200 c/m.

The steam release incident in TK-105-A differed from previous steam release incidents (commonly called "bumps") in that the event occurred while the airlift circulators were reported to be in operation. The event's intensity appeared to be greater also as indicated by breaking of the liquid level electrode and the ejection of droplets of supernate into the tank's instrument enclosure.

Operating efforts immediately after the incident were concerned with securing the contamination and establishing airflow to the airlift circulators. A new liquid level electrode was installed, and the liquid level measured with a high range radiation detection instrument (Victoreen) to confirm the new electrode reading. The new electrode checked with the Victoreen, but a 4-inch discrepancy was noted between the new readings and the expected level based on the old electrode reading. It could not be established with certainty whether there was a physical decrease of 4 inches in apparent tank inventory in addition to self-evaporation or whether the old tape was biased by 4 inches. The leak detection wells and laterals were monitored, but no changes in radiation status were noted.

In the absence of an identified cause of the incident, it had to be assumed additional steam releases or bumps could occur. Two immediate courses of action were pursued. One was to minimize the potential for the accumulation of superheat in the liquid, which could cause additional incidents, through

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the installation of a supplemental air sparger. The second was to install instruments to define the magnitude and rate of the energy release during any subsequent incident.

An air sparger was fabricated for installation in the tank's 4-inch vacuum breaker riser - see Figure 2. However, prior to installation, it was decided to probe the area below the riser because several months earlier an obstruction had been encountered below this riser during a routine sludge depth measurement. This probing confirmed that an obstruction did exist about 8 feet above the normal position of the tank bottom, and that the obstruction could not be avoided by the relatively large lateral movement permitted at the end of the 40-foot long probe by the clearance inside the 4-inch riser pipe. Attempts to install supplemental air sparging were then abandoned, and the airflow to the existing circulators increased to maximum rate.

A definition of the magnitude and rate of energy release during any subsequent incident was needed to put future TK-105-A control activities in appropriate perspective. Should the incidents continue and if serious additional damage to the tank structure were a possibility, costly and unconventional corrective actions would need to be considered. Two key instruments, a vibrometer and a fast response pressure recorder, were located onsite and installed on TK-105-A to obtain the required information.

With the tank behaving normally, special monitoring instruments in service, and intensified tank surveillance in effect to note future unusual tank behavior, a thorough engineering evaluation of the incident and its implications was initiated with technical support from Pacific Northwest Laboratory.(2) This evaluation was to include definition of the tank's structural condition, probable cause of tank deformation, and potential thermal consequences of tank leaks into the soil or overheating of the settled sludge. As this work proceeded, weekly meetings were held between operations and engineering personnel to discuss the progress of the studies and to exchange data as they became available. On a continuing basis, revisions to tank farm equipment systems, addition of backup systems, changes in operating procedures and initiation of additional studies were made as quickly as the need could be identified.

V. ANALYSIS OF TANK CONDITION

Investigation of the tank's inventory status and structural condition was started by careful inspection of the existing instrumentation. Each circulator is equipped with two dip tubes to determine solution flow from the measured pressure differential between the inside and outside of the circulator draft tube. In addition the #1 circulator has a third dip tube to measure supernate specific gravity. Static pressure readings on the #1 and #2 circulators were much lower (see Table 1) than expected indicating that all of the piping to the circulator [illegible] broken or that the circulators were physically elevated about 6 feet. The specific gravity measurement on the #1 circulator was low indicating that the vertical distance between the dip tubes had decreased; either

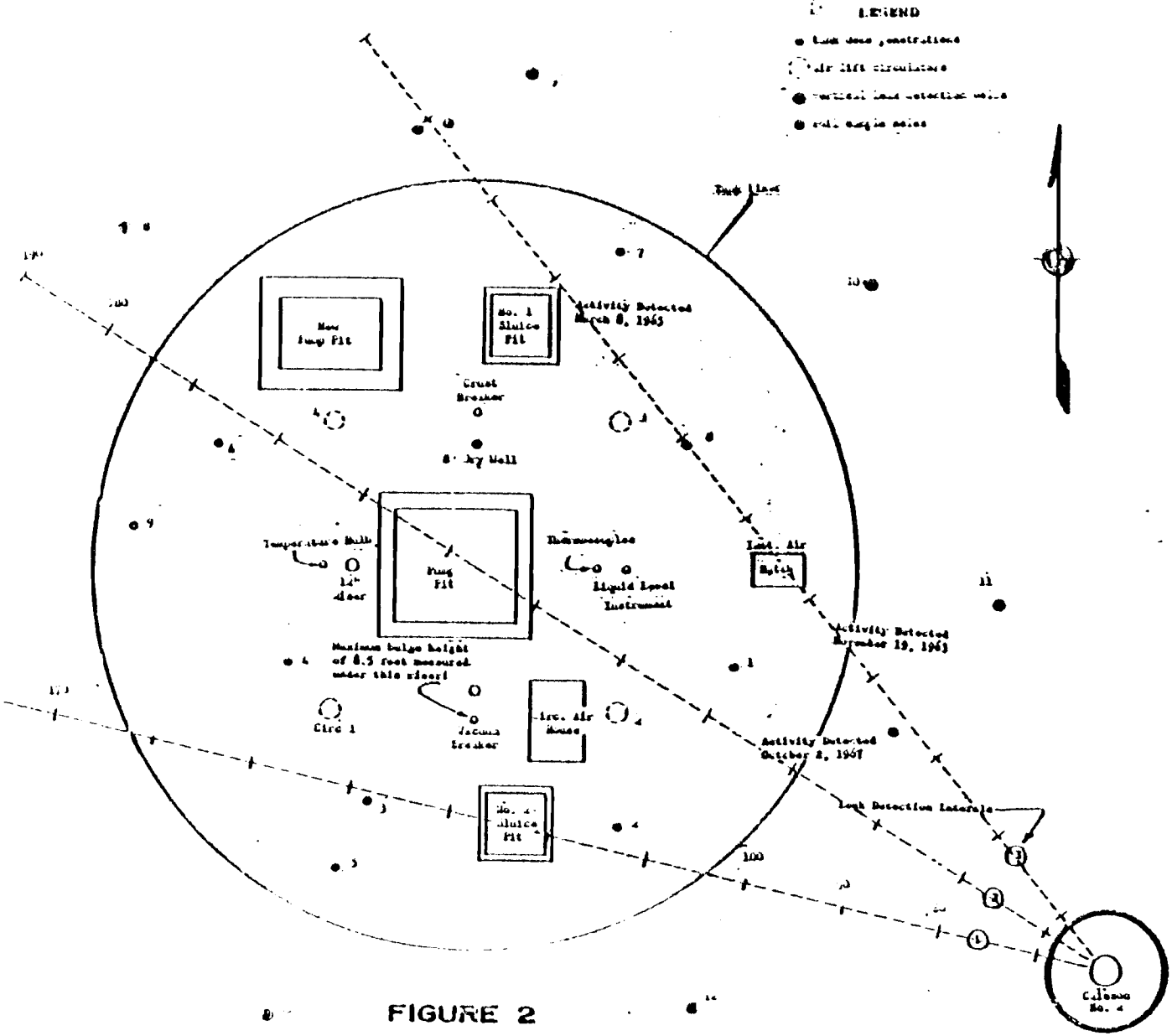

FIGURE 2

TK-105-A Plan View

a pipe was broken or the circulator was tipped. Static pressure readings on the air supply piping to the four circulators also indicated that the #1 and #2 circulator piping was damaged or that the circulators were physically elevated. Static pressure readings taken in the other five tanks were all normal.

TABLE 1
CIRCULATOR STATIC PRESSURE READINGS

Circulator	Air Supply	Inches of Water: High Pressure Dip Tube	Low Pressure Dip Tube	Sp Gr Dip Tube
1	262	222	219	126
2	262	224	222	
3	360	310	307	
4	360	317	314	

Note: If circulators #1 and #2 were not elevated, their static pressure readings would be essentially the same as those of circulators #3 and #4.

The static pressure readings coupled with the detection of an obstruction under the vacuum breaker riser left little doubt that the tank bottom was bulged. To determine the extent of bottom deformation, nine holes were drilled through the tank dome as shown in Figure 2. Sludge measurements and bottom measurements taken through these holes are shown in Table 2. From these measurements a void volume of 80,000 gallons beneath the bottom liner was estimated.

TABLE 2
WX-109-A BOTTOM PROBING MEASUREMENTS

Inches from Normal Position of TK Bottom Plate

Hole	Measurements in Inches: Sludge	Bottom Plate	Sludge Thickness
1	69	52	17
2	53	38	15
3	84½	69½	15
4	105	77½	27½
5	50½	44	6½
6	37	24	13
7	25	4	21
8	54	33	21
9	28	9	19
Vacuum Breaker	146	2	24
New Pump Pit	26	20	6

Note: Hole position given on Figure 2.

Inspection of the two installed temperature instruments shown in Figure 2 indicated normal sludge temperatures. The temperature bulb located west of the pump pit is a single measurement point near the tank bottom, and the thermocouple probe located east of the pump pit contains several thermocouples at various elevations including one near the tank bottom. To positively establish that sludge temperatures were in control, a temporary set of three thermocouples was inserted in the dry well north of the pump pit, and a thermocouple was attached to the bulb in the temperature well west of the pump pit. All four temperature measurements were normal - about 130 C.

Monitoring of the three leak detection laterals under the tank and the 7 leak detection wells along side of the tank did not initially reveal any unexpected indication of radioactive contamination. The location of radiation in the #3 lateral and its intensity remained unchanged at 50,000 c/m as discussed earlier. However, on March 8, about 39 days after the steam release incident, the radiation in the #3 lateral increased by a factor of 60 and then remained constant. No radiation increases were detected in the other laterals or the vertical wells. Three test wells were drilled along side of the tank directly over the lateral that indicated leakage. One well was drilled to a depth of 65 feet and terminated at the same depth as the laterals, 10 feet from the high radiation reading in the #3 lateral. No radioactive contamination was detected in the soil samples removed from the test wells, and the maximum temperature in the test wells was 206 F. These data indicated the leakage was small.

To gain insight into conditions under the bulged liner with respect to the accumulation of heat-producing sludge, a special probe was built to map the temperatures in the leak detection laterals. As expected, the temperatures increased as the probe passed under the tank and began to decrease as it approached the other side. For Tank 105-A, the #3 lateral, which is the one that had intercepted some leakage, had the highest temperatures, with the maximum temperatures (310 F) found to be about 90 feet horizontally from the caisson. Periodic measurements of the maximum lateral temperatures are shown in Figure 3 and do not indicate any heat accumulation under the bulge.

Consideration was given to the use of sonic, ultrasonics, and neutron thermalization techniques to determine if liquid, vapor, or a combination of both exist under the bulge.(3) After preliminary evaluation, only the neutron thermalization technique appeared to be applicable. With laboratory testing and mockup it was concluded a probe at least 12 inches in diameter would have to be lowered into intimate contact with the liner, and then its range would be limited to a depth of 12 inches below the liner. These findings were too pessimistic to proceed with a development program, and work on this approach was terminated.

The intensity of the steam release incident suggested that perhaps some gas phase reaction had participated in the event. Hydrogen formed by radiolysis is normally swept from the tanks with the steam from self-boiling. Gas samples were drawn from TK-103-A which was the least active tank in terms of air or steam bubbling. After water condensation, gas analyses were identical to air and no flammable gases were detectable.

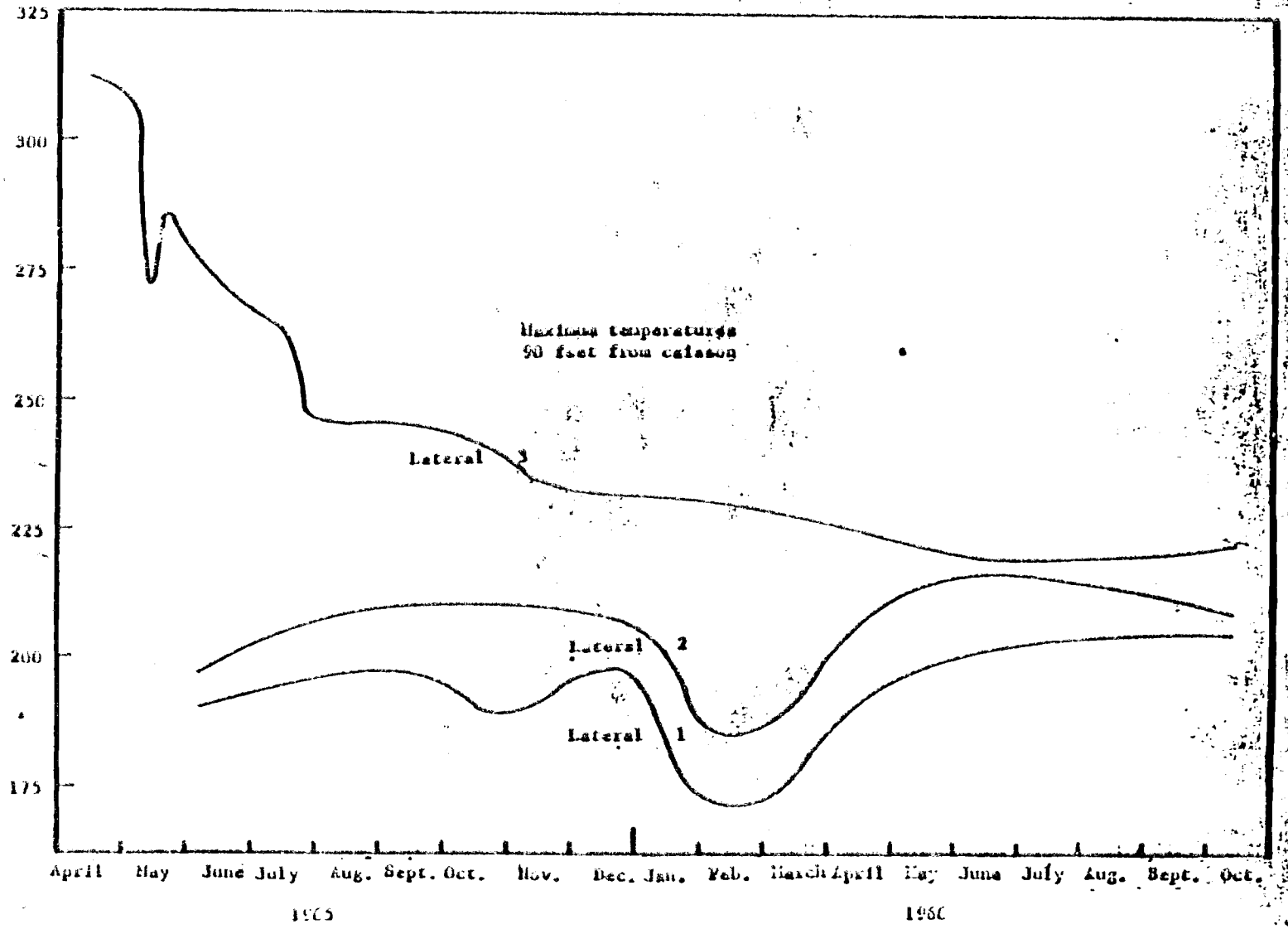

FIGURE 3
TK-105-A Lateral Temperature History

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VI. POSTULATED LINER INSTABILITY MECHANISMS

The postulated tank liner instability mechanisms were quickly reduced to two modes: 1) restraint exerted by the differential thermal expansion between the concrete cylinder and the bottom liner plate; and 2) lifting of the liner plate by water vapor trapped between the bottom liner and concrete. Engineering calculations on the effects of thermal expansion clearly showed that the bottom liner would be stable under a hydrostatic head of 14-15 psig, and that differential thermal expansion could not cause an 8-foot deformation if the tank were empty. For thermal expansion to be the primary cause, the steel plate would have to receive its buckling load from bearing against the concrete wall thus causing a fixed condition at the "T" joint between the cylinder steel and bottom steel plate; therefore, any deflection seen by the plate would have to come from differential thermal expansion and not be supplemented by movement of the steel cylinder. Under these conditions and with the tank empty, a bottom uplift of approximately 1.9 feet could relieve the thermal forces. Uplift by steam pressure between the steel liner and the concrete appears to be the primary cause of liner deformation, with thermal expansion contributing initially. Equations to determine the critical buckling stresses were taken from the "Handbook of Structural Stability, Part III"(4) and the text "Theory of Plates and Shells."(5) Calculations show that the full 8-foot liner displacement could be achieved only if the cylinder wall deformed inward up to the first stiffening ring located two feet from the bottom. The nonsymmetrical buckling as witnessed in TK-105-A is not uncommon. This phenomenon has been described by A. Kaplan and Y. C. Fung.(6) Also, as shown in Figure 2, the position of the dry well in TK-105-A may have influenced the nonsymmetrical buckling mode.

A previous analysis of the TK-113-AX failure supports the postulate of the buckling load being derived from entrapped steam.(7) Before bulging by steam pressure could occur, water would have to accumulate between the steel liner and the concrete, and a sludge temperature would have to be sufficiently high to produce a vapor pressure exceeding the hydrostatic head of liquid in the tank. Both of these conditions were shown to be probable. During startup of the tanks in the AX Tank Farm in 1965, water was driven out of the concrete, collected by channels and accumulated in leak detection wells. Volumes amounting to several hundred gallons were collected from TK-103-AX and TK-104-AX. In A-Farm no channels or leak detection wells were provided for this water to escape. If the water could not escape through cracks developed in the concrete pad or seep through the natural porosity of the concrete, it would remain trapped between the liner and its supporting concrete pad.

The hydrostatic head of liquid in TK-105-A produces a pressure on the tank bottom of 14-15 psig. A temperature of 250 F would produce water vapor pressure that would balance this hydrostatic head, and higher temperatures could generate steam pressures which could cause the liner to lift. Temperature data of record during TK-105-A filling indicate this condition was reached in October, 1964, when the tank was 80 percent f[illegible]d, and this condition still exists.

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A 0.096 to 1 scale model of TK-105-A was constructed to verify the theorized calculations of liner instability caused by applying pressure beneath the bottom plate of the tank.(8) In the model a differential pressure of 0.63 psig produced a bulge height of 4.625 inches. The model bulge occurred at the side of the tank bending in below the first stiffener. Final failure occurred with rupturing of about two inches of the joint which connects the bottom to the side of the tank. Pictures of the scale model are shown in Reference 8.

Visual appearance of the model failure closely resembled the estimated shape of the TK-105-A bulge. Extrapolation of the height of the model bulge to TK-105-A would indicate a bulge 48 inches in height compared to an actual bulge of 102 inches. A difference of this magnitude in a scale model test of this scale reduction is not unusual.

VII. THERMAL AND CHEMICAL CONSIDERATIONS

Dip samples of TK-105-A were obtained in February, 1965, to evaluate the alternatives available for handling the TK-105-A contents in the event a sustained leak were to occur. Sample results are shown in Table 3, and the calculated tank fission product inventory is shown in Figure 4.

TABLE 3
TK-105-A SLURRY COMPOSITION(1)
CURIES/LITER

	Separated Sludge(2)	Supernate
Sr-90	33	0.009
Cs-137	6.5	8.1
Ce-144	216	<0.005
Ru-106	68	<0.02
Zr+Nb-95	220	<0.005

(1) On May 1, 1965, sample taken of slurry above settled sludge.
(2) Centrifuged sample 14 volume percent sludge.

These analyses indicated about 40% of the fission product heat was associated with the settled sludge, and the remaining 60% was associated with the supernate as a slurry. It was concluded that any solution transferred from TK-105-A would have to be received by a self-boiling waste tank containing very little settled sludge to avoid excess sludge temperatures. Further, any long distance transfers to another tank farm could be considered only under conditions of extreme emergency.

Thermal effects that could result from precipitate or solution leaking into the soil were evaluated. As detailed in Reference 9, a volume of precipitate as small as 175 gallons transferred into the soil could result in temperatures in excess of 1900 F at the concrete soil interface. Solution leaks (free of sludge)

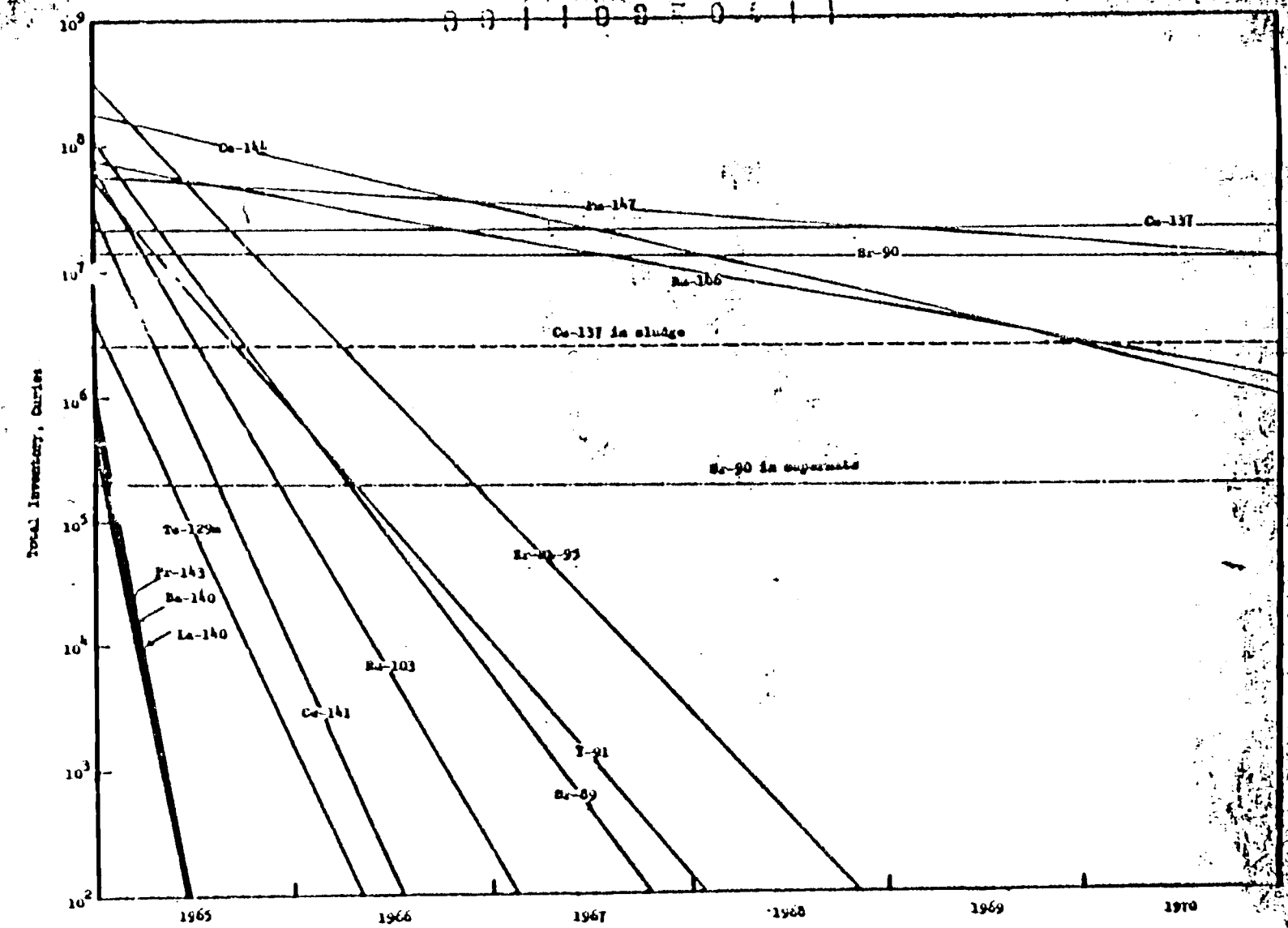


FIGURE 4
TK-105-A Fission Product Inventories

as large as 50,000 to 100,000 gallons were shown to be tolerable from thermal considerations. Laboratory filtration studies with synthetic waste and soil indicate sludge particles as small as two microns would filter out in the first 2 inches of soil. From these laboratory investigations it was concluded that a leak per se would not be hazardous to the tank structure unless it subsequently caused excess sludge temperatures inside the tank. A leak resulting in contamination of groundwater is discussed in the Hazards Analysis - Section XII of this report.

Of primary concern were sludge temperatures that could occur if the solution were removed from the tank and the sludge allowed to dry. Potential equilibrium sludge temperatures and rate of sludge heating, as shown in Figures 5 and 6, were calculated for various waste ages. It was judged that if the solution leaked from the tank and the sludge became dry, catastrophic conditions could follow in a matter of days. Laboratory volatility studies were made with actual tank supernate and sludge to evaluate this potential hazard.(10,11) These data indicated denitration of sludge will begin to occur with NO_2 gas release at about 400 F. At 1500 F cesium, ruthenium and cerium begin to appear in the off-gas with large releases occurring at 2200 F. However, before these temperatures could be reached, the tank structure would be expected to fail. It was therefore concluded that every effort should be made to assure that the sludge remained covered with liquid to prevent overheating.

VIII. TANK EVALUATION CONCLUSIONS

As a result of the various studies conducted on behalf of the TK-105-A waste storage problem, several conclusions were reached in the fall of 1965.

1. The tank had ceased to leak.

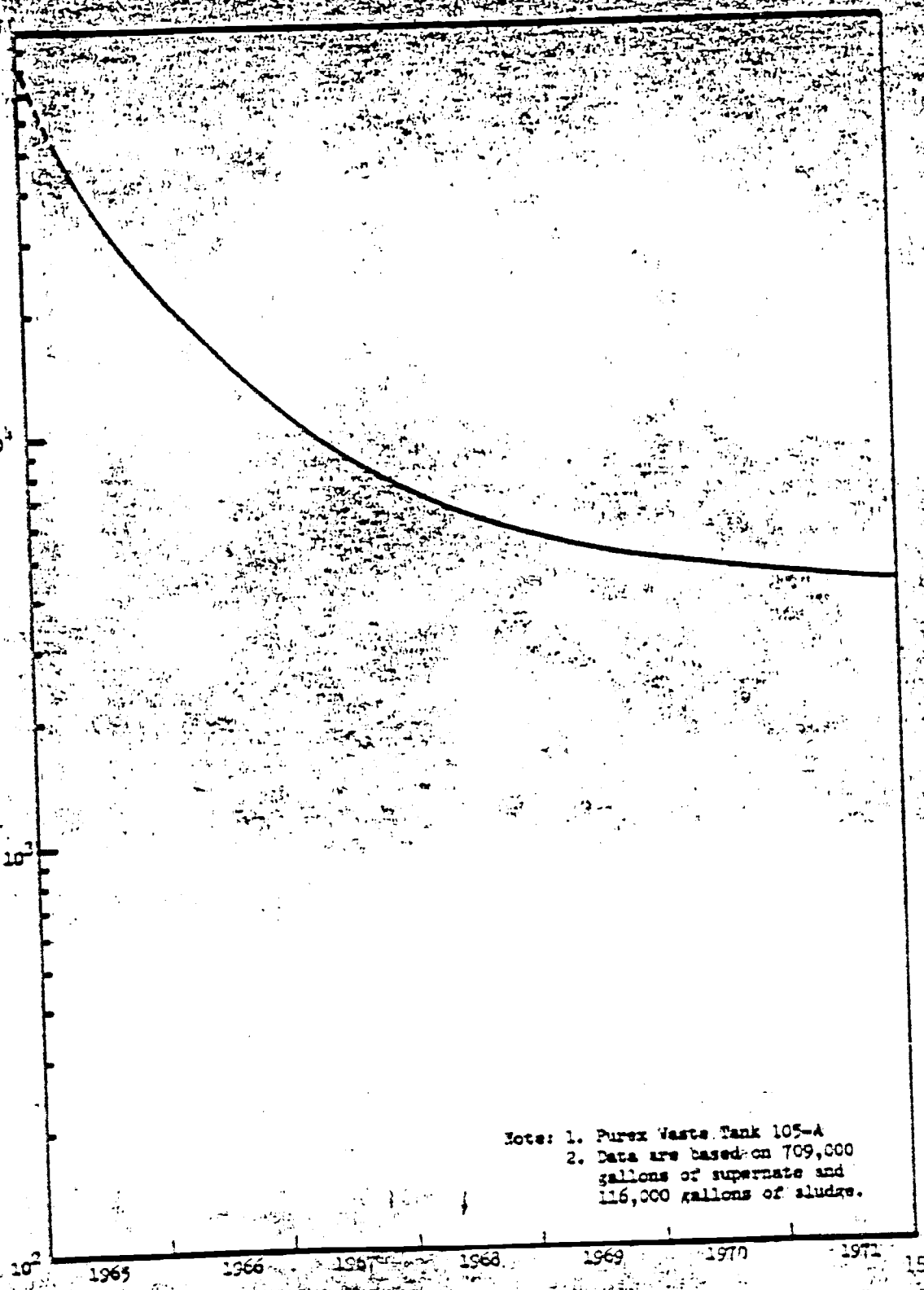
2. No evidence was found to indicate that the leakage was sufficient to create significant potential for contaminating the atmosphere or the groundwater.

3. The tank liner was bulged upward at one point to an elevation of 8.5 feet creating a void space of about 30,000 gallons.

4. The void under the bulge might contain vapor or supernate, but it was considered unlikely that it contained any appreciable amount of sludge.

5. The bottom liner was possibly balanced between the steam pressure underneath and the solution hydrostatic head on top. A method for venting the bulged area should be developed to prevent liner movement during removal of solution from the tank.

6. The probability of leaking sludge from the tank into the soil was very low; but if it should occur, very high temperatures at the concrete-soil interface would result.



FIGURE

Predicted Settled Sludge Temperatures For Uncontrolled Conditions

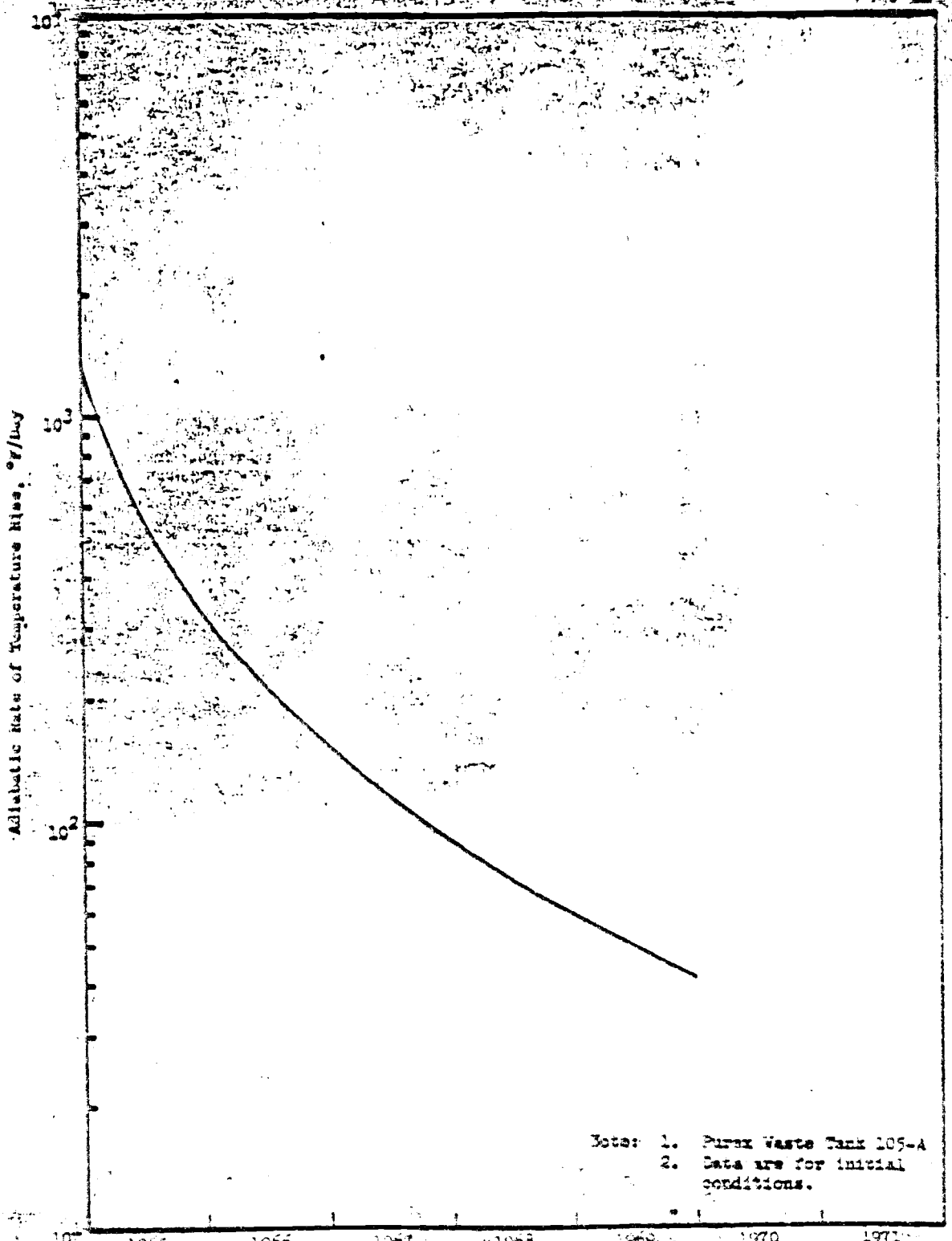


FIGURE 4
Rate of Temperature Rise in Dry Sludge

7. Leakage of filtered supernate into the soil would not result in temperatures at the concrete-soil interface that would cause damage to the structure.

8. If solution were removed or lost from the tank and the sludge allowed to dry, temperatures in excess of 10,000 F could result.

9. If the sludge were overheated, it would denitrate and expel NO_2 gas and later release fission products at higher temperatures.

10. Under all emergency conditions a release of radioactivity to the groundwater would be less serious than a release to atmosphere since the sorption capacity of the soil would delay the movement of radioactivity to the edge of the reservation until most of it decayed.

11. The potential hazard to the environment and the difficulty of emptying the tank would decrease with time as the fission products decay.

IX. OPERATING PLAN

Based on the conclusions of the several studies an operating plan was developed embracing four main objectives:

1) Control the tank sludge temperatures under all conditions of tank failure including the release of liquid to the ground;

2) Provide and maintain capability for emergency sluicing and emptying of the tank;

3) Maintain the tank status as static as possible; and

4) Continue intensive surveillance of tank leak detection and control instrumentation.

The first two objectives were met stepwise by providing the required control capability as rapidly as possible. Initially an emergency water spray unit was built that could be manually inserted through the 4-inch vacuum breaker riser to permit cooling of the sludge on the bulge in the event of sudden tank failure resulting in the complete loss of supernate. As construction efforts got underway, the next capability provided was raw water sluicing over the bulged area. Full sluicing capability with two recirculating sluicers was provided in November, 1965, and finally a tool for venting the bulged area, if required, (see Figure 7) was built and tested in the machine shop under simulated tank conditions.(12)

During this construction period several equipment modifications were made to improve operating control and surveillance of the tank. Recording instruments with alarms were installed on air supply lines to the circulators, and a

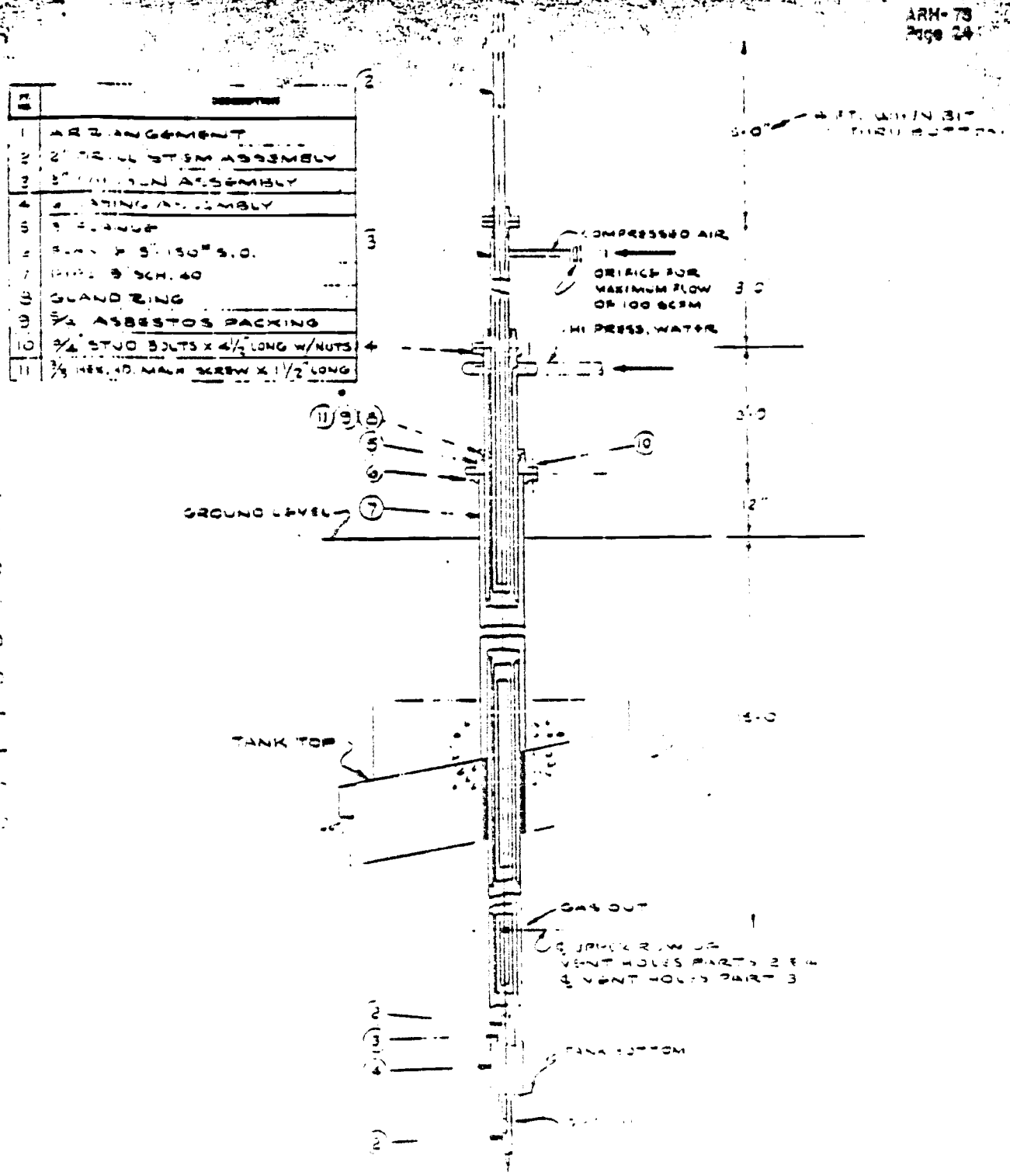


FIGURE 7

Elevation View of Bulge Venting Tool

backup portable air compressor was connected to the air supply system. These changes reduced to a practical minimum the possibility of loss of air to the circulators. Bulge movement detectors were installed at two locations to detect movement or shifting of the bottom liner. Temperature elements were included as an integral part of these instruments. A recent improvement in protecting the tank against pressure surges consisted of equipping the bypassed obsolete contact condensors so they would be activated during any pressure surge in the tank farm vent header. This modification supplements the condensing capability of the surface condensors under steam release conditions.

As the construction effort neared completion, operating procedures for sluicing TX-105-A were prepared. A hazard review covering the new sluicing equipment system and emergency procedures was also completed.(13)

When all arrangements had been completed for emergency sluicing and emptying TX-105-A, the behavior of the tank during the elapsed time since the steam release incident was reviewed. During the review various potential hazards were considered, and a decision was made to maintain TX-105-A in a static condition until such time as the tank was scheduled for Waste Management processing or until there was some evidence of further tank deterioration. The Tank Farm Process Specifications and Standards were revised to require section management approval to alter any operating condition affecting TX-105-A.(14)

X CHANGE IN TANK STATUS

In April, 1967, a cyclic liquid level variation began to occur in TX-105-A. A typical cycle consists of a 9-10 inch drop in liquid level in a matter of minutes followed by a relatively stable period lasting about 20 hours. The liquid level then gradually returns to its original level in about a day. No significant movement of the liner can be detected. The only logical explanation that has been identified for this behavior is that the area between the bulged tank liner and its concrete pad alternates between a vapor and liquid phase. A possible detailed explanation of this behavior and thermal implications follow.

From contour measurements, Table 2, the volume under the bulge is estimated to be about 80,000 gallons. Normally, about 26,000 gallons of the bulge space is postulated to be filled with steam, which flows in a steady stream at rates up to 1000 ft3/min from one or more holes in the liner, the highest of which is at an elevation estimated to be about 4 feet above the normal position of the tank bottom. The lower two-thirds of the bulge is believed to be filled with supernate slurry and an undetermined amount of settled sludge.

Occasionally an instability causes the supernate to begin to flow back through the hole into the vapor space beneath the bulge. The liquid being held by circulation at its atmospheric boiling point is cool enough to condense the steam under the bulge. Laboratory experiments have shown that once a suck-back begins, it will continue until the entire space under the bulge is filled with supernate

[redacted]

slurry. Water addition appears to be a major cause of instability since 20 of the 26 suck-back occurrences since April, 1967, have occurred immediately after addition of water to the tank. Airlift recirculation of the supernate slurry maintains the entire mass of liquid at its normal atmospheric boiling point of 230 F when it enters the bulge. About 18 to 24 hours are required to heat this liquid to its boiling point of 255 F under the hydraulic head under the bulge. After this induction period, steam begins to form under the bulge displacing supernate and slowly raising the apparent liquid level in the tank until steam again issues from the hole. By filling the tank as full as possible, water addition has been avoided for as long as six weeks, permitting stable operation over this period with no suck-back events.

A possible danger in the cyclic operation of the tank lies in the potential for filling the space under the bulge with settled sludge which could overheat and achieve temperatures as high as 2900 F. Thermal calculations based on the 19-hour induction period observed on May 19, 1967, indicated that the total heat transferred to the liquid under the bulge was 300,000 Btu/h immediately after a suck-back. Adjusting for decay and assuming no accumulation of sludge under the bulge, the calculated induction period on August 29, 1967, should be 21.8 hours which is in excellent agreement with the observed induction period of 22 hours. If the sludge associated with the 19 solution suck-backs that occurred between May 19, 1967 and August 29, 1967, had all settled out under the bulge, the induction period would have decreased to 12 hours. Since the observed induction period has not decreased, it can be concluded that the space under the bulge is not acting as a good settling chamber and is not rapidly filling with sludge.

It is of interest to note that if the bulge were to act as a perfect settling chamber with the historical 8.2 day cycle, the sludge would build up to the hole in the liner in about a year at which time about 500,000 Btu/hr of heat would be generated below the bulge with a maximum temperature of 1860 F. If the suck-backs were spaced 6 weeks apart, it would take about 5 years to fill the void, at which time the heat generated would be 190,000 Btu/hr, and the temperature would approach 850 F.

A concentration mechanism is also available which could eventually fill the bulge with solidified supernate; since the water evaporated to form the steam issuing from the bulge must be replaced by supernate slurry at a rate of 0.6 gpm, there must be a continual flow of salt into the bulge. If no cycling had occurred, in about 190 days after steam began to issue from the bulge, the bulge up to the hole would have filled with solidified supernate which could heat to temperatures approaching 600 F. Since cycling did occur, the solution under the bulge was periodically diluted with supernate slurry. With minimum settling of sludge, a steady state condition could be reached. For a supernate sodium concentration of 7 M and the average cycle spacing of 8.2 days, the sodium concentration under the bulge would reach equilibrium at 9 M. If suck-backs were to occur only every six weeks, the Na concentration would reach equilibrium at 17 M which would probably cause the gradual accumulation of precipitated salt.

At the present time (October, 1967) a mixture of settled sludge and solidified supernate beneath the liner would result in a range of temperatures between 450 and 2900 F. Figure 8 summarizes predicted equilibrium temperatures for various blends of solids versus decay time.

XI. REVISED OPERATING PLAN

On October 2, 1967, low-level radiation was detected in the #2 leak detection lateral for the first time, indicating some new seepage or migration of waste from the previous inactive leak. Also, the heat generation rate of the waste in this tank has decreased a factor of four since the steam release event in January, 1965. Potential hazards associated with emptying TK-105-A have decreased but are still large as discussed later. Alternative plans are being evaluated, and preparations are being made to sluice, empty and stabilize the tank.

The various alternatives being considered include three mechanical systems and two different sluicing fluids. An emergency sluicing system involving low sluice fluid pressures (200 psig) and TK-103-A and TK-105-A is now available and could be used. In about 2 months, the 244-AR Vault will be completed and could be used for sluicing the tank. The vault offers several advantages over the emergency sluicing system including remote maintenance capability for a portion of the equipment and temperature control of the sluicing fluid. The vault sluicing system like the emergency system uses low pressure pumps. The third system being considered is the Savannah River high pressure jet system (2500-3000 psig).(15) It is believed to have the advantage of being able to empty a tank faster than the low pressure systems.

Either of the low pressure sluicing systems could use water or high salt supernate as the sluicing fluid. The high pressure Savannah River system would be limited to water. When the leak potential resulting from leaching and removing the salt that is sealing the cracks in the concrete shell is considered, the advantage of sluicing with supernate instead of water is apparent. This advantage may be offset by the Savannah River system's time advantage in sluicing a tank. While the potential for opening up leak areas with high pressure water may be large, the duration of time that material could leak would be reduced. Which system would result in the lowest net release of radioactivity to the ground is open to speculation. However, the length of time that the tank emptying operation takes is also the time period that involves maximum exposure to fission product release hazards. Being able to empty the tank rapidly minimizes this exposure to high risk and is an advantage of the high pressure system.

XII. HAZARDS ANALYSIS

Three situations were postulated to represent conditions that could occur in the event TK-105-A fails completely. Similar waste tank hazard analyses have been made at Oak Ridge National Laboratory.(16)

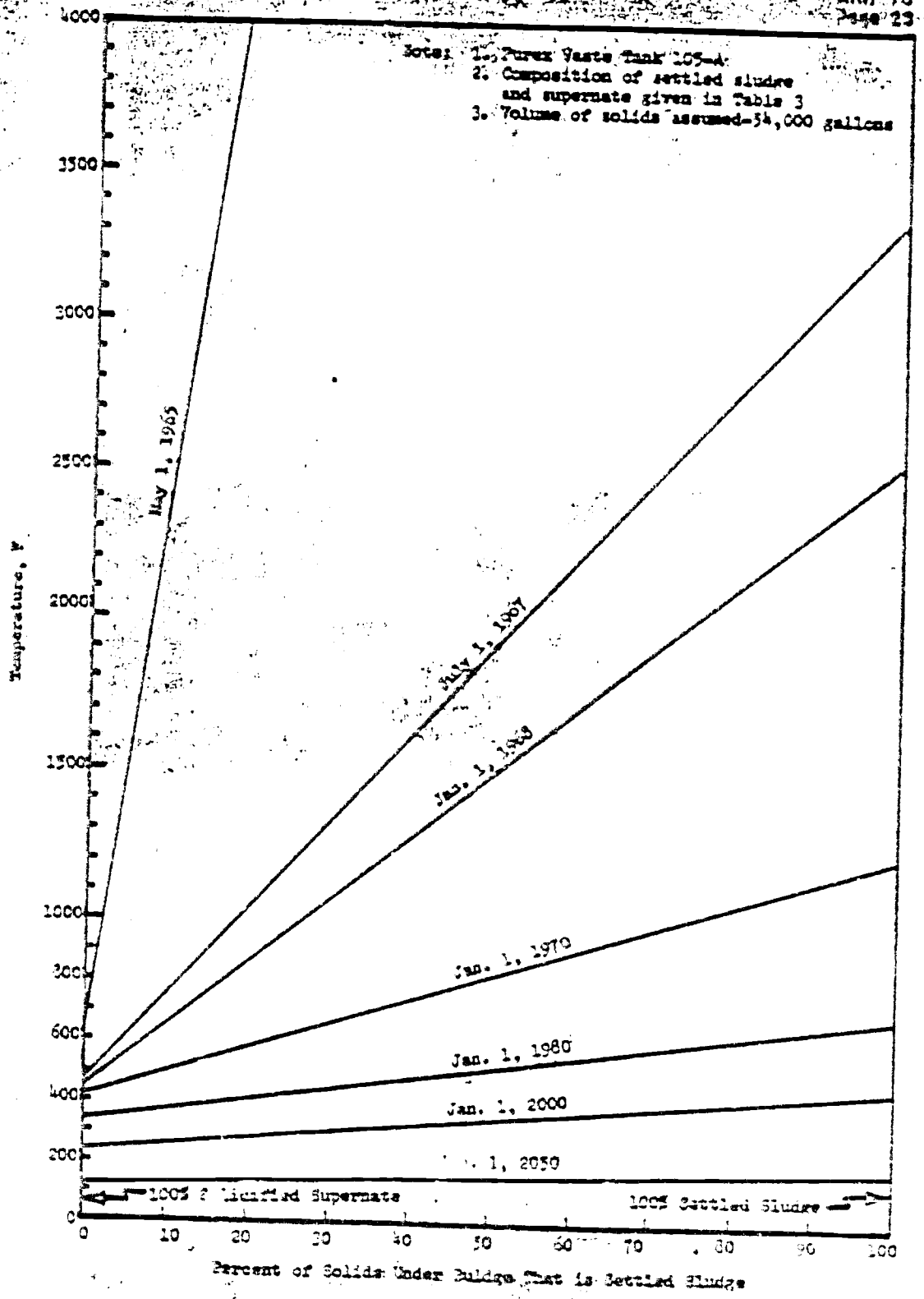


FIGURE 3

Predicted Temperatures Generated In Mixtures Of Settled Sludge And Supernate

Condition 1 - Total tank contents evaporate to dryness and achieve a maximum temperature as controlled by the laws of nature.

Condition 2 - Tank supernate is lost from tank - sludge achieves maximum temperatures as controlled by the laws of nature.

Condition 3 - Tank supernate is removed, sludge is removed except for a quantity trapped beneath the bulged liner. Quantity beneath the liner varies from all solidified supernate to all solidified sludge.

Estimates of the environmental consequences resulting from each of these conditions are presented to provide guidance to management in arriving at decisions which may be required during the TK-105-A sluicing effort. Conditions 1 and 2 are very unlikely to occur, but estimated environmental consequences of these two conditions are included to provide an appreciation of the magnitude of the potential hazards.

An estimate of the inventory of radionuclides in TK-105-A as a function of time is summarized in Figure 4. The environmental consequences of the three postulated conditions have been estimated for four dates: January 1, 1965; May 1, 1965; July 1, 1967; and January 1, 1968, as shown in Table 5.

Condition 1

Volatilization fractions for several radionuclides from both simulated and actual wastes have been measured by Barton.(10, 11) On the basis of these measurements, volatilization fractions, tabulated in Table 4, have been assumed.

The atmospheric release of the volatilized radionuclides is difficult to predict. In this analysis three arbitrary atmospheric release fractions of 1, 0.1 and 0.01, are assumed. For example, for sludge plus supernate an atmospheric release fraction of 1 would assume all of the volatilized cesium would be released to the atmosphere. Since 0.15 is the volatilized fraction assumed for cesium (Table 4), an atmospheric release fraction of 1 in this example corresponds to an atmospheric release for cesium of 15 percent.

Estimates of the dose to bone and total body for the first year following exposure have been made for persons remaining in the cloud for 2 and 24 hours at selected downwind distances. For Condition 1 the limiting mode of exposure is inhalation, and this results in the total body as the most critical organ. Total body doses via this mode of exposure have been estimated using mathematical models described by Watson.(7) Table 5 summarizes these estimated doses. External exposure of persons in the cloud from air-borne radionuclides is insignificant compared to doses received from inhalation. Exposures near the tank would be severe as discussed later.

From Table 5, it can be calcula that a total body dose in excess of 25 rem, 2 hours' exposure at 5 miles or 24 hours' exposure at 18 miles, can be anticipated

TABLE 4
VOLATILIZATION FACTORS
TK-105-A

	Sludge + Supernate(10,11)		Sludge Only(10,11)	
	Synthetic	Tank Waste	Synthetic	Tank Waste
Ru	0.36	0.022	0.0019	-
Cs	0.64	0.091	ND*	-
Sr	-	0.0052	-	-
β-emitters	0.065	-	0.00032	-

* Not Detected $<10^{-6}$

Assumed Volatilization Factors

	Sludge + Supernate	Sludge Only
Ru	0.05	0.0003
Cs	0.15	5×10^{-6}
Sr	0.02	1×10^{-4}
All Other	0.02	1×10^{-4}

TABLE 5
CALCULATED TOTAL BODY DOSE - TK-105-A
CONDITION 1

Distance (Miles)	Exposure Time (hrs)	Date	Dose* for Atmospheric Release Fractions Equal to: 1.0	0.1	0.01
5	2	1/1/65	400	40	4.0
		5/1/65	380	38	3.8
		7/1/67	360	36	3.6
		1/1/68	360	36	3.6
	24	1/1/65	2000	200	20
		5/1/65	1900	190	19
		7/1/67	1800	180	18
		1/1/68	1800	180	18
18	2	1/1/65	100	10	1.0
		5/1/65	99	9.9	0.99
		7/1/67	93	9.3	0.93
		1/1/68	93	9.3	0.93
	24	1/1/65	520	52	5.2
		5/1/65	500	50	5.0
		7/1/67	470	47	4.7
		1/1/68	470	47	4.7

* Rem in first year following exposure.

whenever the fraction of volatilized radionuclides escaping to the atmosphere exceeds 0.05. Although this postulated condition is unlikely, the estimated consequences are of sufficient magnitude as to warrant preventive action to insure that the tank contents do not evaporate to dryness.

Condition 2

It is postulated under this condition that all of the supernate is suddenly lost to the ground, and the remaining sludge layer evaporates to dryness. The environmental consequences of this type failure include contamination of the groundwater and release of volatilized radionuclides to the atmosphere. Due to much lower release fractions from solidified sludge, Table 4, dose estimates at both 5 miles and 10 miles are considerably below permissible occupational dose levels. If water were added to the tank as required to control the sludge temperatures, the release to atmosphere would be prevented. Since total loss of supernate to the ground is assumed, any additional contamination of the groundwater resulting from the addition of cooling water would be insignificant.

The contamination of groundwater at the Columbia River has been estimated on the basis of groundwater flow under existing flow conditions using a simplified model which does not take credit for either ionic exchange with the soil column between the tank and the groundwater or dilution of the released radionuclides in the groundwater.(18)

Figure 9 shows the estimated future strontium-90 and cesium-137 concentrations in groundwater at any distance from the input source as a function of groundwater travel time. The times, indicated in Figure 5, to reach a distance of five miles and the Columbia River assume existing groundwater flow conditions remain unchanged over the next several thousand years. These concentrations are based on radioactive decay assuming that Sr-90 and Cs-137 move at 1/50 and 1/500 the rate of groundwater, respectively. Adsorption studies have shown that these relative migration rates are reasonable estimates for the existing flow conditions.(18) However, if the competing cation concentrations in groundwater should increase (especially calcium and potassium) or if the aquifer elevation should increase and include more inert gravelly soil material, the migration rates could increase. Dispersion (dilution caused by mixing) was not considered. Neglecting this mechanism results in conservative estimates which do not accurately predict initial radionuclide arrival and predict higher than actual peak concentrations.

Though the travel time associated with the present groundwater flow path from the vicinity of the 241-A Tank Farm to the Columbia River is about 27 years, it is highly likely that flow paths (and associated travel times) will change appreciably in the very long period following the accident postulated in this study. Such changes could be relatively drastic in either direction - longer or shorter travel times - depending upon the myriad of possible causation factors (e.g., dam, irrigation, processing modifications, etc.). The infinite number of possible cause and effect relationships do not permit accurate forecasting for new flow conditions. The minimum travel time, for groundwater

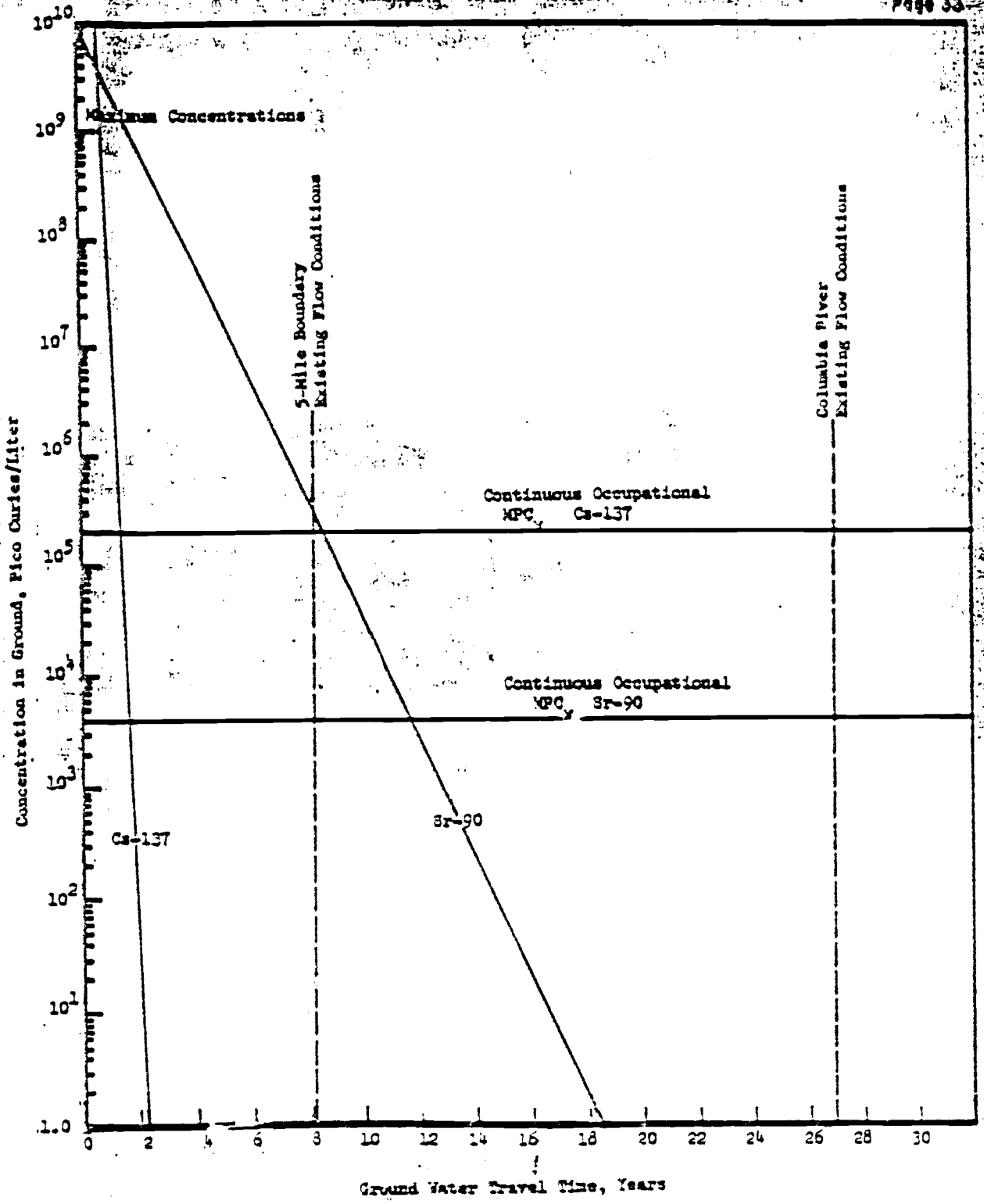


FIGURE 9
Predicted Ground Water Contamination As
A Function of Travel Time

moving from the vicinity of 200 East Area to the Columbia River, noted in previous simulation studies was about 2.5 years.

No credit has been taken for the time of travel of wastes in the vadose zone. This could be essentially infinite in the case of TK-105-A or on the order of several weeks, depending primarily on the volume of waste leaked. Also, the effects of self-heating of waste within the soil matrix was not evaluated insofar as the effects on waste travel are concerned.

Condition 3

Condition 3 results in environmental consequences of considerably less magnitude than either Conditions 1 or 2. If the area under the bulge were completely filled with solidified supernate, the maximum temperature that could occur as of January 1, 1968, would be less than 500 F which would not volatilize significant amounts of fission products. If the area were filled with settled sludge, temperatures of 2500 F could result. However, the volatilization factors for sludge, that are free of supernate, are 4 orders of magnitude lower than for mixtures of sludge and supernate. Thus the maximum consequences would occur when the bulged area contains the maximum amount of solidified supernate in combination with enough settled sludge to produce volatilization temperatures.

On January 1, 1968, the worst case is estimated to be a mixture of 15 volume percent solidified supernate and 85 volume percent settled sludge. The environmental consequences for this worst case and for settled sludge alone are summarized in Table 6.

General

For all release conditions dose rates near the tank farm would be severe. For Condition 1 on January 1, 1968, an atmospheric release fraction of 0.10 would result in estimated dose rates of 1 R/h at 100 meters from the tank. Air contamination would require respiratory protection equivalent to fresh air to avoid excessive exposure from inhalation. Condition 2 on January 1, 1968, would be about 10-fold less severe or an increase in the atmospheric release fraction to 1.0 would produce about the same exposures as described for Condition 1. It is thus apparent that partial loss of sludge temperature control could result in releases that would deny manned access to critical tank farm control equipment with subsequent deterioration to Conditions 1 or 2. It is concluded from this study that the alternative of cooling the tank wastes with water even under conditions of gross leakage of wastes to ground is far less serious than permitting waste temperatures to rise.

TABLE 6
CALCULATED TOTAL BODY DOSE - TK-105-A
CONDITION 3 AS OF JANUARY 1, 1966

Distance (miles)	Exposure Time (hrs)	Type of Wastes in Bulge	Dose for Atmospheric Release Fractions Equal to: 1.0	0.1	0.01
5	2	Supernate + Sludge*	3.9	0.39	0.039
		Sludge **	0.02	0.002	0.0002
	24	Supernate + Sludge	20	2.0	0.20
		Sludge	0.09	0.009	0.0009
18	2	Supernate + Sludge	1.0	0.10	0.010
		Sludge	0.09	0.009	0.0009
	24	Supernate + Sludge	5.1	0.51	0.051
		Sludge	0.02	0.002	0.0002

* Dose for release from supernate + sludge is in REM, total body for first year following inhalation exposure.

** Dose for release from sludge is in REM, bone for first year following inhalation exposure.

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FINAL LETTER REPORT

AEROSOL CONCENTRATIONS RESULTING FROM SPARGING AIR THROUGH VARIOUS SOLUTIONS

C. M. Ruecker
C. M. Andersen

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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Recently, there has been some concern that significant amounts of radioactive aerosols could be released during upset conditions in an aging waste tank. The release of radioactive aerosols could conceivably occur should the airlift circulators cease to function, thereby allowing the heat-producing solids to settle to the bottom of the tank. Consequently, it is postulated that extreme temperatures could build up within the solids layer due to poor transfer of heat to the supernatant. Once the airlift circulators are restarted, large amounts of heat could be released when the solids are resuspended. This sudden release of heat could cause the supernatant to flash, thereby producing steam in amounts sufficient to overwhelm the tank ventilation system. This situation may cause the tank to pressurize, which could result in steam being released to the environment. The escaping steam could potentially carry gaseous radionuclides or radioactive aerosols generated during the event, thus resulting in the release of radioactive materials.

The above accident scenario is commonly referred to as a "tank bump". Recently, Westinghouse Hanford Company (WHC) has attempted to estimate the amount of material that could be released to the environment during such an event. Some simple assumptions were made in order to calculate the amount of steam bypassing the tank ventilation system. The total volume of vapor escaping was then multiplied by an assumed aerosol concentration of 10 μg/L to obtain the mass of waste escaping. The objective of this study was to experimentally determine if this assumed concentration was appropriate.

The program objective was met by sparging air through various solutions and measuring the resulting aerosol concentration. As expected, the aerosol concentration is a function of the total solids loading in the solution. Aerosol concentrations ranging from 0.66 to 4.9 μg/L were measured for air flowing through a vessel containing a sucrose/titanium dioxide mixture at a superficial velocity of 13.4 ft/min. The weight percent dissolved solids for the test solution ranged from 27.9% to 41.6%, while the weight percent insoluble solids varied from 0 to 1.4%. Higher insoluble solids loading could not be achieved, as the agitation within the tank caused by the bubbling action, although quite vigorous, was not sufficient to keep the titanium dioxide suspended. As expected, the outlet concentration was found

to increase exponentially with solids loading, however, the limited data is insufficient to clearly define a curve relating concentration to total solids loading.

A second set of experiments was conducted using a chemical simulant for Neutralized Current Acid Waste (NCAW). The observed aerosol concentrations for these experiments ranged from 10.1 to 16.6 μg/L after correcting for adsorbed water. Although the solids loading was not determined for the NCAW simulant, the weight percent total solids was estimated to be around 50 wt%, thus explaining the higher values than were observed with the sucrose-based simulants.

The measured aerosol concentrations brackets the aerosol concentration assumed by WHC (10 μg/L). However, the measured aerosol concentrations are dry aerosol concentrations, as the water present was evaporated. The value assumed by WHC is a wet aerosol concentration. The data presented here can be converted to wet aerosol concentrations using the weight percent total solids. Using a conservative estimate of 37.5 wt% for NCAW leads to wet aerosol concentrations as high as 26.9 to 44.3 μg/L.

It is recommended that a conservative aerosol concentration of 50 μg/L, based on the results of this study, be used for estimating the amount of waste release during a tank bump. This concentration corresponds to a release rate of 1.1×10^{-7} volumes of waste per volume of escaping vapor if no aerosols are captured enroute to the environment. This predicted release rate is essentially the same as that proposed by Squires (1987), which was arrived at using a different set of assumptions, including a lower assumed aerosol concentration (10 μg/L).

The actual amount of material released should be less than the stated value as the experimentally measured aerosol concentrations, from which this value is based, were obtained at superficial velocities higher than those likely to be encountered during a tank bump. The recommended value is also conservative in the sense that it is assumed that all aerosols created will be released, when in fact some of the material will undoubtedly be removed enroute to the environment through impaction, interception and Brownian diffusion capture mechanisms. No attempt was made to estimate radiation exposure levels based on the predicted release rates, as this was beyond the scope of work identified for this program.

CONTENTS

SUMMARY ii

1.0 INTRODUCTION 1

2.0 EXPERIMENTAL APPARATUS 3

2.1 Test Vessel 3

2.2 Data Collection System 3

2.3 Electrical Aerosol Size Analyzer 5

2.4 Gross Particulate Aerosol Sampling Train 6

3.0 EXPERIMENTAL PROCEDURE 8

4.0 EXPERIMENTAL RESULTS 10

4.1 Experiments Involving a Sucrose Based Simulant 10

4.2 Experiments Involving a Neutralized Current Acid Waste Simulant 12

5.0 DISCUSSION 15

5.1 Effect of Weight Percent Solids 15

5.2 Comparison with Previously Assumed Concentrations 15

5.3 Validity of Assumptions 17

6.0 CONCLUSIONS AND RECOMMENDATIONS 20

7.0 REFERENCES 21

FIGURES

1 Cross-Sectional View of the Test Vessel 4

2 The Electrical Aerosol Size Analyzer Sampling System 5

3 The Gross Particulate Aerosol Sampling Train 6

4 Aerosol Entrainment Mechanism for Bursting Bubbles 18

TABLES

1 Summary of Experimental Results Involving Sucrose 10

2 Comparison of Observed Water Loadings to those for Saturated Conditions 11

3 Composition of Synthetic Current Acid Waste 12

4 Summary of Experimental Results Involving NCAW 12

5 Estimated Gallons of Waste Released to the Environment During a Tank Bump 16

1.0 INTRODUCTION

The aging waste tanks on the Hanford Site contain a mixture of radioactive solids and liquids. The solids are maintained in suspension using airlift circulators. Suspension of the solids is required to prevent these heat-producing solids from concentrating on the floor of the tank. If large amounts of solids were allowed to accumulate in one place, the production of decay heat could lead to unacceptable temperatures within the solids layer as the result of poor transfer of heat to the supernatant.

It has been speculated that temperatures in excess of the boiling point of the waste can be achieved within the solids layer should such a layer be allowed to form. In order for this buildup of heat to occur, an anhydrous solids layer would have to be created. This layer would be separated from the supernatant by a hydrated solids layer. The presence of an anhydrous solids layer would lead to poor heat transfer rates, thus allowing the solids layer to overheat.

The accumulation of heat in the settled solids layer could possibly result in the release of radioactive material when the airlift circulators are restarted, as the heat previously trapped in the solids layer would be released. Release of a significant amount of heat could cause some of the supernatant to flash. The sudden production of vapor in turn could overwhelm the tank farm ventilation system, causing the tank to pressurize. Consequently, vapors in the plenum might begin to escape through leaks in the pump pits, risers and breathers. These escaping vapors could potentially contain any gaseous radionuclides or radioactive aerosols generated during the event.

The accident scenario described above is commonly referred to as a "tank bump". Westinghouse Hanford Company (WHC) estimated the amount of material that could potentially be released during a bump to determine if modifications to the tank farm and/or operating procedures are needed so as to be consistent with the ALARA (as low as reasonably achievable) concept.

The objective of this study is to measure aerosol concentrations resulting from air being sparged through various solutions. The measured concentrations can then be used to estimate the amount of material that could be released during a tank bump, provided that the rupturing of bubbles

at the liquid surface is the dominant mechanism for generating aerosols during a tank bump. In all likelihood, this is a safe assumption.

2.0 EXPERIMENTAL APPARATUS

The test apparatus used during this study consists of four main components: 1) the test vessel, 2) the data collection system, 3) an electrical aerosol size analyzer, and 4) a gross particulate sampling train.

2.1 TEST VESSEL

A cross-sectional view of the test vessel is shown in Figure 1. The test vessel, used to contain the solution being investigated, was fabricated from a 60-in. section of stainless steel 24-in. diameter pipe. Room air was sparged through the solution via the inlet line shown in Figure 1. The inlet line consists of 1-in. diameter black iron pipe. A manual throttling valve and an orifice plate are located in this line to control/monitor the inlet flow rate. The downcomer portion of the inlet line within the vessel is 1-in. stainless steel tubing. The bottom of the downcomer is located 6 in. from the floor of the vessel.

An overflow line, equipped with a siphon break, is situated 36 in. from the floor of the vessel. The test apparatus is also equipped with an internal steam coil which can be used for testing at elevated temperatures. The process gas is drawn out of the vessel through a 2-in. diameter exit line, which is connected to the building's primary off-gas system. The blower in this system is capable of pulling 320 scfm at 6 in. Hg vacuum. A sampling port and a pitot tube flow element are used in this line to measure the exit aerosol concentration and flow rate, respectively. Thermocouples are located in both the inlet and outlet lines, with four others used to monitor the temperature of the solution.

2.2 DATA COLLECTION SYSTEM

Validyne differential pressure transducers are used to measure the pressure drops across the inlet orifice plate and the pitot tube on the exit line. The voltage signals from these transducers are received by a Validyne 380 panel meter where they are converted to pressure drops and corresponding flow rates. The thermocouples are connected to a Fluke 2240C datalogger. A Hewlett Packard 9000 series 216 personal computer is used to monitor the system. The computer is programmed to prompt the panel meter and the

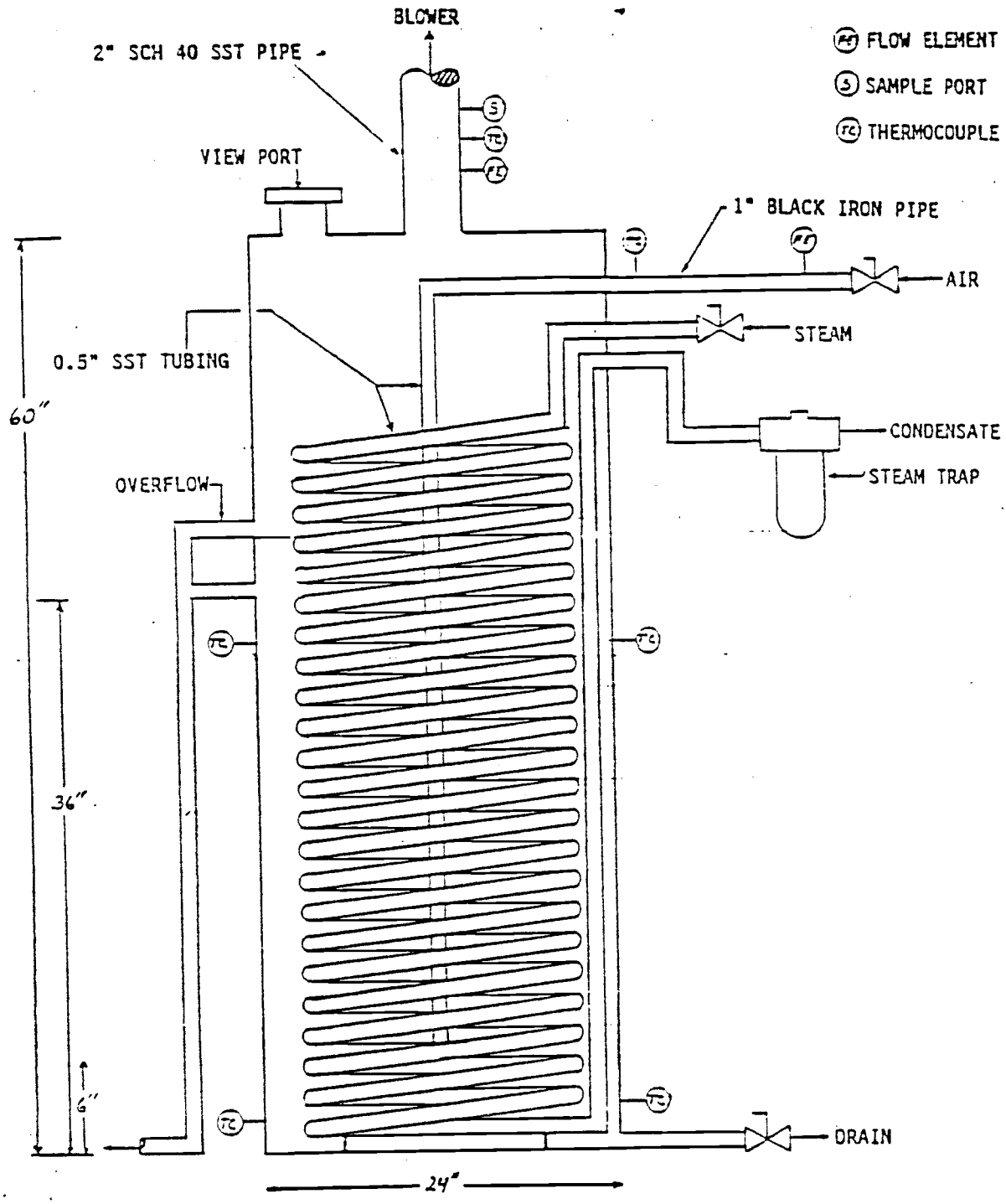

Figure 1. Cross-Sectional View of the Test Vessel.

datalogger for data every 15 seconds. Every fourth reading is recorded on the computer's hard disk so that the data can be analyzed at a later date to obtain mean values for the various process parameters being monitored.

2.3 ELECTRICAL AEROSOL SIZE ANALYZER

An Electrical Aerosol Size Analyzer (EASA) manufactured by Thermo-Systems Inc. (TSI) is used to measure the particle size distribution of aerosols in the 0.01 to 1.0 μm size range. The EASA can also provide an aerosol concentration for particles within this size range. The EASA sampling system is shown in Figure 2. A vacuum pump is used to draw the sample stream through the instrument. A needle valve can be adjusted to maintain the sample flow rate at 4 L/min. Filtered room air is also drawn through the instrument to form a sheath of clean air around the precipitator. The sheath air flow rate is maintained at 46 L/min using a needle valve.

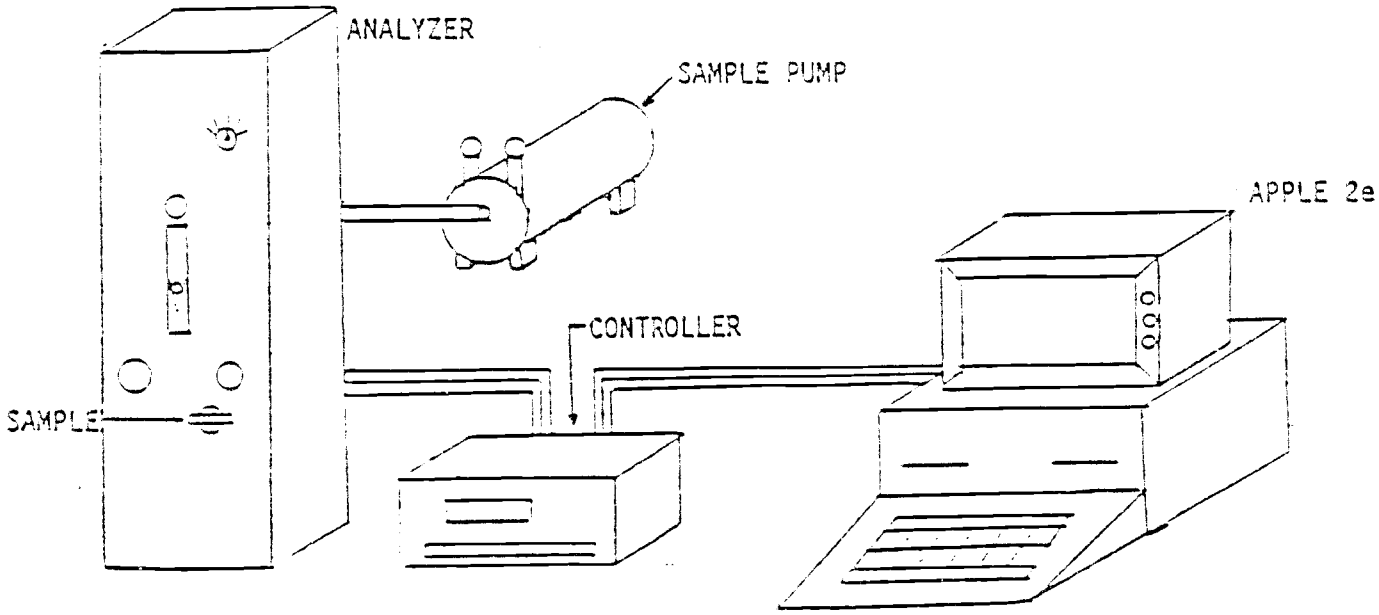

Figure 2. The Electrical Aerosol Size Analyzer Sampling System.

The off gas sample stream enters the diffusion charger inside the EASA where aerosols present in the sample stream are exposed to unipolar positive ions produced by a corona discharge. The charged aerosols enter the mobility analyzer, comprised of a precipitator and an electrometer sensor. The mobility distribution is then measured. The particle size distribution and concentration are inferred from this measurement. An Apple 2e computer is used to receive the raw data. The system is equipped with a data analysis program provided by TSI which uses the raw data to calculate a size distribution and aerosol concentration based on the theory outlined by Liu and Pui (1975). A more detailed description of the EASA is available elsewhere (Liu, Whitby and Pui 1974).

2.4 GROSS PARTICULATE AEROSOL SAMPLING TRAIN

The gross particulate aerosol sampling train is used to determine the gross aerosol mass loading in the exiting off gas. The system is shown in Figure 3. The sampling train consists of a Gelman in-line filter housing

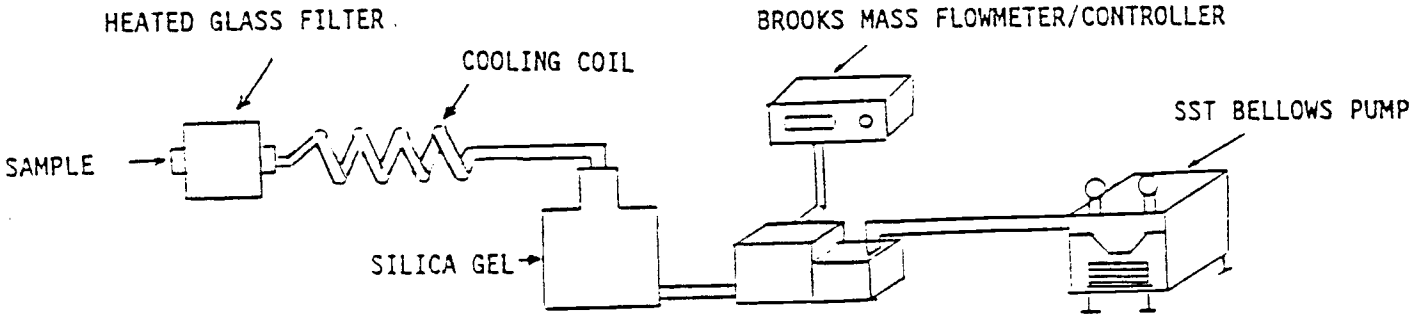

Figure 3. The Gross Particulate Aerosol Sampling Train.

which contains a 47 mm Gelman A/E glass fiber filter, followed by a silica gel bed and a Brook's 5850E mass flow controller. The Gelman A/E glass fiber filter has a filter efficiency ranging from 99.6 to >99.99% for 0.3 μm DOP droplets depending on the superficial velocity (Lippmann 1983). Electrical resistant heating tape is used to prevent any moisture present in the sample stream from condensing on the filter paper.

The sample line leading from the filter housing to the silica gel bed is coiled to increase the residence time so that the sample stream can cool back to room temperature prior to entering the silica gel bed. The water loading in the sample stream can then be determined by the weight gain of the silica gel bed and the volume of gas sampled. An MB-158 vacuum pump manufactured by Metal Bellows Corp. is used to draw a sample stream through the system. The set point control for the mass flow meter allows accurate control of the sample flow rate over the flow range from 0 to 10 L/min.

The gross particulate sampling train was designed so that gas scrubbers could be installed in series in between the stainless steel coil, located on the backside of the filter housing, and the silica gel bed. These scrubbers are used when necessary to remove undesirable vapors to protect the mass flow controller. The scrubbers consist of a downcomer with a fritted glass filter, submerged in a scrubbing solution. The fritted glass filter is used to create small bubbles to increase the contact area between the gas and the scrubbing solution.

3.0 EXPERIMENTAL PROCEDURE

Once the test vessel has been filled with the solution to be investigated, the data acquisition system is started. Air flow through the test vessel is initiated by opening the valve which isolates the apparatus from the primary off-gas system. The air flow rate through the test vessel is set at the desired value by adjusting a manual throttling valve. If the solution is to be heated, the throttling valve on the steam line leading to the internal coil is opened appropriately. While the parameters of interest are coming to steady state, the EASA is used to measure the aerosol concentration in the laboratory to serve as a comparison for the concentrations measured on the outlet.

Once the solution temperature and air flow rate have stabilized at their respective values, the aerosol concentration for the exiting gas can be determined. First the EASA is connected to the sampling port using 1/4-in. stainless steel tubing. The sample stream is drawn through a TSI aerosol neutralizer containing a Kr-85 source, and into a TSI diffusion dryer prior to entering the EASA. Stainless steel tubing is used throughout to prevent the possibility of sampling losses that can occur with some types of plastic tubing (Liu, Pui, Rubow and Szymanski 1985). After three outlet concentration measurements have been made, the EASA is disconnected so that the gross particulate aerosol sampling train can be used.

The filter housing at the inlet to the sampling train is mounted directly to the 1/2-in. diameter stainless steel sampling probe to minimize sampling losses. The sampling probe is directed into the off-gas flow in an attempt to obtain an isokinetic sample. True isokinetic sampling was not achieved, however, as no special attempt was made to match velocities in the sample probe with those in the exit line. This procedure was deemed unnecessary for the size distribution likely to be encountered. This decision was based on the correlations given by Durham and Lundgren (1980).

The sampling probe used during early experiments (Runs #1-4) contained a 90° bend in order to fit into the exit line and still be directed into the flowing off gas). Based on criteria presented by Cheng and Wang (1981), no significant sampling losses are anticipated with this design. The sampling probe was later located closer to the outlet nozzle on the test vessel. This

time the sampling probe was mounted at an elbow so there was no need for a 90° bend in the probe in order for the probe to be directed into the flowing off gas.

As previously mentioned, the filter housing is wrapped with heating tape to prevent any moisture in the sample stream from condensing on the filter paper. Once the sampling train is connected, the power strip for the sampling train is turned on. The mass flow controller is set for a sample flow rate of 3.0 L/min (30% of full scale). The valve isolating the vacuum pump from the sampling train is opened and the time recorded. The system operating pressure is checked (approximately 7 in. Hg vacuum) along with the flow rate to ensure that the system is operating properly. The system is then allowed to run overnight.

Prior to terminating the sampling, the sample flow rate is checked to ensure that it has stayed at its set point and the operating pressure is noted. To terminate the sampling, the ball valve upstream of the vacuum pump is closed, the power strip is turned off, and the time is recorded. The heating tape around the filter housing is removed to allow the filter to cool to room temperature before it is removed. Once the system has cooled, the filter paper is removed and weighed. The silica gel bed is also removed from the system and weighed to determine the weight gain during sampling. The gas scrubbers, if used, are treated similarly.

After the sampling sequence is completed, the system can be isolated from the process blower by closing the appropriate ball valve. Immediately after the air flow through the vessel is discontinued, a sample of the solution is collected through the view port on the top of the vessel. The total amount of suspended solids is then calculated from this sample.

After the experiment has been completed, the data acquisition program is terminated. A data analysis program is then used to calculate averages and standard deviations for all of the parameters monitored during the experiment.

4.0 EXPERIMENTAL RESULTS

Initial experiments were performed using a soluble sucrose solution. Titanium dioxide (which is insoluble) was added in later experiments, and finally a chemical simulant for neutralized current acid waste (NCAW) was used. Attempts were made to measure the aerosol concentration as a function of flow rate using the EASA for each of the test solutions. However, the EASA indicated that the aerosol loading was too low to be measured. It was later learned from the manufacturer that the EASA was originally designed for atmospheric sampling and that they have no experience with the EASA when used for sampling from a negative pressure stream. Unfortunately, they were unable to determine why the system would not function properly when used in this manner. Due to the problems encountered with the EASA, only the data obtained with the gross particulate sampling train are report here.

Because of the long sampling times required to measure the gross aerosol mass loading, only one flow rate could be tested using the particulate sampling train. A flow rate of 40 scfm was chosen, as this flow rate represents the highest flow rate achievable with the experimental equipment and should lead to the highest aerosol concentrations.

4.1 EXPERIMENTS INVOLVING A SUCROSE BASED SIMULANT

A summary of data from the experiments in which a sucrose based simulant was used is given in Table 1.

Table 1. Summary of Experimental Results Involving Sucrose.

Run #	Wt% Solids sucrose	Wt% Solids TiO_2	Solution Temperature (°C)	Flow Rate (scfm)	Water Loading (mg/L)	Aerosol Loading (μg/L)
1	27.9	0.0	12.3	41	12.0	0.66
2	36.5	0.0	12.3	42	11.4	1.84
3	39.5	0.6	14.6	42	14.7	2.07
4	41.6	1.4	14.9	43	13.6	4.87

The liquid level was originally set at 36 inches (the height of the overflow drain). On starting the first experiment, the air bubbles in the solution increased the effective volume of the solution. The level of the solution temporarily rose above the level of the overflow drain. The solution gradually drained until the air/solution interface was at the level of the overflow drain. After the experiment was completed and the air was turned off, the depth of the solution remaining in the vessel was found to be 27 inches. This level served as the starting point in the next test. Each subsequent test was conducted at a slightly reduced level due to evaporation. The slight increase in the volumetric flow rate that occurred with each experiment reflects a small change in the liquid head that the blower must overcome to enable air to flow through the vessel.

As previously mentioned, a bed containing silica gel was used to measure the water content in the off gas. Table 2 shows that the water contents are typical of those expected for saturated air at the exit temperatures observed during the experiments. In some instances the observed water loading was higher than the saturated water loading. In actuality, the observed difference is probably not real, but the result of inaccuracies resulting from reading information from the psychrometric chart. The close agreement between the measured water loading and the expected water loading for saturated air at the operating temperature suggests that there was not a significant amount of entrained water in the off gas. This result is consistent with the measured aerosol concentrations.

Table 2. Comparison of Observed Water Loadings to Those for Saturated Conditions.

Run #	Exit Temperature (°C)	Saturated Water Loading (mg/L)	Observed Water Loading (mg/L)
1	12.6	11.3	12.0
2	13.0	11.7	11.4
3	15.3	13.3	14.7
4	15.7	13.6	13.6

4.2 EXPERIMENTS INVOLVING A NEUTRALIZED CURRENT ACID WASTE SIMULANT

Approximately 50 liters of synthetic current acid waste (CAW) were received from WHC. The composition of the simulant, as reported by WHC, is shown in Table 3.

Table 3. Composition of Synthetic Current Acid Waste

0.88 M $Al(NO_3)_3 \cdot 9H_2O$
0.22 M $NaNO_3$
0.104 M $Fe(NO_3)_3 \cdot 9H_2O$
0.016 M $Cr(NO_3)_3 \cdot 9H_2O$
0.085 M $Ni(NO_3)_2 \cdot 6H_2O$
0.056 M $Fe_2(SO_4)_3 \cdot 9H_2O$
0.653 M HNO_3
0.169 M H_2SO_4
0.206 M HF

The CAW was denitrated at PNL with 1,781 g of a 22 wt% sucrose/0.005 M NaOH solution in the test vessel. The sucrose solution was added to the 50 L of CAW at a flow rate of 3.33 ml/min over an 8-9 hour period. The internal steam coil was used to maintain an average simulant temperature of approximately 68°C during the denitration process. The CAW was then neutralized with 37.5 liters of 19 M NaOH (50 wt%). Enough synthetic neutralized current acid waste (NCAW) was produced to fill 11-1/4 inches of the test vessel.

Three experiments were conducted using the NCAW simulant. The results from these experiments are summarized in Table 4.

Table 4. Summary of Experimental Results Involving NCAW

Run #	Solution Temperature (°C)	Flow Rate (scfm)	Aerosol Loading (μg/L)	Corrected Loading (μg/L)
5	20.4	46.0	28.8	16.6
6	18.2	46.6	26.9	15.5
7	18.0	11.1	17.5	10.1

The first experiment using the NCAW simulant led to an aerosol concentration approximately six times larger than had been observed with the sucrose solutions. Much of this difference was due to the fact that the material being deposited on the filter paper was essentially sodium hydroxide. Since the filter housing was heated during the experiments, the sodium hydroxide was deposited as a dry solid on the filter paper. When the filter paper was removed from the filter housing at the end of the experiment, the sodium hydroxide began to adsorb water from the air, as solid sodium hydroxide is a desiccant.

The amount of water adsorbed was found to be a significant fraction of the total mass, as determined in a separate experiment. A sodium hydroxide pellet was found to adsorb 0.74 g of water per g of NaOH. Applying this relationship to the data in Table 4 results in the corrected values also shown in Table 4. These aerosol concentrations are significantly closer to those observed using the sucrose simulants. The remaining difference is probably due to the fact that the total solids loading for the NCAW simulant was higher than those for the sucrose. Unfortunately, attempts to measure the wt% total and dissolved solids for the NCAW failed when the material corroded through the sample containers when placed in the oven.

True aging waste is reported to be approximately 20 vol% solids with a solids density of 1.5 g/ml and a supernatant density of 1.17 g/ml. These values can be used to arrive at an insoluble solids loading of 25.5 wt%. If the supernatant is assumed to be essentially sodium hydroxide, the wt% dissolved solids in the supernatant would have to be 16 wt% to have a density of 1.17 g/ml (Perry and Green 1984). Since the supernatant comprises 80 vol%, the overall dissolved solids loading is therefore 11.9 wt%. Combining the estimated values for the insoluble and dissolved solids loadings leads to a total solids loading of 37.4 wt%. If this value for the wt% total solids is assumed to hold for the synthetic NCAW, the data would not support the claim that the aerosol concentration increases with increasing solids loading. In reality, the assumptions made at arriving at the estimated solids loading for NCAW are probably nonconservative. The total solids loading is probably closer to 50 wt%, which would then be consistent with the previous claim that the aerosol concentration increases sharply with solids loading.

The first experiment using the NCAW simulant was repeated to verify that the observed aerosol concentration was correct. The second experiment resulted in an aerosol loading within 7.0% of the previous value, thus confirming the results. The next experiment was conducted to verify that higher aerosol concentrations will be encountered at higher flow rates. The off-gas flow rate was dropped by a factor of four, which reduced the aerosol concentration by a little less than 50%, thus validating the decision to only investigate the highest flow rates to obtain conservative results.

5.0 DISCUSSION

The aerosol concentrations observed during this study ranged from 0.66 to 16.6 μg/L (after correcting for adsorbed water). For comparison, in undeveloped areas of the western United States, 24-hr average suspended particulate concentrations in the atmosphere are of the order of 0.001 to 0.01 μg/L. In more developed areas, average daily concentrations of 0.1 μg/L are common. Average daily concentrations from 0.1 to 1.0 μg/L are found in large cities and in areas where soil can be resuspended (Randerson 1984). Thus, the aerosol concentrations measured in this study exceed the atmospheric levels for industrial cities. The concentrations resulting from sparging air through the solutions, however, were still almost two orders of magnitude below those measured in the off gas from a pilot-scale ceramic melter (300 μg/L) during a waste vitrification experiment (Ruecker 1987a).

5.1 EFFECT OF WEIGHT PERCENT SOLIDS

The data in Table 1 show that the aerosol concentration rises at an accelerating rate with increasing solids loading. Unfortunately, the agitation in the test vessel, although very vigorous, was insufficient to keep much of the titanium dioxide suspended. The limited number of tests conducted to date make it difficult to determine if there is a significant difference between insoluble and dissolved solids loadings, or if the weight percent total solids is the most important factor. Unfortunately, weight percent solids loadings for the NCAW experiments could not be obtained in an effort to resolve this issue. It is estimated that the total solids loading was 50 wt%, which would support the previous speculation that the aerosol concentration does indeed increase quickly with solids loading.

5.2 COMPARISON WITH PREVIOUSLY ASSUMED CONCENTRATIONS

Previous calculations used to estimate the amount of material released during a bump assumed an aerosol concentration of 10 μg/L (Squires 1987). This value appears to be bracketed by the values observed during this study, however the aerosol concentrations are defined differently. Squires assumed an aerosol concentration of 10 μg/L and then used a density of 77.8 lb/ft^3 to obtain an estimate of the volume of entrained waste per volume of vapor. The density used appears to be a density for homogeneous NCAW; thus the

aerosol concentration represents the amount of wet airborne material present per liter of escaping vapor. The concentrations reported in this study, on the other hand, are for dry aerosol concentrations.

The corresponding wet aerosol concentrations can be obtained from the data presented here by dividing the dry aerosol concentrations by the weight percent total solids of the solution. Using a conservative estimate of 37.5 wt% total solids for the NCAW simulant leads to wet aerosol concentrations ranging from 26.9 to 44.3 μg/L. Squires' estimated wet aerosol concentration appears to be slightly low based on these numbers.

Squires' value corresponds to a volumetric ratio of 8.0×10^{-9} volumes of waste per volume of escaping vapor based on a waste density of 77.8 lbs/ft^3. A more conservative estimate would be to use a wet aerosol concentration of 50 μg/L. Using the same density for the waste leads to a volumetric ratio of 1.1×10^{-7} volumes of waste per volume of escaping vapor. The amount of material released can be calculated provided the amount of vapor escaping to the environment can be estimated. Estimated volumes of escaping steam have been calculated by Jones (1987) as a function of the downtime for the airlift circulators. The longer the airlift circulators are

Table 5. Estimated Gallons of Waste Released to the Environment During a Tank Bump.

Downtime (hr)	Steam Released (gal)	Vol. Released Using Current Method (gal)	Vol. Released Using Squire's Method (gal)
12	7,000	0.0008	0.0016
18	70,000	0.0075	0.0072
24	125,000	0.0134	0.014
30	195,000	0.0208	0.021
36	260,000	0.0278	0.028
42	325,000	0.0347	0.035
48	375,000	0.0401	0.040
54	440,000	0.0470	0.047
60	500,000	0.0534	0.053
66	560,000	0.0599	0.060
72	615,000	0.0658	0.066

down, the more severe the tank bump will be. Included in Table 5 is the corresponding volume of waste released based on the volumetric ratio of 1.1×10^{-7}. The release volumes reported by Squires (1987) are also included for comparison.

The difference between the two approaches described above is that Squires included an additional term involving partition factors reported by Kimura and Johnson (1987) to increase her volumetric ratio from 8.0×10^{-9} to 1.0×10^{-7}. The use of partition factors was probably not necessary as described in an earlier report (Ruecker 1987b). The net result, however, is that Squires arrived at essentially the same volumetric ratio despite starting with a lower initial aerosol concentration.

An average value of 4×10^{-8} volumes of waste per volume of vapor was measured for tank 101-AZ by Kimura and Johnson. This is a reasonable concentration when compared to the volumetric ratio determined during this study considering the samples were collected within 8.5 to 14.5 feet of the liquid surface while the airlift circulators were operating. The fact that this concentration is lower than the concentrations estimated based on the experimentally obtained aerosol concentrations (1.1×10^{-7}) is not significant, as the lower superficial velocities, experimental error and validity of the assumptions used to extrapolate dose rates to aerosol concentrations could easily explain the discrepancy.

It should be stressed that the above calculations make no attempt to account for material lost on the way to the environment due to impaction, interception or diffusion, which are described in detail by Hinds (1982). The calculations also do not attempt to account for the release of gaseous radionuclides, as this problem is very complicated, waste specific, and relatively unrelated to addressing the question as to whether or not the tank ventilation system needs to be modified to better handle aerosols during a tank bump.

5.3 VALIDITY OF ASSUMPTIONS

The key assumptions behind this study are that the mechanism for generating aerosols during a tank bump is the rupturing of bubbles at the liquid surface and that steam (generated during a bump) will behave similarly to air (used during bump experiments) as a carrier fluid for the

aerosols. The rupturing bubble mechanism has been described by Newitt, Dombrowski and Knelman (1954) as illustrated in Figure 4. As the bubble rises to the surface, it causes the liquid surface to form a hemispherical dome. The bubble's internal pressure produces a depression in the interface. As liquid drains from the dome, a weak spot will form where a secondary cap can form. The subsequent disintegration of the cap gives rise to several submicron aerosols which are carried away by the escaping gas. As the resulting crater is filled, the momentum of the in flowing liquid produces a jet which in turn can produce other aerosols.

The only other conceivable dominant mechanism for producing radioactive aerosols may be a condensation mechanism (Hidy 1984). Prior to a bump, it is possible that very high temperatures could be achieved, causing some semi-volatile compounds to vaporize. These compounds would later condense to form submicron aerosols. More than likely, these aerosols would be formed as the steam bubble rose through the supernatant. Large steam bubbles would quickly break up into smaller bubbles due to viscous drag as they ascended through the supernatant (Valentin 1967).

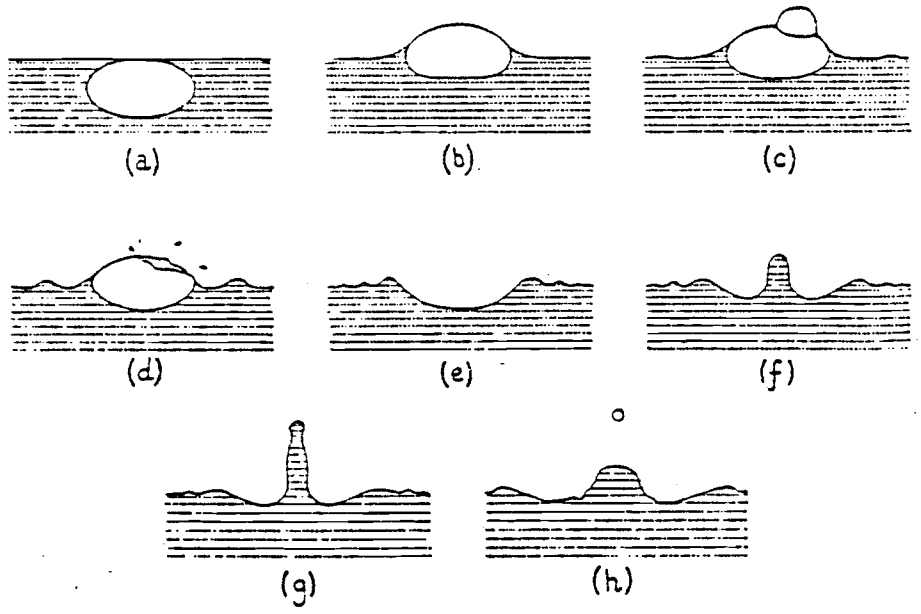

Figure 4. Aerosol Entrainment Mechanism for Bursting Bubbles. (Taken from Newitt, Dombrowski and Knelman 1954).

This phenomenon would tend to minimize the distances required to transport the newly-formed aerosols to the gas-liquid interface where they can be captured in the liquid. Gas circulation within the bubble will further assist in the mass transfer process (Garner and Hammerton 1954). This situation would be essentially equivalent to that for a Submerged-Bed Scrubber, which has been found to be extremely effective at removing even submicron aerosols (Ruecker and Scott 1987). In addition, if enough heat were removed to cause steam to condense, the aerosol removal process would be even further enhanced by a mechanism referred to as flux-force/ condensation (Calvert and Englund 1984).

Any other proposed mechanism in which the aerosols are formed within the supernatant layer would also be suspect due to the same reasoning as used above; the aerosols would more than likely be removed from the vapor as the bubble travels through the supernatant. The only way the rupturing bubble mechanism would not be the dominant mechanism is if the bump were severe enough to cause compounds to vaporize and remain in the vapor state until carried up into the plenum or beyond.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, it is apparent that the previously assumed concentration of 10 μg/L (wet aerosol concentration) used by Squires to estimate release levels during a bump is slightly low. Higher aerosol concentrations were measured during this study when a synthetic NCAW solution was used, 26.9 to 44.3 μg/L. This data suggests that a more conservative value of 50 μg/L should be used. The superficial velocities within the test vessel were, however, several orders of magnitude higher than those likely to be encountered during a bump. Because aerosol generation decreases with superficial velocity, the aerosol concentrations reported here should be conservative.

The estimated volumes of waste released by Squires are no different than those reported here despite the fact that she used a lower aerosol concentration. Squires compensated for her low estimate for the aerosol concentration by including another term which was probably not necessary. The second term was overly conservative, thus the net result was that she arrived at the same volumetric ratio as derived here. Based on the information resulting from this study, the estimated amount of material likely to be released from a tank bump is 1.1×10^{-7} volumes of waste per volume of escaping vapor.

It should be stressed, however, that radioactive aerosols are not the only source of radioactivity being released during a tank bump. The release of gaseous radioactive nuclides may account for the majority of the radiation escaping to the environment should a severe tank bump occur. On the other hand, the estimated release is conservative as no attempt has been made to account for aerosol losses on the way to the environment due to impaction, interception and Brownian diffusion. Small bumps will more than likely not have high enough escape velocities to entrain a significant amount of material. The release of radioactive aerosols should not be a significant factor in the total amount of radiation released during a tank bump, provided the bump is not so severe that the integrity of the tank and its ventilation system are compromised.

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APPENDIX D: AGING WASTE TANK BUMP SCENARIO CALCULATIONS

Internal Letter

Rockwell International

Date: May 6, 1987

No: 65611-87-086

TO: (Name, Organization, Internal Address)
R. M. Marusich

FROM: (Name, Organization, Internal Address, Phone)
B. L. Jones

3-3429

Subject: Tank Bump and Associated Release Calculation

Ref.
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(e) IL 65950-87-295, T. G. Hansen to B. L. Jones, "Aging Waste Tank Pressurization Flow Rates (Tank Bump)", May 9, 1987

Reevaluation of tank bump scenarios was requested in support of the aging waste Safety Analysis Report (SAR) revision. Past tank bump calculations have been based on the operating history of aging waste tanks and numerous assumptions. The Tank Farm and Evaporator Process Technology Unit (TF&EPTU) has developed a more "definable" tank bump scenario for current aging waste operations. The calculations will be developed by using known flow equations and thermodynamic principles.

The intent of this study is to develop a relationship between airlift circulator (ALC) downtime and volume of vapor released to the environment. The data will be supplied to the Safety Analysis Group where they will determine the amount of aging waste released to the environment and associated dose rates. It is important to keep in mind the assumptions used in this calculation are, in most cases, conservative and are continuously being refined as new information is received, Appendix C.

CONCLUSIONS/RESULTS

The result of the calculations are shown in Figure 1. The graph represents the volume of vapor released as a function of ALC downtime. A comprehensive conclusion could not be reached due to time constraints and uncertainties of ALC downtime, percent aerosol and the concentration of the aerosol. The three uncertain parameters will be assigned a value and units by the Safety Analysis Group. To obtain the total amount of aging waste released to the environment one would multiply the volume of vapor released (Figure 1) by the percent aerosol and aerosol concentration. The calculations are given in Appendix A.

Rockwell International

METHODOLOGY/DISCUSSION

The following methodology was used in the evaluation of tank bump scenario:

1. An assessment of the available pathways for release to the environment was made.

2. The total heat generated in the settled solids as a function of time was calculated.

3. Heat released as the solids are resuspended and the resulting volumes of steam generated were calculated.

4. Average steam flow rates during the bump event were calculated.

5. Tank pressures and resulting flow rates through the ventilation system and the environmental pathway were calculated.

6. Releases to the environment were calculated.

Each of these steps will be discussed in detail below.

ASSESSMENT OF THE ENVIRONMENTAL PATHWAY

Tank Farm and Evaporator Process Engingeering has determined the physical pathways available for vapor to escape during a tank pressurization. The pathways consist of three 1 inch diameter breather holes and the transfer lines to the 152-AX diversion box. The flow through each pathway is characterized by the Blasius equation for compressible flow. The ventilation system was characterized by the Darcy flow equation for non-compressible flow. In this particular case the two equations do not vary significantly, therefore, either equation can be use. The calculations for the flow through the environmental pathways are given in (Ref. (e)), and are shown in Appendix B.

HEAT AND STEAM GENERATED

The temperature generated in the settled solids is calculated using the HEATING5 computer code. It is assumed that the waste in the tank has a heat generation rate of 4 million BTU/hr and 20 percent solids (71"). The resulting sludge temperatures are calculated as a function of time settled. Figure 2 shows the results of this sludge temperature calculation through 72 hours of airlift circulator downtime.

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VOLUME OF STEAM GENERATED

Resuspension of the settled solids causes a sudden release of heat into the waste liquids. This sudden heating of the liquid causes steam generation and the bump event. All but 19 inches of solids would be mixed and heat would be dumped into the liquid until the solids and liquid temperatures equilibrate. The liquid is assumed to remain at its boiling point (230 F, Ref. (b)), therefore, all the heat released into the liquid would produce steam. This calculation is conservative in that the heat transfer is assumed to be instantaneous and the solids are mixed within an 8 hour period. Normally, the heat transfer would not be instantaneous and the airlift circulators could take longer than 8 hours to resuspend the solids. It is believed that once the bump is initiated the boiling of the liquid will enhance the mixing of the solids. Currently, there is insufficient data to characterize the heat transfer or the solids resuspension rate, therefore, it is assumed that the heat will be released in a negative exponential fashion. The negative exponential was chosen solely for its characteristic of a sudden peak that quickly diminishes.

A curve representing steam generation as a function of time can be developed for each case of ALC downtime. Figure 3 shown an example for a 72 hour ALC downtime.

STEAM FLOW RATES

Using Figure 3, or a similar curve developed for other ALC downtimes, average steam flow rates for the "bump" event can be calculated. An important point is that the flow rate must exceed 9400 cubic feet per minute in order to pressurize the tank. Once the flow rate drops below 9400 (CFM) the tank is no longer pressurized. The curve is integrated from zero to the time at which the flow decreases to 9400 CFM to obtain the total steam generated during the tank pressurization. This number is divided by the time of the pressurization to determine an average steam flow rate during the event.

TANK PRESSURES AND FLOW RATES

A curve was developed which shows tank pressures and resulting flows through the ventilation system and the environmental pathways (Figure 4). The average steam flow rate calculated can then be used to determine the flow through each pathway. Peak pressures during the event can also be calculated.

RELEASE TO THE ENVIRONMENT

The volumes of vapor released through the riser are multiplied by the percent aerosol and aerosol concentration to obtain the total concentrated aging waste released to the environment. The percent aerosols and aerosol concentration will be assigned by the Safety Analysis Group.

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RELEASE TO THE ENVIRONMENT (cont.)

To simplify this overall process, calculations were performed for ALC downtimes from 0 to 72 hours. These were then summarized in a figure which reflects volume of vapor released via the environmental pathways as a function of ALC downtime (Figure 1).

B. L. Jones, Engineer
Tank Farm & Evaporator
Process Technology Unit

Att.

cc: G. L. Dunford
D. R. Ellingson
T. G. Hansen
M. A. Hevland
D. W. Lindsay
D. E. McKenney
L. A. Mihalik
L. K. Mudge
D. J. Squires
J. C. Womack
J. J. Zimmer

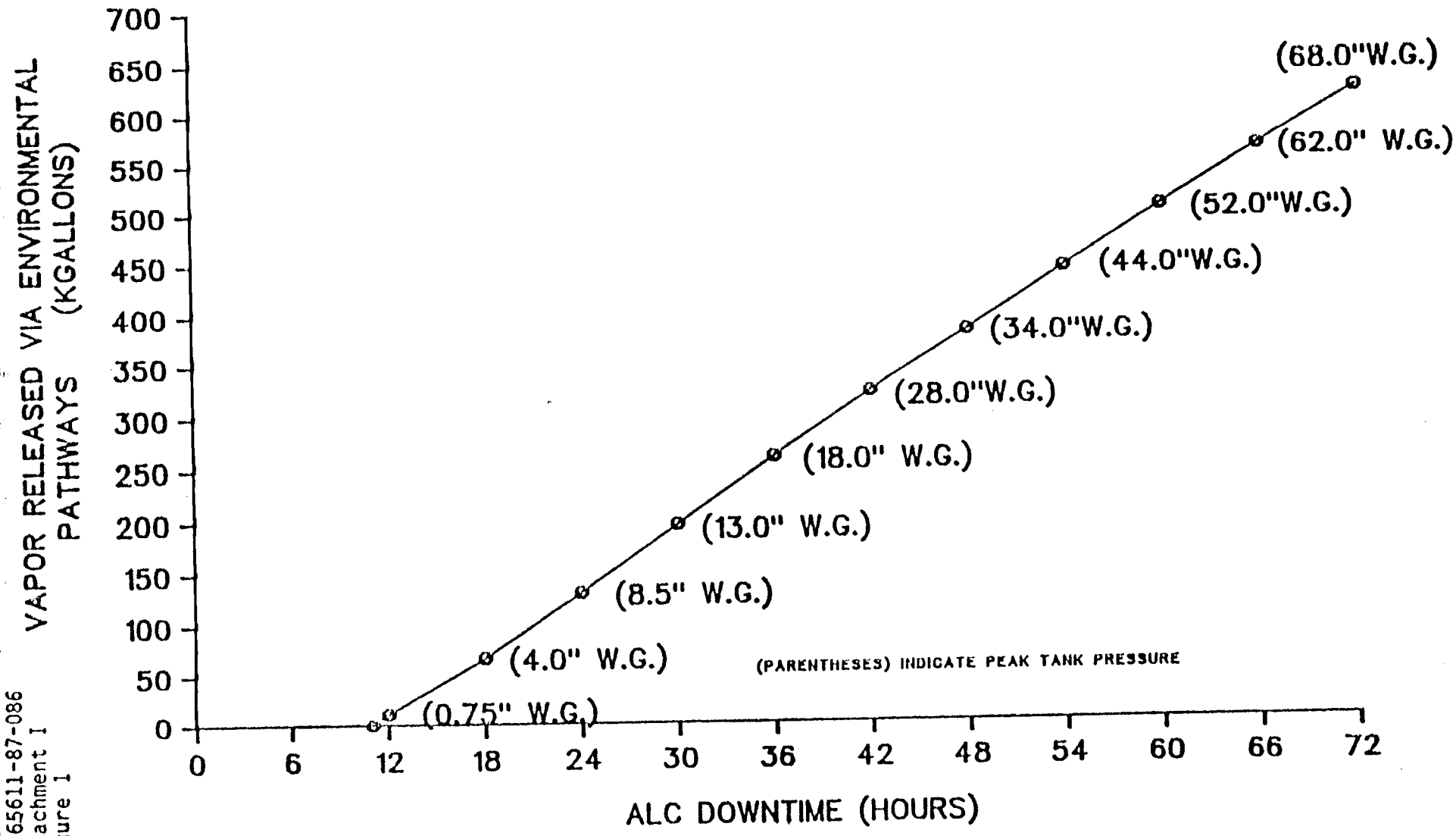

Figure 1. Volume of vapor released via tank environmental pathways.

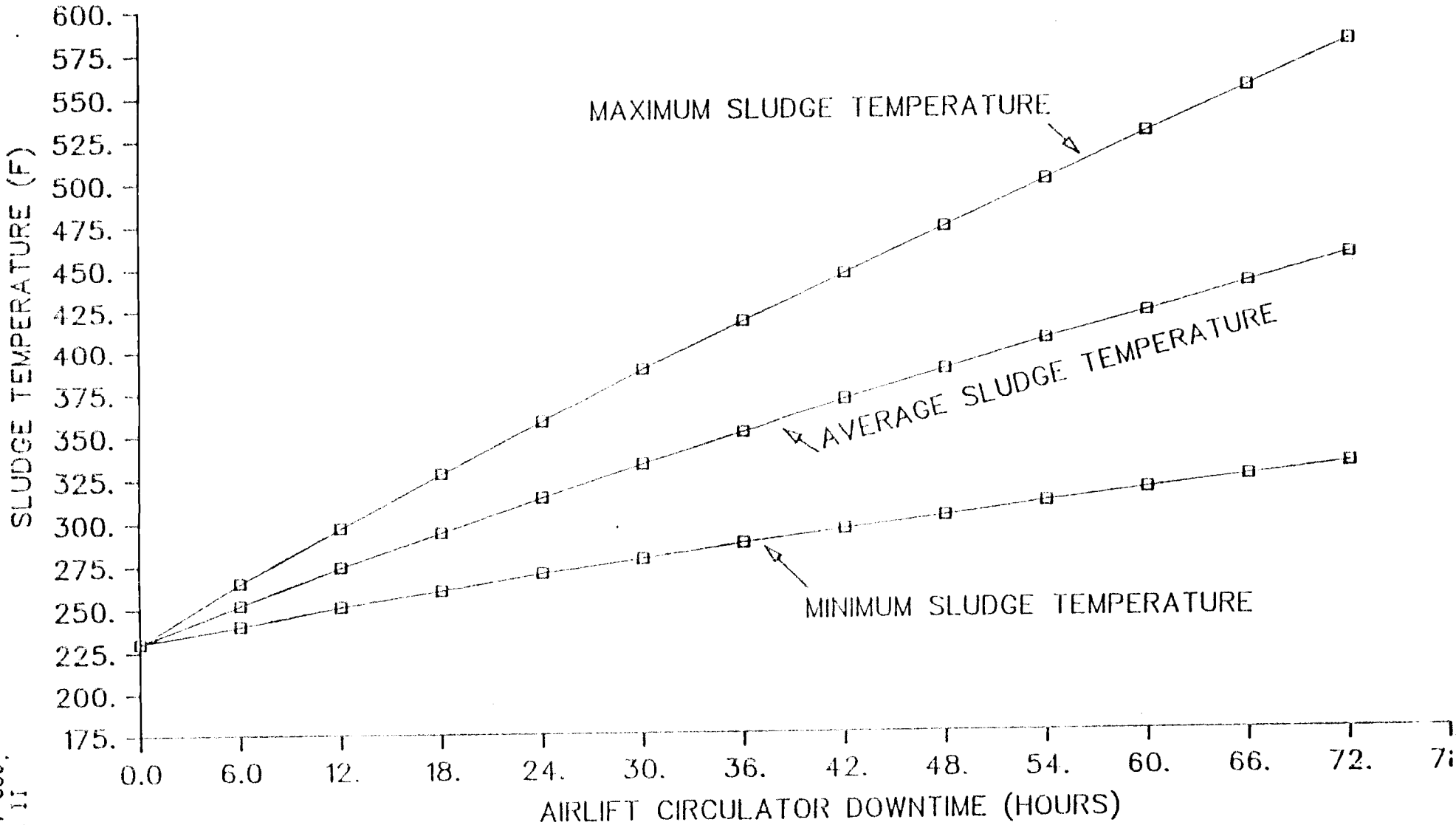

Figure 2. Aging waste sludge temperatures as a function of airlift circulator downtime.

Bumplet

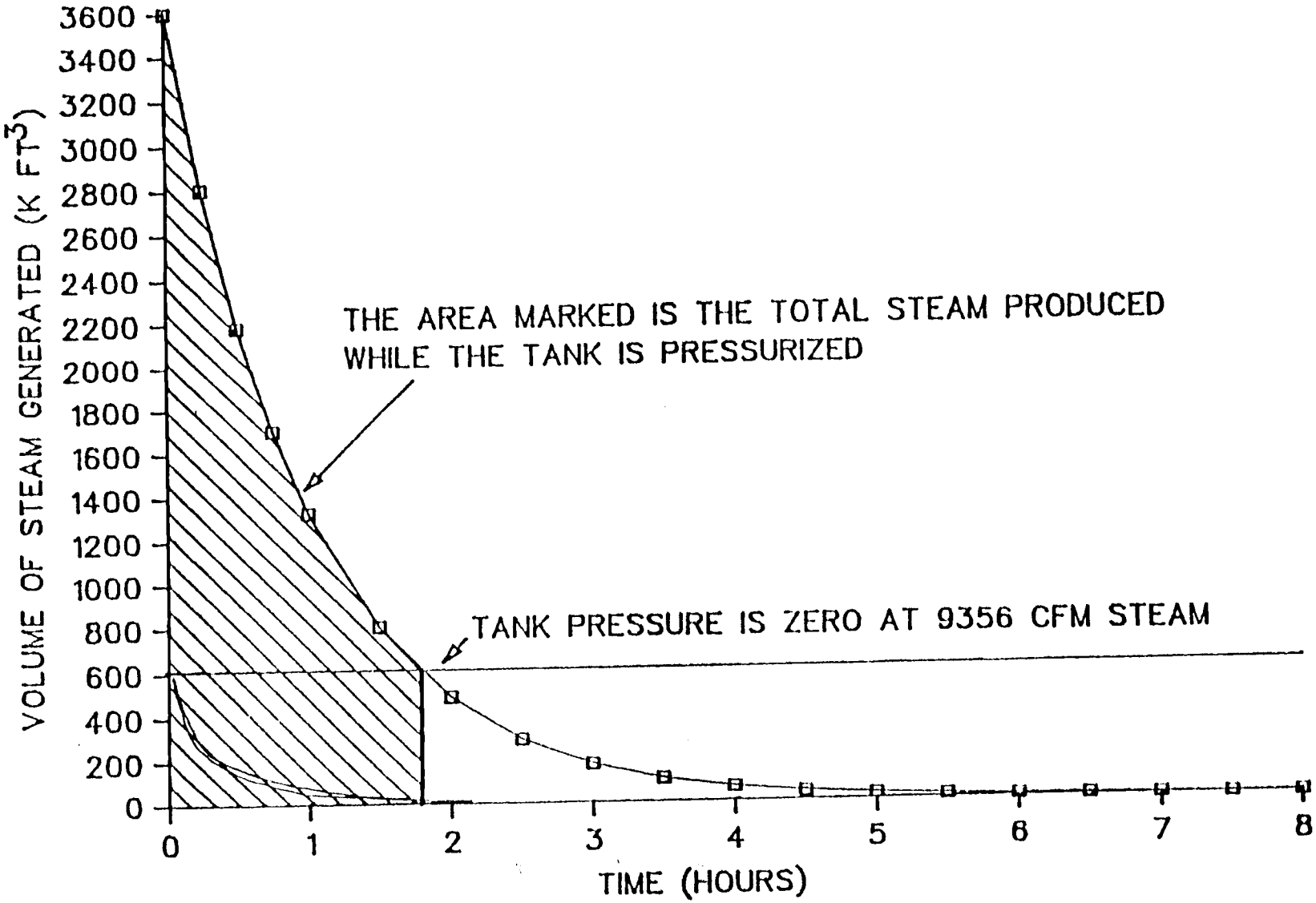

Figure 3. Release charateristics of the steam generated. This figure is specific to the 72 hour ALC downtime.

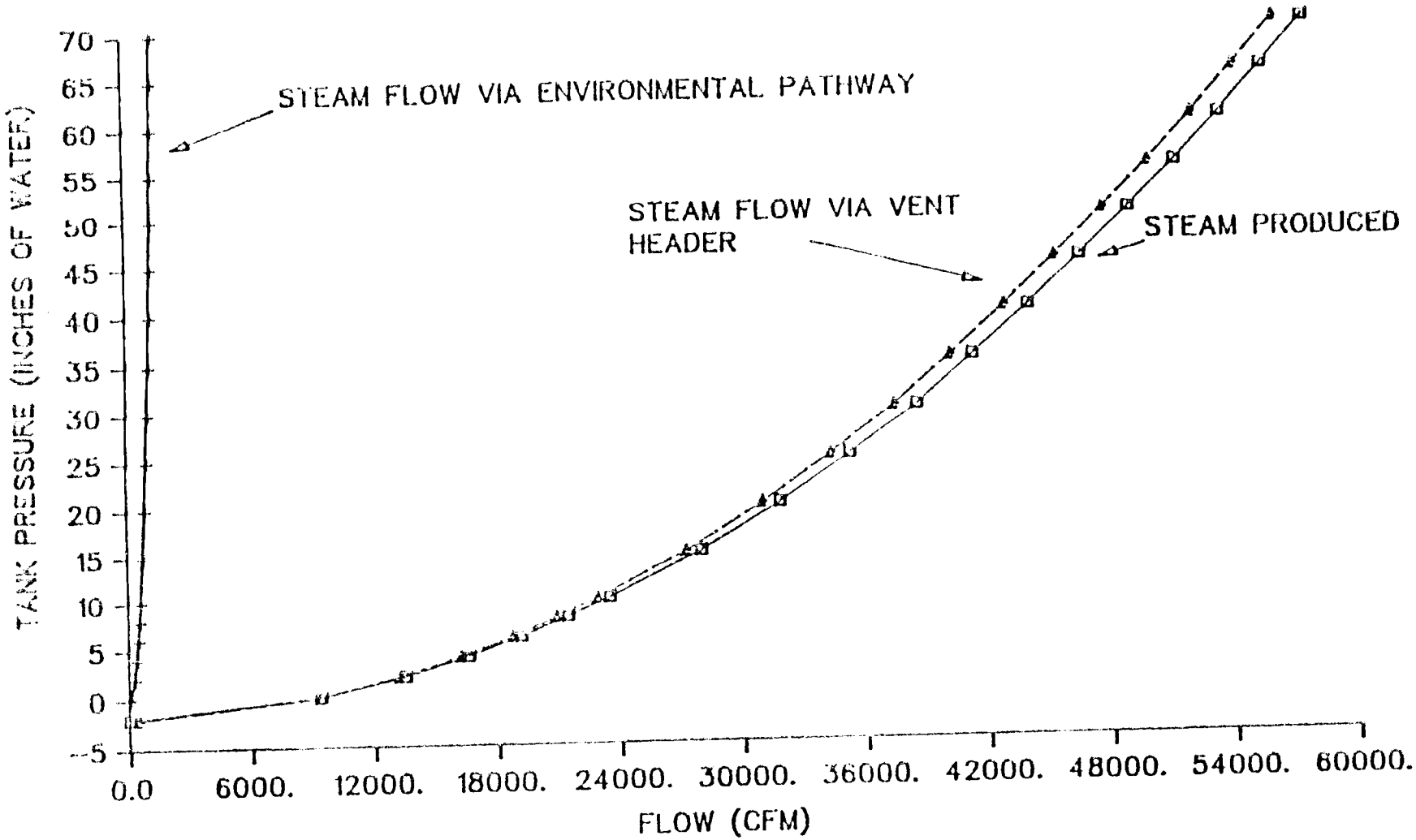

Figure 4 Vapor flow rates as a function of tank pressures

APPENDIX A

AGING WASTE TANK BUMP SCENARIO CALCULATIONS

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DESIGN ANALYSIS

PAGE 1 of 8
JOB NO.
DATE 4-13-87
BY B.L. Jones
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FOR
LOCATION
SUBJECT SHINY WASTE TANK BUMP

NOMENCLATURE:

A = CROSS SECTIONAL AREA OF PIPE or orifice, IN SQUARE feet.

C_p = heat capacity AT CONSTANT PRESSURE.

D = INTERNAL PIPE DIAMETER IN Feet

f_T = FRICTION factor IN complete Turbulent Zone

g = Acceleration of gravity

h_{evp} = LATENT heat OF EVAPORATION

L_r = Length of The pipe Riser in feet

L_v = Length of The vent header pipe in feet

$\dot{m}$ = Mass in POUNDS-Mass

P = Pressure IN POUNDS per SQUARE INCH GUAGE

q = RATE OF FLOW, IN cubic feet per SECOND

Q_T = TOTAL AMOUNT OF HEAT IN BTU

R_e = Reynolds Number

T = Temperature IN Degrees Fahrenheit

$\bar{V}$ = SPECIFIC VOLUME OF FLUID IN CUBIC FOOT PER POUND

$\mathcal{V}$ = MEAN VELOCITY OF FLOW IN FEET PER MINUTE

V = VOLUME OF FLUID IN cubic Feet.

μ_c = ABSOLUTE VISCOSITY, IN POUNDS Mass per foot SECOND.

Δ = Differential between to POINTS.

RD-6400-160 (R-2-72)

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PAGE 2 of 8
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ENVIRONMENTAL PATHWAY

THE ENVIRONMENTAL PATHWAYS AND FLOW RATES ARE Developed IN Ref ( ), Appendix b. THE FLOW Rates ARE increased by 50% for CONSERVATISM. FROM THIS AND THE ALC FLOW RATE you CAN Determine THE VENT HEADER FLOW RATES.

ALC FLOW RATE = 154 SCFM (22 ALC'S @ 7 SCFM EACH)

CONVERTING FROM SCFM TO CFM...

154 SCFM	690°K	14.7 psia
	492°K	14.628 psia

= 217 CFM

TOTAL VENT FLOW AT -2" W.G. is

217 CFM + 256 (Ref(C))

VENT FLOW = 473 CFM

SD-6400-060 (R-2-79)

HEAT GENERATED FOR A FULL AGING WASTE TANK

$\rho_{SOLIDS} = 103 \frac{lbm}{FT^3}$ (Ref d)

$C_{p_{SOLIDS}} = 0.3 \frac{BTU}{lbm\,°F}$ (Ref d)

ASSUME ALL BUT 19" OF SOLIDS RESUSPEND
ASSUME SOLIDS WILL COOL TO LIQUID TEMPERATURE INSTANTANEOUSLY

$T_{LIQUIDS} = 230°F$ (Ref b)

$T_{SOLIDS} = 420°F$ (see figure 2)

72" OF SOLIDS

$\boxed{\text{EQN 3}}$ $Q_T = \dot{m} C_p \Delta T$

$$\dot{m} = (71" - 19")\left(2750 \frac{GAL}{inch}\right)\left(\frac{FT^3}{7.4805\ GAL}\right)\left(103 \frac{lbm}{FT^3}\right)$$

$$\dot{m} = 1{,}969{,}000\ lbm$$

$$Q_T = (1{,}969{,}000\ lbm)\left(.3 \frac{BTU}{lbm\,°F}\right)(454°F - 230°F)$$

$$\boxed{Q_T = 152\ MBTU}$$

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PAGE 4 of 8
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DATE 4-13-87
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SUBJECT Aging Waste Tank Bump

STEAM GENERATION

$h_{evap} = 970.3 \frac{BTU}{lb}$ @ 14.7 psia (Ref c)

$\bar{V}_{steam} = 26.8 \frac{FT^3}{lb}$ @ 14.7 psia (Ref c)

$$V = \frac{Q_T}{h_{evap}} \cdot \bar{V}_{steam}$$

$$V = \left[\frac{132 \text{ M BTU}}{970.3 \frac{BTU}{lb}}\right]\left[26.8 \frac{FT^3}{lb}\right]$$

$$\boxed{V = 3.6 \text{ E6} FT^3}$$

THE VAPOR WILL BE GENERATED IN AN NEGATIVE EXPONENTIAL FASHION

$\boxed{\text{EQN 4a}}$ $y = ae^{-x}$

$a = 3.1 \text{ M } FT^3$

x = TIME IN HOURS

y = FT^3 REMAINING VOLUME IN THE TANK

EQN 4.b $\boxed{y = 3.6 \times 10^6 e^{-x}}$

BD-6400-060 (R-2-79)

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PAGE 5 of 3
JOB NO.
DATE 4-13-87
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SUBJECT AGING WASTE TANK BUMP

STEAM FLOW VS TANK PRESSURE

Darcy's FLOW EQUATION FOR NON-Compresible fluid flow IS USED TO CHARACTERIZE BOTH THE ENVIROMENTAL PATHWAY AND THE VENT HEADER AS a FUNCTION OF TANK pressure.

TANK RISER FLOW

$D = .2509'$ or $3''$

$g = 32.2\ FT/s^2$

$\rho_{steam} = .06\ \frac{lbm}{FT^3}$ (Ref 2)

$f_T = .004$ (Ref 2)

$L_r = 10$ ft.

$\mu_e = 9.07 \times 10^{-6} \frac{lbm}{FT \cdot S}$ (Ref C)

SUBSTITUTING THIS DATA INTO THE DARCY EQUATION RESULTS IN

$$\boxed{\text{EQN 5}} \quad V = \sqrt{\frac{(P_T - 14.7)(144)(.2509)(2)(32.2)}{(.06)(.004)(10')}}$$

$$\therefore \quad Q = VA$$

SUBSTITUTE TANK pressures AND CALCULATE ASSOCIATED FLOWS. THE ReyNOLDS Number was CALCULATED AND FOUND THAT THE FRICTION FACTOR IS CONSTANT AT .004. (Ref 2, Pg 5-22, Fig 5-26)

@ $P_T = 1''$ W.G. or .036 psig

$$R_e = \frac{(.2509\ ft)(1860.8\ FT/s)(.06\ \frac{lbm}{FT^3})}{9.07 \times 10^{-6}\ \frac{lbm}{FT \cdot S}}$$

$R_e = 348,461$ corresponds to $f = .004$

3D-6400-(80) (8-2-79)

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PAGE 6 of 8
JOB NO.
DATE 4-13-87
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VENTILATION HEADER FLOW

$D = 1.667$ ft
$g = 32.2$ ft/s^2
$\rho_{steam} = .06$ lbm/ft^3 (Ref 2)
$f_T = .004$ (Ref 2)
$L_V = 910'$
$\mu_e = 8.07 \times 10^{-6}$ $\frac{lbm}{ft \cdot s}$ (Ref c)

SUBSTITUTING THIS DATA INTO THE DARCY EQUATION RESULTS IN

$$\boxed{\text{EQN 6}} \quad v = \sqrt{\frac{(P_T - 14.7)(144)(1.667)(2)(32.2)}{(.06)(.004)(910')}}$$

SUBSTITUTE TANK PRESSURES AND CALCULATE ASSOCIATED FLOWS. THE REYNOLDS NUMBER WAS CALCULATED AND THE FRICTION FACTOR WAS FOUND TO BE CONSTANT AT .004 (Ref 2, Pg 5-22, Fig 5-26)

@ $P_T = 1''$ W.G. psig

$$Re = \frac{(1.667)(110.2 \frac{ft}{s})(.06 \frac{lbm}{ft^3})}{8.07 \times 10^{-6} \frac{lbm}{ft \cdot s}}$$

$Re = 1,365,498$ Corresponds to $f = .004$.

FIGURE 4. SHOWS THE PLOT OF RISER FLOW AND VENT FLOW VS TANK PRESSURE. THE STEAM FLOW IS DEVELOPED BY ADDING THE VENT FLOW AND RISER FLOW TOGETHER

30-6400-060 (R-2-79)

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PAGE 7 of 8
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SUBJECT AGING WASTE TANK BOMB

RELEASE TO THE ENVIRONMENT

EXAMPLE : 72 HOURS ALC DOWNTIME

FROM FIGURE 4 YOU CAN SEE THAT AT 0" W.G. IN THE TANK THE STEAM FLOW RATE IS 9400 CFM. IF YOU INTEGRATE THE CURVE IN FIGURE 3 OVER A VERY SMALL TIME PERIOD YOU WILL FIND A FLOW RATE OF 9400 CFM BY TRIAL AND ERROR. AT THIS TIME THE TANK WILL BE 0" W.G. THEN IT IS POSSIBLE TO GET THE AVERAGE STEAM GENERATION BY INTEGRATING THE CURVE FROM ZERO TO THE TIME THE TANK REACHES 0" WG. FOR THE WORST CASE (72 HOURS ALC DOWNTIME) THE TANK IS PRESSURIZED FOR 1.85 HOURS

$$y = 3.6 \times 10^6 e^{-x}$$

$$\int_{0}^{1.85} -3.6 \times 10^6 e^{-x}$$

$$= -566053 - (-3{,}600{,}000)$$

$$= 3{,}033{,}946 \text{ FT}^3$$

$$\text{AVG. FLOW} = \frac{3{,}033{,}946}{1.85 \text{ hours} \left(\frac{60 \text{ min}}{\text{hr}}\right)} = 27{,}332 \frac{\text{FT}^3}{\text{MIN}}$$

FROM FIGURE 4 YOU CAN OBTAIN THE AVG RISER FLOW DURING THIS TIME WHICH IS 740 CFM

TOTAL STEAM TO EXIT THROUGH THE RISER IS

$$(740 \text{ CFM})(1.85 \text{ hours})\left(\frac{60 \text{ min}}{\text{hr}}\right) = 82{,}000 \text{ FT}^3 \text{**}$$

SD-6400-060 (R-2-79)

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PAGE 8 of 8
JOB NO.
DATE 4-13-87
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To obtain the maximum tank pressure you can take the integral over a small time around zero.

$$\int_0^{.1} 3.6\times10^6\, e^{-x} =$$

$$3.6\times10^6 - 3.257\times10^6$$

$$= \frac{343.585\ FT^3}{(.1)(60\ \frac{MIN}{hr})} = 57{,}100\ \frac{FT^3}{MIN}$$

From Figure 4 you can get the maximum tank pressure by reading 57100 CFM on the total steam curve and picking off the associated tank pressure

$$\boxed{\text{Tank pressure} = 68''\ W.G.}$$

* To obtain the total aging waste released to the enviroment you would multiply the total steam via the riser by the percent aresol and concentration of the aerosol. This was not done here because the airlift circulator downtime, percent aerosol, aerosol concentration have not been determine. This will be addressed by safety analysis group.

(i.e. $(82{,}000\ FT^3)(1\%\ \text{Aerosol})(.001\ \text{Concentration})(7.4805\ \frac{GAL}{FT^3})$
$= 6$ GALLONS OF AGING WASTE

SD-6400-060 (R-2-79)

APPENDIX B

ENVIRONMENTAL PATHWAYS AND ASSOCIATED FLOW CALCULATIONS

Internal Letter

Rockwell International

Date: May 14, 1987

No. 65950-87-333

TO: (Name, Organization, Internal Address)

B. L. Jones

FROM: (Name, Organization, Internal Address, Phone)

T. G. Hanson

3-3515

Subject: Aging-Waste Tank Pressurization Flow Rates (Tank Bump)

Ref: Letter, May 6, 1987, T. G. Hanson to B. L. Jones, "Aging-Waste Tank Pressurization Flow Rates"

Attachments to the reference provided estimates of the rates at which vapors might escape an aging-waste tank due to a tank bump. The estimates were generated by a computer program. An error has since been discovered in the program, leading to low estimated flow rates for the higher pressure drops considered (those above about 10 inches water gauge). A corrected computer program, together with the altered flow rate estimates, are attached to this letter.

We apologize for any inconvenience this error may have caused.

T. G. Hanson, Engineer
Waste Concentration Unit

TGH:ljg

cc: G. L. Dunford
S. R. Johnson
J. T. Kruszka
R. M. Marusich
L. A. Mihalik
D. J. Squires

```
10 REM PROGRAM FOR COMPUTING AIR FLOW RATES ON TANK PRESSURIZATION
20 REM BY T. G. HANSON                                    MAY 12, 1987
30 REM
40 REM CALCULATES THE FLOW RATE IN CFM, USING RELATION FROM PERRYS
50 REM FOR ISOTHERMAL COMPRESSIBLE FLOW, AND THE VON KARMON-NIKURADSE
60 REM EQUATION RELATING FRICTION FACTOR TO REYNOLD'S NUMBER
70 REM
90 REM PROMPT FOR PHYSICAL CONDITIONS
95      DEFDBL A-Z
100     INPUT "ROUTE OF AIR FLOW"; J$
110     INPUT "LENGTH (FT)"; L
120     INPUT "HYDRAULIC RADIUS (FT)"; D
130     INPUT "CROSS-SECTIONAL AREA (SQ FT)"; A
140     INPUT "VISCOSITY (LB/FTxS)"; U
150 REM PRINT TABLE HEADINGS
160     LPRINT "FLOW PATH:", J$
165     LPRINT
170     LPRINT "PHYSICAL CONDITIONS:"
175     LPRINT "LENGTH = ";L;" FT  HYDRAULIC RADIUS = ";D;" FT"
176     LPRINT "X-SECTIONAL AREA = ";A;" SQ FT  VISCOSITY = ";U;" LB/FTxS"
178     LPRINT
180     LPRINT "dP","REYNOLDS","FLOW RATE","GOOD"
182     LPRINT "(IN WG)","NUMBER","(CFM)","VALUE?"
185     LPRINT
200 REM INITIALIZE CONSTANTS: R = GAS CONSTANT, B = GRAVITATIONAL CONSTANT,
205 REM M = MOLECULAR WEIGHT, T = TEMPERATURE, Q = OUTLET (ATMOSPHERIC) PRES.
210     R = 1546: B = 32.174: M = 29: T = 674: Q = 2116.2
220 REM INITIALIZE VARIABLES
230     C = 0: X = 1'                                 COUNTING VARIABLES
235     Z = 0: Z1 = 0'                                dP VARIABLES
250     C1 = 9: X1 = .05
260 REM GENERATE RESULTS
300     IF C > C1 THEN 600
310             C = C + 1
320             Z = Z1 + X1*C
330             H = 5.2*Z'                            dP IN LB/SQ FT
340             P = Q + H
350             S = (P*M)/(R*T)'                      COMPUTE DENSITY
400             F = .01
405 REM ITERATIVE LOOP BASED ON FRICTION FACTOR
410             K = 1 + ((4.61*D)/(F*L))*.4343*LOG(P/Q)
420             G = SQR((P^2 - Q^2)*((B*D*M)/(F*L*R*T*K)))
440             N = 4*(G*D)/U'                          REYNOLDS NUMBER
445             E2 = F
450             E = (1/(1.7*LOG(N*SQR(E2))-.4))^2'FRICTION FACTOR
452             IF ABS(E-E2) < (5E-08) THEN 460
454                     E2 = E
456                     GOTO 450
460             IF ABS(E-F) < (5E-08) THEN 490
470                     F = E
480                     GOTO 410
490             V = G/S
500             Y = 60*V*A
0
```

```
505 REM PRINT RESULTS
510             LPRINT USING "##.##          ";Z,
514             LPRINT USING "##.#^^^^          ";N,
518             LPRINT USING "###.#          ";Y,
519 REM CHECK IF N IN TURBULENT RANGE
525             IF (N < 4000) THEN 590
530                     LPRINT "YES"
540                     GOTO 300
590             LPRINT "NO"
595             GOTO 300
600     C = 0
610     IF X > 1 THEN 660'                          INCREASE INCREMENT SIZE
620             X1 = .1'                            FOR dP > 0.5
625             C1 = 4
630             Z1 = Z
640             X = X + 1
650             GOTO 300
660     IF X > 2 THEN 700'                          INCREASE INCREMENT SIZE
670             X1 = 1'                             FOR dP > 1.0
675             C1 = 8
680             Z1 = Z
690             X = X + 1
695             GOTO 300
700     IF X > 3 THEN 800'                          INCREASE INCREMENT SIZE
710             X1 = 5'                             FOR dP > 10.0
720             C1 = 14
730             Z1 = Z
740             X = X + 1
750             GOTO 300
800     INPUT "NEW FLOW PATH Y OR N";O$'            PROMPT FOR RERUN
820     IF O$ <> "Y" THEN 999
830             LPRINT
840             GOTO 100
999     END
0
```

5/12/87

FLOW PATH: SIDE-FILL LINES TO 152-AX

PHYSICAL CONDITIONS:
LENGTH = 170 FT HYDRAULIC RADIUS = .0625 FT
X-SECTIONAL AREA = .049 SQ FT VISCOSITY = .00001418 LB/FTxS

dP (IN WG)	REYNOLDS NUMBER	FLOW RATE (CFM)	GOOD VALUE?
0.05	3.2D+03	9.0	NO
0.10	4.8D+03	13.5	YES
0.15	6.1D+03	17.1	YES
0.20	7.2D+03	20.3	YES
0.25	8.1D+03	23.1	YES
0.30	9.1D+03	25.6	YES
0.35	9.9D+03	28.0	YES
0.40	1.1D+04	30.2	YES
0.45	1.1D+04	32.3	YES
0.50	1.2D+04	34.4	YES
0.60	1.3D+04	38.1	YES
0.70	1.5D+04	41.6	YES
0.80	1.6D+04	44.9	YES
0.90	1.7D+04	48.1	YES
1.00	1.8D+04	51.0	YES
2.00	2.7D+04	75.6	YES
3.00	3.4D+04	94.9	YES
4.00	4.0D+04	111.4	YES
5.00	4.5D+04	126.1	YES
6.00	5.0D+04	139.5	YES
7.00	5.5D+04	151.8	YES
8.00	5.9D+04	163.3	YES
9.00	6.3D+04	174.1	YES
10.00	6.7D+04	184.4	YES
15.00	8.4D+04	229.2	YES
20.00	9.9D+04	266.6	YES
25.00	1.1D+05	299.0	YES
30.00	1.2D+05	327.9	YES
35.00	1.4D+05	354.0	YES
40.00	1.5D+05	377.8	YES
45.00	1.6D+05	399.8	YES
50.00	1.7D+05	420.1	YES
55.00	1.8D+05	439.0	YES
60.00	1.9D+05	456.7	YES
65.00	1.9D+05	473.3	YES
70.00	2.0D+05	489.0	YES
75.00	2.1D+05	503.8	YES
80.00	2.2D+05	517.8	YES
85.00	2.3D+05	531.0	YES

FLOW PATH: SHIELDING PLUG

PHYSICAL CONDITIONS:
LENGTH = 5.19 FT HYDRAULIC RADIUS = .0219 FT
X-SECTIONAL AREA = .006 SQ FT VISCOSITY = .00001418 LB/FTxS

dP (IN WG)	REYNOLDS NUMBER	FLOW RATE (CFM)	GOOD VALUE?
0.05	3.9D+03	3.9	NO
0.10	5.8D+03	5.8	YES
0.15	7.4D+03	7.3	YES
0.20	8.7D+03	8.6	YES
0.25	9.9D+03	9.8	YES
0.30	1.1D+04	10.9	YES
0.35	1.2D+04	11.9	YES
0.40	1.3D+04	12.9	YES
0.45	1.4D+04	13.8	YES
0.50	1.5D+04	14.6	YES
0.60	1.6D+04	16.2	YES
0.70	1.8D+04	17.7	YES
0.80	1.9D+04	19.1	YES
0.90	2.1D+04	20.4	YES
1.00	2.2D+04	21.6	YES
2.00	3.2D+04	32.0	YES
3.00	4.1D+04	40.0	YES
4.00	4.8D+04	46.9	YES
5.00	5.4D+04	52.9	YES
6.00	6.0D+04	58.4	YES
7.00	6.5D+04	63.4	YES
8.00	7.0D+04	68.0	YES
9.00	7.5D+04	72.4	YES
10.00	7.9D+04	76.5	YES
15.00	9.8D+04	93.9	YES
20.00	1.1D+05	108.0	YES
25.00	1.3D+05	119.8	YES
30.00	1.4D+05	129.9	YES
35.00	1.5D+05	138.8	YES
40.00	1.6D+05	146.5	YES
45.00	1.7D+05	153.5	YES
50.00	1.8D+05	159.7	YES
55.00	1.9D+05	165.2	YES
60.00	2.0D+05	170.3	YES
65.00	2.0D+05	174.8	YES
70.00	2.1D+05	179.0	YES
75.00	2.2D+05	182.8	YES
80.00	2.3D+05	186.3	YES
85.00	2.3D+05	189.5	YES

Internal Letter

Rockwell International

Date: May 6, 1987

No. 65950-87-295

TO: (Name, Organization, Internal Address)

B. L. Jones

FROM: (Name, Organization, Internal Address, Phone)

T. G. Hanson

3-3515

Subject: Aging-Waste Tank Pressurization Flow Rates (Tank Bump)

Refs: (a) Morton M. Denn, Process Fluid Mechanics, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1980.

(b) Letter, April 9, 1987, T. G. Hanson to D. J. Squires, "Aging-Waste Tank Pressurization Flow Rates"

Attachments to this letter constitute estimates of the rate at which vapors might escape an aging-waste tank, due to a tank bump. Two paths are considered, under a range of pressure drops. One path for vapor escape is through breather pipes which penetrate the pump and sluice pit riser shielding plugs. These breather pipes directly connect an aging-waste primary tank with the pump or sluice pits that enclose the upper ends of the pipes. Previous calculations [reference (b)] have shown that the cover blocks capping the pits do not substantially restrict flow to the atmosphere, compared to the breather pipes. The other path for vapor escape is through the side-fill transfer lines to the 241-AX-152 diverter station.

Vapor flows over these paths were previously calculated for tank pressurization. However, the maximum pressure drop that was considered then was limited. The calculations used the Blasius equation to determine friction factor from Reynold's number. This equation does not apply at a Reynold's number of greater than 1×10^5, and this maximum Reynold's number limited solutions for flow across the two paths to a pressure drop of less than a 20 inches water gauge (in. WG).

It is believed that a tank bump may cause a pressurization of more than 20 in. WG. Calculating flow rates for greater pressure drops required using another friction factor-Reynold's number relation, the von Karman-Nikuradse equation [see reference (a)]. The entire turbulent regime is well represented by this equation. However, it is implicit for friction factor, so the solution algorithm is slightly more complicated than that used previously for tank pressurization.

A computer program was used to determine vapor flow rates for several pressure drops from 0.05 in. WG to a maximum 85 in. WG (see attachments). Solution involved estimating a friction factor to determine mass flow rate and Reynold's number. The calculated Reynold's number was used to obtain a new friction factor. This algorithm was then repeated until the friction factor obtained was close to the friction factor supplied. Results were tested to determine if the estimated values were good, based on whether the calculated Reynold's number fell within the turbulent range.

Rockwell International

B. L. Jones
Page 2
May 6, 1987

Note that flow from a tank to the atmosphere via the breather pipes must consider the number of breather pipes per tank. In AZ Tank Farm, a shielding plug is mounted in the central pump pit and both of the sluice pits of each tank, for a total of 3 paths per tank. In AY Tank Farm, a shielding plug will be mounted in the central pump pit and each of the four sluice pits of each tank prior to aging-waste service. However, modified cover blocks at the AY-01D and AY-02D sluice pits seal the paths through these two pits, so that the total is 4 paths per tank.

In the case of the side-fill lines, where flow may enter the 152-AX diverter pit, estimated flow rates are substantially the same as the total predicted flows through the breather pipes on a single tank: 51 cfm into 152-AX for a 1.0 in. WG pressurization, as compared to 66 cfm through the breather pipes on an AZ tank. The 152-AX diverter pit, however, is ventilated by the 702-A ventilation system through a 2-inch line. A portion, and perhaps all, of the flow due to tank pressurization will be drawn from the pit into the vent header.

The calculated estimates assume the following:

- Isothermal flow. While flow may be more nearly adiabatic, the values determined using relations for adiabatic flow deviate little from values determined using relations for isothermal flow.

- Fully developed flow. This requires sustained pressurization, and does not consider transient conditions such as dilution by air in the area of flow.

- No losses due to entrance effects, bends, or surface roughness. Inclusion of these sources of loss would further reduce the estimated flow rates.

In addition, flow through the vent header is not considered.

If you have any questions regarding these estimates, please feel free to contact me.

T. G. Hanson, Engineer
Waste Concentration Unit

TGH:ljg

cc: G. L. Dunford
S. R. Johnson
J. T. Kruszka
R. M. Marusich
L. A. Mihalik
D. J. Squires

```
10 REM PROGRAM FOR COMPUTING AIR FLOW RATES ON TANK PRESSURIZATION
20 REM BY T. G. HANSON                                    MAY 4, 1987
30 REM
40 REM CALCULATES THE FLOW RATE IN CFM, USING RELATION FROM PERRYS
50 REM FOR ISOTHERMAL COMPRESSIBLE FLOW, AND THE VON KARMON-NIKURADSE
60 REM EQUATION RELATING FRICTION FACTOR TO REYNOLD'S NUMBER
70 REM
90 REM PROMPT FOR PHYSICAL CONDITIONS
95       DEFDBL A-Z
100      INPUT "ROUTE OF AIR FLOW"; J$
110      INPUT "LENGTH (FT)"; L
120      INPUT "HYDRAULIC RADIUS (FT)"; D
130      INPUT "CROSS-SECTIONAL AREA (SQ FT)"; A
140      INPUT "VISCOSITY (LB/FTxS)"; U
150 REM PRINT TABLE HEADINGS
160      LPRINT "FLOW PATH:", J$
165      LPRINT
170      LPRINT "PHYSICAL CONDITIONS:"
175      LPRINT "LENGTH = ";L;" FT  HYDRAULIC RADIUS = ";D;" FT"
176      LPRINT "X-SECTIONAL AREA = ";A;" SQ FT  VISCOSITY = ";U;" LB/FTxS"
178      LPRINT
180      LPRINT "dP","REYNOLDS","FLOW RATE","GOOD"
182      LPRINT "(IN WG)","NUMBER","(CFM)","VALUE?"
185      LPRINT
200 REM INITIALIZE CONSTANTS: R = GAS CONSTANT, B = GRAVITATIONAL CONSTANT
205 REM M = MOLECULAR WEIGHT, T = TEMPERATURE, Q = OUTLET (ATMOSPHERIC) PR
210      R = 1546: B = 32.174: M = 29: T = 674: Q = 2116.2
220 REM INITIALIZE VARIABLES
230      C = 0: X = 1'                                  COUNTING VARIABLES
235      Z = 0: Z1 = 0'                                 dP VARIABLES
250      C1 = 9: X1 = .05
260 REM GENERATE RESULTS
300      IF C > C1 THEN 600
310                C = C + 1
320                Z = Z1 + X1*C
330                H = 5.2*Z'                           dP IN LB/SQ FT
340                P = Q + H
350                S = (P*M)/(R*T)'                     COMPUTE DENSITY
400                F = .01
405 REM ITERATIVE LOOP BASED ON FRICTION FACTOR
410                K = 1 + ((4.61*D)/(F*L))*LOG(P/Q)
420                G = SQR((P^2 - Q^2)*((B*D*M)/(F*L*R*T*K)))
440                N = 4*(G*D)/U'                          REYNOLDS NUMBER
445                E2 = F
450                E = (1/(1.7*LOG(N*SQR(E2))-.4))^2'FRICTION FACTOR
452                IF ABS(E-E2) < (5E-08) THEN 460
454                        E2 = E
456                        GOTO 450
460                IF ABS(E-F) < (5E-08) THEN 490
470                        F = E
480                        GOTO 410
490                V = G/S
500                Y = 60*V*A
0
```

```
505 REM PRINT RESULTS
510                 LPRINT USING "##.##          ";Z,
514                 LPRINT USING "##.#^^^^          ";N,
518                 LPRINT USING "###.#          ";Y,
519 REM CHECK IF N IN TURBULENT RANGE
525                 IF (N < 4000) THEN 590
530                         LPRINT "YES"
540                         GOTO 300
590                 LPRINT "NO"
595                 GOTO 300
600       C = 0
610       IF X > 1 THEN 660'                          INCREASE INCREMENT SIZE
620                 X1 = .1'                          FOR dP > 0.5
625                 C1 = 4
630                 Z1 = Z
640                 X = X + 1
650                 GOTO 300
660       IF X > 2 THEN 700'                          INCREASE INCREMENT SIZE
670                 X1 = 1'                           FOR dP > 1.0
675                 C1 = 8
680                 Z1 = Z
690                 X = X + 1
695                 GOTO 300
700       IF X > 3 THEN 800'                          INCREASE INCREMENT SIZE
710                 X1 = 5'                           FOR dP > 10.0
720                 C1 = 14
730                 Z1 = Z
740                 X = X + 1
750                 GOTO 300
800       INPUT "NEW FLOW PATH Y OR N";O$'            PROMPT FOR RERUN
820       IF O$ <> "Y" THEN 999
830                 LPRINT
840                 GOTO 100
999       END
0
```

FLOW PATH: SHIELDING PLUG

PHYSICAL CONDITIONS:
LENGTH = 5.19 FT HYDRAULIC RADIUS = .0219 FT
X-SECTIONAL AREA = .006 SQ FT VISCOSITY = .00001418 LB/FTxS

dP (IN WG)	REYNOLDS NUMBER	FLOW RATE (CFM)	GOOD VALUE?
0.05	3.9D+03	3.9	NO
0.10	5.8D+03	5.8	YES
0.15	7.4D+03	7.3	YES
0.20	8.7D+03	8.6	YES
0.25	9.9D+03	9.8	YES
0.30	1.1D+04	10.9	YES
0.35	1.2D+04	11.9	YES
0.40	1.3D+04	12.8	YES
0.45	1.4D+04	13.7	YES
0.50	1.5D+04	14.6	YES
0.60	1.6D+04	16.2	YES
0.70	1.8D+04	17.7	YES
0.80	1.9D+04	19.0	YES
0.90	2.1D+04	20.4	YES
1.00	2.2D+04	21.6	YES
2.00	3.2D+04	31.8	YES
3.00	4.0D+04	39.7	YES
4.00	4.7D+04	46.4	YES
5.00	5.3D+04	52.2	YES
6.00	5.9D+04	57.4	YES
7.00	6.4D+04	62.2	YES
8.00	6.9D+04	66.5	YES
9.00	7.3D+04	70.6	YES
10.00	7.7D+04	74.3	YES
15.00	9.4D+04	90.1	YES
20.00	1.1D+05	102.2	YES
25.00	1.2D+05	112.0	YES
30.00	1.3D+05	120.0	YES
35.00	1.4D+05	126.8	YES
40.00	1.5D+05	132.6	YES
45.00	1.5D+05	137.5	YES
50.00	1.6D+05	141.8	YES
55.00	1.7D+05	145.5	YES
60.00	1.7D+05	148.8	YES
65.00	1.8D+05	151.7	YES
70.00	1.8D+05	154.2	YES
75.00	1.9D+05	156.4	YES
80.00	1.9D+05	158.4	YES
85.00	2.0D+05	160.2	YES

FLOW PATH: SIDE FILL LINES TO 152-AX

PHYSICAL CONDITIONS:
LENGTH = 170 FT HYDRAULIC RADIUS = .0625 FT
X-SECTIONAL AREA = .049 SQ FT VISCOSITY = .00001418 LB/FTxS

dP (IN WG)	REYNOLDS NUMBER	FLOW RATE (CFM)	GOOD VALUE?
0.05	3.2D+03	9.0	NO
0.10	4.8D+03	13.5	YES
0.15	6.1D+03	17.1	YES
0.20	7.2D+03	20.3	YES
0.25	8.1D+03	23.1	YES
0.30	9.1D+03	25.6	YES
0.35	9.9D+03	28.0	YES
0.40	1.1D+04	30.2	YES
0.45	1.1D+04	32.3	YES
0.50	1.2D+04	34.3	YES
0.60	1.3D+04	38.1	YES
0.70	1.5D+04	41.6	YES
0.80	1.6D+04	44.9	YES
0.90	1.7D+04	48.1	YES
1.00	1.8D+04	51.0	YES
2.00	2.7D+04	75.5	YES
3.00	3.4D+04	94.8	YES
4.00	4.0D+04	111.3	YES
5.00	4.5D+04	126.0	YES
6.00	5.0D+04	139.3	YES
7.00	5.4D+04	151.5	YES
8.00	5.9D+04	163.0	YES
9.00	6.3D+04	173.7	YES
10.00	6.7D+04	183.9	YES
15.00	8.4D+04	228.2	YES
20.00	9.8D+04	265.1	YES
25.00	1.1D+05	297.0	YES
30.00	1.2D+05	325.2	YES
35.00	1.3D+05	350.6	YES
40.00	1.4D+05	373.6	YES
45.00	1.5D+05	394.8	YES
50.00	1.6D+05	414.2	YES
55.00	1.7D+05	432.3	YES
60.00	1.8D+05	449.1	YES
65.00	1.9D+05	464.8	YES
70.00	2.0D+05	479.5	YES
75.00	2.1D+05	493.3	YES
80.00	2.1D+05	506.3	YES
85.00	2.2D+05	518.6	YES

APPENDIX C

LIST OF ASSUMPTIONS

ASSUMPTIONS

1. 50% Contingency was given to the environmental pathway flow rates.

2. The solids temperatures were developed from HEATING5 computer code. The computer code does not account for percolation or evaporation.

3. Heat load in the waste solids is 4 million BTU/hr and the tank waste has 20% solids.

4. Maximum ALC downtime will be no longer than 72 hours.

5. All but 19" of solids would be resuspended when the ALC's are restarted. This was assumed because during normal operations up to 19" of solids in a full tank are expected to settle the ALC's are used.

6. Boiling temperature of the liquid waste is 230°F.

7. The heat transfer occurs instantaneously as solids resuspend.

8. The solids resuspension takes place over 8 hours in a negative exponential fashion.

9. Heat is transferred until the solids and liquid temperatures equilibrate.

10. The capacity of other tanks on the vent system to buffer a pressurization is not considered.

Burping Source term Calculation

Based on data acquired during a "burp" the following condition are used to calculate the burp source term

positive pressure within the tank	3.0 in. wg
moisture contained in the air space	increase by a factor of 21.5
duration of burp	70 minutes

The moisture generation during the burp would be 9,125 gal/hr

Using a 10^{-2} radionuclide concentration rate to account for the increased rate of "boiling" the curie content of the burp would be equal to 21,636 Ci/hr

Accounting for the 70 min duration this relates to a source term of 25,242 Ci for a 70 min burp

3.3 in wg in tank press = 7275 ft min 6" pipe = 1819 ft³/min
35 in wg in tank press = 23,696 ft min 6" pipe = 5924 ft³/min

time to empty vapor space
3.3 in wg = 60 361 ft³ / 1819 ft³ per min = 33.18 min

35 in wg = 60 361 ft³ / 5924 ft³ per min = 10.19 min

Bump Moisture = 250 (25) = 6250 gals
= 148 125 cu in per vapor space

9,29 gal/hr

3.3 in wg: 23,694 ft/m

Ft^2

3.3 1819 ft^3/m

6" pipe

.25 ft^2 pipe

Calculations:

Volume released $\frac{P_1 V}{T_1} = \frac{P_2 V_2}{T_2}$ assume $T_1 = 190\,°C$ (463 °K)

$T_2 = 30\,°C$ (303 °K)

Pressure conversion (in wg) to (mm Hg)

$lb/in^2 = 1/27.673$ in wg

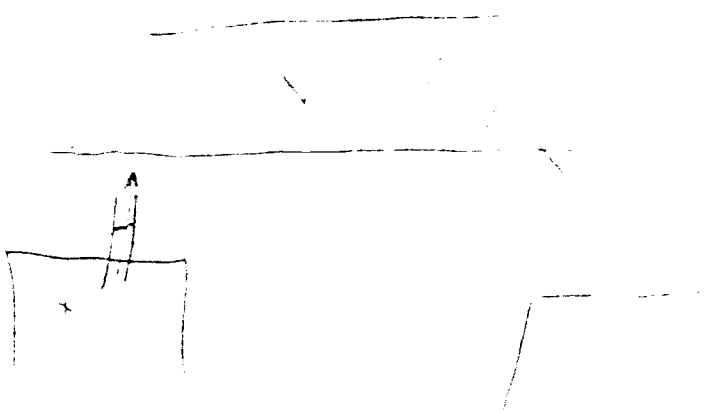
$$\frac{3.3 \text{ in wg}}{} \Big/ \frac{lb\ in^2}{27.673 \text{ in wg}} \Big/ \frac{mm\ Hg}{51.715\ lb/in^2} = \begin{matrix} .062 \\ .0023\ m \end{matrix}$$

$P_1 = 760.062$

$P_2 = 760.00$

$$V_2 = \frac{P_1 V_1 T_2}{T_1 P_2} = \frac{(760.062)(1.703\ m^3)\ 303}{463 \quad 760} \qquad 1,114.6\ m^3$$

$\frac{dV}{dt}$



Such factors as moisture content or compaction can radically alter the thermal conductivity of the specimen. Unfortunately, the conditions of the samples were not very well documented. Physical conditions of the samples were categorized by such loose terms as "very wet", "damp coffee grounds", or "dry soft powder". Useful knowledge is the fact that the "dry soft powder" had the lowest thermal conductivity reading, as would be expected. The value of 0.08 BTU/(hr ft F) is of interest in the event that the solids should dry out.

The tank thermal response modeling work, Reference (a), resulted in a high, low, and weighted average values of 1.97, 0.37, and 1.10 BTU/(hr ft F) respectively. Whereas modeling involves its own inaccuracies, the work was based on undisturbed samples and the modeling itself is representative of the future end use of the values obtained. The values, as a whole, are greater than those of Reference (b), and may reflect either the fact that the solids were undisturbed, or that there exists some additional mechanism in the tank environment that boosts the effective conductivity of the solids.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of References (a) and (b), a range of thermal conductivities for tank solids of 0.35 to 2.0 BTU/(hr ft F) should be adopted for the modeling of tanks under normal operating conditions (i.e.; moist, supernatant covering the solids, etc.). For a scenario in which solids were to dry out, a thermal conductivity as low as 0.08 BTU/(hr ft F) would not be unreasonable.

D.W. Rodenhizer, Engineer
Waste Management Separations
Process Technology Unit

kmw

Westinghouse Hanford Company

Internal Memo

From: Waste Management Separation Process Technology Unit 65610-87-139
Phone: 373-3297 2750E/A219/200E
Date: September 30, 1987
Subject: THERMAL CONDUCTIVITY OF TANK WASTE SOLIDS

To: WJ Powell 2750E/A120/200E

cc: JN Appel 2750E/200E
GL Dunford 2750E/200E
DR Groth 2750E/200E
NR Kerr MO-222/200E
JT Kruszka 2750E/200E
LA Mihalik 2750E/200E
DWR File/LB

REFERENCES:

(a) IL 65610-84-118, D.C. Riley to K.G. Carothers, "70 KBTU/hr Limit Review for Double Shell Tanks."

(b) ARH-CD-378, July 1975, D.G. Bouse, "Thermal Conductivity of Hanford Waste Tank Solids & SX Tank Farm Soil Samples."

INTRODUCTION

Thermal conductivities of tank waste solids are a vital part of any modeling effort aimed at determining the thermal response of tank wastes. Actual values for these properties are not well known and cannot be readily ascertained by theoretical means based on the composition of the waste in question. Previous work has focused on direct measurement of tank waste solids samples; Reference (b), and on modeling tank thermal response to implicitly obtain conductivities; Reference (a). This letter represents a merging of these works into a range of values to be used for thermal conductivity of tank solids in future analyses.

DISCUSSION

The thermal properties of aging waste solids are assumed to be similar to those of non-aging waste solids. Aging and non-aging wastes vary in composition, but the ranges of values for the thermal properties are limited, and are expected to remain the same.

Direct measurement of the thermal conductivities of tank solids samples, Reference (b), resulted in a high, low, and average values of 1.07, 0.08, and 0.40 BTU/(hr ft F) respectively. Measurements of samples removed from their operating environments, however, always carry the risk of involving inaccuracies due to changes in sample conditions.

Hanford Operations and Engineering Contractor for the US Department of Energy

Westinghouse Hanford Company

Internal Memo

From: Tank Farm & Evaporator Process Technology Unit 13311A-87-192
Phone: 373-3429 2750E/A227/200E R2-11
Date: December 4, 1987
Subject: THERMAL CONDUCTIVITY OF AGING WASTE SOLIDS.

To: R.M. Marusich R3-02

cc: D.R. Ellingson R1-80
D.E. McKenney DEM R2-11
L.A. Mihalik LAM R2-11
J.J. Zimmer R2-05

References: (1) RHO-LD-171, G.D. Campbell, "Heat Transfer Analysis for In Situ Disposal of Nuclear Wastes in Single- and Double-Shell Underground Storage Tanks", October, 1981.

(2) Internal Memo, D.W. Rodenhizer, "Thermal Conductivity of Tank Waste Solids", September, 30, 1987.

The Tank Farm and Evaporator Process Technology Unit has been requested to verify that the proper thermal conductivity (k) has been used in the analysis of an aging waste tank bump. The tank bump report assumes the HEATING5 computer code uses a thermal conductivity of 1.0 BTU/hr.ft. F (see Reference 1). A recent letter was issued designating that the worst case thermal conductivity can be as low as .08 BTU/hr.ft. F for dried solids (see Reference 2). To determine the effect of the thermal conductivity a number of runs were made for a 72 hour heat period. The data input to HEATING5 computer code is listed below.

Specific Heat (BTU/lb.F)	Thermal Conductivity (BTU/hr.ft.F)	Density (lb/ft^3)	Average Temperature (F)
.2	3.0	113	444
.2	2.0	113	448
.2*	1.0*	113*	454
.2	.25	113	459
.2	.08	113	460

* These numbers represent what was actually used as input to the HEATING5 computer code for the aging waste tank bump.

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13311A-87-192

The results show that the thermal conductivity does not have a large impact on solids heat-up for the time period examined (72 hours). The calculations are based on the solids being at a constant thermal conductivity throughout the heat-up period. Realistically, the thermal conductivity would change during the solids heat-up as a function of moisture in the solids. The wet flocculent solids are assumed to have a thermal conductivity of 3.0 BTU/hr.ft.F. with a decreasing thermal conductivity as the moisture is driven from the solids. The HEATING5 computer code is unable to use a variable thermal conductivity, therefore 1.0 BTU/hr.ft.F was chosen as a representative number since the thermal conductivity will vary from 3.0 to .08 BTU/hr.ft.F.

If you have any questions pertaining to this subject please contact me.

B. L. Jones, Engineer
Tank Farm & Evaporator
Process Technology Unit

kjr

Westinghouse Hanford Company

Internal Memo

From: Tank Farm & Evaporator Process Technology Unit 13311A-87-201
Phone: 373-3429 2750E/A227/200E R2-11
Date: December 18, 1987
Subject: HEATING5 UTILIZATION IN AGING WASTE TANK BUMP ANALYSIS

To: D.E. McKenney

cc: J. N. Appel R2-05
R. B. Bendixson R2-05
D. R. Ellingson R1-80
L. A. Mihalik LAM R2-11
A. R. Schade R3-09
J. C. Womack R2-18
J. J. Zimmer R2-05
BLJ File/LB

Reference: Internal Memo, B. L. Jones to R. M. Marusich, "101-AZ Tank Bump and Associated Release Calculation," September 1, 1987.

The purpose of this letter is to clarify and discuss the HEATING5 computer code, inputs to the HEATING5 program and the HEATING5 output data.

HEATING5 Computer Code Introduction.

This section is a condensed introduction to the HEATING5 computer code. The completed introduction is attached (see Attachment 1).

HEATING5 is a generalized heat conduction code designed to solve steady-state and/or transient heat conduction problems in one- two- or three-dimensional Cartesian or cylindrical coordinates. The thermal conductivity, density and specific heat may be both spatially and temperature-dependant. The thermal conductivity can be anisotropic. Materials may undergo a change of phase. Heat generation rates may be dependent on time, temperature and position, and boundary temperatures may be time-dependent. The boundary conditions, which may be surface-to-boundary or surface-to-surface, may be fixed temperatures or any combination of a prescribed heat flux, forced convection, natural convection and radiation. The boundary condition parameters may be time- and/or temperature-dependent.

The point successive over-relaxation iterative method and a modification of "Aitken δ^2 extrapolation process" are used to solve the finite difference equations which approximate the partial differential equations for a steady-state problem. The transient problem may be solved using any one of several finite difference schemes. These include an implicit technique which can range from Crank-Nicolson to the Classical Explicit Procedure, an explicit method which is stable for a time step of any size, and the Classical Implicit Procedure, which involves the first forward time difference. The solution of the system

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of equations arising from the implicit technique is accomplished by the point successive over-relaxation iteration, and includes procedures to estimate the optimum acceleration parameter. The time step size for implicit transient calculations may be varied as a function of the maximum temperature change at a node. Transient problems involving materials with change-of-phase capabilities cannot be solved using the implicit technique with this version of HEATING5.

HEATING5 Inputs and Assumptions

This section will cover the inputs to HEATING5 that were used in the 101-AZ tank bump analysis (see Reference). There are many inputs so this letter will group them into pertinent sections and discuss each input in some detail.

TANK MODEL GEOMETRY

The tank geometry was input into the HEATING5 computer code as radial and axial coordinates. Tank 101-AZ was used as the model (typical aging waste double-shell tank). This included the primary tank, annulus tank, wall concrete, floor concrete and thermal concrete. The waste volumes include 10 inches of cold solids, 53 inches of new solids (15% by volume) and 970,000 gallons of liquid waste. Attached is the actual model that was input into HEATING5 (see Attachment 2).

MATERIAL CHARACTERISTICS

The materials used in the conduction problem are listed with their thermal conductivity, specific heat, and density. The solids thermal conductivity is the only questionable input. This thermal conductivity will range from 3.0 to .08 BTU/hr.ft.F. The completed list of material input characteristics are given below.

Material	Thermal Conductivity (BTU/hr.ft.F)	Specific Heat (BTU/lb.F)	Density (lb/ft^3)
Concrete	.54	.21	144.0
Hot Solids	1.0	.20	113.0
Cold Solids	1.0	.20	113.0
Soil	.25	.22	113.0
Insulating Concrete	.11	.20	62.0
Air	.016	.24	.071
Supernatant	.392	1.0	62.4

BOUNDARY CONDITIONS

The boundary conditions were selected based on geological data and worst case assumption. The boundary conditions for the double shell tank model are listed below:

1) A 70 F forced convection and ground level (assumed).

2) A 55 F isothermal temperature boundary at a depth of 200 feet. This is due to the water table which runs at a constant 55 F (actual geological data).

3) A 70 F adiabatic boundary at 60 feet radially. This assumption simulates a tank in the middle of a large array of tanks, all generating the same amount of heat.

4) The liquid-solid interface is at a constant temperature (190 F). This assumes that all the heat released to the liquid will turn to steam/vapor and exit the system. (190 F reflects the actual temperatures seen in Tank 101-AZ).

RADIOISOTOPE DECAY

The final input of importance is the radioisotope decay function. This is entered into the program as a material heat generation half-life. In this case that will be the solids. The half-life is calculated to be 443 days.

HEATING5 Output Data.

The output data is in the form of temperatures at different nodes throughout the tank model. The number of nodes can be changed and varied in this model to reflect large distances between different materials. The output for tank 101-AZ at 210 hrs heat-up time is attached (see Attachment 4). The 210 hour heat-up time was chosen because at this time the tank would just pressurize if a tank bump occurred. The minimum solids temperature for the 101-AZ tank is 251 F and the maximum is 310 F, which is an average temperature of 280.5 F. The cold solids temperature is important because the thermal couples are located 3 to 4 inches from the tank bottom and will be covered completely with cool solids. The temperature at 210 hrs is 298 F, which is a maxium 12 F difference.

Recalculation with a thermal conductivity of 0.08 BTU/hr.ft.F results in the time required to achieve conditions critical to a bump occurring decreasing to 126 hours (see Attachment 3). This is considered very conservative in that the low thermal conductivity value is assumed to be in effect throughout solids heat-up (even when the solids are wetted).

B. L. Jones, Engineer
Tank Farm & Evaporator
Process Technology Unit

kjr

Attachments 4

I. INTRODUCTION

HEATING5 is the latest version of "The HEATING Program," where HEATING is an acronym for Heat Engineering and Transfer in Nine Geometries. HEATING was originally developed by Liguori and Stephenson (Ref. 1) from Fowler and Volk's generalized heat conduction code, GHT (Ref. 2). Other modifications to HEATING have been reported previously (Ref. 3 and 4).

HEATING5, a modified version of HEATING3 (Ref. 4), has been stored on disks at the Computing Centers at Oak Ridge National Laboratory (ORNL) and the Oak Ridge Gaseous Diffusion Plant (ORGDP) and is available to users in Oak Ridge. This report, which is designed as a user's manual, discusses the capabilities of HEATING5.

The major improvement in the code is the incorporation of an implicit scheme to solve transient problems. Of the three basic algorithms which are available in HEATING5 to solve transient problems, the implicit scheme is the recommended approach for most problems. This scheme is written generally to include the Crank-Nicolson finite difference equations, the classical implicit or backwards Euler finite difference equations, or a linear combination of the two. The resulting system of equations is solved by the point successive overrelaxation iterative method, and the technique includes procedures to estimate the optimum acceleration parameter as a function of time. The time step size for the implicit transient calculations can be controlled explicitly through the input data or implicitly by specifying the maximum temperature change or maximum percent of relative change in temperature allowed at a node over a time step. The temperature-dependent parameters may be reevaluated as a function of the number of iterations for steady-state problems. Another modification allows selected materials to undergo a change of phase. However, the implicit technique for transient problems cannot be used for problems involving materials with change-of-phase capabilities with this version of HEATING5. Another feature which has been added to the code is the capability of solving one-dimensional, spherical models. Among other improvements incorporated in the new code are input and output modifications designed to facilitate data preparation and interpretation of results. The input formats for the material parameters, the heat generation rate functions and the initial temperature functions have been changed. The position-dependent functions and the time-dependent functions have been deleted. Analytical and tabular functions have been added to aid in the definition of input parameters. An option to allow the user to write his own subroutines to evaluate many of the input parameters has been added to the code. Thus, if an input parameter cannot be described with the built-in analytical or tabular functions, then the user may easily supply his own algorithm to evaluate the parameter. This concept is referred to as user-supplied subroutines. The boundary condition parameters may be time- and/or temperature-dependent or if they are defined in user-supplied subroutines, they can also be position-dependent. The thermal conductivity, density and heat capacity can also be time-dependent if they are defined in user-supplied subroutines. For two- and three-dimensional problems, the temperatures in each plane are printed in the form of a map which depicts the material boundaries. This feature enables one to monitor the temperature distribution in a plane with minimal effort. A nodal map accompanies the first temperature map which allows one to readily locate a node and its temperature.

The numerical techniques for the steady-state and transient calculations are discussed in Section 2. The use of the code to solve physical problems is presented in Section 3. An outline of the input data is included in Section 3.8. An output description is presented in Section 4.

The appendices include information on the control cards necessary to use the code at ORNL and ORGDP, nomenclature, information on the use of user-supplied subroutines, and sample problems.

The user is cautioned that this code is not a black box which digests the input data and automatically yields the correct solution to the physical problem. Care must be exercised in correctly simulating the physical problem as well as in interpreting the results from the code.

For steady-state problems, one must experiment with the mesh spacing in order to gain confidence in the numerical solution to a model of a physical problem. For instance, numerical solutions must be obtained for several different mesh spacings, then these solutions must be compared and the differences that are noted at points of interest must be acceptable. In addition, one must also experiment with the convergence criterion. When the criterion is satisfied, it only guarantees that the temperatures did not change more than a specified amount over the previous iteration. This is sufficient for many problems, but it is possible to have a problem which is converging so slowly that the convergence criterion is satisfied even though the last iterate is a very poor estimate of the true solution to the model. Again, one must make several calculations with different convergence criteria and compare the results before obtaining confidence in the solution. For transient problems, one must experiment with the size of the time increment as well as study the effects of varying the mesh spacing and convergence criteria.

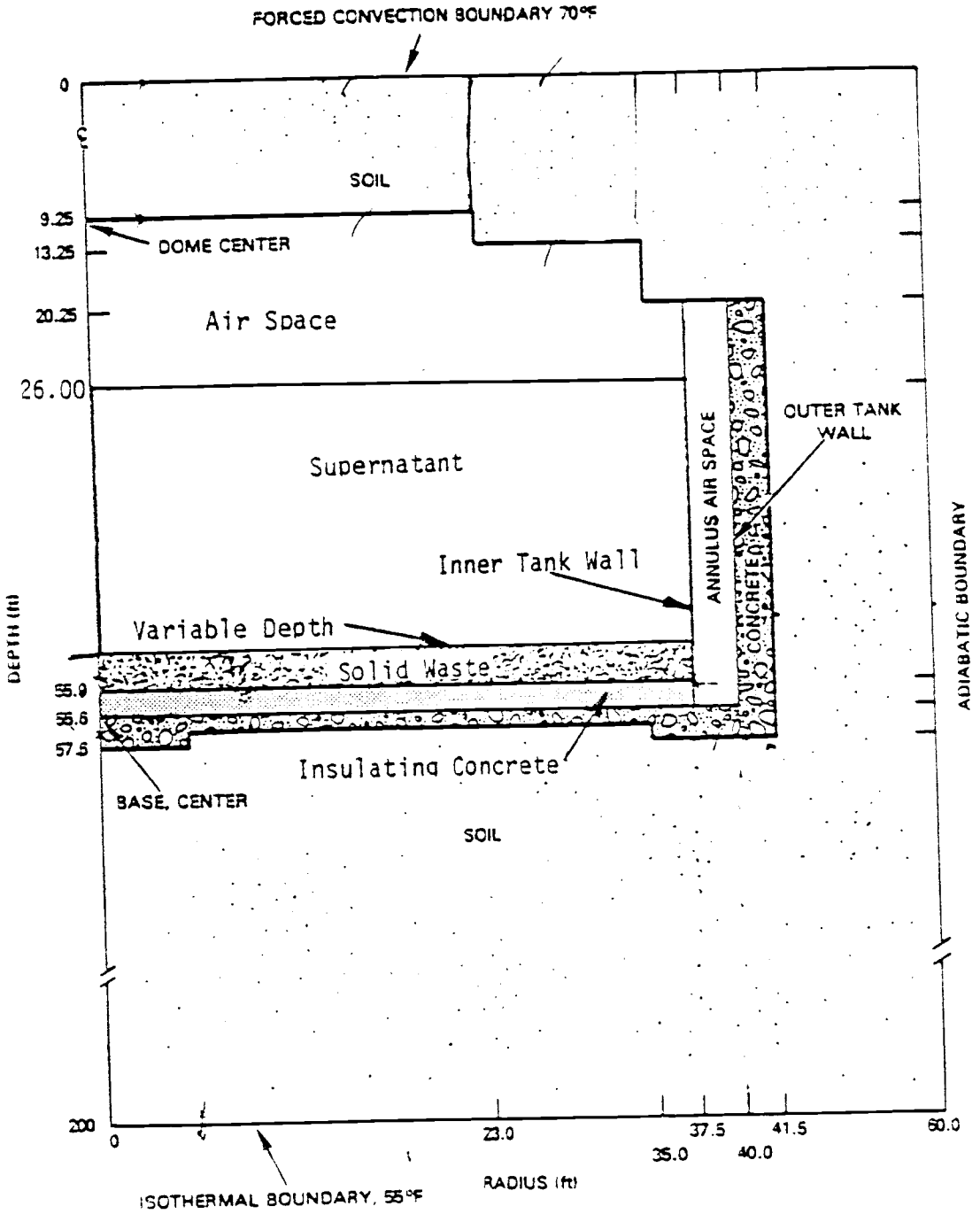
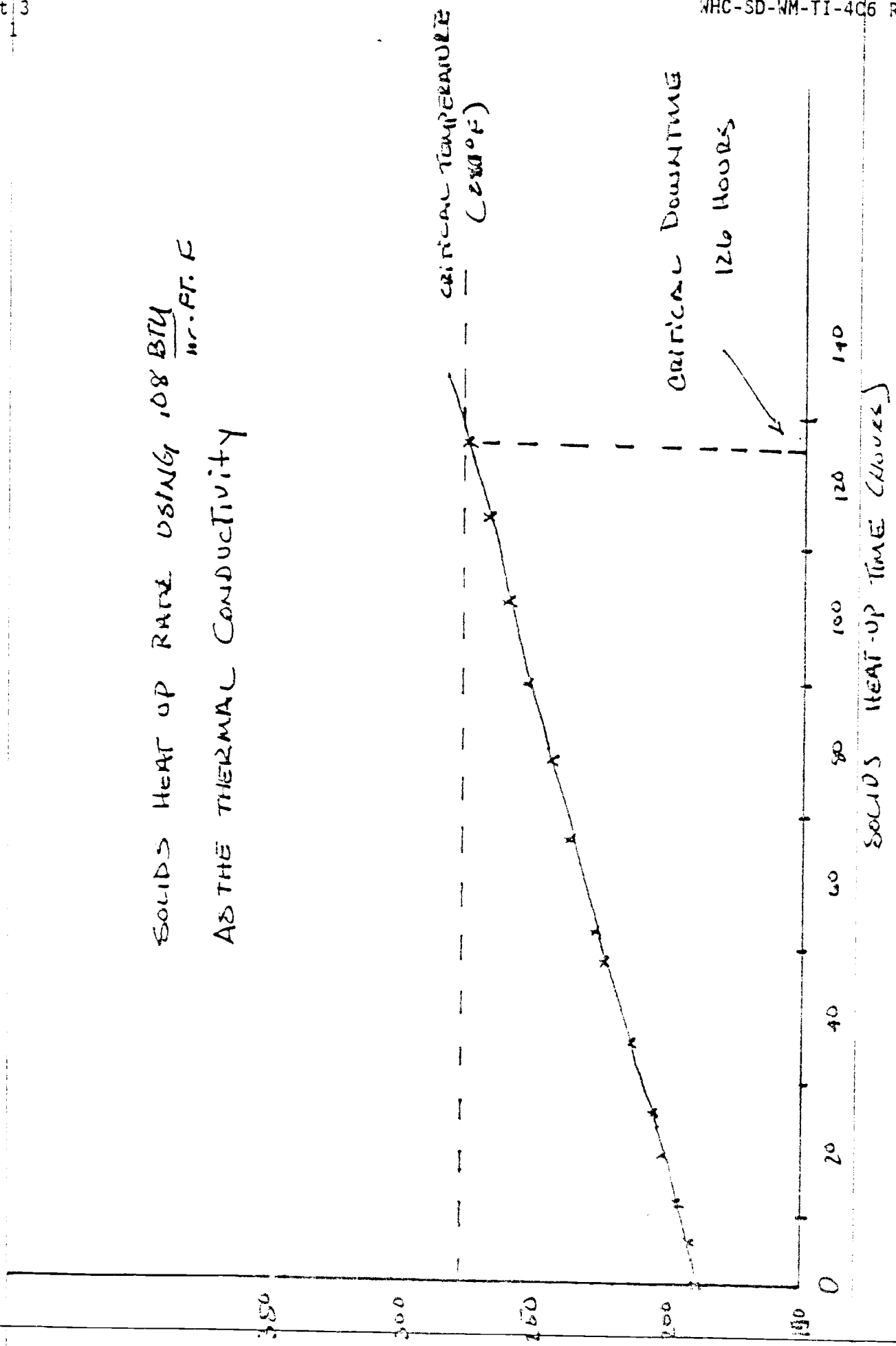


FIGURE 1. Double-Shell Tank Heat Transfer Model.


SOLIDS HEAT UP RATE USING 108 BTU/HR.-FT. F
AS THE THERMAL CONDUCTIVITY
CRITICAL TEMPERATURE (250°F)
CRITICAL DOWNTIME
126 HOURS
SOLIDS HEAT-UP TIME (HOURS)
SLUDGE TEMPERATURE (°F)
0
20
40
60
80
100
120
140
150
200
250
300
350

HEATING5 AGING WASTE TANK HEAT GEN 7BTU/HR DATE: 081987 TIME: 084456

TRANSIENT TEMPERATURE DISTRIBUTION AFTER 38 TIME STEPS, TIME = 2.10000+002

GROSS GRID	FINE GRID	DISTANCE	1	2	3	4	5	6	7	8	9	10	11
			.00	5.00	14.00	23.00	29.00	35.00	37.50	40.00	40.75	41.50	60.00
1	1	.00	71.57	71.57	71.56	71.35	71.10	70.94	70.73	70.45	70.28	70.10	69.99
	2	3.08	110.23	110.23	110.05	104.81	98.23	94.18	88.81	81.53	77.20	72.48	69.79
	3	6.17	149.73	149.72	149.41	140.53	126.14	118.12	107.40	92.92	84.31	74.92	69.58
2	4	9.25	188.22	188.19	188.00	185.60	154.29	142.88	126.19	104.37	91.48	77.40	69.37
3	5	13.25	100	.00	.00	188.80	188.03	184.21	151.62	119.01	100.74	80.97	69.13
4	6	20.25	100	.00	.00	.00	.00	187.78	183.33	129.06	112.73	95.41	69.28
	7	22.17	100	.00	.00	.00	.00	.00	188.91	111.18	108.61	104.65	70.00
	8	24.08	100	.00	.00	.00	.00	.00	188.95	110.63	109.71	108.57	70.34
5	9	26.00	189.54	189.51	189.30	188.76	188.83	187.95	187.71	111.02	110.35	109.66	70.44
	10	32.80	191.24	191.22	191.08	190.81	190.72	190.43	190.34	111.13	110.45	109.77	70.45
	11	39.60	196.53	196.52	196.46	196.33	196.25	196.08	196.00	111.20	110.48	109.78	70.45
	12	46.40	212.44	212.44	212.42	212.35	212.26	212.06	211.96	111.50	110.66	109.84	70.47
6	13	53.20	251.19	251.21	251.21	251.16	251.02	250.64	250.38	116.23	114.64	112.47	72.28
7	14	54.20	309.82	310.08	310.21	310.18	310.04	308.95	304.84	128.35	125.32	120.88	81.42
8	15	55.00	297.56	298.09	298.35	298.32	298.18	296.66	289.81	143.38	137.76	130.87	94.13
9	16	55.60	227.34	230.24	231.59	231.59	231.47	227.79	208.13	161.79	149.53	140.70	108.23
10	17	56.60	207.50	212.24	214.39	214.40	214.30	209.89	196.91	173.59	167.10	161.23	141.03
11	18	57.60	191.27	190.94	190.80	190.80	190.80	190.85	189.91	186.54	185.64	185.08	181.92
	19	105.07	145.00	145.00	145.00	145.00	145.00	145.00	145.00	145.00	145.00	145.00	144.99
	20	152.53	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
12	21	200.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	190.000000
2	55.000000
3	70.000000
4	190.000000
5	.000000

SLUDGE TOP
SLUDGE BOTTOM
COOL SOLIDS.

THE CURRENT TIME STEP (DELTAT) = 6.00000000+000

ELAPSED CPU TIME IS 44.07 SECONDS

THE MAXIMUM TEMPERATURE IS - 3.10214+002 (+-0.1)

MAX. TEMP. APPEARS AT NODES - 126 127

THE MINIMUM TEMPERATURE IS - 5.50000+001 (+-0.1)

MIN. TEMP. APPEARS AT NODES - 201 202 203 204 205 206 207 208 209 210 211

NO TIME	TIME	NO ITER	MAX HEAT RESIDUAL	BETA	L1 NORM OF TEMP DIFF	RHO (ITERATION)	RHO (JACOBI)	NO ITER	L1 NORM OF TEMP DIFF	NODE	MAX TEMP CHANGE	NODE	MAX PERCENT TEMP CHANGE
	216.000		210.000		699.493								
39	2.16000+002	1	1.13211-005	1.05500+000	.00000	.00000	.00000	1	8.55053-006				
39	2.16000+002	2	4.43039-007	1.05500+000	.00000	.00000	.00000	2	3.17679-008	137	1.20628+000	137	1.59132-001
39	2.16000+002	1	1.05067-007	1.05500+000	.00000	.00000	.00000						

Westinghouse
Hanford Company

Internal
Memo

From: Tank Farm Process Technology Section 13314-88-041
Phone: 3-4834 2750E/A200/200E R2-11
Date: March 29, 1988
Subject: FUTURE AGING WASTE TANK OPERATIONS (NO N REACTOR CASE)

To:				
	J. N. Appel	R2-05	G. L. Jones	L4-31
	R. B. Bendixson	R2-05	N. R. Kerr	R2-93
	M. S. Benecke	L4-36	D. E. McKenney DEM	R2-11
	D. A. Clapp	R3-02	D. C. Riley	R2-11
	A. J. DiLiberto	R2-05	L. M. Sasaki	R2-05
	G. L. Dunford	R1-51	R. L. Shaver	R2-11
	G. D. Forehand	R1-43	L. C. Stegen	R2-05
	R. L. Guillen	S6-81	J. A. Voogd	B2-03
	M. T. Jansky	B2-50	J. C. Womack	R2-18
	L. E. Johnson	X5-72	D. J. Washenfelder	R1-43
	B. L. Jones	R2-11	LAM File/LB	

References: 1) Personal Communication, W. B. Wolfe, February 1988.

2) Memo, J. D. Ludowise to R. D. Wojtasek, "Basis for Projecting Hanford Site Waste Volumes for the Period Fiscal Year 1988-2017," January 22, 1988.

This letter provides an analysis of future aging waste tank operations based on discontinued operation of the N Reactor and continued reprocessing of the current irradiated fuel backlog. In particular, aging waste volumes, radionuclide concentration, heat loads, and sludge levels are discussed with respect to tank space and design needs.

Introduction

Changes in the production missions at the Hanford site have significantly changed the volume and characteristics of aging waste which is expected to be stored in the double-shell tanks. These changes alter future tank space needs, particularly the need for construction of the AQ Tank Farm and the conversion of Tank 107-AN for aging waste use. In addition, design parameters and shielding for projects involving the AY and AZ aging waste tanks are affected. The information here provides support to decisions regarding these projects.

A backlog of both weapons and fuels grade material is currently being stored in the fuel basins, and it is presumed that this backlog will be reprocessed in the PUREX Plant. However, it is assumed that no new fuel will be irradiated in the N Reactor and that no non-N Reactor fuel will be reprocessed.

Summary

Even with an aggressive PUREX Plant operation schedule and upper-bounding aging waste characteristics, the AY and AZ tank farms provide sufficient storage capacity for current and future aging waste. The AQ Tank Farm and conversion of 107-AN are not required for aging waste operation.

The maximum waste heat generation rate in a single aging waste tank is projected to be 700,000 BTU/hr, and the maximum total for the AY/AZ Tank Farms is projected to be 1,200,000 BTU/hr. Even with additional provision for steam coil operation, the total heat generation rate will be significantly below the previously anticipated design requirement of 15 million BTU/hr. Figures 1 and 2 show future aging waste heat generation rates for the individual AY and AZ tanks as well as for the combined tank farms.

Upper-bounding radionuclide concentrations for a single tank and the combined tank farms are listed in Table 1. Substantial decreases in short-lived radionuclide concentrations decrease design and shielding requirements. Decreases in the total quantities of long-lived radionuclides may decrease ventilation system treatment needs.

Discussion

Fuel Reprocessing Schedule

Currently, the fuel storage basins contain 715 metric tonnes of uranium (MTU) of weapons grade irradiated fuel and 1764 MTU of fuels grade material (Reference 1). In addition, the N Reactor is currently charged with approximately 365 MTU of fuel, some of which is partially irradiated (Reference 1). This fuel is expected to be discharged during the early part of fiscal year (FY) 1989.

It was assumed in the analysis that the fuel will be reprocessed in the PUREX Plant according to the schedule shown in Table 2. The weapons grade reprocessing schedule is consistent with the no N Reactor case provided in Reference 2. To provide an upper-bounding heat generation rate, the order of particular campaigns was chosen such that fuel with the highest heat generation is reprocessed first (to the extent that this was consistent with References 1 and 2). It was also assumed that the fuel discharged from the N Reactor in FY 1989 is reprocessed immediately.

The schedule for reprocessing the fuels grade material is somewhat accelerated compared to Reference 2. This provides an upper-bounding source term, and is not unrealistic with regards to PUREX Plant capacities.

FIGURE 1: PROJECTED HEAT LOADS FOR 102-AZ

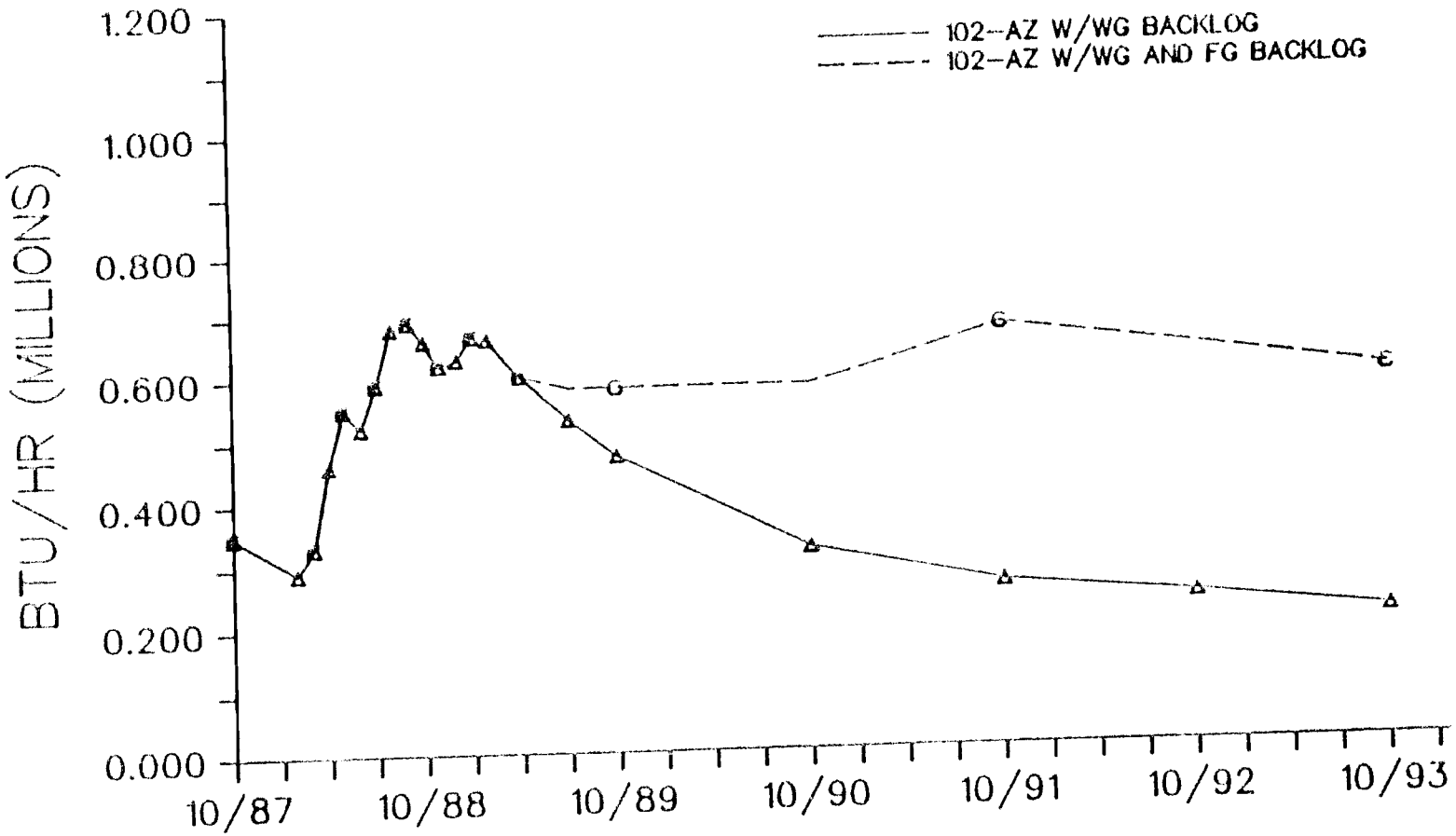
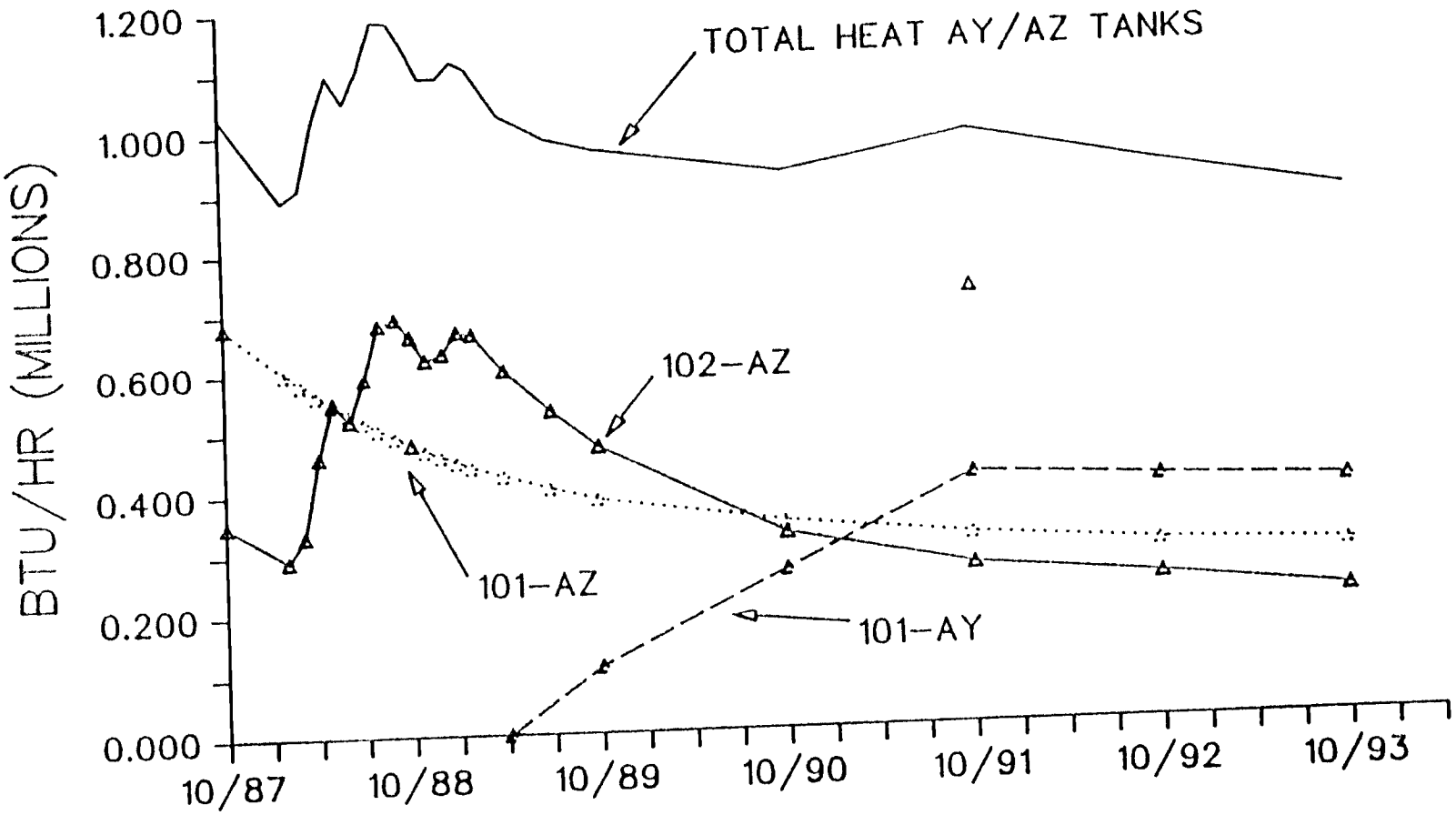


FIGURE 2:PROJECTED HEAT LOADS FOR AY/AZ TANKS



The isotopic content of the fuel stored in the basins was evaluated based on the irradiation history and actual discharge dates. The isotopic content of the partially irradiated fuel now contained in the N Reactor was assumed to be the equivalent of 100 MTU of weapons grade fuel with a discharge date of January 20, 1987. The waste volume from reprocessing the partially irradiated fuel was still calculated based on 365 MTU.

Fuel from sources other than the N Reactor was not considered in the following analysis because no projects are currently planned to accommodate its reprocessing. However, reprocessing of fuel from the Fast Flux Test Facility (FFTF) and fuel blankets from the Pressurized Water Reactor (PWR) II at Shippingport has been considered in the past. An analysis of the effects of waste from those fuels is given in Appendix B.

Aging Waste Tank Fill

The AY and AZ tanks are the designated aging waste tanks. Tank 101-AZ reached its maximum aging waste fill in March 1986. The waste in 101-AZ is now "aging" and new waste additions are not planned. Tank 102-AZ is the current active aging waste receiver. If a third aging waste receiver tank is required, it is assumed that Tank 101-AY will be used.

One of two operating specifications is expected to limit the fill of 102-AZ. The sludge level/sludge temperature limit could bound 102-AZ waste additions if the level of settled solids continues to increase at the rate initially observed in 102-AZ. Given the observed solids accumulation rate, it was determined that at a minimum all of the waste from weapons grade reprocessing could be added to 102-AZ without exceeding the specification. This would leave 1764 MTU of waste from the fuels grade reprocessing, which could then be stored in 101-AY without exceeding any operating specifications. This evaluation is presented in Appendix A.

If, as is postulated, the sludge accumulation rate decreases significantly with further waste additions, the 5M sodium limit would be more likely to limit the fill of 102-AZ. The sodium concentration in the tank before February 1988 was 1.6M with a fill of 328". The maximum currently allowed during routine operations is 5M Na at 358". If the PUREX process generates aging waste at the projected rate of 245 gal/hot MTU (5M sodium basis), an additional 2840 MTU could be processed in filling 102-AZ. This would essentially accommodate the entire 2844 MTU of available fuel.

At a waste generation rate of 276 gal/MTU (observed in FY 1986), waste from reprocessing approximately 2500 MTU could be stored in 102-AZ. At a rate of 435 gal/hot MTU (observed in FY 1985), tank 102-AZ could accommodate an additional 1600 MTU reprocessing. The remaining 344 MTU and 1244 MTU respectively in the latter two cases could be accommodated

by 101-AY.

Retrieval of aging waste for B Plant pretreatment is expected to begin in FY 1991. For each tank of aging waste retrieved, a tank of transuranic solids will be generated which must be stored in an aging waste tank. These activities can be supported by the existing AY/AZ tanks.

The various tank fill scenarios are shown in Figure 3. In all cases, the aging waste volumes anticipated in the future can be stored adequately in the AY/AZ tanks. Two to three tank volumes will contain the aging waste (or TRU solids generated by pretreatment of the aging waste) and the fourth tank volume will provide one million gallons spare capacity, either in a single tank or distributed between two tanks. Neither AQ Tank Farm nor conversion of 107-AN to an aging waste spare is required to support aging waste operations.

Radionuclide Concentrations

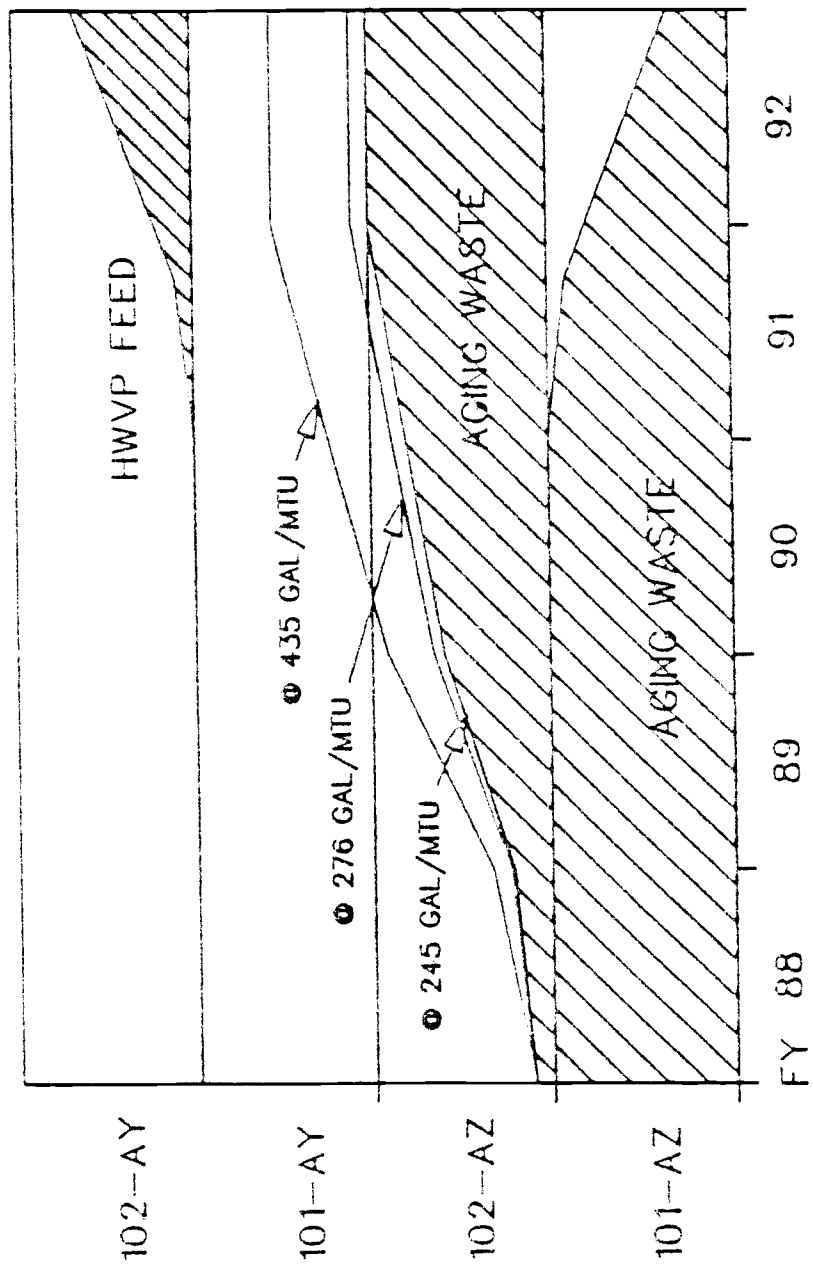
Table 1 provides three upper-bounding source terms. Column 1 represents the source term with the maximum concentrations of short-lived radionuclides. This coincides with the peak heat generation rate during reprocessing of the weapons grade backlog during FY 1988-89. Column 2 provides the source term with the maximum concentrations of long-lived radionuclides. This represents filling 102-AZ with waste from both the weapons grade and fuels grade reprocessing, and may occur as early as FY 1991. Column 3 indicates the maximum combined AY/AZ radionuclide inventory, and coincides with the end of all fuel reprocessing.

Because there will be no fresh fuel for PUREX Plant reprocessing, concentrations of short-lived radionuclides have decreased several orders of magnitude. This could reduce shielding requirements in projects involving the AY/AZ tanks such as core sampling.

The concentrations of long-lived radionuclides in a single tank remain the same order of magnitude, but decrease for the overall AY/AZ system because of less total fuel reprocessing. This may decrease treatment needs in the tank ventilation system. The new source terms should be evaluated for impacts on planned upgrades to the AY/AZ tank support systems.

B Plant pretreatment of aging waste will affect radionuclide inventories in the aging waste tanks. During the pretreatment washing process, most of the soluble radionuclides and potentially most of the volatile radionuclides will be separated into a stream which will go to non-aging waste tanks. The solids which are returned to the aging waste tanks will be depleted in those radionuclides. This effect should be considered in evaluations of future AY/AZ upgrades.

FIGURE 3: AGING WASTE TANK USAGE



Heat Generation Rates

The heat load projections for 102-AZ for two bounding scenarios are shown in Figure 1. The maximum waste heat generation in both cases is approximately 700,000 BTU/hr, of which a maximum of 610,000 BTU/hr is associated with the solids phase. (The difference is the contribution from soluble Cs-137/Ba-137m.)

The projected heat generation rates for 101-AZ, 102-AZ and 101-AY are shown together in Figure 2. This assumes the case where waste from weapons grade fuel processing is stored in 102-AZ and waste from fuels grade processing is stored in 101-AY. It can be seen that the heat generation in 101-AZ and 101-AY will always be less than the potential maximum in 102-AZ.

The total heat generation rate for the two tank farms is also shown on Figure 2. This total is independent of the distribution of waste among the four available tanks. The maximum aging waste tank farm heat generation rate will be 1.2 million BTU/hr during FY 1988-89, decreasing to 1 million BTU/hr in FY 1991.

Linda Mihalik

L. A. Mihalik, Engineer
Tank Farm Process Technology Section

kjr

Attachments

Attachment
Page 1
TABLE 1

13314-88-041

UPPER-BOUNDING RADIONUCLIDE INVENTORIES

Isotope	Maximum Single Tank--Short-Lived Isotopes (Ci)	Maximum Single Tank--Long-Lived Isotopes (Ci)	Maximum Total AY/AZ Tank Farms (Ci)
H-3	2.2E+03	6.0E+03	9.1E+03
C-14	1.2E+02	4.7E+02	7.0E+02
Fe-55	2.8E+04	2.4E+04	3.9E+04
Ni-59	1.1E+01	4.3E+01	6.3E+01
Co-60	7.1E+02	1.2E+03	1.9E+03
Se-79	2.4E+01	8.9E+01	1.3E+02
Sr-89	1.6E+04	5.8E-02	5.8E-02
Sr-90	4.4E+06	1.4E+07	2.1E+07
Y-90	4.4E+06	1.4E+07	2.1E+07
Y-91	6.1E+04	1.3E+00	1.3+00
Zr-93	1.1E+02	4.1E+02	6.1E+02
Nb-93m	2.6E+01	1.8E+02	2.6E+02
Zr-95	1.3E+05	6.9E+00	6.9E+00
Nb-95	2.8E+05	1.5E+01	1.5E+01
Nb-95m	9.8E+02	5.1E-02	5.1E-02
Tc-99	8.0E+02	3.0E+03	4.4E+03
Ru-103	1.4E+03	1.3E-04	1.3E-04
Rh-103m	1.2E+03	1.2E-04	1.2E-04
Ru-106	3.3E+06	7.5E+05	1.0E+06
Rh-106	3.3E+06	7.5E+05	1.0E+06
Pd-107	2.9E+00	1.3E+01	1.9E+01
Ag-110	1.1E+01	1.1E+00	1.3E+00
Ag-110m	8.5E+02	8.3E+01	9.8E+01
Sn-113	7.9E+01	3.6E-01	3.7E-01
Cd-113m	1.6E+03	4.8E+03	7.2E+03
In-113	7.9E+01	3.6E-01	3.7E-01
Cd-115m	6.2E+00	4.1E-06	4.1E-06
Sn-119m	3.0E+03	2.7E+02	3.2E+02
Sn-121m	8.9E+00	7.5E+01	9.0E+01
Sn-123	6.2E+03	5.4E+01	5.5E+01

Attachment
Page 2
TABLE 1

13314-88-041

UPPER-BOUNDING RADIONUCLIDE INVENTORIES

Isotope	Maximum Single Tank--Short-Lived Isotopes (Ci)	Maximum Single Tank--Long-Lived Isotopes (Ci)	Maximum Total AY/AZ Tank Farms (Ci)
Te-123m	4.1E-02	2.4E-04	2.5E-04
Sb-124	2.4E+00	6.9E-05	6.9E-05
Sb-125	3.5E+05	3.3E+05	5.3E+05
Te-125m	8.3E+04	8.0E+04	1.3E+05
Sn-126	3.7E+01	1.5E+02	2.1E+02
Sb-126	5.2E+00	2.1E+01	3.0E+01
Sb-126m	3.7E+01	1.5E+02	2.1E+02
Te-127	1.1E+04	3.8E+01	3.8E+01
Te-127m	1.1E+04	3.8E+01	3.9E+01
Te-129	4.9E+00	2.9E-08	2.9E-08
Te-129m	7.5E+00	4.4E-08	4.4E-08
I-129	1.1E-01	4.4E-01	6.3E-01
Cs-134	2.7E+05	2.4E+05	3.4E+05
Cs-135	2.1E+01	7.9E+01	1.2E+02
Cs-137	5.1E+06	1.7E+07	2.5E+07
Ba-137m	4.8E+06	1.6E+07	2.4E+07
Ce-141	2.2E+02	6.6E-07	6.6E-07
Pr-143	4.3E-06	1.0E-26	1.0E-26
Ce-144	1.3E+07	1.7E+06	2.1E+06
Pr-144	1.3E+07	1.7E+06	2.1E+06
Pr-144m	1.6E+05	2.4E+04	2.6E+04
Pm-147	8.2E+06	6.7E+06	1.1E+07
Pm-148	1.1E+00	2.2E-07	2.2E-07
Pm-148m	1.9E+01	3.9E-06	3.9E-06
Sm-151	8.6E+04	2.5E+05	4.0E+05
Eu-152	2.5E+02	1.1E+03	1.5E+03
Gd-153	6.5E+00	6.0E-01	7.0E-01
Eu-154	3.6E+04	1.4E+05	1.9E+05
Eu-155	6.9E+04	9.6E+04	1.6E+05
Tb-160	2.6E+00	4.4E-04	4.4E-04

Attachment
Page 3
TABLE 1

13314-88-041

UPPER-BOUNDING RADIONUCLIDE INVENTORIES

Isotope	Maximum Single Tank--Short-Lived Isotopes (Ci)	Maximum Single Tank--Long-Lived Isotopes (Ci)	Maximum Total AY/AZ Tank Farms (Ci)
U-234	6.4E-01	1.5E+00	2.7E+00
U-235	2.7E-02	6.2E-02	1.1E-01
U-236	5.2E-02	1.5E-01	2.6E-01
U-238	4.7E-01	1.2E+00	2.0E+00
Np-237	1.5E+01	6.1E+01	9.0E+01
Pu-238	4.2E+01	1.9E+02	2.7E+02
Pu-239	2.9E+02	7.4E+02	1.3E+03
Pu-240	8.1E+01	2.9E+02	4.4E+02
Pu-241	4.3E+03	1.6E+04	2.3E+04
Am-241	1.8E+04	1.8E+05	2.0E+05
Am-242	1.6E+01	1.6E+02	1.9E+02
Am-242m	1.6E+01	1.6E+02	1.9E+02
Am-243	2.6E+00	2.6E+01	3.1E+01
Cm-242	2.0E+02	1.4E+02	1.6E+02
Cm-244	5.3E+02	6.0E+03	7.0E+03
TOTAL CI	6.2E+07	7.3E+07	1.1E+08
TOTAL HEAT (BTU/HR)	6.9E+05	7.0E+05	1.0E+06
TOTAL HEAT MINUS Cs/Ba (BTU/HR)	6.1E+05	4.2E+05	5.9E+05

Attachment
Page 4
TABLE 2

13314-88-041

ASSUMED PUREX PROCESSING SCHEDULE

DATE	MTU (WEAPONS GRADE)	MTU (FUELS GRADE)
02/88 - 09/88	600	
10/88 - 01/89	480	
02/89 - 09/89		600
10/89 - 09/90		600
10/90 - 04/91		564

APPENDIX A

One operational limit used in aging waste tanks is based on keeping the total heat content of the settled aging waste solids below the minimum which could pressurize the tank if that heat was suddenly transferred to the liquid. A curve has been developed plotting sludge level versus average sludge temperature; the operating limit states that the point of actual sludge level/temperature must be on or below that curve, or waste additions must cease. Projected sludge levels and temperatures for Tank 102-AZ were evaluated to determine whether this operating specification would limit waste additions prior to completing the weapons grade fuel reprocessing.

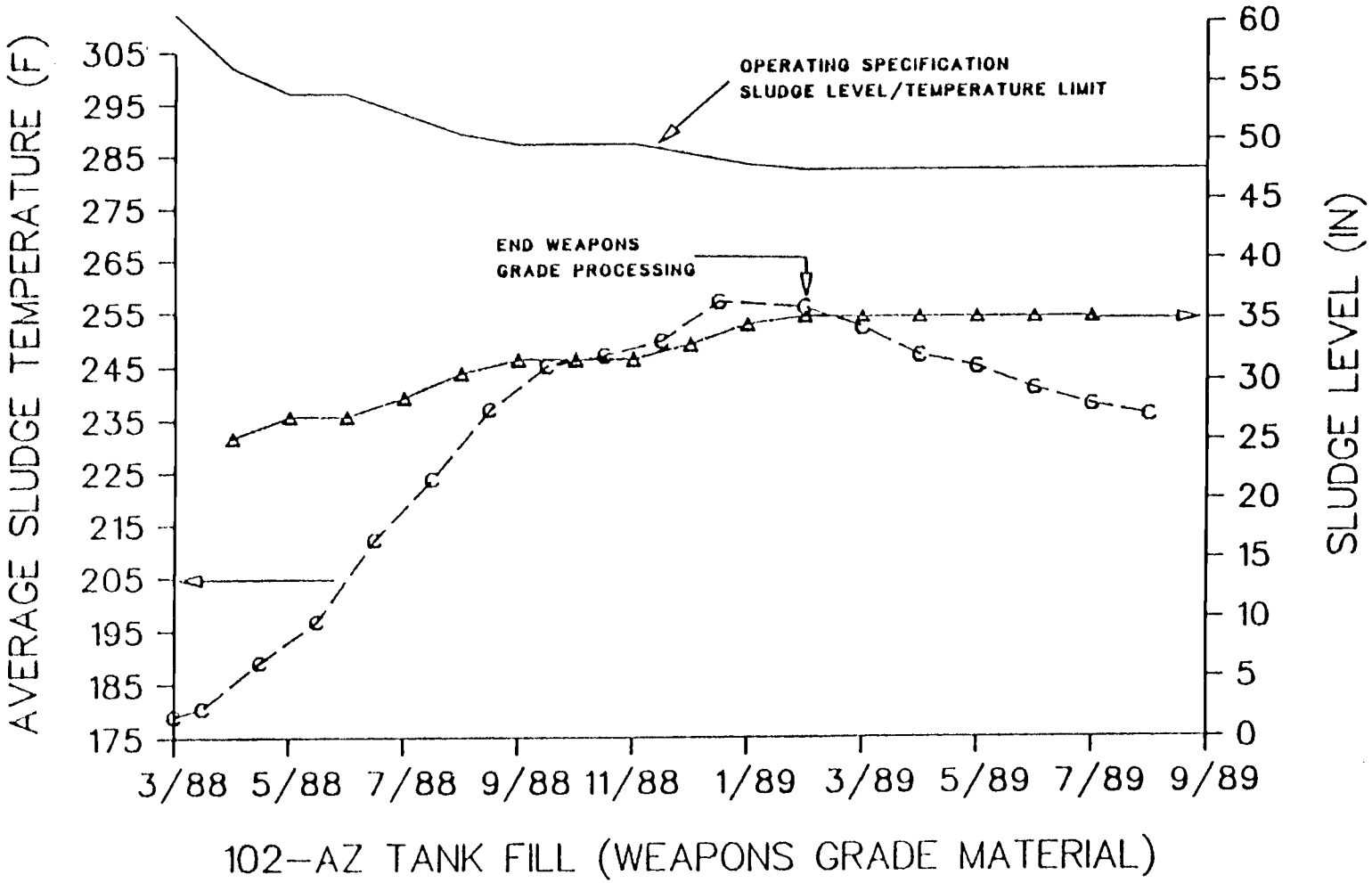
A high rate of sludge accumulation was observed initially in Tank 102-AZ, the equivalent of 1.6" of new settled solids per 100 hot MTU processed. This is anticipated to be the highest rate of sludge accumulation during future waste additions to 102-AZ. At this rate, an additional 13" solids (815 hot MTU) would be added to the 23" solids already in 102-AZ, for a total of 36". The sludge level accumulation is shown in Figure 4, along with the maximum temperature allowed for that sludge level.

The monthly values for heat generation rate as shown in Figure 1 were used to calculate average sludge temperatures during each month of 102-AZ operation, using the HEATING5 heat transfer code. The key assumptions in the analysis were as follows:

- The weapons grade fuel was assumed to be processed at approximately 100 MTU per month, up to the annual rate specified in Table 2.
- The bottom solids layer consists of 10" of "cold" solids topped by new solids at a depth of 1.6" per 100 hot MTU reprocessed.
- All of the heat-generating isotopes except Cs-137/Ba-137m occur in the solids.
- All of the solids heat-generation occurs in the settled solids. (This is the equivalent of saying there are not suspended solids, a conservative assumption.)
- The supernatant temperature was set at 190°F.
- Airlift circulators facilitate heat removal from the supernatant but do not provide solids mixing.

The resulting sludge temperatures are shown in Figure 4 for the period during which the weapons grade material would be reprocessed. Both the average sludge temperature and the maximum at the center of the sludge are plotted. As can be seen, the average sludge temperature rises to a peak of 255°F, well below the allowable limit.

FIGURE 4: PROJECTED 102-AZ SLUDGE LEVELS AND TEMPERATURES



The same evaluation was made with lower rates of sludge accumulation; the result was lower peak temperatures. Suspension of any portion of the heat-generating solids also results in lower peak sludge temperatures. Lower sludge temperatures also occur if the supernatant temperature is less than 190°F; this is a significant conservatism, since with the low overall heat load and continuous ALC operation, steam coil operation would be required just to maintain the solution temperature as high as 190°F.

The conclusion is that, even with an upper-bounding sludge accumulation rate and heat generation rate, the addition of waste from all of the weapons grade material processing will not cause 102-AZ operation to exceed the sludge level/temperature specification.

Should waste from all of the fuels grade material be added to 101-AY, the total heat generation rate in that tank would not exceed 450,000 Btu/hr. Only 250,000 Btu/hr of heat generation would be associated with the solids. In combination with a maximum of 28" of new solids, this would not be sufficient to exceed the sludge level/temperature limit.

APPENDIX B

Previous mission planning at Hanford has included the possibility of reprocessing fuel from FFTF and fuel blankets from the PWR II at Shippingport. The PUREX Plant modifications necessary to reprocess these fuels are not currently planned. However, if a means of reprocessing them is developed and employed in the future, it is reasonable to expect that the waste from these fuels could also be accommodated in the AY/AZ tanks.

The FFTF fuel would consist of 10.9 metric tonnes heavy metal (MTHM). The dilution required to reprocess this fuel would generate the equivalent of 126 MTU of waste per MTHM, or a total of 1370 MTU equivalents of waste. The PWR fuel would consist of 17 MTHM with a dilution factor of 3 MTHM per MTU, or 51 MTU. The total MTU equivalent would be 1421 MTU.

As a worst case, it was assumed that tanks 101-AZ and 102-AZ were full and that tank 101-AY contained waste from all of the fuels grade reprocessing, generated at a rate of 435 gal/MTU (770,000 gal). This would leave approximately 214,000 gal of tank space (5M Na basis), which could accommodate the aging waste from the FFTF and PWR II fuels if it was generated at a rate of 150 gal/MTU or less. The shear-leach process originally proposed for reprocessing these fuels generated aging waste at a rate of 60 gal/MTU (5M sodium basis), which falls within the allowable rate. Even greater flexibility would be available if aging waste generation rates for N-fuel reprocessing are below 435 gal/MTU, as is expected.

The isotopic distributions of FFTF fuel and the PWR II fuel blankets are somewhat different than N Reactor fuel, and the processing schedule has not been established, so exact radionuclide inventories for these wastes cannot be provided. However, approximate heat load contributions have been estimated.

The PWR II waste is anticipated to contribute very little to total heat generation rates. Assuming the FFTF fuel discharges occur between 1983 and 1993, and that the average discharge is 1 MTHM, the heat load added to the AY/AZ tank system should at most be about 400,000 Btu/hr. If this waste is added to 101-AY, and 101-AY already contains the waste from reprocessing the fuels grade material, the total heat in 101-AY would be about 800,000 Btu/hr. This would be only slightly greater than the maximum heat loads discussed earlier in this memo. Should plans for reprocessing the FFTF fuel be finalized in the future, it is recommended that impacts be evaluated more precisely.

Westinghouse Hanford Company

Internal Memo

From: Tank Farm Process Technology Unit 13314-88-086
Phone: 373-3429 2750E/A227/200E R2-11
Date: May 16,1988
Subject: AGING WASTE TANK BUMP SENSITIVITY TO THERMAL CONDUCTIVITY AND HEAT CAPACITY, INCORPORATING THE ASSUMPTION OF N-REACTOR SHUTDOWN.

To: L. A. Mihalik R2-11

cc: R. B. Bendixsen R2-07
L. A. Bergmann R1-51
G. L. Borsheim R2-18
D. A. Clapp R3-02
G. L. Dunford R1-51
D. R. Ellingson R3-09
G. L. Jones R3-02
D. E. McKenney R2-11
J. J. Zimmer R2-05
~~BLJ File~~/LB

Reference: (1) Internal Memo, L.A. Mihalik to J.N. Appel, "Future Aging Waste Tank Operations (No N-Reactor Case)," March 29, 1988.

(2) Internal Memo, B. L. Jones to R. M. Marusich, "101-AZ Tank Bump and Associated Release Calculation," September 1, 1987.

(3) RHO-LD-171, G.D. Campbell, "Heat Transfer Analysis for IN Situ Disposal of Nuclear Wastes in Single- and Double- Shell Underground storage Tanks," October, 1981.

This memo provides an evaluation of the effect of varying thermodynamic properties on heat build-up in the settled solids and also evaluates a tank bump scenario where the airlift circulators (ALC's) are operational but all the heat generating solids are assumed to be settled. The two cases incorporate the effects of N-reactor shutting down.

INTRODUCTION

The thermodynamic properties of aging waste solids have been difficult to measure in the past due to small sample sizes and large radiation fields. The values used today are based on analyses of simulated aging waste and similar waste types (Reference 3). The thermal conductivity, heat capacity and volume were determined to be the least known and potentially the most important variables in calculating the solids temperature profile and resulting tank bump potential. The tank bump phenomenon is defined as the result of aging waste solids settling and heating to a sufficient temperature that, upon resuspension, they cause a vapor generation rate great enough to overwhelm the ventilation system.

To achieve a tank bump from super-heated solids, it is required that a sufficient solids mass and heat generation rate be present to obtain a minimum of 20,000,000 BTU stored heat in excess of heat necessary to bring the tank supernatant to boiling (Reference 2). The 20 million BTU stored heat is the minimum heat required to pressurize a typical aging waste double wall tank (AZ or AY).

In Case 1, the volume and thermodynamic properties of the solids are varied to evaluate the heat stored in the settled solids as a function of time after the ALC's have stopped. A best case, worst case and control case using selected values of solids volumes and thermodynamic properties were then evaluated to determine the time required to achieve a tank bump potential. The worst case value for a thermodynamic property is one that would produce a tank bump in the shortest amount of ALC downtime. The opposite is true for the best case value. The control case uses the best estimate of the solids volume and thermodynamic properties. The Case 1 parameters are stated below.

CASE 1. THERMAL CONDUCTIVITY AND HEAT CAPACITY SENSITIVITY EVALUATION.

TOTAL HEAT LOAD ..... 690,000 BTU/Hr (Reference 1)
SOLIDS HEAT LOAD ..... 610,000 BTU/Hr (Reference 1)
SOLIDS DEPOSITION ..... 10 - 30% (HOT SOLIDS) PLUS 10" (COLD SOLIDS)
AIRLIFT CIRCULATORS ..... FAILURE AT TIME ZERO
THERMAL CONDUCTIVITY .... 0.1 - 1.0 BTU/hr.FT.^{o}F
HEAT CAPACITY ..... 0.1 - 1.0 BTU/lbm.^{o}F
DESIRED RESULTS ..... EFFECT OF THERMAL CONDUCTIVITY CHANGES
..... EFFECT OF HEAT CAPACITY CHANGES
..... BEST CASE TANK BUMP
..... WORST CASE TANK BUMP
..... CONTROL CASE TANK BUMP

Case 2 examines the scenario of a tank containing the maximum projected heat load (Tank 102-AZ with all remaining weapons grade fuel processed - Reference 1). The heat generating solids are assumed to be settled, even though the ALC's are in operation. The potentials for a tank bump and exceeding the tank structural temperature limits are evaluated. The Case 2 parameters are stated on the following page.

CASE 2. TANK BUMP EVALUATION UNDER NORMAL OPERATIONS.

TOTAL HEAT LOAD ..... 690,000 BTU/Hr (Reference 1)
SOLIDS HEAT LOAD ..... 610,000 BTU/Hr (Reference 1)
SOLIDS DEPOSITION ..... 26" (HOT SOLIDS) PLUS 10" (COLD SOLIDS)
AIRLIFT CIRCULATORS ..... OPERATING
DESIRED RESULTS ..... AVERAGE SOLIDS TEMPERATURE
..... MAXIMUM SOLIDS TEMPERATURE
..... EXPECTED THERMOCOUPLE READING

* - A complete list of material characteristics are outlined in the HEATING5 INPUTS AND ASSUMPTIONS section.

RESULTS/CONCLUSIONS

The ALC downtime needed to produce a potential tank bump is relatively insensitive to the solids thermal conductivity and heat capacity. The solids thermal conductivity was varied from 0.1 to 1.0 BTU/hr.Ft.^{o}F while the heat capacity was held constant at 0.3 BTU/lbm.^{o}F. Varying the thermal conductivity resulted in a two hour difference in ALC downtime to obtain a potential tank bump (Attachment 1). The solids heat capacity was also varied from 0.1 to 1.0 BTU/lbm.^{o}F while the solids thermal conductivity was held constant at 1.0 BTU/hr.Ft.^{o}F. The results showed a 25 hour difference in ALC downtime to obtain a potential tank bump (Attachment 2). The reason for this insensitivity is because the exchange of heat between solids and supernatant has little effect on the estimate of steam generated by the heat stored in the combined solids and supernate. The only reason for a difference in the time to achieve a tank bump is due to the heat lost through the tank bottom and walls. Therefore exact thermodynamic values are not needed for the type of tank bump scenarios used in this evaluation. The thermodynamic property information gathered from Case I is used as well as varying the solids volume and the initial liquid temperature to develop the best, worst and control case scenarios (Attachment 3). The ALC downtime required to achieve the potential for a tank bump is more distinguishable for the best, worst and control cases, Attachment 3, but can be attributed to the variation in solids volume and initial supernatant temperatures.

Case 2 is a control case prediction of the solids and knuckle temperature during the fill cycle of tank 102-AZ, which is currently projected to be the aging waste tank that will have the highest heat load. The ALC are assumed to be operating but all the heat generating solids are settled. This temperature projection represents the worst case scenario under a "normal" operating condition. The results of the evaluation showed that the aging waste solids did not reach a sufficient temperature to produce the potential for a tank bump (780 ^{o}F avg assuming all solids resuspend, Appendix A) and the knuckle temperature

did not exceed structural limits of 380 F (Attachment 4). The evaluation was calculated using the control case solids thermal conductivity (1.0 BTU/hr.Ft.^{o}F) and heat capacity (0.3 BTU/lbm.^{o}F). The settled solids volume was assumed to be 10% by volume with a 10 inch cold solids heel. The supernatant temperature was varied from 160 F to 190 F. The limit of 190 F was chosen because it is the highest supernatant temperature observed from past aging waste tanks with a similar heat load. The reason for the tank to only reach a maximum temperature 190 ^{o}F in the supernatant is due to the evaporative cooling from ALC operation. If the heat capacity is substantially lower, the solids temperature could increase to a point where the structural limit is a concern. TFPTS recommends that the thermodynamic properties be evaluated from synthetic NCAW solids and the results verified from analysis of the aging waste core sample expected in late FY 1988.

HEATING5 INPUTS AND ASSUMPTIONS

This section covers the inputs to HEATING5 that were used in the original aging waste tank bump analysis (Reference 2). The inputs are grouped into pertinent sections and discussed in some detail.

TANK MODEL GEOMETRY

The tank geometry was input into the HEATING5 computer code as radial and axial coordinates. Aging waste tanks in AY and AZ tank farm are used as the model. This included the primary tank, annulus tank, wall concrete, floor concrete and thermal concrete. The waste volumes include 10 inches of cold solids, variable new solids (10 to 30% by volume) and 661,000 to 858,000 gallons of liquid waste.

MATERIAL CHARACTERISTICS

The materials used in the conduction problem are listed with their thermal conductivity, specific heat, and density. The solids thermal conductivity and heat capacity are the only questionable input. The thermal conductivity will be in the range of 0.1 to 1.0 BTU/hr.ft.^{o}F. and the heat capacity will be in the range of 0.1 to 1.0 BTU/lbm.^{o}F The completed list of material input characteristics are given on the following page (Reference 3).

Material	Thermal Conductivity (BTU/hr.Ft.^{o}F)	Specific Heat (BTU/lb.^{o}F)	Density (lb/Ft^3)
Concrete	.54	.21	144.0
Hot Solids	0.1 to 1.0	0.1 to 1.0	103.0
Cold Solids	0.1 to 1.0	0.1 to 1.0	103.0
Soil	.25	.22	113.0
Insulating Concrete	.11	.20	62.0
Air	.016	.24	.071
Supernate	.392	1.0	62.4

BOUNDARY CONDITIONS

The boundary conditions were selected based on geological data and conservative assumptions. The boundary conditions for the double-shell tank model are listed below:

1) A 70 ^{o}F forced convection boundary at ground level (assumed).

2) A 55 ^{o}F constant temperature boundary at a depth of 200 feet. This is due to the water table which runs at a constant 55 ^{o}F (actual geological data).

3) A 70 ^{o}F adiabatic boundary at 50 feet radially. This assumption simulates a tank in the middle of a large array of tanks, all generating the same amount of heat.

4)* The liquid-solid interface is initially assumed to be at a temperature of 190 ^{o}F and is raised by tracking the heat balance and assuming that the total heat generated is stored in the solids and liquid (no loss to the environment). The temperature of the liquid is allowed to increase until it reaches the boiling point where it remains constant for the duration of the solids heat-up. This is the only means for HEATING5 to raise the liquid temperature uniformly (no stratification). This is a conservative assumption since some heat will always be lost to the environment.

* This assumption was not used for Attachment 4 and the worst case scenario of Attachment 3. Attachment 4 assumes a supernatant

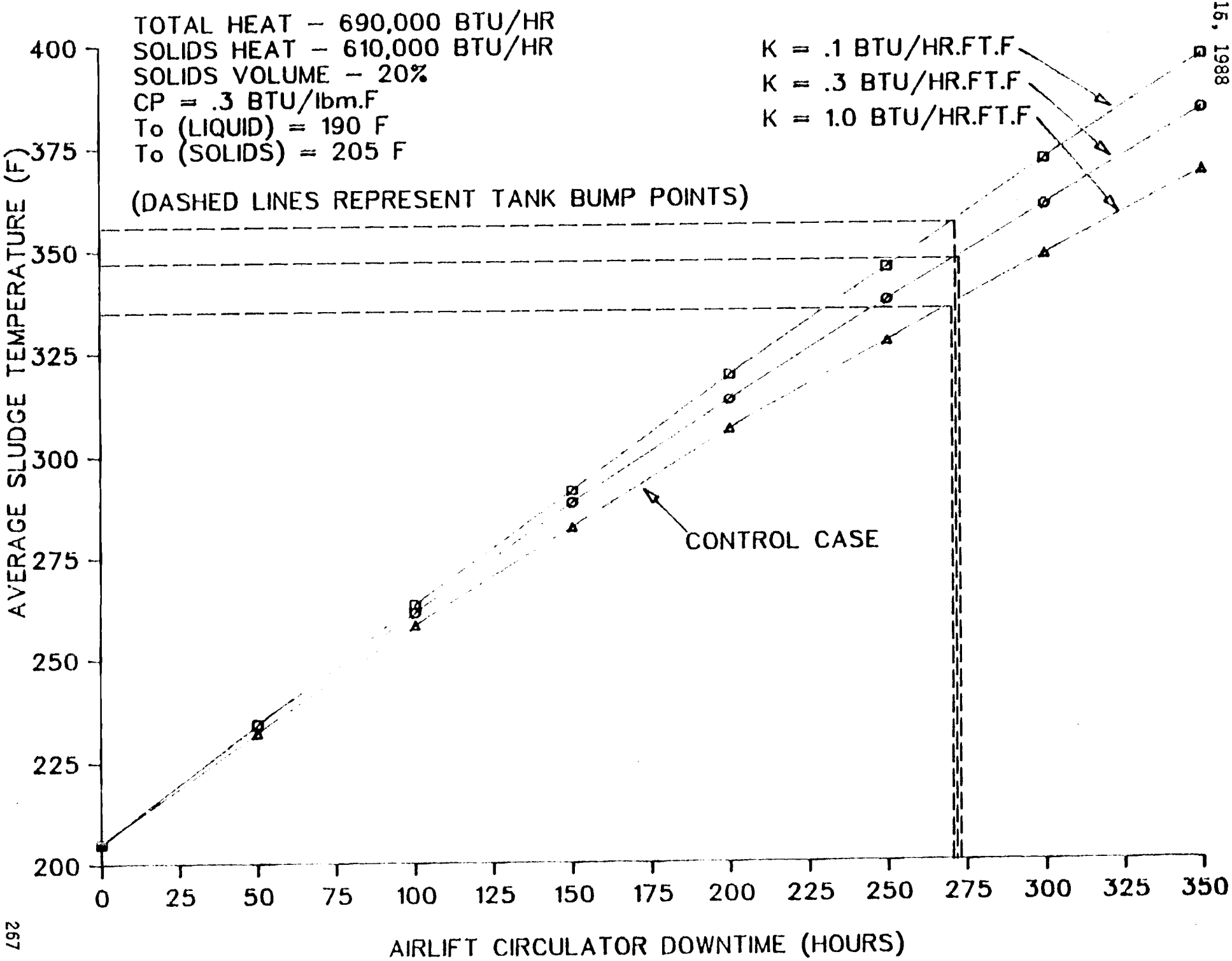
temperature increase similar to past aging waste tanks with similar heat loads (Tank 101-AZ). The maximum supernatant temperature in tank 101-AZ (190 ^{o}F) is due to the evaporative cooling from ALC operation. The worst case scenario of Attachment 3 is assumed to begin at the boiling temperature, therefore a supernatant temperature increase function is not needed.

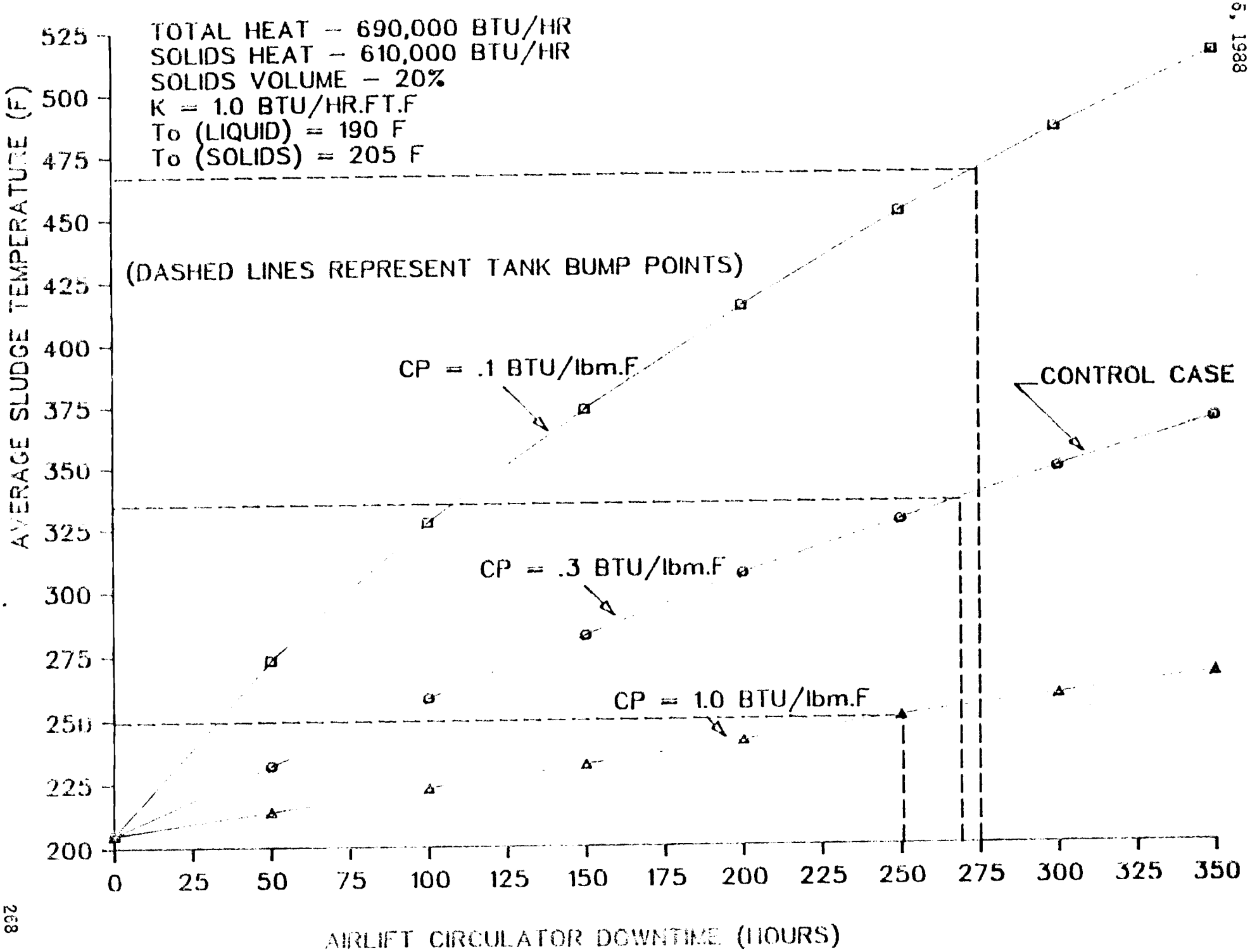
B. L. Jones, Engineer
Tank Farm Process Technology Section

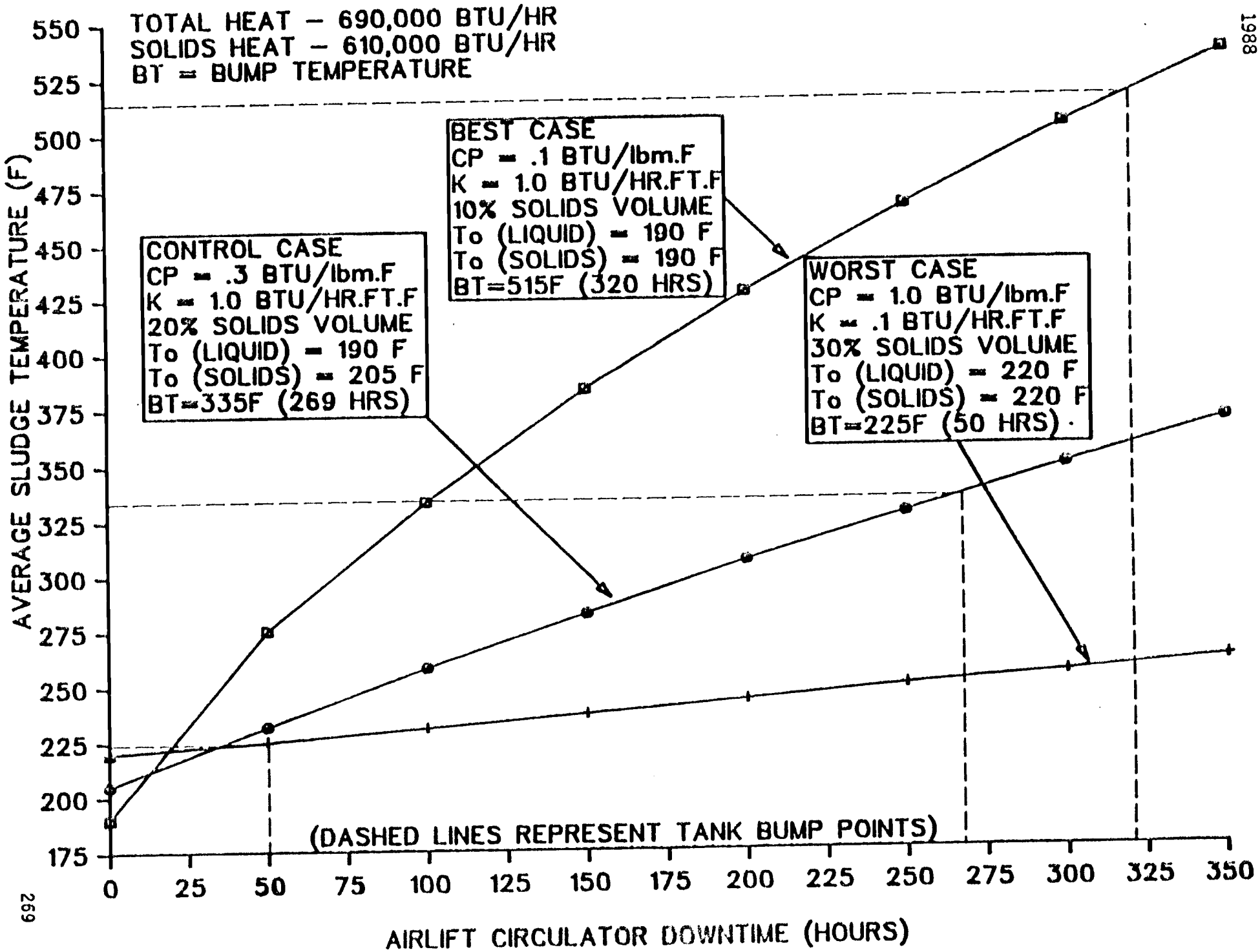
kjr

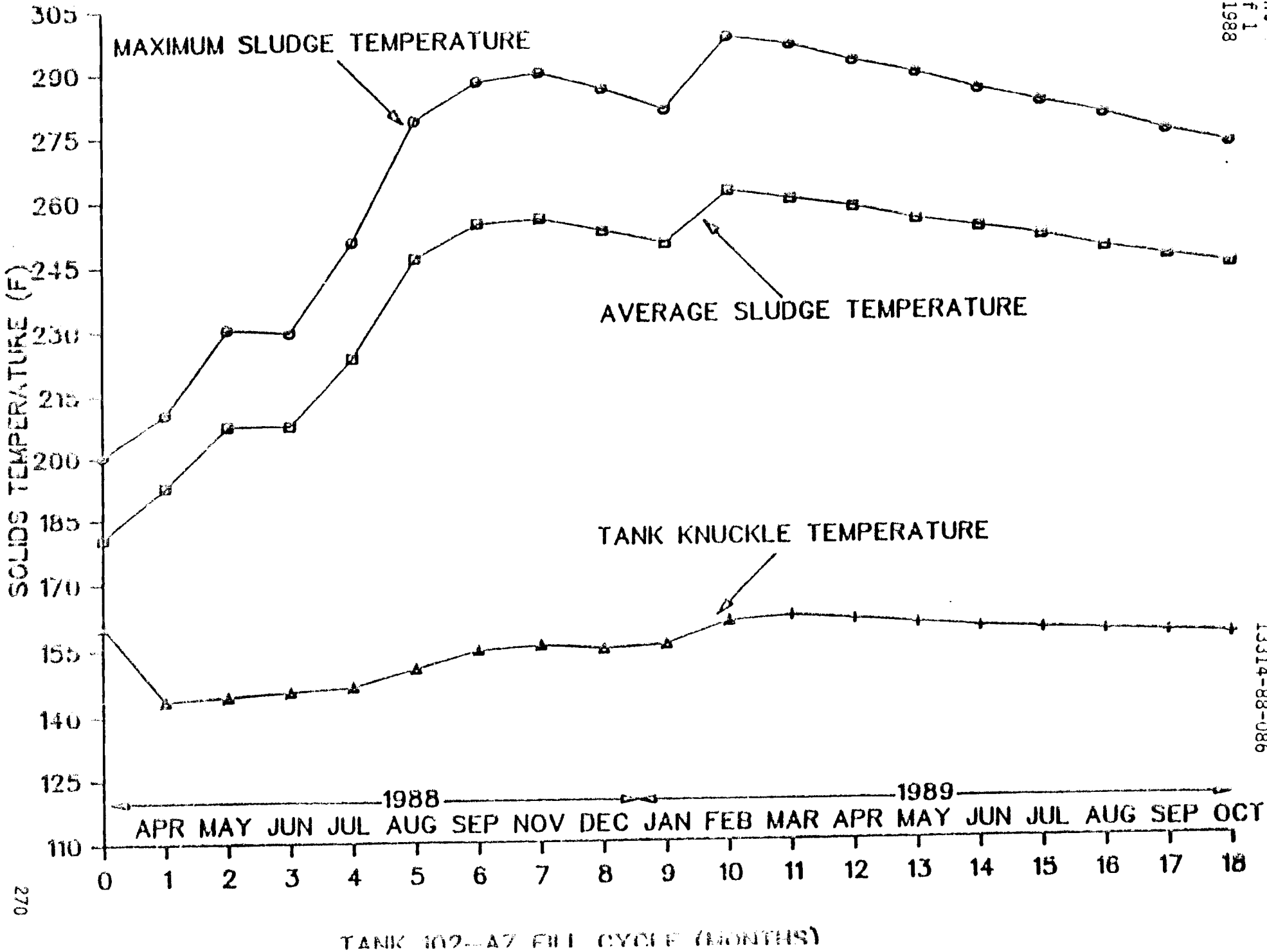
Attachments 4

ATTACHMENTS


TOTAL HEAT – 690,000 BTU/HR
SOLIDS HEAT – 610,000 BTU/HR
SOLIDS VOLUME – 20%
CP = .3 BTU/lbm.F
To (LIQUID) = 190 F
To (SOLIDS) = 205 F
(DASHED LINES REPRESENT TANK BUMP POINTS)
K = .1 BTU/HR.FT.F
K = .3 BTU/HR.FT.F
K = 1.0 BTU/HR.FT.F
CONTROL CASE
AVERAGE SLUDGE TEMPERATURE (F)
400
375
350
325
300
275
250
225
200
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
AIRLIFT CIRCULATOR DOWNTIME (HOURS)


TOTAL HEAT – 690,000 BTU/HR
SOLIDS HEAT – 610,000 BTU/HR
SOLIDS VOLUME – 20%
K = 1.0 BTU/HR.FT.F
To (LIQUID) = 190 F
To (SOLIDS) = 205 F
(DASHED LINES REPRESENT TANK BUMP POINTS)
CP = .1 BTU/lbm.F
CP = .3 BTU/lbm.F
CP = 1.0 BTU/lbm.F
CONTROL CASE
AVERAGE SLUDGE TEMPERATURE (F)
525
500
475
450
425
400
375
350
325
300
275
250
225
200
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
AIRLIFT CIRCULATOR DOWNTIME (HOURS)


TOTAL HEAT – 690,000 BTU/HR
SOLIDS HEAT – 610,000 BTU/HR
BT = BUMP TEMPERATURE
CONTROL CASE
CP = .3 BTU/lbm.F
K = 1.0 BTU/HR.FT.F
20% SOLIDS VOLUME
To (LIQUID) = 190 F
To (SOLIDS) = 205 F
BT=335F (269 HRS)
BEST CASE
CP = .1 BTU/lbm.F
K = 1.0 BTU/HR.FT.F
10% SOLIDS VOLUME
To (LIQUID) = 190 F
To (SOLIDS) = 190 F
BT=515F (320 HRS)
WORST CASE
CP = 1.0 BTU/lbm.F
K = .1 BTU/HR.FT.F
30% SOLIDS VOLUME
To (LIQUID) = 220 F
To (SOLIDS) = 220 F
BT=225F (50 HRS)
(DASHED LINES REPRESENT TANK BUMP POINTS)
AVERAGE SLUDGE TEMPERATURE (F)
AIRLIFT CIRCULATOR DOWNTIME (HOURS)
550
525
500
475
450
425
400
375
350
325
300
275
250
225
200
175
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350


MAXIMUM SLUDGE TEMPERATURE
AVERAGE SLUDGE TEMPERATURE
TANK KNUCKLE TEMPERATURE
SOLIDS TEMPERATURE (F)
305
290
275
260
245
230
215
200
185
170
155
140
125
110
1988
1989
APR MAY JUN JUL AUG SEP NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
TANK 102-AZ FILL CYCLE (MONTHS)

APPENDIX A

Solids Temperature Calculation to Achieve a Potential Tank Bump

To achieve a tank bump the supernatant must reach the boiling temperature of 220 °F plus an additional 20 million BTU's of heat stored in the solids (Reference 2) to vaporize enough liquid to overwhelm the ventilation system. The following calculations represent the minimum required temperature in the solids to raise the supernatant from 190 °F to 220 °F plus an additional 20 million BTU's stored heat.

Nomenclature:

QL = Heat in the liquid.
ML = Mass of the liquid.
CpL= Heat capacity of the liquid
TL = Liquid temperature change

QS = Heat in the solids
MS = Mass of the solids
CpS= Heat capacity of the solids
TS = Solids temperature change

ASSUMPTIONS:

* 26" heat generating solids and 10" cold solids.
* Initial temperature of the supernatant is 190 °F.
* 322" of supernatant in the tank.

1) The heat required to raise the supernatant 30 °F ...

$C_{pL} = 1.0\ BTU/lbm\,°F \quad \Delta T_L = 30°F \quad \rho_L = 62.4\ lbm/FT^3$

$$M_L = [322\ IN]\left[\frac{2750\ GAL}{IN}\right]\left[\frac{FT^3}{7.4805\ GAL}\right]\left[\frac{62.4\ lbm}{FT^3}\right] = 7{,}386{,}565\ lbm$$

$$Q_L = (M_L)(C_{pL})(\Delta T_L) = [7{,}386{,}565\ lbm]\left[1.0\ \frac{BTU}{lbm\,°F}\right][30°F] = \underline{221{,}596{,}952\ BTU}$$

2) Required heat stored to achieve a potential tank bump ...

$$Q_S = Q_L + 20\ MBTU's$$

$$Q_S = 221{,}596{,}952 + 20{,}000{,}000 = 241{,}596{,}952\ BTU$$

3) Required solids temperature to achieve a potential tank bump ...

$C_{pS} = 0.3\ BTU/lbm\,°F \quad \rho_S = 103\ lbm/FT^3$ Temperature of solids 190°F (min.)

$$M_S = [36\ IN]\left[\frac{2750\ GAL}{IN}\right]\left[\frac{FT^3}{7.4805\ GAL}\right]\left[\frac{103\ lbm}{FT^3}\right] = 1{,}363{,}144\ lbm$$

$$Q_S = (M_S)(C_{pS})(\Delta T_S) = 241{,}596{,}952\ BTU = [1{,}363{,}144\ lbm]\left[0.3\ \frac{BTU}{lbm\,°F}\right][\Delta T_S]$$

$$\Delta T_S = \frac{241{,}596{,}952\ BTU}{[1{,}363{,}144\ lbm]\left[0.3\ \frac{BTU}{lbm\,°F}\right]} = \underline{590\ °F}$$

REQUIRED SOLIDS TEMPERATURE IS 190 °F + 590 °F

$$\boxed{780°F}$$

Project 14217
REVIEW OF TANK HEATING ANALYSES
Final Letter Report

INDEPENDENT REVIEW OF AGING WASTE TANK "BUMP" ANALYSES

William L. Kuhn

May 18, 1988

Prepared for the
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Westinghouse Hanford Company
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

TABLE OF CONTENTS

CONCLUSIONS 1

INTRODUCTION 3

NOMINAL TANK BUMP SCENARIO 4
NOMINAL CONDITIONS 4
SIMPLE HEAT BALANCE 5
EFFECT OF LARGER HEATING RATE 7
ANALYSIS OF FUNCTIONAL FORM FOR RATE OF RESUSPENSION OF SLUDGE 8
Figure 1. NEGATIVE EXPONENTIAL FUNCTION FOR RESUSPENSION OF SLUDGE 10

CONSERVATISM IN ANALYZING ROLLOVER OF SUPERHEATED LIQUID 11
STABILITY OF TEMPERATURE PROFILE 11
GROWTH OF NATURAL CONVECTION CELLS 12

ANALYSIS OF QUIESCENT SOLID/LIQUID CONDUCTION 14
MATHEMATICAL ANALYSIS 14
CALCULATION OF TEMPERATURES AND HEAT ADDITION 16
Figure 2. TEMPERATURE RISE AT MIDPLANE OF SLUDGE 18
Figure 3. TEMPERATURE RISE PROFILES: CASE 4 19
Figure 4. TEMPERATURE RISE PROFILES: CASE 4 20
Figure 5. EFFECT OF THERMAL CONDUCTIVITY ON 300 HR PROFILE 21
Figure 6. HEAT CONDUCTED INTO QUIESCENT LIQUID 22
DISCUSSION OF EFFECTS OF THERMOPHYSICAL PROPERTIES OF SLUDGE 23
EFFECT OF BOILING AT SURFACE OF SLUDGE 23
EFFECT OF INCREASED TOTAL HEATING RATE 26
EFFECT OF PERMANENT LAYER OF SOLIDS 27

SETTLING OF SLURRY SOLIDS 28
ASSUMED PARTICLE SIZE DISTRIBUTION 28
SETTLING OF MULTISIZED PARTICLE SUSPENSIONS 29
RESULTS OF SETTLING CALCULATIONS 31
DEPOSITION OF HEAT FROM SETTLING PARTICLES 31
Figure 7. ASSUMED LOG NORMAL PARTICLE SIZE DISTRIBUTION 32
Figure 8. PARTICLE VELOCITIES RELATIVE TO FLUID 33
CONDUCTION OF HEAT FROM ACCUMULATING SLUDGE DURING SETTLING 34
Figure 9. SETTLING RATE OF SLURRY 35
Figure 10. HEAT DEPOSITED IN LIQUID BY SOLIDS DURING SETTLING 36

APPENDIX A. FUNCTIONAL FORMS FOR RATE OF RESUSPENSION OF SLUDGE 39

APPENDIX B. APPROXIMATE ANALYTICAL EXPRESSION FOR CONDUCTION BETWEEN SLUDGE AND SUPERNATE 43

TABLES OF NUMERICAL RESULTS
Table 1. Results of Conduction Calculations: Case 1 47
Table 2. Results of Conduction Calculations: Case 2 49
Table 3. Results of Conduction Calculations: Case 3 51
Table 4. Results of Conduction Calculations: Case 4 53
Table 5. Results of Conduction Calculations: Case 5 55
Table 6. Results of Conduction Calculations: Case 6 57
Table 7. Results of Settling Calculations, zones 59
Table 8. Results of Settling Calculations, particles 60

CONCLUSIONS

1. Small temperature differences (e.g., 1°F) between the free surface and the bulk of the slurry are expected to result in natural convection. Because of evaporative cooling at the free surface, such temperature differences would occur if the slurry were ever quiescent. That is, natural convection would result from an initially stratified temperature distribution at the top of the supernate, thereby preventing the continuation of such stratification.

   Liq. stratification does not occur

2. Solids initially suspended are expected to be in the 1 to 100 micron size range. The settling rates of a slurry in this particle size range are so slow that velocities as small as 0.01 ft/sec caused by natural convection may prevent settling of most of the solids.

3. At a 690,000 BTU/hr total heat generation rate, about 300 hours is needed to add the 230 million BTU needed to raise the mixed tank contents 30°F to the atmospheric boiling point.

4. If settling of solids upon loss of air lift circulator operation is assumed, then it is conservative to assume that none of the solids are initially settled. If some solids are assumed to be permanently settled, then the conduction of heat generated within permanently settled solids to resuspendable solids is less important than the fact that only the energy stored in resuspendable solids can be mixed into the supernate.

5. If settling of all or part of the solids is assumed, the amount of steam generated during pressurization of a waste tank during a tank "bump" does not depend strongly on the functional form assumed for the rate of resuspension of sludge, since the amount is controlled mainly by a simple heat balance over the total volume of sludge resuspended. However, the rate of generation of steam would be sensitive to the functional form.

6. If *both* instantaneous settling of sludge *and* subsequent thermal stratification of supernate are assumed, then, for the 690,000 BTU/hr case, conduction of heat from sludge to the supernate would cause the supernate to boil at the interface with the sludge before more than about 15 million BTU are stored in stratified supernate. The consequences of increasing the total heating rate above 690,000 BTU/hr may not be important, since the onset of boiling at the surface of settled sludge will cause release of about the same amount of stored energy at the time it occurs irrespective of the heating rate. Also, higher heating rates might prevent settling at all due to boiling convection in the initial slurry.

7. Any natural convection in supernate initially stratified at the interface with the sludge is expected to grow upward and involve all of the supernate.

8. From 2% to 23% of the heat stored could be stored in thermally stratified supernate, depending on the thermophysical properties of the sludge.

9. The combined heat deposited by settling solids and conducted out of the accumulating sludge during settling are estimated; the consequences are found to be controlled by the boiling point at the sludge/supernate interface, similar to the situation for conduction from an instantaneously settled sludge.

10. The sensitivity of conducted heat stored in stratified supernate is not very sensitive to the thermophysical properties of the sludge. The effect of the properties on the total energy stored is smaller still.

INTRODUCTION

The U.S. Department of Energy (DOE) is storing certain high-level waste, termed "aging waste," in underground storage tanks at Hanford. The tanks are managed for DOE by the Westinghouse Hanford Company (WHC). The waste is in the form of a slurry (primarily iron oxides, on the order of 10-20 vol%) in a concentrated salt solution (primarily sodium salts, up to about 5M). The slurry is normally agitated by 22 airlift circulators; this agitation is assumed to help keep solids suspended in the supernate. Both the solids and supernate include radionuclides that generate heat, with the majority of the heat generated in the solids. The heat is normally expelled largely by evaporative cooling into air passed through the slurry by the airlift circulators.

One concern regarding the storage of the waste is the possibility that interruption of operation of the airlift circulators will allow suspended solids to settle; in this case heat would be no longer expelled by evaporative cooling. This could allow thermal energy to be stored in settled solids and in the supernate, *assuming* that the contents of the tank somehow become quiescent. Presumably the stored energy could be released suddenly, for example upon resumption of operation of the airlift circulators. This, in turn, could result in a sudden generation of steam that exceeds the capacity of condensers in tank vent systems.

A sudden generation of steam caused by release of stored thermal energy has been termed a "tank bump," and is believed to have occurred in the past, although not necessary because of the thermophysical processes considered here. A reevaluation of tank bump scenarios was requested in support of revision of a Safety Analysis Report for aging waste storage tanks. In response to this, WHC staff completed an internal report[(a)] on the subject. WHC requested[(b)] subsequently that Pacific Northwest Laboratory provide an independent review of this work. The purpose of this report is to provide and document that review.

(a) Internal letter, B. L. Jones to R. M. Marusich, "Tank Bump and Associated Release Calculation," No. 65611-87-086, dated May 6, 1987.
(b) Letter, G. L. Borsheim to W. L. Kuhn, "Independent Review of Aging Tank 'Bump' Analyses," dated February 12, 1988.

NOMINAL TANK BUMP SCENARIO

The emphasis of this report is to review calculations pertinent to a nominal tank bump as described by Jones[a]. To this end one can consider a number of constraints or basic relationships related to phenomena that would occur during steam generation in a tank, as discussed below.

NOMINAL CONDITIONS

Except where noted, we assume all solids are initially suspended. The basic conditions are assumed to be:

- During uninterrupted operation, slurry in a waste tank is both perfectly mixed and evaporatively cooled by 22 airlift circulators (ALC's).
- The cross-sectional area at the bottom of the slurry is 2750 gal/in[b], or 4411.46 ft^2[c].
- The depth of the slurry is 30 ft[d] and the solids loading is 10 vol%[d], so that when settled the solids form a layer 3 ft thick. Hence, the volume of solids is 4411.46 ft^2 x 3 ft = 13234 ft^3, and the volume of supernate is 4411.46 ft^2 x (30 - 3) ft = 119109 ft^3.

Since the partial pressure of steam in the tank plenum cannot exceed the ambient tank pressure (i.e., cannot pressurize the tank) until the temperature of the slurry reaches at least its atmospheric boiling point, it is important to consider how much heat must be added to attain this point and how fast this point is attained. The nominal case considered in this report is:

- The total heat generation rate is 690,000 BTU/hr, with 610,000 BTU/hr generated by slurry solids and the balance by the supernate[e].

(a) Internal letter, B. L. Jones to R. M. Marusich, "Tank Bump and Associated Release Calculation," No. 65611-87-086, dated May 6, 1987.
(b) Appendix A of Westinghouse internal report No. 65661-87-086
(c) (2750 gal/in)(231 in^3/gal)/(144 in^2/ft^2) = 4411.46 ft^2
(d) Informal discussion with Westinghouse staff
(e) Originally specified as 4×10^6 BTU/hr; changed to the values cited during informal discussions with Westinghouse staff during the course of this work

- The evaporative cooling caused by the air sparge of the ALC's will maintain the slurry temperature at about 30°F below its atmospheric boiling point of 220°F[a].
- The density of the solids is assumed to be 103 lb/ft^3[b].
- The heat capacity (specific heat) of the solids is 0.3 BTU/lb/°F[b]; this value is varied in part of this report to determine its effect on the results of certain calculations.
- The density of the supernate is approximated to be that of water, 62.37 lb/ft^3, and similarly the heat capacity of the supernate is approximated to be 1 BTU/lb/°F.

Consequently, the masses of solids and supernate in the tank are

$$\text{Solids:} \quad (103\ lb/ft^3)(13234\ ft^3) = 1.363\times10^6\ lb$$
$$\text{Liquid:} \quad (62.37\ lb/ft^3)(119109\ ft^3) = 7.242\times10^6\ lb$$

SIMPLE HEAT BALANCE

The principal constraint on the amount of steam generated is the amount of heat that must be added to generate it. Starting from the moment the ALC's stop, the heat required to raise the temperature of the mixed tank contents 1°F is

$$(1.363\times10^6\ lb)(0.3\ BTU/lb/°F) + (7.242\times10^6\ lb)(1\ BTU/lb/°F) = 7.65\times10^6\ BTU/°F$$

Therefore, in order to raise the temperature of the mixed tank contents 30°F to its atmospheric boiling point, $(7.65\times10^6\ BTU/°F)(30°F) = 2.3\times10^8$ BTU must be added. The time required to do this if the tank were adiabatic would be $(2.3\times10^8\ BTU)/(6.9\times10^5\ BTU/hr) = 333$ hrs. However, the tank will not be adiabatic, with some heat being lost by conduction through the boundaries of the tank, and hence the actual time required to attain boiling (which would

(a) Informal discussion with Westinghouse staff
(b) G. D. Campbell, "Heat Transfer Analysis for In Situ Disposal of Nuclear Wastes in Single- and Double-Shell Underground Storage Tanks," RHO-LD-171, Rockwell Hanford Operations, October 1981, Table 2.

occur first at the top of the supernate) would be something greater than, but on the order of, 333 hours.

LIKELIHOOD OF NATURAL CONVECTION

If the temperature in the tank is uniform at the moment operation of the ALC's ceases and then we imagine that all convection suddenly stops, a return of convection driven by temperature differences would be expected. From the above analysis, the temperature in a quiescent slurry would rise at the rate

$$(690{,}000\ \text{BTU/hr})/(7.55\times10^{6}\ \text{BTU/°F}) = 0.09\ \text{°F/hr}$$

More importantly, the temperature at the top of the slurry would decrease because of evaporative cooling at its surface, and because with the assumed quiescence there would be no mixing with hotter supernate from below. The resulting temperature difference, even if very small, could cause natural convection in the tank.

Correlations for steady-state laminar natural convection occurring from horizontal surfaces[(a)] have been developed for Grashof numbers in the range 10^4 to 10^7. The Grashof number is a dimensionless group used to correlate the intensity of natural convection, and has the form[(b)]

$$Gr = (L^3\ g\ \beta\ \Delta T\ \rho^2)/\mu^2$$

where L is a characteristic length (for the correlation cited above, it is the area of the surface divided by its perimeter), g is the acceleration of gravity (32.17 ft/sec^2), β is the bulk expansion coefficient (in this case about 3.7×10^{-4}/°F)[(c)], ΔT is a characteristic temperature difference (°F) (in

(a) Kays, W. M., and M. E. Crawford, Convective Heat and Mass Transfer, 2nd Ed., McGraw-Hill, New York (1980) p. 328 (reference to work of Lloyd, J. R., and W. R. Moran, J. Heat Transfer, 96, 443 (1974))
(b) Bird, R .B., W. E. Stewart, and E. N. Lightfoot, Transport Phenomena, John Wiley & Sons, New York (1960) Equation 9.9-17
(c) Inferred from variations of 30 w% sodium nitrate solution with temperature (see Perry, J. H., Chemical Engineers' Handbook, 4th Edition, McGraw-Hill, New York (1963) p. 3-77, Table 3-110)

this case the difference between the temperature at the surface and the temperature of the bulk fluid), ρ is the density of the fluid (assuming a specific gravity of 1.2, it is 1.2 x 62.37 lb/ft^3 = 74.8 lb/ft^3), and μ is the viscosity of the fluid (assumed to be about that of water, or 6.7×10^{-4} lb/ft-sec). The relevant surface in our case is the top surface of the slurry. Since it is a circle 75 ft. in diameter (D), the ratio of area to perimeter is $(\pi D/)^2/(\pi D) = D/4$, = (75 ft)/4 = 18.75 ft. Substituting this for L in the Grashof number, and assuming for reference a 1°F temperature difference, the Grashof number is found to be

$$(18.75\ ft)^3(32.17\ ft/sec^2)(3.7\times10^{-4}/°F)(1°F)(74.8\ lb/ft^3)^2 / (6.7\times10^{-4}\ lb/ft\text{-}sec)^2 \approx 10^{12}$$

This result is 5 orders of magnitude beyond the range (10^4 to 10^7) for which laminar natural convection is expected at a horizontal surface. Therefore, even for the assumed 1°F temperature difference, initially quiescent tank contents would lapse into turbulent natural convection. Moreover, since the ALC's would cause the tank contents to be in motion initially, the large Grashof number suggests that the contents would not become quiescent.

EFFECT OF LARGER HEATING RATE

The time required to attain boiling in a mixed tank depends strongly on the heating rate. There is roughly an inverse relation between time to reach boiling and the heating rate for a given required temperature rise. If the heating rate is greater, the initial temperature, established by evaporation during operation of the ALC's, would be closer to the atmospheric boiling point, so that the temperature rise required to reach boiling would depend on the heating rate.

For some value of heat generation rate, the tank contents would be boiling even during operation of the ALC's. When the contents are initially at the atmospheric boiling point, any addition of heat not lost by conduction out of the tank would result in an equivalent amount of steam.

As discussed below, if boiling occurs even during evaporative cooling by the ALC's, then the boiling convection could likely prevent settling of initially suspended solids from occurring at all. Or, if the temperature is kept just below the atmospheric boiling point, the time to attain boiling at the local hydrostatic head at the surface of settled sludge would be reduced, preventing the supernate from remaining quiescent.

Therefore, an increased rate of heat generation may reduce the chance of a tank bump by reducing the chance that solids will settle.

ANALYSIS OF FUNCTIONAL FORM FOR RATE OF RESUSPENSION OF SLUDGE

An analysis of the consequences of assuming different functional forms for the rate of resuspension of sludge suggests that the form may not be important to the amount of steam generated.

Recent calculations by Westinghouse staff[(a)] have been based on the assumption of a resuspension time on the order of 8 hours, where this is the time constant in a negative exponential function describing the rate of resuspension of sludge:

$$\text{Rate} = R_o \exp(- t/t_o)$$

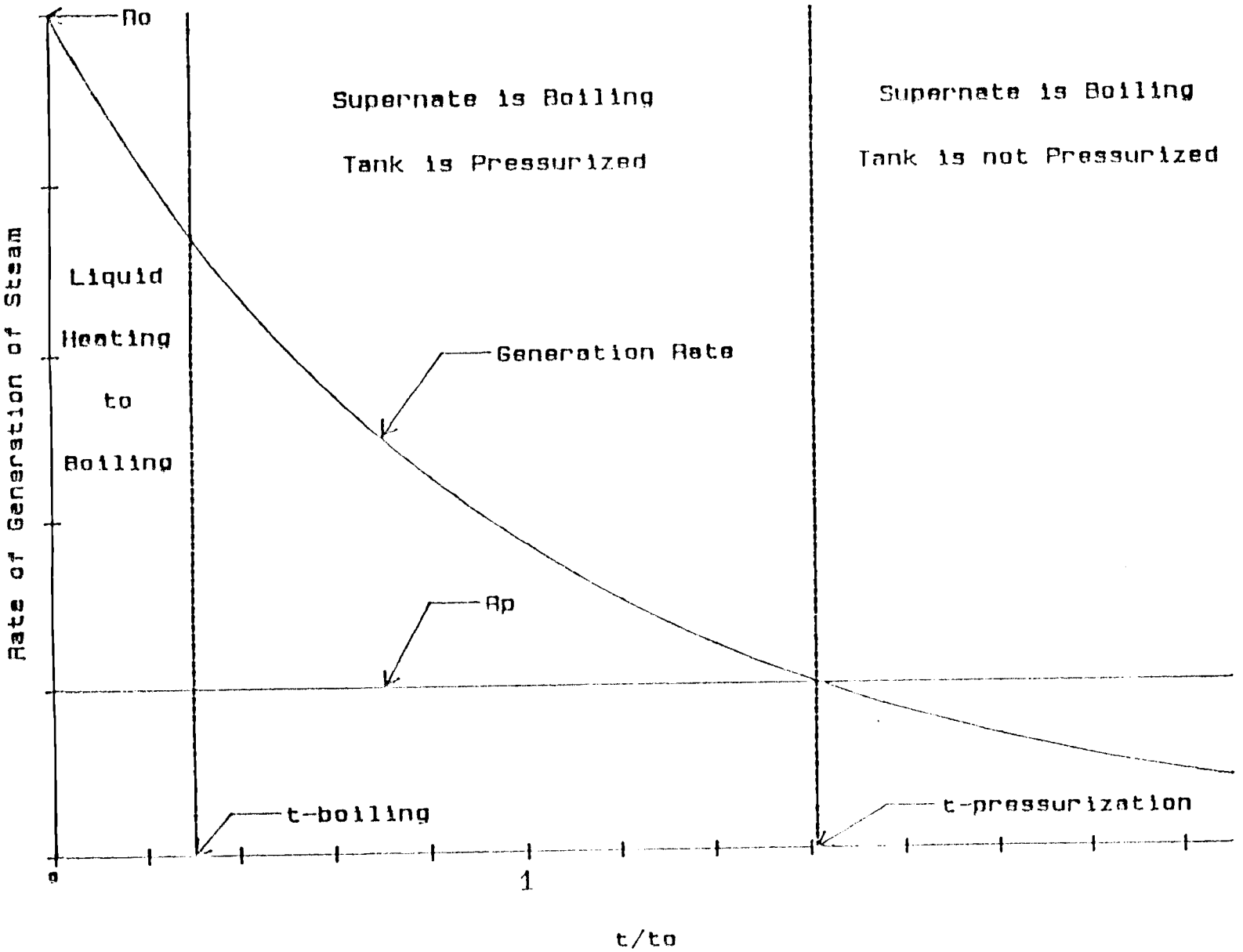
where R_o is the initial rate, ft^3/hr, and t_o is the time constant, hr. Figure 1 shows some of the features of this functional form, including certain times and rates discussed in Appendix A.

The importance of the value of t_o depends on the value of the rate of resuspension of sludge at which the resulting steam generation rate pressurizes the tank, R_p. The rate, which decreases with time, decreases to R_p at some time $t = t_p$. As discussed in Appendix A, so long as $t_p \gg t_o$, an estimate of the volume of steam generated while the tank is pressurized is insensitive to the value of t_o. However, the pressurization itself depends strongly on the rate of generation of steam, and hence strongly on R_o, which, for constant total volume of sludge resuspended, depends inversely on t_o.

(a) Internal Westinghouse report No. 65611-87-036, "Tank Bump and Associated Release Calculation," B. L. Jones to R. M. Marusich, dated May 6, 1987.

Therefore, the volume of steam generated during pressurization can be insensitive to t_o, but the pressure (and hence the venting velocity of the steam) during the pressurization will depend strongly on t_o.

Figure 1. NEGATIVE EXPONENTIAL FUNCTION FOR RESUSPENSION OF SLUDGE



CONSERVATISM IN ANALYZING ROLLOVER OF SUPERHEATED LIQUID

Since, if the contents of a tank remain or become well-mixed, some 300 hours are required before boiling will occur, it is important to consider how localized heating of thermally stratified supernate might occur, and what the consequences would be if by some process heated supernate moved to the surface without appreciable mixing and flashed to steam at the reduced hydrostatic head there.

If the supernate remains quiescent while being heated by thermal conduction from solids on the bottom of the tank, or by solids as they settle to the bottom, then because of the increased hydrostatic pressure at the bottom the supernate the temperature can locally increase above the boiling temperature existing at the top of the supernate. Therefore, if after such non-uniform heating, the thermally stratified supernate "rolls over," carrying the heated supernate to the surface and the cooler supernate to the bottom, then the heated supernate suddenly could be above its new local boiling point, and part of it could flash to steam.

During settling, a density profile will exist until most of the solids are settled that we assume can stabilize thermal stratification of the supernate—that is, stabilize against a temperature gradient that would otherwise cause natural convection and consequent mixing. It is also conceivable that salts dissolved from the top of the settled sludge layer as its temperature rises could cause a stabilizing density gradient, keeping the supernate quiescent. For the purposes of this report we *assume* stabilizing gradients can occur, and estimate the amount of thermal energy that could be stored in thermally stratified supernate.

STABILITY OF TEMPERATURE PROFILE

Although we assume stratification can occur, it is important to consider why it might occur to better understand how and why it could be disrupted.

Heating of a quiescent liquid from below is a classic cause of instability, where the resulting density profile—decreasing downward—causes natural convection and vertical mixing in the liquid. However, during settling of solids concentration gradients are set up where the density of

the settling slurry is greater at the bottom than the top, and where for this reason heat is deposited more at the bottom of the slurry than at the top. It is possible for the resulting density profile—increasing downward during settling—to be stabilizing, causing the fluid to remain quiescent. There is a balance between the effect of increased temperature to decrease the density (destabilizing) and the effect of increased solids volume fraction to increase the density (stabilizing) at the bottom of the supernate. The balance can be in favor of concentration gradients over temperature gradients, but not concentration gradients over density gradients caused by boiling.

GROWTH OF NATURAL CONVECTION CELLS

It is important to consider that stratification, if it occurs, will be confined to the bottom of the supernate. If the fluid is not stabilized, such that natural convection occurs, then the result will be large convection cells extending from the sludge to the free surface of the liquid, as discussed below.

The tendency for natural convection to occur depends on the length scale of the system. The outbreak and intensity of natural convection depends on the Grashof Number, a dimensionless group described above. It is proportional to the cube of a characteristic length. For the case of the growth (i.e., *not* a steady-state situation) of convection across a narrow temperature gradient, the characteristic length would be the length over which the temperature difference occurs. Hence, the tendency toward natural convection in this case is very sensitive to the length over which the driving temperature difference extends itself.

Convection cells in the supernate would begin in a region near the sludge, assuming that stratification occurs at the bottom of the supernate where the boiling point is highest. This would increase the rate of heat transfer over the region in which convection occurs. There would be increased heat transfer from the sludge to the top of the region of convection, causing an increased temperature gradient and consequent natural convection at the interface of the region with the cooler liquid above. This additional convection would serve to extend the position of the steep

temperature gradient temperature upward. Extending the temperature difference over a taller region would sharply increase the Grashof Number, reinforce the convection, and extend the temperature difference still further upward. This progression of the temperature gradient upward would continue until the convection cells extend to the top of the supernate. Once the entire supernate is involved, a steady-state pattern would be established. Then from a dimensional analysis[(a)] one would find that the strength of the natural convection depends on the geometry of the tank as a whole and a Grashof number calculated using the depth of the tank contents as the characteristic length.

If the liquid were stabilized by concentration gradients, this would occur near the interface with the sludge, because either the sludge would be the source of the concentration gradient, or the gradient would be caused by settling of solids to the interface. Therefore, a region of stabilization would not be maintained immediately above a region of convection located at the interface.

Hence, either natural convection would be stabilized, or it would cause mixing of the entire supernate. If the supernate is stabilized, the heat transfer can be analyzed in terms of a quiescent sludge and liquid, and mathematically becomes equivalent to conduction of heat in two solid slabs in contact, where heat is generated in one of them. If it is not stabilized, the temperature in the supernate will increase slowly while remaining nearly uniform because of mixing. In this case the entire supernate would have to be heated to its atmospheric boiling point before any of the supernate could flash to steam, precluding the "rollover" hypothesis entirely. Therefore, the conservative case is that of a stabilized supernate remaining quiescent and storing conducted thermal energy near its lower surface prior to rollover of the heated region to the top of the supernate.

(a)Bird, R. B., E. N. Lightfoot, W. E. Stewart, Transport Phenomena, John Wiley & Sons, New York (1960) Section 10.6.

ANALYSIS OF QUIESCENT SOLID/LIQUID CONDUCTION

Westinghouse staff have used the HEATING-5 code to predict 2-dimensional temperature distributions in an aging waste tank. Because the ratio of height of settled sludge to tank diameter is small (about 0.04), at the center of the tank the temperature profiles in the sludge and in supernate near the sludge should be well approximated by a 1-dimensional analysis. A 1-dimensional analysis is presented here to:

- Partially verify the 2-dimensional calculations, we have implemented an analytical solution to a closely related 1-dimensional problem already available in the literature. The results are tabulated for use by Westinghouse staff in comparing them to HEATING-5 calculations.
- provide insight into the extent of thermal stratification that could occur in the supernate.

Our analysis of conduction from an internally heated solid into a quiescent liquid is for the case of instant settling of solids into a uniform layer. It does not consider quantitatively the existence of a permanent layer of solids upon which settling of further solids occurs. The consequences of such a layer are discussed qualitatively at the end of this section.

MATHEMATICAL ANALYSIS

A mathematical analysis of the 1-dimensional heating problem is described and developed in Appendix B. The basic assumptions used are:

- Conduction is described by Fourier's second law
- The sludge and supernate are always quiescent and initially at the same temperature
- The heating rates per unit volume in the sludge and supernate are different but both uniform within the sludge or supernate
- The supernate is treated mathematically as though it extended infinitely upward from the sludge
- The temperature at the bottom of the sludge is assumed to rise slowly such that it matches the temperature in the supernate far from the

sludge (i.e., at "infinity"). This is assumed to allow use of an available analytical solution, and is nearly the same as assuming a constant (zero) temperature rise at the bottom. Consideration of more complicated boundary conditions is beyond the scope of this report; the ones chosen are sufficient for the purposes of the report.

This problem is solved in the literature[(a)]. The solution is an infinite series, described in Appendix B. It provides the temperature rise relative to that in the supernate far away from the sludge. To this result we then add this temperature rise to obtain the temperature rise relative to the initial temperature, $T' - T_0$. The results are presented in this form so they are correct independent of the initial temperature. Therefore, the results presented in Tables 1 to 6 are for the temperature rise $T' - T_0$, for either the solid (sludge) or liquid (supernate).

From the infinite series solutions we can also find the amount of heat conducted from the solid to the liquid as a function of time, as discussed in Appendix B. It is the temperature rise in the liquid relative to $T_0 + S_L t$, where S_L is the adiabatic rate of temperature rise in the supernate, times the density and specific heat of the liquid, integrated from the bottom surface of the liquid up to infinity, and multiplied by the area of the surface of the sludge. The result is another infinite series, also described in Appendix B.

The solutions were implemented by a FORTRAN computer code that was verified by repeating part of the calculations ("Tsurf" and "BTU" of Tables 1 to 6, for certain times and cases) using spreadsheet software.

(a)H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Second Edition, Oxford University Press, London (1959), Section 12.8(II).

CALCULATION OF TEMPERATURES AND HEAT ADDITION

For all of the calculation we assumed dimensions and properties consistent with recent Westinghouse calculations. The values used were:

Area of Solid Layer	4411.46	ft^2
Depth of Solid	3	ft
Depth of Supernate	27	ft
Heating Rate in Solids	610	kBTU/hr
Heating Rate in Liquid	80	kBTU/hr
Total Heating Rate	690	kBTU/hr
Thermal Conductivity of Liquid[a]	0.377	BTU/hr/ft/°F
Specific Heat of Liquid	1	BTU/lb/°F (water)
Density of Solids	103	lb/ft^3
Density of Liquid	62.37	lb/ft^3 (water)

The thermal conductivity and specific heat of the sludge are discussed below.

The results of the computer calculations are presented in Tables 1 to 6 and Figures 2 to 6. The temperatures are presented in tabular form so that a comparison can be made by Westinghouse staff with 2-dimensional HEATING-5 calculations.

Tables 1 to 6 present the temperature rise at the midplane of the solid, "Tctr", (i.e., down half the depth of the sludge) and the temperature rise at the solid/liquid interface, "Tsurf", as a function of time out to 300 hours. Each of the tables corresponds to a set of values for the thermal conductivity and specific heat (heat capacity) of the solid (sludge), as listed at the top of the tables.

(a)Roughly estimated to be that of water at 60°C. k = 0.00156 cal/sec/cm/°C [Bird, R. B., W. E. Stewart, E. N. Lightfoot, Transport Phenomena, John Wiley & Sons, New York (1960), Table 8.1-2.] x(3600 sec/hr)x(30.48 cm/ft)/(252 cal/BTU)/(1.8 °C/°F) = 0.377 BTU/hr/ft/°F

The six cases considered in this report are:

Case	k(solid), BTU/hr/ft/°F	Cp(solid), BTU/lb/°F
1	0.065	0.3
2	0.1	0.3
3	0.3	0.3
4	1.0	0.3
5	1.0	0.1
6	1.0	1.0

The results are also summarized in Figure 2, where the midplane sludge temperature is shown for all 6 cases as a function of time. In addition, the temperature profiles (relative to $T_0 + S_L t$) in the solid and liquid for cases 1 and 4 were computed. The results for case 4 (thermal conductivity = 1 BTU/hr/ft/°F) are presented in Figures 3 and 4. The profiles at 300 hours for case 1 and case 4 are compared in Figure 5.

The heat conducted into the liquid, listed in the column entitled "BTU", is also presented in Tables 1 to 6 for the 6 cases. The fraction of the heat generated in the solid layer that has been conducted to the liquid is listed in the column entitled "Fract." The fraction of the heat generated in the solid that is conducted to the liquid ranges from .02 to .26 over time for the various cases. The fraction of the total heat generated that is generated in the solids is 610/690 = .88. The fraction of the total heat generated that would be stored non-uniformly in the liquid because of conduction from the solid would range from 0.88 x 0.26 = 23% to 0.88 x 0.02 = 1.8%. Therefore, relatively little of the heat generated would be stored by thermal stratification in the supernate.

The amount of heat conducted is also summarized in Figure 6, which shows the results for cases 1 to 6. The results can also be examined to develop a perspective about heat conduction phenomena for the hypothesized situation.

Figure 2. TEMPERATURE RISE AT MIDPLANE OF SLUDGE

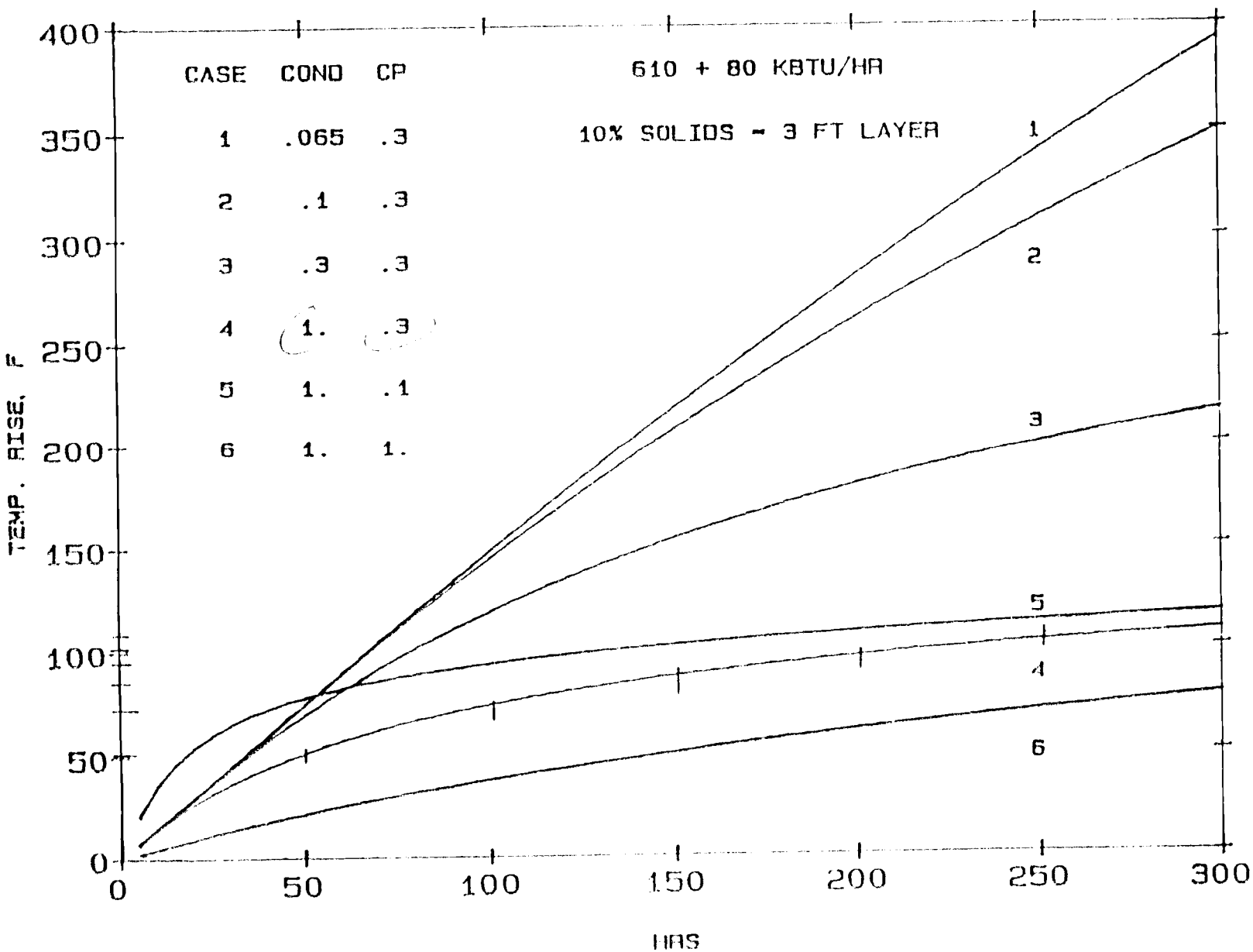


Figure 3. Temperature Rise Profiles for Case 4

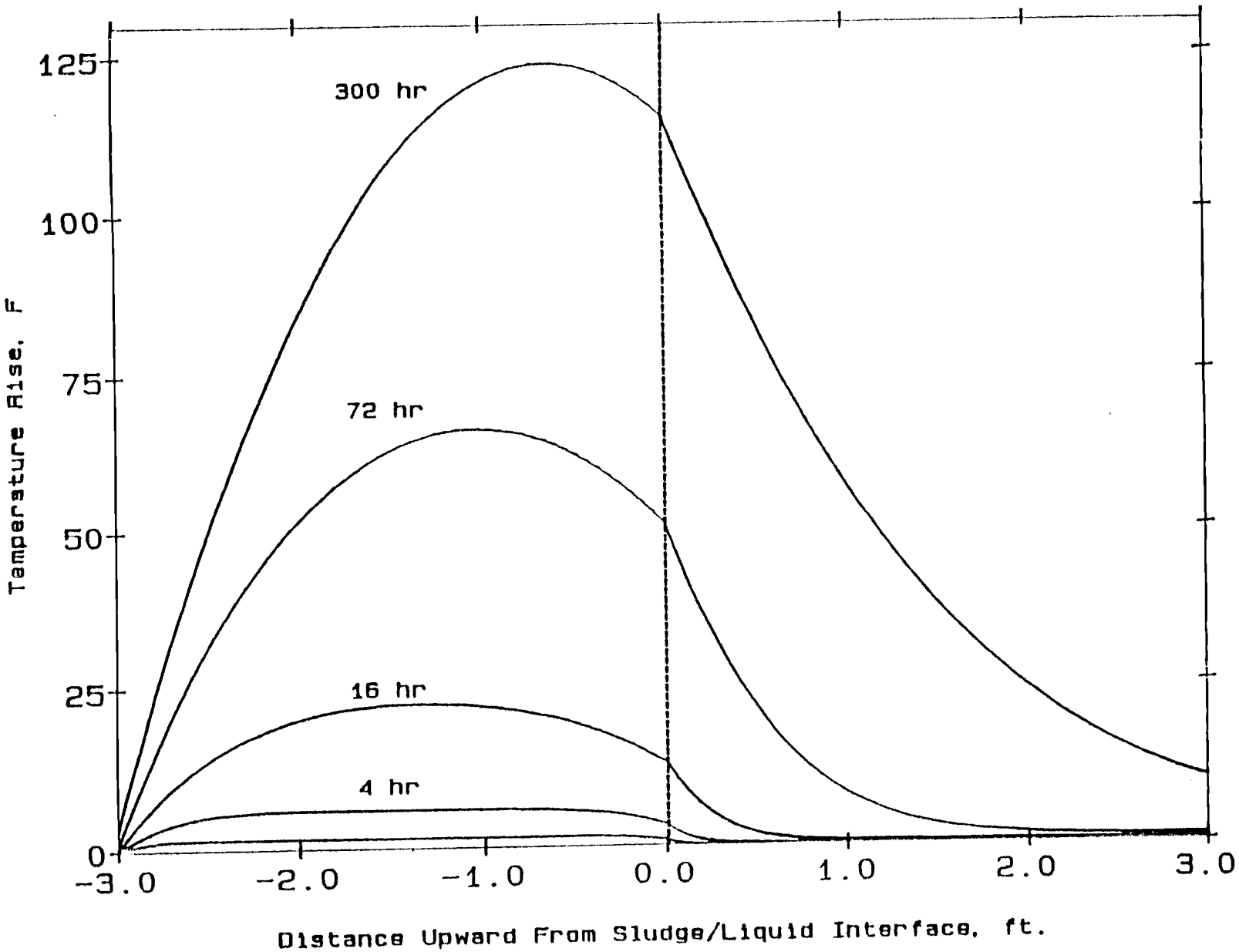


Figure 4. Temperature Rise Profiles for Case 4

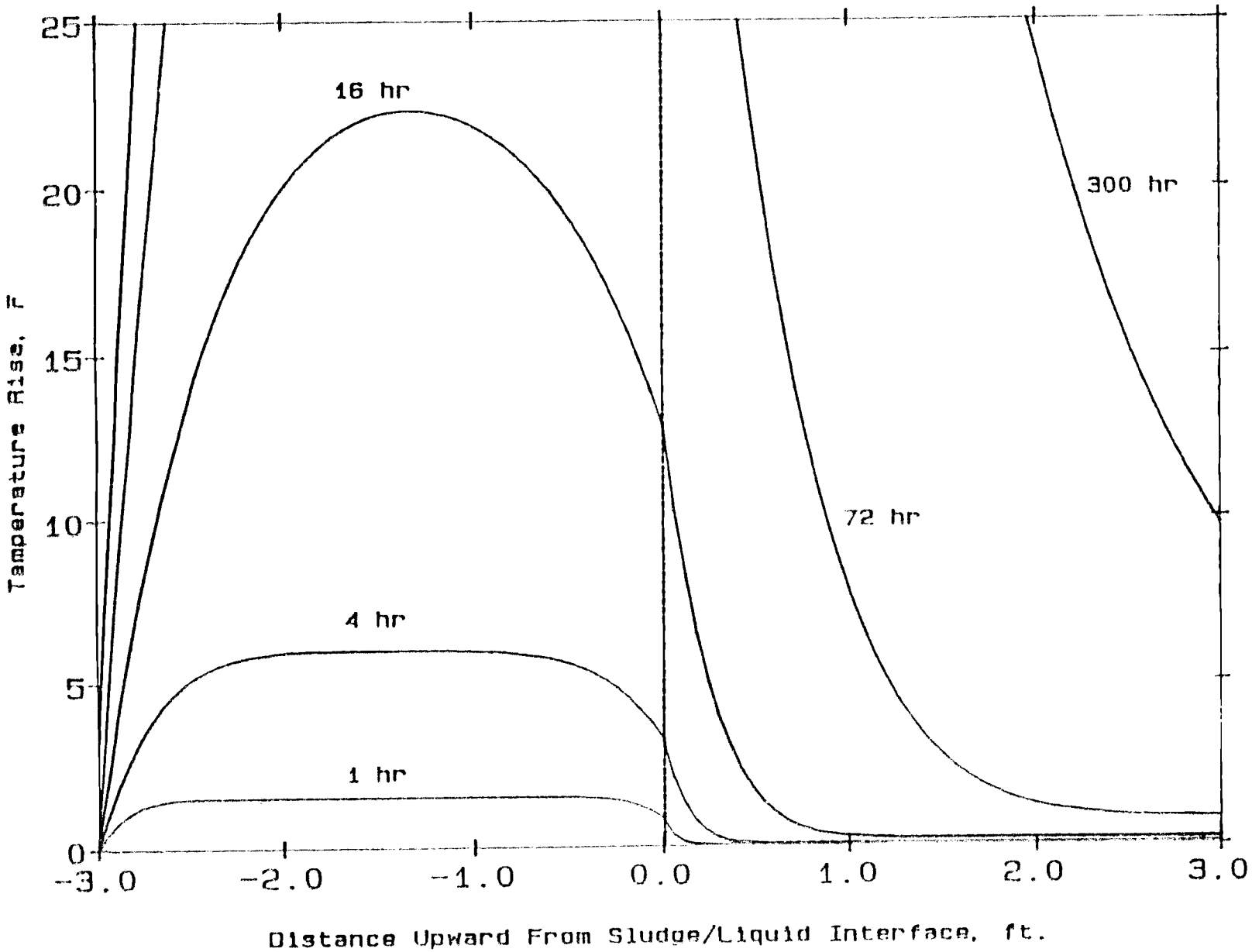


Figure 5. EFFECT OF CONDUCTIVITY ON 300 HR PROFILE

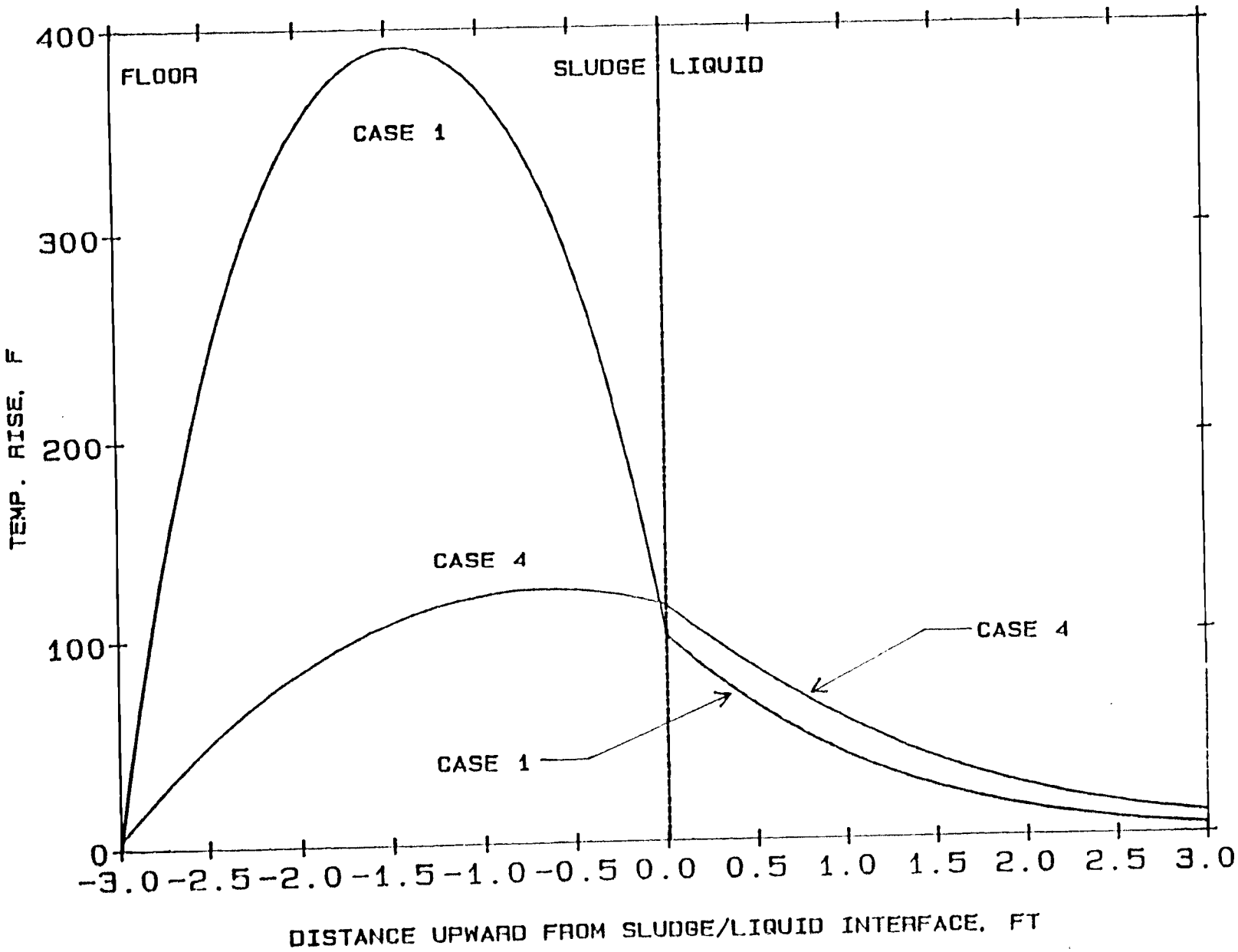
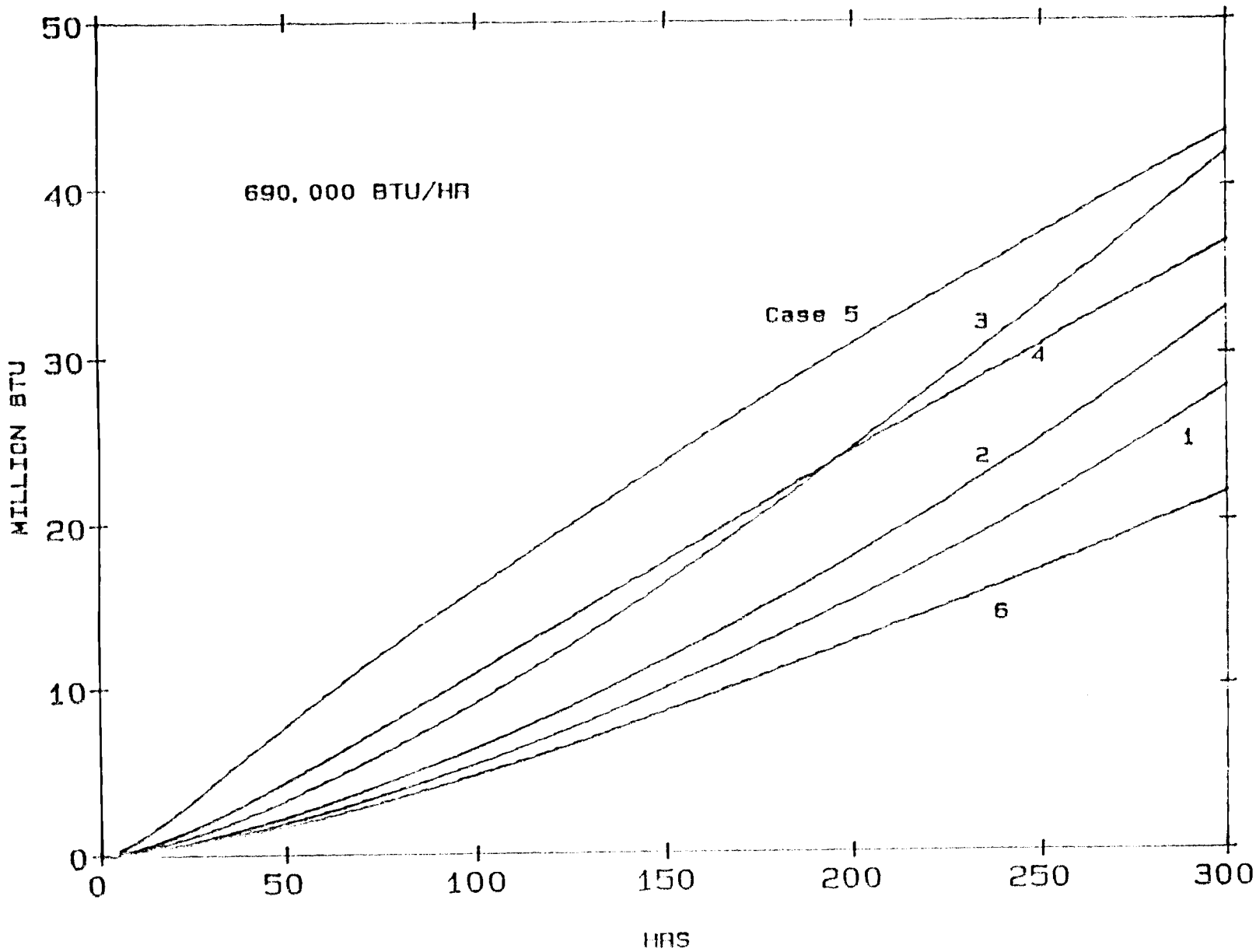


Figure 6. HEAT CONDUCTED INTO QUIESCENT LIQUID



DISCUSSION OF EFFECTS OF THERMOPHYSICAL PROPERTIES OF SLUDGE

From Figure 6 we see that the heat conducted from the solid to the liquid varies from about 20 to 40 million BTU at 300 hours for the different cases. The range is only a factor of 2, even though the thermal conductivity is varied by a factor of 15 and the specific heat by a factor of 10. Hence, the effect of these thermophysical properties is not dramatic. However, if the thermal energy stored by both the solid and the liquid is considered, the effect of the thermophysical properties would be still smaller. This is because the combined energy stored by the solid and liquid is not affected by the conduction of heat from one to the other. The effect of the thermophysical properties is then limited (in our 1-dimensional analysis) to conduction of heat out the bottom of the tank. This effect is seen in Figure 5, where for case 4 the high thermal conductivity assumed for the sludge results in substantial heat being lost the bottom of the tank, where z = -D, or -3 ft. The effect is apparent from the much lower temperature profile.

This effect is also increased by time. In Figures 3 and 4 the flat temperature profiles up to about 72 hours result from little heat lost from the solid by conduction compared to the heat stored that corresponds to the temperature rise. The extreme case is found at 1 hour in Figure 3. But by 300 hours the temperature profile approaches a parabolic form characteristic of a steady-state conduction situation. Once a steady-state profile is attained, no additional heat is stored in the solid, with the generation being matched by conduction out the boundaries of the layer, and about half of this loss would be from the tank to its lower surroundings. Hence, as time increases the relative importance of thermophysical properties on the total thermal energy stored in the tank increases.

EFFECT OF BOILING AT SURFACE OF SLUDGE

The surface temperatures "Tsurf" presented in Tables 1 to 6 are the maximum temperature rise in the liquid at any given time. For the nominal case considered here, the temperature must rise 30°F to attain the atmospheric boiling point. To determine the boiling point at the bottom of the supernate the hydrostatic head must be estimated. Based on informal

discussions with Westinghouse staff, we assumed the specific gravity of the supernate to be 1.2, thereby deviating from the value of 1 assumed above in order for the conduction calculations to be consistent with Westinghouse calculations. The difference is not very important for the conduction calculations, particularly regarding the amount of heat conducted to and stored by the supernate, but the difference is important to a calculation of hydrostatic head. We note that for sodium nitrate solutions at 100°C a specific gravity of 1.2 corresponds to 35 wt% sodium nitrate[a], or 3.4M.

The hydrostatic head at the surface of the sludge would then be (62.37 lb/ft^3)(1.2)(32.17 ft/sec^2)(27 ft)(2.1584×10^{-4} psi/($lb/ft/sec^2$)) = 14.0 psi. The total pressure would be 14.7 + 14.0 = 28.7 psi. The boiling point of pure water at this pressure is 247.7°F[b], or a rise of 36°F. If we assume a similar rise for the supernate, the total temperature rise that must occur at the sludge interface to attain the local boiling point would be 30 + 36 = 66°F. The times required to attain this temperature rise and the heat conducted into the liquid at that time are found from Tables 1 to 6 to be:

Case	Time, hrs	Heat Conducted, million BTU
1	195	14.7
2	165	13.4
3	120	11.9
4	105	11.6
5	60	9.4
6	245	16.7

Note that the heat conducted up to the time boiling ensues varies much less than does the time. This is simply because the temperature rise in the liquid is closely related to the heat conducted into it, since the thermophysical properties of the liquid are not varied among the cases.

Therefore, although the heat conducted is predicted to reach up to 40 million BTU after 300 hours, it does not seem possible for the liquid to remain quiescent this long. When boiling ensues, the heat stored in the

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(a) Chemical Engineers' Handbook, Fourth Edition, J. H. Perry, Ed., McGraw-Hill, New York (1963) p. 3-77, Table 3-110
(b) J. H. Perry (ed.), Chemical Engineer's Handbook, Fourth Edition, McGraw-Hill, New York (1963), p. 3-192 (Table 3-260 "Saturated Steam: Pressure Table")

liquid will be distributed over the remaining supernate. If the mixing is very non-uniform, some of the heat could result in a volume of supernate flashing to steam if it moved to the lower local pressure at the top of the supernate without appreciable mixing with cooler supernate.

The amount of steam that could be generated by the stored energy would correspond to that fraction of the stored energy that is not expended in raising the temperature 30°F to the atmospheric boiling point. This fraction would be about 36/66 = 0.55; multiplying this times the stored energy—on the order of 15 million BTU, as discussed above—gives about 8 million BTU available to generate steam. However, the energy resulting in generation of steam could be much less because of mixing of hot and cooler supernate after boiling ensues.

A second likely effect of boiling would be to begin resuspension of the sludge. Assuming a particle size distribution for the solids (see the discussion of settling, below), the smallest particles would be at the top of the sludge layer. This suggests that any boiling convection would easily incorporate the top of the sludge. This in turn should reinforce the boiling since the heat stored in the sludge, which is hotter than the liquid (e.g., see Figures 3 and 4), would be deposited in the liquid as the sludge is resuspended. We cannot say whether this effect would grow to cause complete resuspension of the sludge. If it does, the times at which boiling begins, which are sensitive to the thermophysical properties of the sludge, would determine the amount of stored energy that might be flashed to steam. At a total heating rate of 690,000 BTU/hr and an initial temperature 30°F below the atmospheric boiling point, it may be that the times at which boiling would ensue would be too early for enough energy to be stored to generate appreciable steam by the nominal mechanism of complete mixing of sludge and supernate, since that time would have to be on the order of 300 hours to raise the temperature to the atmospheric boiling point, as discussed above.

In connection with the above effects, the likelihood of superheating supernate above its local boiling point should also be addressed. Since the settled solids are formed by precipitation, they could be completely wetted by the supernate. Therefore, in principle the supernate could be heated above the boiling point even in the presence of such solids; that is, without nucleation occurring. However, radiolysis caused by gamma- and beta-

radiation will generate hydrogen and oxygen gas as well as other radiolytic species. Recombination of radiolytic species to water is strongly inhibited by scavenging of hydroxyl radicals by anions[a], and cannot occur appreciably in a concentrated salt solution except at very high partial pressures of hydrogen. Since the total pressure cannot exceed the hydrostatic pressure in a waste tank, hydrogen will not recombine appreciably with other species to reform water, and hence hydrogen bubbles will form in the sludge. Such bubbles serve to nucleate boiling, and will prevent appreciable superheat of the supernate near the sludge where the temperature would first reach the local boiling point.

Finally, one can also question whether boiling would occur in supernate at the surface of newly settled sludge rather than in the sludge itself. The sludge, with an assumed density of 103 lb/ft^3, has a specific gravity of 1.65[b], which is only 1.65/1.2 = 1.38 times the assumed density of the supernate, and only 1.65/4 = 0.41 times the assumed density (4 g/cm^3, see below under "settling") of sludge particles. This suggests that a sludge of this density must actually include considerable water, which in turn suggests that this water, in the presence also of radiolytically generated hydrogen or oxygen bubbles, could boil when the local boiling point is reached. Since in the cases considered here the temperatures in the sludge are considerably higher than in adjacent supernate, it is possible that thermal stratification of supernate could be disrupted by boiling of water in a layer of newly settled sludge before boiling in the supernate itself occurs.

EFFECT OF INCREASED TOTAL HEATING RATE

If the total heating rate were 4 million BTU/hr, but if the initial temperature were still 30°F below the atmospheric boiling point, then the time required to attain boiling in a quiescent supernate at the top of the sludge would decrease roughly in proportion to the heating rate, while the

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(a) Simonson, S. A., and W. L. Kuhn, "Predicting Amounts of Radiolytically Produced Species in Brine Solutions", International Symposium on the Scientific Basis for Radioactive Waste Management, Boston, MA, 14 Nov 1983, CONF-831174-31 (1983)

(b) $(103\ lb/ft^3)(454\ g/lb)/(30.48\ cm/ft)^3 = 1.65\ g/cm^3$

heat conducted into the supernate would roughly increase proportionately. The net effect should be that about the same amount of energy is stored in the quiescent liquid at the time that it would be mixed due to the onset of boiling. Hence, an increase in heating rate would probably not affect conclusions regarding the consequences of mixing caused by boiling.

Similarly, if boiling at the bottom of the supernate caused complete resuspension of the sludge, then the total energy stored would be roughly the same irrespective of the heating rate, since the time to attain boiling and the rate of storage of energy vary inversely with each other as the heating rate is varied. The thermophysical properties of the sludge would still determine the time to boiling, as above.

If the heating rate is as large as 4 million BTU/hr, one should determine if the slurry will be kept below boiling at all during operation of the airlift circulators. If not, then given the settling velocities estimated below, it seems unlikely that there could be appreciable settling of suspended solids in the face of boiling convection. If the slurry is kept below boiling but to a lesser degree, then for the nominal case the time required to attain boiling at the surface of settled sludge would be further reduced.

EFFECT OF PERMANENT LAYER OF SOLIDS

If a portion of the solids were not suspended by the airlift circulators, then there would be a permanent layer in which a steady-state, parabolic temperature profile will be established, with the top temperature equal to the slurry temperature. If the total heating rate were the same as above, but with the solids divided evenly between a permanently settled layer and the slurry, then the layer that settles when ALC operation ceases would be only 1.5 ft thick. This could cause slightly more heat to be conducted to the liquid, and the heat generation in the permanent layer would tend to make the bottom boundary condition for the newly settled layer more adiabatic. The main effect would be that only half of the solids would be resuspended, and hence less heat would be mixed with the supernate when resuspension occurs. Therefore, the assumption that all solids are initially suspended is conservative with respect to the conclusions of this report.

SETTLING OF SLURRY SOLIDS

We assume that, while airlift circulators (ALC's) are in operation, the agitation is sufficient to keep a certain fraction of solids in the tank mixed with the supernate as a slurry. There may also be solids that remain on the bottom; if so, we treat these as part of the unchanging floor of the tank and restrict our analysis of settling to those solids that can be kept suspended by the ALC's. We also assume that if operation of the ALC's ceases, then settling of the solids ensues; we wish to know how fast this occurs and how quiescent the supernate must become for it to occur.

ASSUMED PARTICLE SIZE DISTRIBUTION

From analyses[a] of existing tank supernate, we have a rough idea of the particle size distribution. Based on this, but simplified somewhat for the purpose of our analysis, we assume a log-normal distribution with respect to particle diameter with a mean of 10μ and with 95% of the particle volume falling between 1μ and 100μ. The distribution is described in Figure 7. The total solids concentration was not inferred from supernate analyses, but rather was assumed to be 10% by volume, based on informal discussions with Westinghouse staff. The density of the particles is assumed to be 4 g/cm^3, a value intermediate between the densities[b] of hematite (crystalline ferric oxide), 5.12 g/cm^3, and ferric hydroxide, 3.4-3.9 g/cm^3. We assumed the viscosity of the heated, saline supernate to be that of pure water at room temperature, 2.42 lb/ft/hr. All calculated settling rates are inversely proportional to the viscosity.

(a)Letter, B. B. Peters to April Coroneos, March 10, 1988.
(b)Perry, J. H., Chemical Engineers' Handbook, 4th Edition, McGraw-Hill, New York (1963) p. 3-10 (Table 3-1, "Physical Properties of the Elements and Inorganic Compounds")

SETTLING OF MULTISIZED PARTICLE SUSPENSIONS

Sedimentation of multisized suspensions of particles has been discussed in the literature by Selim et al.[a]. During the course of our work we discovered an error in this work, and in the prerequisite work reported by Mirza and Richardson[b], that became important for our calculations. We confirmed the error in the literature with Dr. Selim (Department of Chemical and Petroleum-Refining Engineering, Colorado School of Mines, Golden, CO 80401), and corrected the theory for use in the analyses presented here. With this correction, the method of Selim et al. was used to calculate the settling rates in a waste tank, except that once the correction was made we were able to achieve convergence of the iterative calculations involved using simple successive substitution rather than the Newton-Raphson method used by Selim et al. The calculations were implemented by writing a computer code of some 700 lines of FORTRAN, which is documented in the computer file ZONEVELS.FOR (named after the phenomenon of particles dividing into zones that fall at different velocities during settling).

To approximate a continuous particle size distribution, we assumed a discrete, log normal distribution of 21 sizes with the concentration of particles of each size calculated using the distribution parameters described above. The slurry is predicted to differentiate into a "stack" of 21 layers or zones, one for each particle size. The bottom zone contains all particle sizes and falls the fastest. All but the largest particles are partially left behind as the zone falls, leaving them in the next zone up (i.e., next to the bottom). The zone next to the bottom contains all but the largest particle sizes and falls second fastest. All but the two largest particle sizes are partially left behind as the zone falls, leaving them in the next zone up (i.e., two up from the bottom). The next zone up contains all but the two largest particle sizes, and falls third fastest, and so on up to the top zone, which contains only the smallest particles and falls slowest. Supernate above the top zone contains no suspended solids. During settling

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(a)M. S. Selim, A. C. Kothari, and R. M. Turian, "Sedimentation of Multisized Particles in Concentrated Suspensions," AIChE Journal, vol 29, p. 1029-1038 (1983)
(b)S. Mirza and J. F. Richardson, "Sedimentation of Particles of Two or More Sizes," Chem. Engr. Sci., vol 34, p. 447-454 (1979)

the concentrations and velocities in a given zone do not change, even though the locations of the tops and bottoms of the zones continuously fall. Once the velocities and concentrations are calculated, the time until any given zone disappears by settling can be predicted, as can the amount of sediment that has accumulated or any other consequence of the settling process.

The results of settling calculations are summarized in Tables 7 and 8 and Figures 7 through 10. In Table 7 the results are presented in terms of the 21 zones that form because of the 21 discrete particle sizes. For each zone, the largest particle size in the zone, the velocity at which the top of the zone falls, the fraction of the solids settled when the zone has settled, the time at which the zone has settled, and the heat that has been deposited by all of the settling solids up to that time are listed. In Table 8 the results are presented in terms of particle sizes. The initial concentration of the particles for each of the 21 sizes, the cumulative fraction of the solids volume occupied by the increasing sizes, and the slip velocity for the particle sizes when they are in the initial mixed slurry (which is also the slip velocity for each size for particles in the lowest zone: zone 21) are listed.

Figure 7 shows the particle size distribution resulting from the assumptions of a log-normal distribution with mean of 10 microns and with 95% of the particle volume between 1 and 100 microns. Figure 8 shows the resulting distribution of "slip velocities" of the particles. The slip velocity is the velocity with which a particle falls relative to the surrounding fluid. The fall of solids displaces the fluid upward, so that the settling velocity is slightly smaller (specifically, slightly more negative, where a positive velocity is downward) than the slip velocity for a given particle. The smallest particles in the lowest zones exhibit negative velocities, meaning that they are being carried upward by fluid being displaced upward by the fall of the larger particles. The settling velocity of the largest particle in a given zone is the rate of fall of the top of the zone.

RESULTS OF SETTLING CALCULATIONS

The slip velocity is of interest because it can be compared to fluid velocities to determine is settling can occur at all. That is, if the fluid is moving upward, for example due to natural convection, with a velocity exceeding the slip velocity for some particle size, then particles of that size at that location will not settle. From Figure 8 it is apparent that most of the slip velocities are very small, given the assumptions about the particle size distribution noted above. Most of the particles have slip velocities less than 0.01 ft/sec. Even very slight large-scale convection caused by heat generation in the slurry, let alone caused by boiling, would suffice to keep most of the slurry suspended.

A particle falling at 0.01 ft/sec would need 300 hours to fall from the top of the 30 ft. high layer of slurry to the bottom of the tank. The actual percent of the solids settled versus time is shown in Figure 9. Because of the size distribution and the initial proximity of some particles to the bottom of the slurry, about half of the solids are settled (*if* the slurry is perfectly quiescent) after about 10 hours. However, 90% of the solids are not settled until after 160 hours.

DEPOSITION OF HEAT FROM SETTLING PARTICLES

As the particles settle, they deposit their generated heat to the supernate through which they pass. The total heat being generated and deposited by the suspended solids at any given time during settling is the total heat generation rate of the solids multiplied by the fraction of solids still suspended. The fraction still suspended is just unity minus the fraction settled, where the fraction settled is that shown in Figure 9. Integrating the fraction settled over time and multiplying by 610,000 BTU/hr gives the heat deposited versus time, which is shown in Figure 10. The heat deposited is about 3.5 million BTU at 9 hours when 50% of the solids have settled, about 10 million BTU at 45 hours when 75% has settled, about 20 million BTU at 160 hours when 90 % has settled, and ultimately reaches about 40 million BTU at 1500 hours when settling is complete.

Figure 7. ASSUMED LOG NORMAL PARTICLE SIZE DISTRIBUTION

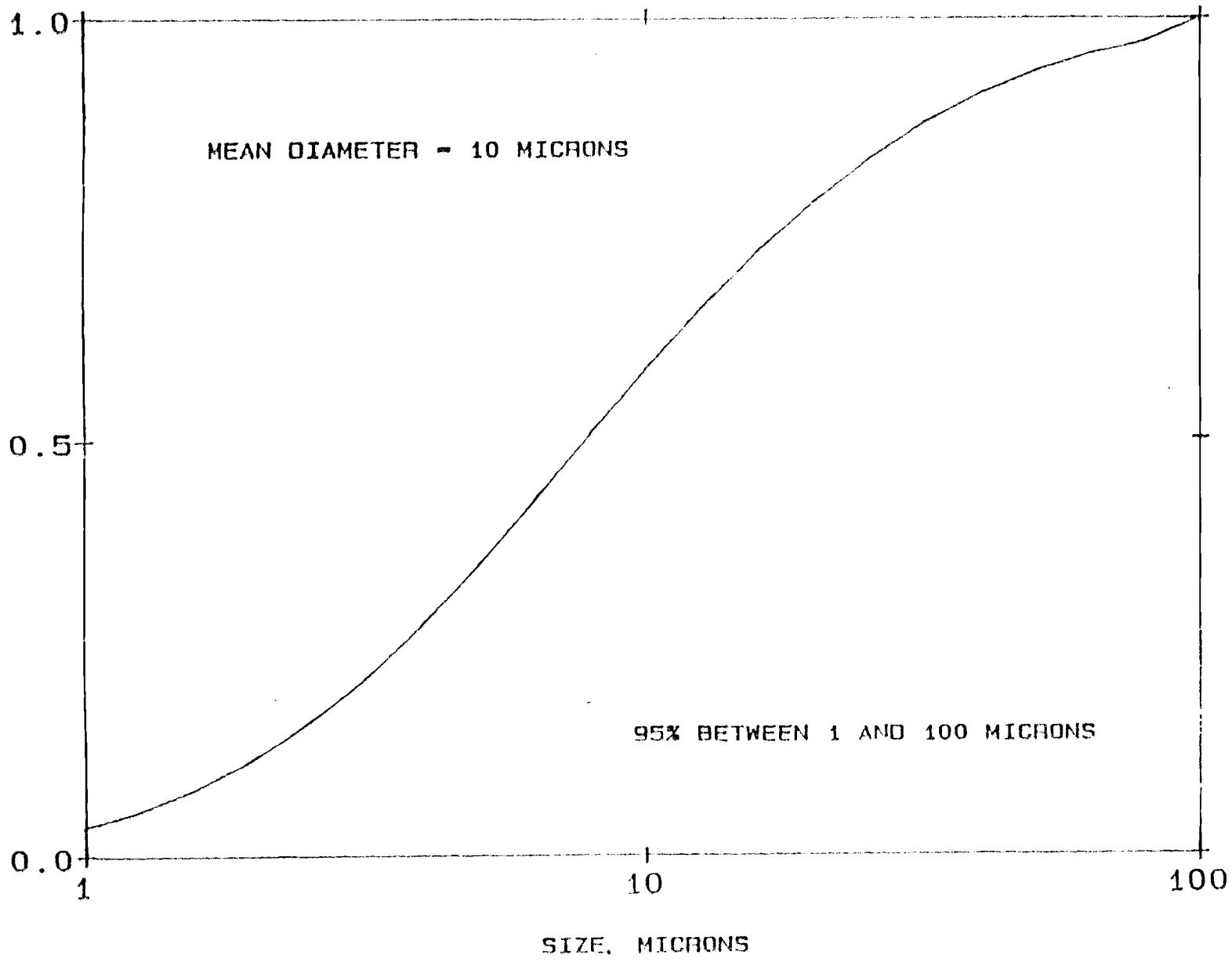
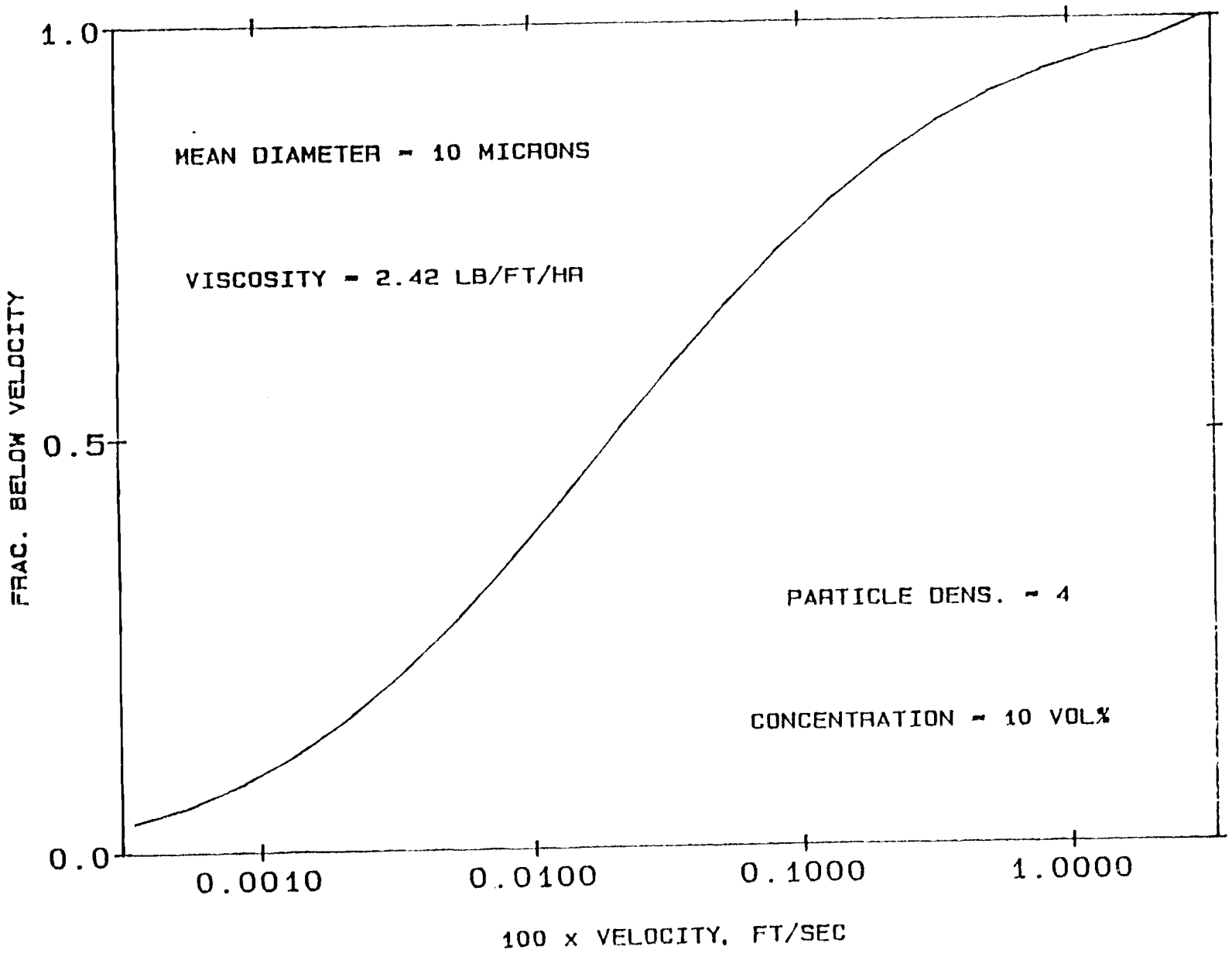


Figure 8. PARTICLE VELOCITIES RELATIVE TO FLUID



CONDUCTION OF HEAT FROM ACCUMULATING SLUDGE DURING SETTLING

A rough estimate of the conduction of heat out of the accumulating sludge back into the supernate can be obtained by assuming the settling occurs at a constant rate, and taking this to be the rate at which settling is occurring when 50% of the solids have settled. This occurs at about 9 hrs, as is apparent from Table 7, at which point the rate of increase is found to be 1.92% per hour, such that an additional 26 hours would be estimated to elapse to reach 100% settled. Therefore, 100% settled would be projected to occur at 35 hours (after 35 hours the actual fraction settled is 70-75%). The rate 1.92% per hour, given that the sludge layer is 3 ft. thick when 100% settled, would correspond to a rate of growth of .0575 ft/hr at the 50% settled point.

These approximate descriptions of the results of the settling calculations can be used to bound the amount of heat that would be conducted to the supernate from the accumulating sludge as settling occurs. If we assume first that no conduction occurs, in order to set an upper bound on the temperature in the accumulating sludge, then we have that the sludge heats adiabatically and the temperature in it is just the adiabatic heating rate multiplied by the time any part of the sludge has been settled. This time is the depth into the sludge divided by the velocity at which the surface of the sludge is rising. The volumetric heating rate in the sludge is the heating rate divided by the cross-sectional area and the sludge depth, which is (610,000 BTU/hr)/(4411.46 ft^2 x 3 ft) = 46 BTU/hr/ft^3. The volumetric heating rate divided by the density and the specific heat of the sludge gives the adiabatic heating rate, which is

$$(46\ \text{BTU/hr/ft}^3)/(103\ \text{lb/ft}^3 \times 0.3\ \text{BTU/lb/°F}) = 1.5\ \text{°F/hr}.$$

Figure 9. SETTLING RATE OF SLURRY

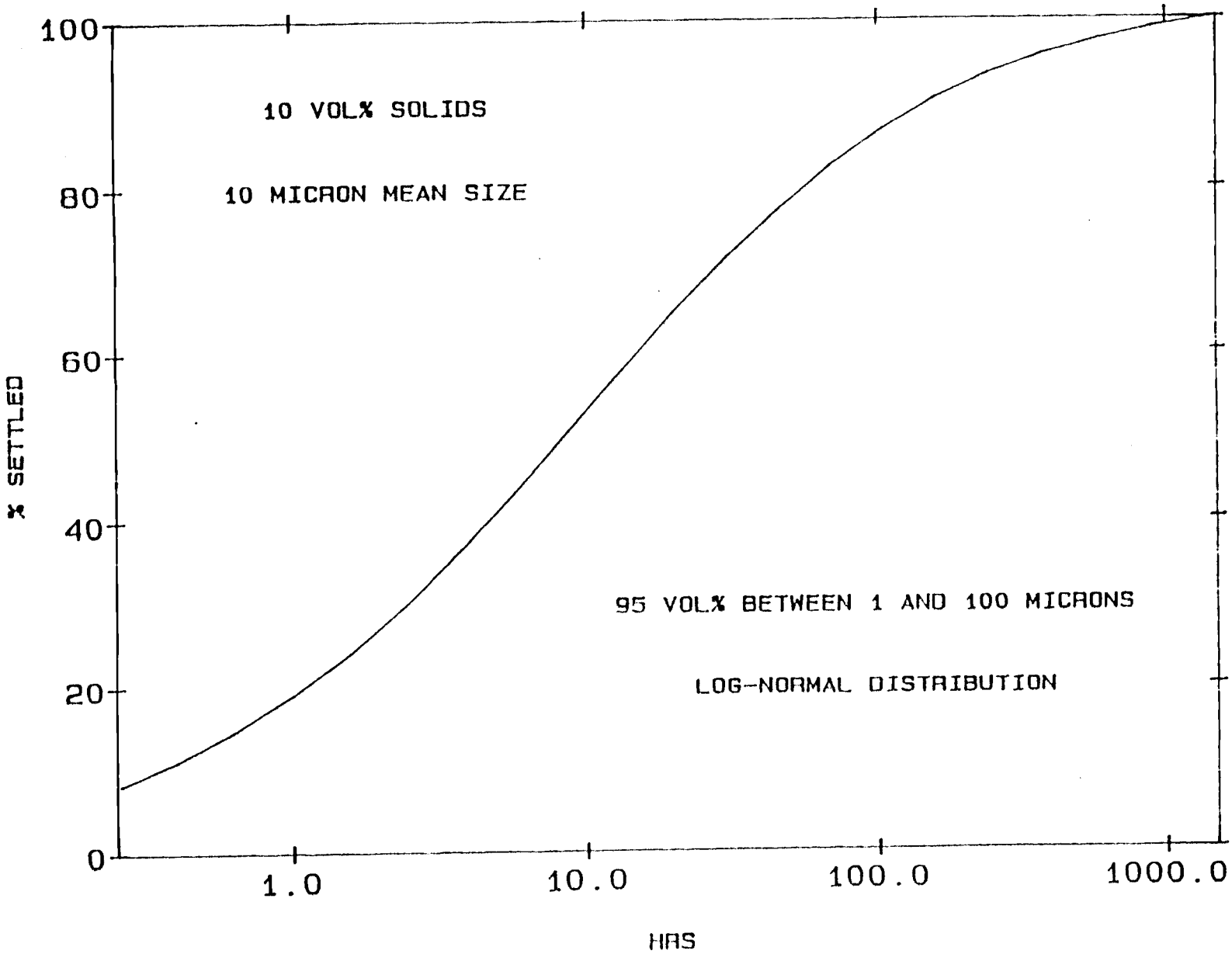
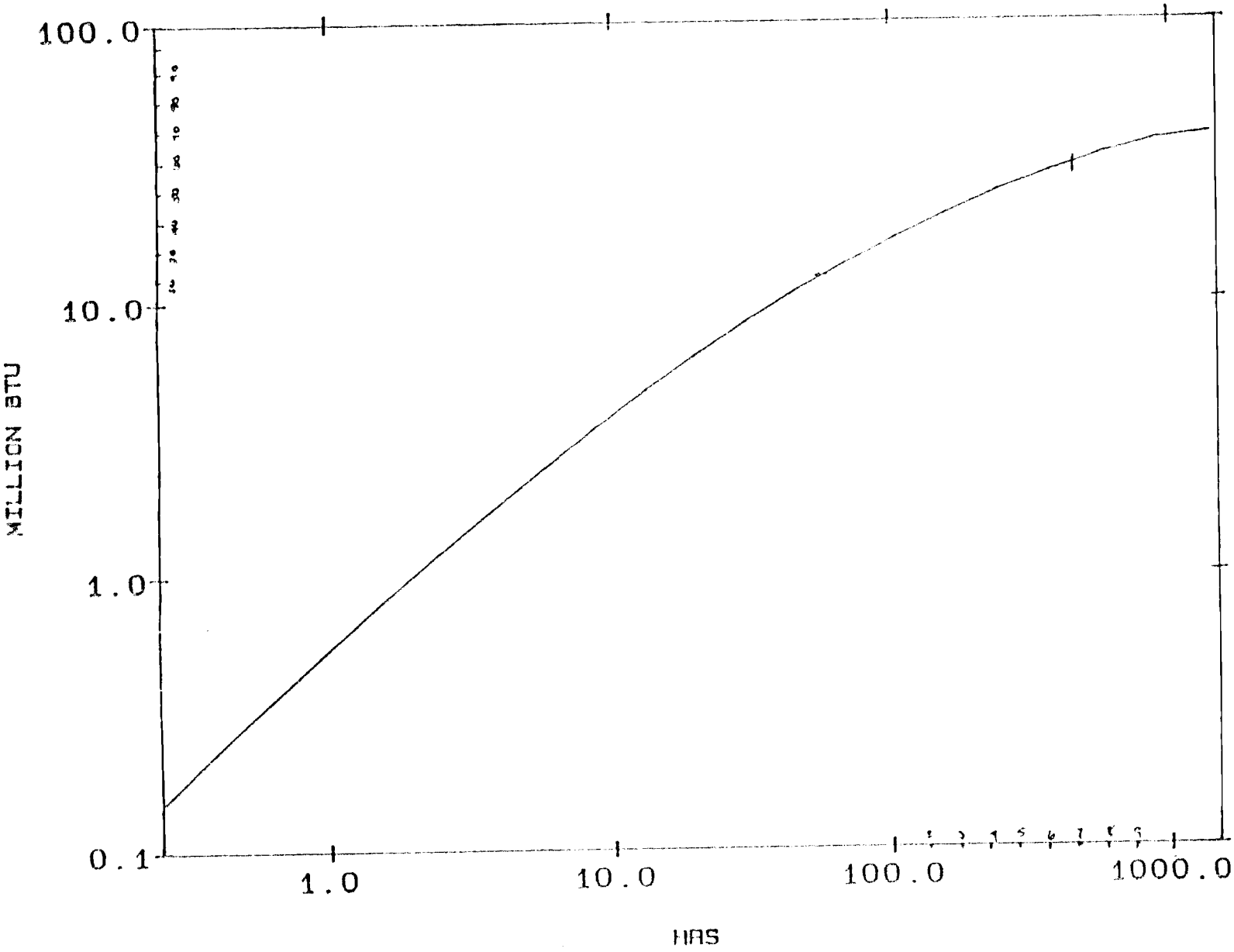


Figure 10. HEAT DEPOSITED IN LIQUID BY SOLIDS DURING SETTLING



Given the "50% settled" velocity for the accumulation of the sludge, 0.0575 ft/hr, the adiabatic temperature gradient would be (1.5 °F)/(.0575 ft/hr) = 26 °F/ft. This is an upper bound on the gradient that would occur if conduction out of the solid to the supernate occurred while the settling occurred. Multiplying this by the nominal thermal conductivity of the sludge, 1 BTU/hr/ft/°F, and by the cross-sectional area, 4411.46 ft^2, gives 0.115 million BTU/hr. Over the 35 hours *projected* (in this simplistic analysis) to reach 100% settling solids at 0.0575 ft.hr, the upper bound on the heat conducted would be 35 x 0.115 = 4 million BTU. The cumulative heat generated over this time by solids already settled is the cumulative heat generated by all solids over the time minus the cumulative heat generated by solids not yet settled. From Table 7 we find that the cumulative heat deposited by solids not yet settled after 35 hours is about 9 million BTU, so that (35 hr x 610,000 BTU/hr) - 9 million BTU = 12.4 million BTU would have been generated in the accumulating settled solids. Therefore, the upper bound on heat conducted to the liquid during settling corresponds to 4/12.4 = 32% of the heat generated in the accumulating sludge layer during the first 35 hours of settling, which seems physically reasonable.

The total heat stored in the supernate during settling would depend on the time over which the supernate could be stabilized by settling. Stabilization could end because of the end of the concentration gradient caused by settling, or because of the onset of boiling, as discussed above regarding conduction out of an instantaneously precipitated sludge. Our approximate analysis of heat transfer occurring during settling shows that the effect would be the transfer of about 9 + 4 = 13 million BTU *as though* over 35 hours; after this, conduction out of a 3 ft. layer of sludge would continue similar to that out of an instantaneously settled sludge. However, conduction out of an instantaneously settled sludge was shown above to be limited to about 10 to 15 million BTU before boiling ensues. Therefore, since the temperature profiles in the liquid would be qualitatively the same whether settling was instantaneous or not—that is, steepest at the bottom—we can expect that the 13 million BTU transferred during non-instantaneous settling would also have the effect of raising the temperature at the bottom of the supernate to near the local boiling point, such that little additional conduction of heat from the sludge could occur before

boiling ensues. Density gradients caused by boiling would be substantial and result in convection and mixing even with a residual density gradient remaining during the completion of settling.

APPENDIX A

FUNCTIONAL FORMS FOR RATE OF RESUSPENSION OF SLUDGE

Table of Notation

Symbol	Meaning	Symbol	Meaning
CGR	Denotes "Constant Generation Rate" Functional form	t_b	Time at which volume V_b of sludge is resuspended, hr
NEF	Denotes "Negative Exponential Function"	t_o	Time constant for functional form, hr
R	Rate of resuspension of sludge, ft^3/hr	t_p	Time at which $R=R_p$
R_p	Rate of resuspension of sludge that adds heat at a rate that generates steam at a rate causing pressurization of the tank, ft^3/hr	V_b	Volume of sludge that must be resuspended before enough heat is mixed with supernate to cause boiling of mixed contents of tank, ft^3
t	Time, hr	V_{tot}	Total volume of resuspendable sludge, ft^3

Recent calculations by Westinghouse staff[(a)] have been based on the assumption of a resuspension time on the order of 8 hours, where this is the time constant in a negative exponential function (NEF) describing the rate of resuspension:

$$\text{Rate} = R_o \exp(- t/t_o)$$

where R_o is the initial rate, ft^3/hr, and t_o is the time constant, hr. Figure 1 shows some of the features of the function, as well as times and

(a) Internal letter, B. L. Jones to R. M. Marusich, "Tank Bump and Associated Release Calculation," No. 65611-87-086, dated May 6, 1987.

rates discussed below. The total volume of sludge resuspended, V_{tot}, would be this rate integrated from zero to infinity, which is readily shown to be $R_o t_o$; therefore, $R_o = V_{tot}/t_o$.

Of interest is the volume of steam that is generated while the tank remains pressurized above a certain limit. Since, once the boiling point is attained, the volume of steam produced and rate of production of steam is proportional to the volume of sludge resuspended and the rate of resuspension of sludge. If we consider first the NEF, then the volume resuspended is given by the time integral of the rate, which is

$$V(t) = V_{tot} [1 - \exp(- t/t_o)]$$

We define t_b as the time required to resuspend the volume of sludge V_b that must be resuspended to bring the supernate temperature to the boiling point, so that

$$V_b = V(t_b) = V_{tot} [1 - \exp(-t_b/t_o)]$$

Hence, $t_b = - t_o \ln[1 - (V_b/V_{tot})]$. At this point steam generation begins at a rate proportional to the rate of resuspension of sludge, which decreases continuously.

The volume of sludge V_p resuspended from when boiling begins, when $t = t_b$, to when the rate of generation decreases to the rate R_p where the tank is no longer pressurized, when $t = t_p$, is proportional to the volume of steam generated, and is

$$V_p = V(t=t_p) - V(t=t_b) = V_{tot} [(1 - \exp(-t_p/t_o)) - (1 - \exp(-t_b/t_o))]$$

The time t_p is found from $R_p = (V_{tot}/t_o) \exp(-t_p/t_o)$, whence

$$t_p = - t_o \ln(R_p t_o/V_{tot})$$

Substituting this and the expression for t_b into the expression for V_p gives

$$V_p = V_{tot} [(1 - (R_p t_o/V_{tot})) - (1 - [1-(V_b/V_{tot})])]$$
$$= V_{tot} - R_p t_o - V_b$$

This is then proportional to the volume of steam generated while the rate of generation is sufficient to pressurize the tank.

If, instead of assuming a NEF, a constant generation rate (CGR) of steam is assumed to occur for a period of time t_o, then the rate for that time is $R_o = V_{tot}/t_o$. If t_o here is the same as t_o for the NEF, then the constant rate R_o here is the same as the initial rate R_o for the NEF. The time for pressurization to cease is now just t_o, and hence the volume of steam generated before this time is proportional to the sludge resuspended between t_b and this time, which is now

$$V_p^{CRG} = R_o(t_o - t_b) = (V_{tot}/t_o) (t_o - t_o[-\ln(1 - (V_b/V_{tot}))])$$
$$= V_{tot} (1 - [-\ln(1 - (V_b/V_{tot})])$$

compared to

$$V_p^{NEF} = V_{tot} - R_p t_o - V_b$$

where the superscripts denote which function of time describes the rate of resuspension of the sludge.

For the constant generation rate (CGR) case, the volume V_b is insensitive to the time constant t_o because V_{tot} is constant. For the negative exponential function (NEF) case, the importance of t_o depends on the value of R_p; so long as R_p is small compared to $(V_{tot}-V_b)/t_o$, the value of t_o is unimportant. Equivalently, so long as t_p/t_o is large the value of t_o is unimportant.

Also, if V_b is small compared to V_{tot}, then we have approximately $\ln(1-(V_b/V_{tot})) = -V_b/V_{tot}$ and hence $V_p^{CRG} = V_{tot} - V_b$. The ratio is

$$(V_p^{NEF} / V_p^{CGR}) = 1 - R_p t_o/(V_{tot}-V_b)$$

So, if again R_p is not too large, the ratio of sludge suspended and hence the ratio of steam produced while the tank is pressurized does not depend much on

the choice among these one-parameter functions describing the rate of resuspension of the sludge, where in both cases the single parameter is a time constant.

Finally, since, as shown above, if $t_p \gg t_o$ then V_p is insensitive to t_o for either the NEF or CGR cases, and so an estimate of the volume of steam generated while the tank is pressurized, which is proportional to V_p, is insensitive to t_o. However, the pressurization itself depends strongly on the rate of generation of steam, and hence strongly on R_o, which, for constant V_{tot}, depends inversely on t_o. Therefore, the volume of steam generated during pressurization can be insensitive to t_o, but the pressure (and hence the venting velocity of the steam) during the pressurization will depend strongly on t_o.

APPENDIX B

APPROXIMATE ANALYTICAL EXPRESSION FOR CONDUCTION BETWEEN SLUDGE AND SUPERNATE

Table of Notation

Symbol	Meaning	Symbol	Meaning
C_p	Specific Heat, BTU/lb/°F	S	Adiabatic rate of increase of temperature (heat generation rate per unit volume divided by the density and specific heat of the medium), °F/hr
D	Depth of settled sludge, ft		
k	Thermal conductivity, BTU/hr/ft/°F		
L (subscript)	Denotes in liquid (supernate)	S (subscript)	Denotes in sludge
T	Temperature relative to sum of initial temperature and temperature rise at z=1 in supernate, °F	t	Time, hr
		z	Distance upward from sludge/ supernate interface, ft
T'	Temperature, °F	α	Thermal diffusivity (thermal conductivity divided by density and specific heat), ft^2/hr
T_o	Initial temperature, °F		
		ρ	Density, lb/ft^3

If suspended solids are assumed to settle instantly when the operation of the airlift circulators is interrupted, and if the supernate is assumed to remain quiescent above the sludge, then the ensuing transport of heat within and between the sludge and supernate occurs in accordance with Fourier's Second Law[(a)]. For the 1-dimensional case, Fourier's Second Law becomes

(a)R. B. Bird, W. E. Stewart, and E. N. Lightfoot, Transport Phenomena, John Wiley and Sons, New York (1960), Section 10.1.

$$\frac{\partial T'}{\partial t} = \alpha \frac{\partial^2 T'}{\partial z^2} + S$$

where T' is temperature, °F, α is the thermal diffusivity, ft^2/hr, t is time, hr, z is vertical position, ft, and S is the heat generation rate per unit volume divided by the density and specific heat of the medium, °F/hr. The prime (') denotes the actual temperature, as opposed to the relative temperature defined for convenience below. This equation must be solved for both the supernate and the sludge regions. If there were no conduction from the solid (sludge) to the liquid (supernate), the temperature in either would remain uniform, i.e., constant with z. Then the temperature in the liquid would be $T_L' = T_o + S_L t$, where T_o is the initial temperature in both the solid and the fluid. If we define $T_L = T_L' - T_o - S_L t$ and $T_S = T_S' - T_o - S_L t$, then the partial differential equations (Fourier's Second Law) for the solid and liquid become

$$\frac{\partial T_L}{\partial t} = \alpha_L \frac{\partial^2 T_L}{\partial z^2}$$

$$\frac{\partial T_S}{\partial t} = \alpha_S \frac{\partial^2 T_S}{\partial z^2} + (S_S - S_L)$$

The boundary conditions in terms of T' are:

$$T_L' = T_S' \quad \text{and} \quad -k_L \frac{\partial T_L'}{\partial z} = -k_S \frac{\partial T_S'}{\partial z} \quad \text{at } z = 0$$

$$\frac{\partial T_L'}{\partial z} \to 0 \quad \text{as } z \to \infty \quad \text{and} \quad T_S' = T_o + S_L t \quad \text{at } z = -D$$

where the solid/liquid interface is a z = 0, the bottom of the sludge is at z = -D (depth), the top of the liquid is assumed to be far away (z approaches ∞, and k_S and k_L are the thermal conductivity of the solid and liquid. The boundary condition at z = -D is chosen for convenience so that the boundary condition there will become T = 0, which is desired so that the problem

corresponds to one already solved in the literature. Since the temperature at the bottom of the sludge will in fact increase, our boundary condition on T' is probably better than assuming that T' = 0. Converting from T' to T (= $T' - T_o - S_L t$) gives the boundary conditions for T:

$$T_L = T_S \quad \text{and} \quad -k_L \frac{\partial T_L}{\partial z} = -k_S \frac{\partial T_S}{\partial z} \quad \text{at } z = 0$$

$$\frac{\partial T_L}{\partial z} \to 0 \quad \text{as} \quad z \to \infty$$

$$T_S = 0 \quad \text{at} \quad z = -D$$

This problem is solved in the literature[(a)]; the solution is an infinite series:

$$T_S = (S_S - S_L)t \left\{ 1 - 4 \sum_{n=0}^{\infty} a^n \left[i^2\text{erfc}\frac{(2n+1)D+z}{2\sqrt{(\alpha_S t)}} - a\, i^2\text{erfc}\frac{(2n+1)D-z}{\sqrt{(\alpha_S t)}} + \frac{\sigma}{1+\sigma} i^2\text{erfc}\frac{2nD-z}{2\sqrt{(\alpha_S t)}} - \frac{\sigma}{1+\sigma} i^2\text{erfc}\frac{(2n+2)D+z}{2\sqrt{(\alpha_S t)}} \right] \right\}$$

$$T_L = \frac{4(S_S-S_L)t}{1+\sigma} \sum_{n=0}^{\infty} a^n \left[i^2\text{erfc}\frac{2nD+hz}{2\sqrt{(\alpha_S t)}} + i^2\text{erfc}\frac{(2n+2)D+hz}{2\sqrt{(\alpha_S t)}} - 2i^2\text{erfc}\frac{(2n+1)D+hz}{2\sqrt{(\alpha_S t)}} \right]$$

$$\text{where} \quad h = \frac{\alpha_S}{\alpha_L} \qquad \sigma = \frac{hk_L}{k_S} \qquad a = \frac{\sigma-1}{\sigma+1}$$

and where i^2erfc is the second integral of the complementary error function, a tabulated function.

The series provides the temperature rise relative to $T_o + S_L t$. To this we then add $S_L t$ to obtain the temperature rise relative to the initial temperature, $T' - T_o$. The results presented in this form are correct independent of the initial temperature. The results presented in Tables 1 to 6 are for the temperature <u>rise</u> $T' - T_o$, for either the solid (sludge) or liquid (supernate).

(a)H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Second Edition, Oxford University Press, London (1959), Section 12.8(II).

From the infinite series solutions we can also find the amount of heat conducted from the solid to the liquid as a function of time. It is the temperature rise in the liquid relative to $T_0 + S_L t$ times the density and specific heat of the liquid, integrated from the bottom surface of the liquid up to infinity, and multiplied by the area of the surface of the sludge. Since the integration is over z and time is held constant, integration of the infinite series solution for T_L reduces to term-by-term integration of the function i^2erfc. The result is the infinite series

$$Q = (\text{Area})\ \rho_L C_{pL} \frac{4(S_S - S_L)t}{1+\sigma} \frac{2\sqrt{(\alpha_S t)}}{h} \sum_{n=0}^{\infty} a^n \left[i^3\text{erfc}\frac{2nD}{2\sqrt{(\alpha_S t)}} + i^3\text{erfc}\frac{(2n+2)D}{2\sqrt{(\alpha_S t)}} - 2i^3\text{erfc}\frac{(2n+1)D}{2\sqrt{(\alpha_S t)}} \right]$$

where i^3erfc is the third integral of the complementary error function, and is also a tabulated function. These series were implemented by a FORTRAN computer code of about 300 lines documented as the file CP.FOR. The code was verified by repeating part of the calculations ("Tsurf" and "BTU" of Tables 1 to 6, for certain times and cases) using spreadsheet software.

OUTPUT FROM CP.FOR GENERATED AS OF 19-APR-1988 11:26:30 PAGE 47 OF 26

Table 1. Results of Conduction Calculations: Case 1

hrs	Temperature Rise, °F Tctr	Tsurf	Heat Conducted BTU	Fract
5	7.46	1.73	6.030e+04	0.020
10	14.92	3.46	1.700e+05	0.028
15	22.37	5.19	3.130e+05	0.034
20	29.83	6.91	4.820e+05	0.040
25	37.29	8.64	6.740e+05	0.044
30	44.75	10.37	8.860e+05	0.048
35	52.21	12.10	1.120e+06	0.052
40	59.66	13.83	1.360e+06	0.056
45	67.12	15.56	1.630e+06	0.059
50	74.56	17.28	1.910e+06	0.062
55	82.00	19.01	2.200e+06	0.066
60	89.43	20.74	2.500e+06	0.068
65	96.84	22.47	2.820e+06	0.071
70	104.24	24.20	3.160e+06	0.074
75	111.61	25.93	3.500e+06	0.077
80	118.95	27.66	3.860e+06	0.079
85	126.27	29.38	4.220e+06	0.081
90	133.55	31.11	4.600e+06	0.084
95	140.80	32.84	4.990e+06	0.086
100	148.00	34.57	5.390e+06	0.088
105	155.17	36.30	5.800e+06	0.091
110	162.29	38.03	6.220e+06	0.093
115	169.36	39.75	6.650e+06	0.095
120	176.39	41.48	7.080e+06	0.097
125	183.37	43.21	7.530e+06	0.099
130	190.29	44.94	7.990e+06	0.101
135	197.16	46.67	8.450e+06	0.103
140	203.98	48.40	8.930e+06	0.105
145	210.75	50.12	9.410e+06	0.106
150	217.46	51.85	9.900e+06	0.108
155	224.12	53.58	1.040e+07	0.110
160	230.72	55.31	1.090e+07	0.112
165	237.26	57.04	1.140e+07	0.113
170	243.75	58.76	1.190e+07	0.115
175	250.18	60.49	1.250e+07	0.117
180	256.55	62.22	1.300e+07	0.119
185	262.87	63.94	1.360e+07	0.120
190	269.13	65.67	1.410e+07	0.122
195	275.33	67.39	1.470e+07	0.123
200	281.48	69.12	1.520e+07	0.125
205	287.57	70.84	1.580e+07	0.126
210	293.60	72.57	1.640e+07	0.128
215	299.58	74.29	1.700e+07	0.130
220	305.50	76.01	1.760e+07	0.131

225	311.37	77.74	1.820e+07	0.132
230	317.19	79.46	1.880e+07	0.134
235	322.95	81.18	1.940e+07	0.135
240	328.65	82.90	2.000e+07	0.137
245	334.30	84.62	2.070e+07	0.138
250	339.90	86.33	2.130e+07	0.140
255	345.45	88.05	2.190e+07	0.141
260	350.94	89.76	2.260e+07	0.142
265	356.39	91.48	2.320e+07	0.144
270	361.78	93.19	2.390e+07	0.145
275	367.12	94.90	2.460e+07	0.146
280	372.41	96.61	2.520e+07	0.148
285	377.65	98.32	2.590e+07	0.149
290	382.84	100.03	2.660e+07	0.150
295	387.98	101.73	2.730e+07	0.152
300	393.08	103.44	2.800e+07	0.153

Table 2. Results of Conduction Calculations: Case 2

hrs	Temperature Rise, °F Tctr	Tsurf	Heat Conducted BTU	Fract
5	7.46	2.02	7.090e+04	0.023
10	14.92	4.05	2.000e+05	0.033
15	22.37	6.07	3.680e+05	0.040
20	29.83	8.10	5.670e+05	0.046
25	37.29	10.12	7.930e+05	0.052
30	44.74	12.14	1.040e+06	0.057
35	52.19	14.17	1.310e+06	0.061
40	59.62	16.19	1.600e+06	0.066
45	67.02	18.21	1.910e+06	0.070
50	74.39	20.24	2.240e+06	0.073
55	81.72	22.26	2.590e+06	0.077
60	89.00	24.29	2.950e+06	0.081
65	96.22	26.31	3.320e+06	0.084
70	103.38	28.33	3.710e+06	0.087
75	110.47	30.36	4.120e+06	0.090
80	117.49	32.38	4.540e+06	0.093
85	124.43	34.41	4.970e+06	0.096
90	131.30	36.43	5.410e+06	0.099
95	138.08	38.45	5.870e+06	0.101
100	144.78	40.48	6.340e+06	0.104
105	151.40	42.50	6.820e+06	0.107
110	157.93	44.52	7.310e+06	0.109
115	164.38	46.54	7.820e+06	0.111
120	170.74	48.56	8.330e+06	0.114
125	177.01	50.59	8.860e+06	0.116
130	183.21	52.61	9.400e+06	0.118
135	189.31	54.62	9.940e+06	0.121
140	195.34	56.64	1.050e+07	0.123
145	201.27	58.66	1.110e+07	0.125
150	207.13	60.68	1.160e+07	0.127
155	212.91	62.69	1.220e+07	0.129
160	218.60	64.70	1.280e+07	0.131
165	224.22	66.71	1.340e+07	0.133
170	229.75	68.72	1.400e+07	0.135
175	235.21	70.73	1.470e+07	0.137
180	240.59	72.73	1.530e+07	0.139
185	245.90	74.73	1.590e+07	0.141
190	251.14	76.73	1.660e+07	0.143
195	256.30	78.72	1.720e+07	0.145
200	261.39	80.72	1.790e+07	0.147
205	266.40	82.71	1.860e+07	0.149
210	271.35	84.69	1.930e+07	0.150
215	276.23	86.67	1.990e+07	0.152
220	281.05	88.65	2.060e+07	0.154

225	285.79	90.63	2.130e+07	0.155
230	290.47	92.60	2.210e+07	0.157
235	295.09	94.57	2.280e+07	0.159
240	299.65	96.53	2.350e+07	0.160
245	304.14	98.49	2.420e+07	0.162
250	308.57	100.44	2.500e+07	0.164
255	312.94	102.39	2.570e+07	0.165
260	317.26	104.33	2.650e+07	0.167
265	321.51	106.27	2.720e+07	0.168
270	325.71	108.21	2.800e+07	0.170
275	329.86	110.14	2.870e+07	0.171
280	333.94	112.06	2.950e+07	0.173
285	337.98	113.98	3.030e+07	0.174
290	341.96	115.90	3.110e+07	0.176
295	345.89	117.81	3.190e+07	0.177
300	349.77	119.71	3.270e+07	0.179

Table 3. Results of Conduction Calculations: Case 3

hrs	Temperature Rise, °F Tctr	Tsurf	Heat Conducted BTU	Fract
5	7.46	2.91	1.030e+05	0.034
10	14.91	5.82	2.910e+05	0.048
15	22.34	8.73	5.340e+05	0.058
20	29.68	11.64	8.220e+05	0.067
25	36.86	14.55	1.150e+06	0.075
30	43.83	17.46	1.510e+06	0.083
35	50.59	20.37	1.900e+06	0.089
40	57.10	23.27	2.330e+06	0.095
45	63.38	26.18	2.770e+06	0.101
50	69.43	29.08	3.250e+06	0.107
55	75.24	31.97	3.750e+06	0.112
60	80.84	34.85	4.270e+06	0.117
65	86.23	37.73	4.810e+06	0.121
70	91.41	40.59	5.370e+06	0.126
75	96.41	43.43	5.950e+06	0.130
80	101.22	46.26	6.550e+06	0.134
85	105.86	49.07	7.170e+06	0.138
90	110.34	51.85	7.800e+06	0.142
95	114.66	54.62	8.450e+06	0.146
100	118.83	57.36	9.110e+06	0.149
105	122.86	60.08	9.790e+06	0.153
110	126.75	62.78	1.050e+07	0.156
115	130.52	65.44	1.120e+07	0.159
120	134.16	68.08	1.190e+07	0.163
125	137.69	70.70	1.260e+07	0.166
130	141.10	73.29	1.340e+07	0.168
135	144.41	75.85	1.410e+07	0.171
140	147.62	78.38	1.490e+07	0.174
145	150.74	80.88	1.560e+07	0.177
150	153.76	83.36	1.640e+07	0.179
155	156.69	85.80	1.720e+07	0.182
160	159.53	88.22	1.800e+07	0.184
165	162.30	90.61	1.880e+07	0.186
170	164.99	92.98	1.960e+07	0.189
175	167.60	95.31	2.040e+07	0.191
180	170.15	97.62	2.120e+07	0.193
185	172.63	99.90	2.200e+07	0.195
190	175.04	102.16	2.280e+07	0.197
195	177.39	104.38	2.370e+07	0.199
200	179.68	106.58	2.450e+07	0.201
205	181.91	108.76	2.540e+07	0.203
210	184.08	110.91	2.620e+07	0.205
215	186.21	113.03	2.710e+07	0.206
220	188.28	115.13	2.790e+07	0.208

225	190.30	117.20	2.880e+07	0.210
230	192.28	119.25	2.960e+07	0.211
235	194.21	121.27	3.050e+07	0.213
240	196.10	123.27	3.140e+07	0.214
245	197.94	125.25	3.220e+07	0.216
250	199.75	127.20	3.310e+07	0.217
255	201.51	129.13	3.400e+07	0.218
260	203.24	131.04	3.490e+07	0.220
265	204.93	132.93	3.570e+07	0.221
270	206.58	134.79	3.660e+07	0.222
275	208.21	136.64	3.750e+07	0.224
280	209.80	138.46	3.840e+07	0.225
285	211.35	140.26	3.930e+07	0.226
290	212.88	142.05	4.020e+07	0.227
295	214.38	143.81	4.110e+07	0.228
300	215.85	145.55	4.200e+07	0.229

Table 4. Results of Conduction Calculations: Case 4

hrs	Temperature Rise, °F Tctr	Tsurf	Heat Conducted BTU	Fract
5	7.44	4.01	1.420e+05	0.047
10	14.55	8.02	4.020e+05	0.066
15	20.97	12.02	7.390e+05	0.081
20	26.71	15.99	1.140e+06	0.093
25	31.85	19.89	1.580e+06	0.104
30	36.48	23.71	2.070e+06	0.113
35	40.68	27.41	2.600e+06	0.122
40	44.51	30.99	3.150e+06	0.129
45	48.02	34.44	3.730e+06	0.136
50	51.25	37.76	4.330e+06	0.142
55	54.24	40.96	4.950e+06	0.147
60	57.02	44.02	5.580e+06	0.152
65	59.60	46.97	6.220e+06	0.157
70	62.02	49.80	6.870e+06	0.161
75	64.29	52.51	7.530e+06	0.165
80	66.42	55.12	8.200e+06	0.168
85	68.43	57.63	8.870e+06	0.171
90	70.32	60.04	9.540e+06	0.174
95	72.12	62.36	1.020e+07	0.176
100	73.82	64.59	1.090e+07	0.179
105	75.44	66.74	1.160e+07	0.181
110	76.97	68.82	1.230e+07	0.183
115	78.44	70.82	1.300e+07	0.185
120	79.84	72.75	1.360e+07	0.186
125	81.18	74.61	1.430e+07	0.188
130	82.46	76.41	1.500e+07	0.189
135	83.69	78.15	1.570e+07	0.190
140	84.86	79.84	1.640e+07	0.192
145	86.00	81.47	1.700e+07	0.193
150	87.08	83.05	1.770e+07	0.194
155	88.13	84.58	1.840e+07	0.194
160	89.14	86.07	1.900e+07	0.195
165	90.11	87.51	1.970e+07	0.196
170	91.05	88.91	2.040e+07	0.197
175	91.96	90.26	2.100e+07	0.197
180	92.84	91.59	2.170e+07	0.198
185	93.69	92.87	2.240e+07	0.198
190	94.51	94.12	2.300e+07	0.199
195	95.31	95.33	2.370e+07	0.199
200	96.08	96.52	2.430e+07	0.199
205	96.83	97.67	2.500e+07	0.200
210	97.56	98.79	2.560e+07	0.200
215	98.26	99.89	2.620e+07	0.200
220	98.95	100.96	2.690e+07	0.200

225	99.62	102.00	2.750e+07	0.200
230	100.27	103.02	2.810e+07	0.201
235	100.90	104.01	2.880e+07	0.201
240	101.52	104.98	2.940e+07	0.201
245	102.12	105.93	3.000e+07	0.201
250	102.71	106.86	3.060e+07	0.201
255	103.28	107.76	3.130e+07	0.201
260	103.84	108.65	3.190e+07	0.201
265	104.39	109.52	3.250e+07	0.201
270	104.92	110.37	3.310e+07	0.201
275	105.44	111.20	3.370e+07	0.201
280	105.95	112.02	3.430e+07	0.201
285	106.45	112.81	3.490e+07	0.201
290	106.94	113.60	3.550e+07	0.201
295	107.42	114.36	3.610e+07	0.200
300	107.88	115.12	3.670e+07	0.200