GALVANIZING KETTLE LIFE

by

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ABSTRACT

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The prediction of life under varying conditions of stress and temperature is a major problem in the design of machines. Available data are usually obtained in tests under constant, non-varying conditions and test data under varying conditions are usually limited. If variable condition data are available it usually does not exactly correspond to the data required. The designer is then faced with either setting up the necessary test equipment to obtain the necessary data, or establishing a theory to relate steady state data to the variable conditions, or some combination of both.

In this thesis both test equipment and a life-fraction theory were used to determine the design and ultimate life of a galvanizing kettle. The test equipment was used to obtain actual field condition data. This data was then used to determine the constants in the analytical equations used in the design so as to relate actual conditions to theory.

The equations representing temperature, wear rate, static stress, thermal stress and rupture stress fitted with suitable constants to represent the field data are combined by a life fraction theory for a theoretical kettle life. This was done for various kettle designs of different plate thicknesses, plate depths, and heat transfer rates to obtain optimum conditions. The complexity of the problem required computer solution.

For the case involving variable temperature and stress, the life-fraction theory estimates the life by assuming that during any small interval of time the specimen loses some fraction of its life which is independent of the stress and temperature history. Failure occurs when the sum of these fractions is equal to unity. In the case of gradual varying stress or temperature an analytical solution is possible for simple cases. For complex cases of gradual varying stress or temperature or when both stress and temperature vary under simple or complex conditions a computer solution is necessitated to approximate the analytical approach by a number of finite steps.

The basic assumption in this thesis is that once the kettle is loaded and put into service the stress increases gradually and the temperature decreases gradually to failure. Although this assumption is not strictly true, it is on the safe side since any unloading of the kettle will reduce the stress and temperature conditions to safe values and contribute only to the extension of the kettle's life. However, it should be noted that carelessness in the field in the initial start up of the kettle or careless shutdowns or restarts of the kettle can alter the kettle life drastically. Slow start ups and shutdowns are also assumed with no thermal or mechanical shocks.

The importance of knowing the serviceable life of a machine to prevent catastrophic failures cannot be underestimated in these days of increased liability; not withstanding the economics of utilizing materials to the maximum efficiency and economy.

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LIST OF SYMBOLS

SYMBOL	DEFINITION	UNITS OR REFERENCE
a_o	Constant (5 equations-5 unknowns)	See Eq. (123)
a_1	Constant (5 equations-5 unknowns)	See Eq. (123)
a_2	Constant (5 equations-5 unknowns)	See Eq. (123)
a_3	Constant (5 equations-5 unknowns)	See Eq. (123)
a_4	Constant (5 equations-5 unknowns)	See Eq. (123)
A	Moment factor for plates	See Eq. (45)
A_a	Area exposed to heat transfer	$ft.^2$
A_b	Surface area exposed to heat loss	$ft.^2$
A_c	Creep stress correction factor	See Eq. (44)
A_k	Alloy layer heat transfer coefficient on inside of kettle	$btu\text{-}in/ft^2\text{-}hr\text{-}^oF$
A_r	Surface radiation losses	$btu/ft^2\text{-}hr$
A_t	Alloy layer thickness	in.
b	Analogous beam width	in.
b_o	Constant (3 equations-3 unknowns)	See Eq. (100)
b_1	Constant (3 equations-3 unknowns)	See Eq. (100)
b_2	Constant (3 equations-3 unknowns)	See Eq. (100)
B	Kettle width	in.
B_a	Parabolic rate constant	See Eq. (58)
B_b	Constant, independent of temperature	See Eq. (66)
B_c	Constant, characteristic of the reaction	See Eq. (58)
B_d	Constant, independent of temperature	See Eq. (66)
B_e	Constant, chemical reaction, independent of temperature	See Eq. (67)

LIST OF SYMBOLS CONTINUED

SYMBOL	DEFINITION	UNITS OR REFERENCE
B_f	Constant, chemical reaction, independent of temperature	See Eq. (68)
B_g	Constant for rupture life	See Eq. (69)
B_h	Life constant (Class I)	See Eq. (79)
B_i	Life constant (Class II)	See Eq. (81)
B_j	Life constant (Class III)	See Eq. (83)
B_k	Life constant (Class IV)	See Eq. (85)
B_m	Constant, maximum shear theory	See Eq. (71)
B_n	Constant, maximum shear theory	See Eq. (75)
B_o	Constant, characteristic of the reaction	See Eq. (59)
B_p	Constant, time-to-rupture	See Eq. (83)
$b(T_r)$	Constant which is a function of temperature ($\log B_j$)	See Eq. (88)
c	Distance to neutral axis	in.
C	Rupture life factor	See Eq. (135)
d	Beam stress distribution thickness for creep relaxation	See Eq. (44)
D	Kettle depth	in.
e	Exponential function	See Eq. (66)
E	Youngs modulus	psi
f	Function	See Eq. (76)
F	Fraction life	See Eq. (130)
F_L	Fraction life	hours
F_s	Fraction sum	hours
g	Function	See Eq. (77)

LIST OF SYMBOLS CONTINUED

SYMBOL	DEFINITION	UNITS OR REFERENCE
h	Analogous beam height	in.
H'	Zinc conductive heat transfer coefficient	btu-in/ft^2-hr-^{o}F
H	Zinc convective heat transfer coefficient	btu/ft^2-hr-^{o}F
H_t	Distance from plate to thermocouple	in.
I	Moment of inertia	in.^{4}
J	Plate stiffness	See Eq. (37)
K	Overall heat transfer coefficient	btu/ft^2-hr-^{o}F
L	Kettle length	in.
m	Creep relaxation exponent	See Eq. (44)
M	Moment in side plate	in.-lbs.
M_c	Moment correction for creep relaxation	See Eq. (44)
M_o	Moment on bottom plate	See Eq. (48)
M_x	Moment in x direction	See Eq. (36)
M_y	Moment in y direction	See Eq. (36)
n	Attrition rate exponent	See Eq. (59)
P	Side plate thickness	in.
P_k	Steel heat transfer coefficient	btu-in/ft^2-hr-^{o}F
P_s	Mean specific heat of steel	btu/lb-^{o}F
P_w	Weight of steel pipe being processed	lbs/hr.
q	Pressure on bottom of kettle	psi
Q	Heat rate into kettle thru kettle plate	btu/ft^2-hr.

LIST OF SYMBOLS CONTINUED

SYMBOLS	DEFINITION	UNITS OR REFERENCE
Q_L	Total heat losses to atmosphere	btu/hr.
Q_p	Total production heat requirements	btu/hr.
Q_t	Total heat requirement	btu/hr.
r	Rupture life exponent (varying)	See Eq. (135)
R	Reaction	See Fig. (10)
R_a	Reaction	See Fig. (10)
R_b	Reaction	See Fig. (10)
R_e	Exponent for generalized life equation	See Eq. (129)
R_g	Gas constant	See Eq. (66)
R_h	Rupture hours for life	hours
R_{h_1}	Sub-life increment for rupture	hours
R_{h_2}	Sub-life increment for rupture	hours
R_{h_n}	Sub-life increment for rupture	hours
R_s	Rupture life sum	hours
s	Rupture life exponent (constant)	See Eq. (79)
s'	Rupture life exponent (function of stress)	See Eq. (81)
s''	Rupture life exponent (function of temperature)	See Eq. (83)
s'''	Rupture life exponent (function of stress and temperature)	See Eq. (85)
S	Static stress	psi
S_a	Stress varying linearly with time	psi/hr.

LIST OF SYMBOLS CONTINUED

SYMBOLS	DEFINITION	UNITS OR REFERENCE
S_c	Stress modified for creep	psi
S_i	Initial stress, not zero	psi
S_k	Limiting stress	psi
S_s	Actual stress (Static minus thermal)	psi
S_t	Thermal stress	psi
S_x	Stress component in x direction	psi
S_y	Stress component in y direction	psi
S_1	Principal stress	psi
S_2	Principal stress	psi
S_3	Principal stress	psi
t	Time-to-rupture under increasing stress	hours
T	Time increment in hours to rupture life	hours
T_a	Ambient temperature	^{o}F
T_b	Absolute temperature	^{o}ABS.
T_c	Initial temperature, not zero	^{o}F
T_i	Temperature on the inside of the galvanize zinc-iron alloy layer next to the molten zinc	^{o}F
T_m	Temperature on the separating surface between the iron and the alloy	^{o}F
T_o	Skin temperature on outside plate	^{o}F
T_r	Temperature in middle of plate	^{o}F
T_t	Temperature varying linearly with time	^{o}F/hr.

LIST OF SYMBOLS CONTINUED

SYMBOLS	DEFINITION	UNITS OR REFERENCE
T_z	Zinc temperature at thermocouple in the molten zinc	^oF
T_1	Sub-time increments	hours
T_2	Sub-time increments	hours
T_n	Sub-time increments	hours
U	Activation energy	See Eq. (58)
U_a	Energy change, independent of temperature	See Eq. (66)
w	Displacement	in.
W	Zinc density	lbs/ft^3
W_r	Wear rate	in/100 hrs
X	Coordinate axis	
x	x component	
Y	Coordinate axis	
y	y component	
Z	Coordinate axis	
z	z component	
α	Coefficient of expansion	in/in
θ	Slope due to uniform load q	See Eq. (49)
θ_r	Kettle bottom plate angle of rotation	See Eq. (51)
μ	Poissons ratio	See Eq. (33)
ψ	Function	See Eq. (78)

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CHAPTER I

INTRODUCTION

Hot Galvanizing

A galvanizing operation is basically a furnace which heats a kettle full of molten zinc. Steel products, such as pipe, are immersed in this molten zinc. The iron or steel surface must first be thoroughly cleaned and freed from oxide, for which acid pickling (generally by dipping in hot dilute sulfuric acid) is most commonly employed. The clean material is then dipped for a few seconds in molten zinc at a temperature between 840°F to 860°F. Usually the zinc bath is covered with a layer of flux---molten sal ammoniac (NH_4Cl).

The hot galvanized coating is not simply a layer of zinc on iron. Molten zinc alloys readily with iron, by diffusion of iron into the zinc coating, different alloy layers grow outward from the steel base. Micrographs of galvanized material (except electrogalvanized) show an outer zone of zinc, an inner one of iron or steel, and in between these, several zones of zinc-iron alloys rich in zinc. All phases of the iron-zinc constitution diagram are normally present in the coating; with the zeta phase, represented by the composition $FeZn_{13}$, constituting the major portion of the usual alloy layer.

The protection afforded by zinc to galvanized iron or steel is of two kinds: one, the natural protection due to covering with a rustproof metal, and the other arising from the fact that zinc is above iron in the electropotential series of metals, so that even where there is a break or pit in the coating the exposed iron is protected electrochemically. The zinc and iron form a galvanic couple in which minute currents flow from the zinc (anode) to the iron (cathode), relegating oxidation to the zinc surface and maintaining a reducing condition at the iron surface. Since the zinc itself is gradually oxidized, and since the electrochemical action may not be sufficiently strong to overcome severly corrosive conditions, the time and amount of protection afforded by galvanized coatings is approximately proportional to their thickness.

Statement of the Problem

Figure 1 shows a galvanizing operation. The cold pipe (ambient temperature) is fed into the kettle by hand or automatically, and is lifted by a man with a "dipper" hook or automatically, as shown, to the magnetic rolls whereupon it is withdrawn from the kettle. The pipe then goes on to further processing.

Figure 2 shows a cross section through the furnace and kettle. Superimposed over the kettle is the deflection pattern (exaggerated for clarity) caused by the static molten zinc load.

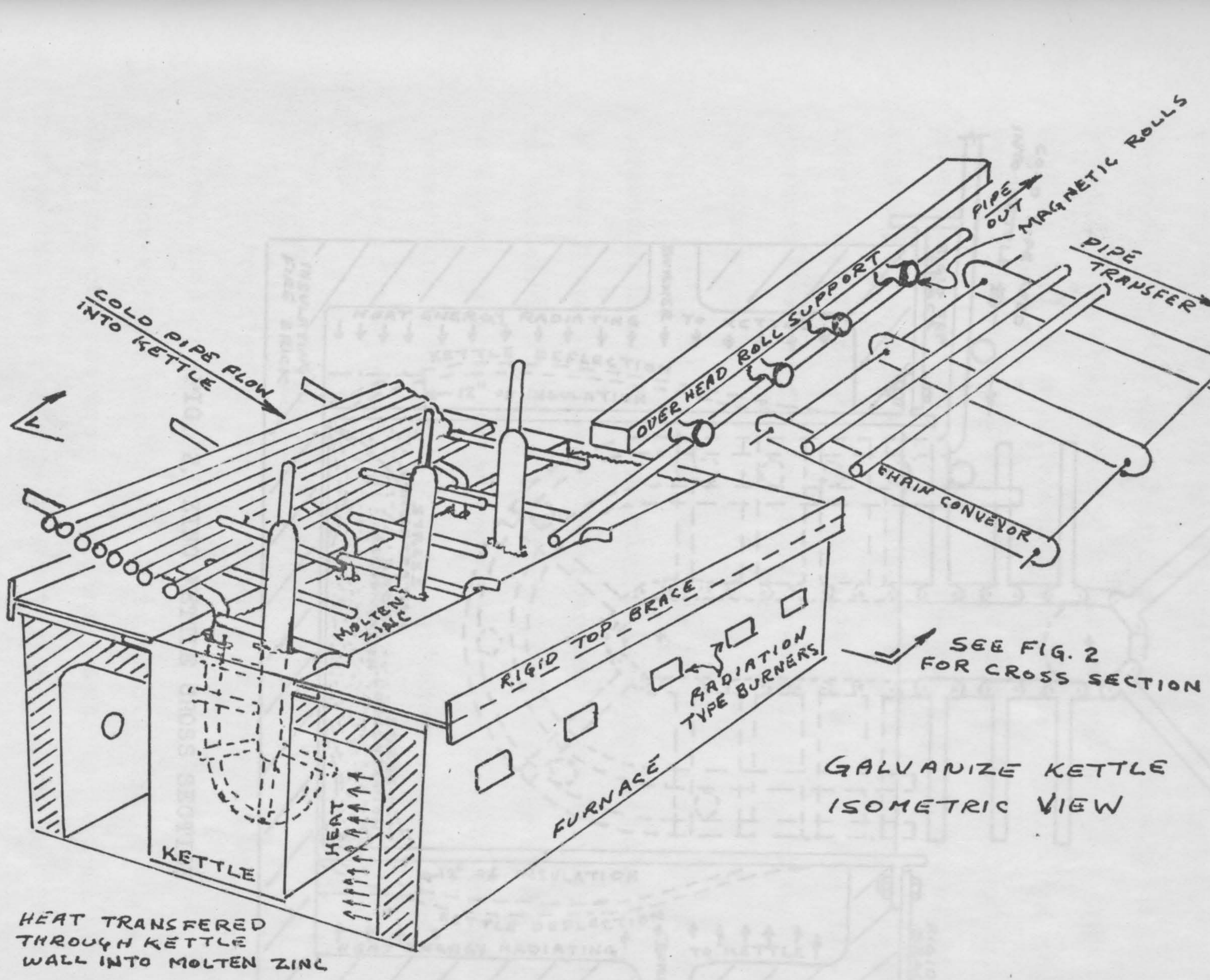

FIG. 1. GALVANIZING OPERATION

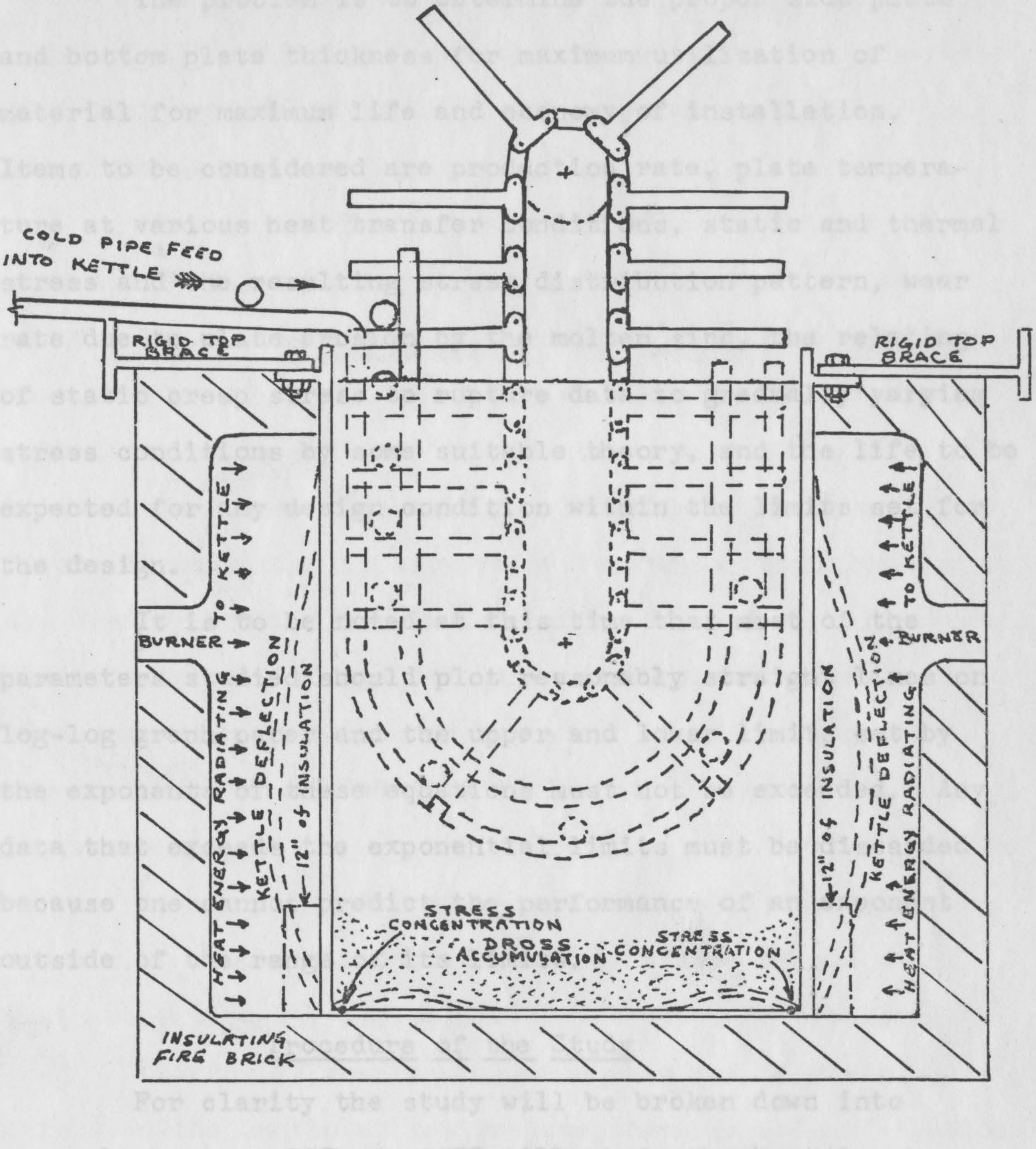

FIG. 2. ZINC KETTLE CROSS SECTION

The problem is to determine the proper side plate and bottom plate thickness for maximum utilization of material for maximum life and economy of installation. Items to be considered are production rate, plate temperature at various heat transfer conditions, static and thermal stress and the resulting stress distribution pattern, wear rate due to plate erosion by the molten zinc, the relating of static creep stress to rupture data to gradually varying stress conditions by some suitable theory, and the life to be expected for any design condition within the limits set for the design.

It is to be noted at this time that most of the parameters studied should plot reasonably straight lines on log-log graph paper and the upper and lower limits set by the exponents of these equations must not be exceeded. Any data that exceeds the exponential limits must be discarded because one cannot predict the performance of an exponent outside of the range of its limits.

Procedure of the Study

For clarity the study will be broken down into several chapters. Chapter II will study the heat input rate for various production rates. This chapter will also study the temperatures at various points in various plates due to the heat input rate and lay the foundation for Chapter III and Chapter IV. Basic heat convection and conduction equations are used and general equations are written to represent the specific problem at hand.

Although it is common knowledge that heat conduction and convection coefficients vary with temperature, it is assumed that they are constant within the range prescribed; as is often the case.

Chapter III studies stress due to the static molten zinc load and stress due to the thermal gradient in the plate. The static stress in the plate is derived from a beam analogy of the plate stress at the mid-point of the galvanize kettle and the thermal stress is derived from basic thermal stress equations. The effect of the combined stress distribution is surveyed with stress reduction due to St. Venants Principle being accounted for. The yield stress, ultimate stress, Youngs Modulus and other mechanical properties vary with temperature; but shall be assumed constants for the range specified. General equations are written to represent the data.

An analysis of the stress concentration at the lower corners of the kettle is made and the effect of the side plate moment on the bottom plate evaluated and discussed.

Chapter IV studies the wear rate due to the zinc attack on the kettle at various temperatures and an equation is derived from field data representing these conditions. In this case the wear rate is variable within the range specified. This is a precise part of the problem because the range of the wear rate is great in the temperature range prescribed.

Chapter V predicts creep rupture time by assuming the maximum shear stress theory as the creep rupture criterion. From this is deduced the form of the correlation between stress, temperature and time-to-failure for static test data derived experimentally. A review of various classes of data are presented and general equations representing the various forms presented. At this point, had our problem been static and not gradually varying, a solution would have been found for time-to-failure by appropriately substituting the general equation for temperature derived in Chapter II and the general equation for stress derived in Chapter III into the general equation for time-to-failure derived in Chapter V. However, due to the fact that our temperature and stress is gradually varying an additional theory is required to relate the static data previously derived to the gradually varying condition caused by the kettle thinning due to wear by the zinc attack.

Chapter VI predicts the life of the kettle by assuming the life-fraction theory. Analytical solutions are presented for simple cases and a computer solution is presented for this complex case. Individual computer solutions are given for production rate, temperature, static stress, thermal stress and wear rate and a program is presented for the solution of up to nine equations with nine unknowns for the evaluation of the exponents of the static time-to-rupture equations. Parts of the above individual programs are then used to make up the master program for calculating the gradually varying time-to-rupture life.

It should be noted that the symbols used in the derivation of the general equations such as "T_i" (temperature of zinc-iron alloy next to molten zinc) appear as "TI" in the computer program to minimize confusion. This notation procedure will be used throughout this thesis unless noted otherwise.

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CHAPTER II

METHOD OF CALCULATING HEAT RATES

Introduction

The galvanizing kettle functions as a means of transferring heat received from the combustion system of the furnace to the molten zinc in the kettle. The energy is transferred to where it is used by passing through the heated steel wall between the source of the heat and the molten metal. It is important to know the laws which govern the flow of energy through the wall because this energy rate governs the wall temperatures which in turn govern the mechanical and life properties of the kettle.

The internal surface of a traditional iron kettle or "pot" as it is sometimes called, is covered with a zinc iron alloy, the thickness of which varies with the thermal conditions and the way the kettle is operated. Thus the kettle wall may be considered to consist of two layers with different conductivities, if we neglect the possible, but unlikely, build up of corrosion on the outside of the kettle plate due to contact with the hot gases. Field experience indicates this to be a valid assumption for gas fired furnaces.

Theory for Determination of Heat Rate Constants

The equation for steady state, one dimensional heat transfer by conduction and convection can be found in any standard engineering heat transfer text and for the case under consideration is given by:[1]

$$Q = K\ (T_o - T_z) \qquad (1)$$

In the case under consideration, steady state conditions are maintained for the determination of the required constants. The heat transfer rate, Q, is calculated from the load conditions on the kettle. The plate skin temperature, T_o, next to the combustion chamber, is measured experimentally by a thermocouple attached (by welding) to the surface. The molten zinc temperature, T_z, is measured by a thermocouple in the molten zinc. From this experimentally determined data the overall heat transfer coefficient, K, is determined.

The heat transfer coefficient, K, is defined in any standard engineering text on heat transfer and for the case under consideration is given by:[2]

$$K = \frac{1}{P/P_k + A_t/A_k + 1/H} \qquad (2)$$

For this case, P, is the thickness of the plate; P_k is the heat conduction coefficient of the plate material as

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[1] Alan J. Chapman, Heat Transfer (2nd ed.: New York: MacMillan Company, 1967), p. 473.

[2] Chapman, Heat Transfer, p. 472.

determined from tables; A_t is the thickness of the representative samples measured in the field; H is the convective heat transfer coefficient between the side plate and the molten zinc (established experimentally).[3] The heat conduction rate, A_k, can then be determined.

The unit heat transfer rate Q in BTU/FT^2-HR may be defined as:

$$Q = Q_t/A_a \tag{3}$$

where Q_t is the total heat requirement in BTU/HR and A_a is the total area exposed to heat transfer in square feet. The total heat transfer, Q_t, required is:

$$Q_t = Q_p + Q_L \tag{4}$$

where Q_p is the heat required in BTU/HR to heat the production load and Q_L is the heat required in BTU/HR for heat losses to the atmosphere. The heat loss Q_L may be defined:

$$Q_L = (A_r)(A_b) \tag{5}$$

where A_b is the zinc surface area in square feet and A_r is the radiation loss in BTU/FT^2-HR (determined experimentally).[4] The production heat requirement Q_p may be calculated from standard specific heat calculations at the production rate

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[3] I. Nizzola, <u>Heat Transfer Through The Walls of a Galvanizing Pot</u> (Edited proceedings 8th International Conference on Hot Dip Galvanizing at London in June, 1967: Edited by the Zinc Development Association, London: Industrial Newspapers Limited, 1969) pp. 157-168.

[4] R. W. Baily, <u>Thermal Considerations in Heating Galvanizing Baths</u> (Edited proceedings First International Conference on Hot Dip Galvanizing at Copenhagen in July, 1950: Edited by The Zinc Development Association, London: Industrial Newspapers Limited, 1968) p. 29.

in pounds per hour at the selected temperature of the zinc bath and we have:

$$Q_p = (P_s)(P_w)(T_z - T_a) \qquad (6)$$

where P_s is the mean specific heat in BTU/LB-°F,[5] P_w is the production rate in pounds, T_a is the temperature of the pipe being charged into the kettle in degrees Fahrenheit, T_z is the molten zinc temperature in degrees fahrenheit.

Calculations for the Determination of Heat Rate Constants

For these calculations a pipe galvanizing kettle 5 feet wide, 6 feet deep and 25 feet long inside dimensions, with side and bottom plates 2 inches thick will be used. The kettle is made of galvanizing quality A-285 fire box steel (.10% maximum carbon) and is not supported anywhere along its length except at the top and bottom as shown in Figure 2 in Chapter I. The molten zinc bath is held at 840°F and pipe at the steady rate of 32,000 pounds per hour is processed. The estimated heat loss, Q_L, from the surface of the zinc bath is 2,000 BTU/FT^2-HR.[6] From equation (5) we have:

$$Q_L = (2{,}000 \text{ BTU/FT}^2\text{-HR})(5 \text{ FT})(25 \text{ FT}) = 250{,}000 \text{ BTU/HR} \qquad (7)$$

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[5] Chapman, Heat Transfer, p. 557.

[6] Baily, Thermal Considerations in Heating Galvanizing Baths, p. 29.

[7]The mean specific heat for steel is 0.14 BTU/LB-$^\circ$F and the pipe is charged into the kettle at 60°F and brought up to the 840°F temperature of the bath (usual practice) before it is removed. From equation (6) we have:

$$Q_p = (0.14\ \text{BTU/LB-}^\circ\text{F})(32{,}000\ \text{LB/HR})(840 - 60^\circ\text{F}) \qquad (8)$$

and $$Q_p = 3{,}494{,}000\ \text{BTU/HR} \qquad (9)$$

The sum of equations (8) and (9) is the total heat required or $$Q_p = 3{,}494{,}000 + 250{,}000 = 3{,}744{,}000\ \text{BTU/HR} \qquad (10)$$

From Figure 2, Chapter I, the effective exposed height of plate for heat transfer is 4.5 feet and the effective length is 25 feet. We then have 112.5 square feet of effective heat transfer area for one side or a total of 225 square feet for both sides. From equation (3):

$$Q = 3{,}744{,}000/225 = 16{,}640\ \text{BTU/FT}^2\text{-HR} \qquad (11)$$

Any production rate can be calculated for any heat rate as demonstrated above by hand. The calculations for Table 1 were done by computer and the program can be found in Appendix A. The surface radiation losses are 2000, 2100, 2200 and 2300 BTU/FT^2-HR for 840, 850, 860 and 870°F kettle molten zinc temperatures, respectively. All other values are constants as determined above.

From the type K,[8] chromel-alumel twisted wire type thermocouple, which was welded to the outside of the kettle

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[7] Chapman, Heat Transfer, p. 557.

[8] ASTM STP 470, Manual On the Use of Thermocouples In Temperature Measurement (Philadelphia: ASTM, 1970) pp. 136-147.

TABLE 1

GALVANIZING KETTLE HEAT RATE VERSUS KETTLE TEMPERATURE FOR PRODUCTION IN POUNDS FOR 225 SQUARE FOOT HEAT TRANSFER AREA

Heat Rate (Q)	Production Rate in Pounds (P_w)[a]			
BTU/FT^2-HR	840°F	850°F	860°F	870°F
8000.0	14194.1	13901.4	13616.1	13337.7
9000.0	16254.6	15935.8	15625.0	15321.9
10000.0	18315.0	17970.2	17633.9	17306.0
11000.0	20375.5	20004.5	19642.9	19290.1
12000.0	22435.9	22038.9	21651.8	21274.3
13000.0	24496.3	24073.2	23660.7	23258.4
14000.0	26556.8	26107.6	25669.6	25242.5
15000.0	28617.2	28142.0	27678.6	27226.6
16000.0	30677.7	30176.3	29687.5	29210.8
17000.0	32738.1	32210.7	31696.4	31194.9
18000.0	34798.5	34245.0	33705.4	33179.0
19000.0	36859.0	36279.4	35714.3	35163.1
20000.0	38919.4	38313.8	37723.2	37147.3

[a] See Appendix A For Computer Program and Data Used.

plate next to the combustion chamber at the maximum stress location (to be presented in Chapter III), a reading of 999°F was obtained for T_o at the steady state conditions presented previously. From equation (1):

$$16640 = K(999 - 840^{\circ}F) \qquad (12)$$

then:

$$K = 104.65 \text{ BTU/FT}^2\text{-HR-}^{\circ}F \qquad (13)$$

Knowing the value for K, the overall heat transfer coefficient, we can now calculate A_k for the zinc-iron alloy layer. From equation (2) we have:

$$K = \frac{1}{P/P_k + A_t/A_k + 1/H} \qquad (14)$$

The units thereof are listed on the next page.

P = Plate Thickness = 2 Inches
P_k = Steel Heat Trans. Coeff. = 320 BTU-IN/FT^2-HR-$^\circ$F[9]
A_t = Alloy Layer Thickness = .125 Inches (Normal Case)
A_k = Alloy Heat Trans. Coeff. To Be Calculated
H = Convection Coeff. For Zinc = 500 BTU/FT^2-HR-$^\circ$F[10]
K = Overall Coeff. Calculated Above

We can now calculate A_k

$$104.65 = \frac{1}{2/320 + .125/A_k + 1/H} \qquad (15)$$

then $$A_k = 95.72 \text{ BTU-IN/FT}^2\text{-HR-}^\circ\text{F} \qquad (16)$$

The value will be rounded off to A_k=96.

The above data has established all the constants necessary to calculate the temperature at any point in the plate for any heat transfer value, Q, assumed. The calculations are simple but tedious, a computer program for evaluating the temperature distribution across the plate was written and it can be found in Appendix B. Table 2 shows the temperature distribution under various conditions and a discussion thereof follows.

Temperature Analysis

When the galvanizing operation is running under normal conditions at 850°F maximum zinc temperature in the kettle, a .125 inch alloy layer is built up on the inside surface of the plate. Convection conditions prevail becuase of

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[9] Babcock and Wilcox, Steam, Its Generation and Use (37th ed: New York: McKibbin and Son, 1955) p. 71.

[10] Nizzola, Heat Transfer Through The Walls of A Galvanizing Pot, p. 136.

TABLE 2

TEMPERATURE DISTRIBUTION FOR DIFFERENT ALLOY LAYER THICKNESS IN A 2 INCH PLATE WITH ZINC TEMPERATURE IN KETTLE HELD AT 850°F UNDER RUNNING CONDITIONS AND STOPPED CONDITIONS.[b]

Input Heat Rate Q	.125 Layer Temperature					.250 Layer Temp.		.500 Layer Temp.	
	Run TO	TR	TM	TI	Stop TO	Run TO	Stop TO	Run TO	Stop TO
	Col.1	Col.2	Col.3	Col.4	Col.5	Col.6	Col.7	Col.8	Col.9
8000	926.4	901.4	876.4	866.0	950.0	937	960	958	991
9000	936.0	907.8	879.7	868.0	962.5	948	974	971	998
10000	945.5	914.3	883.0	870.0	975.0	958	988	985	1014
11000	955.1	920.7	886.3	872.0	987.5	969	1002	998	1030
12000	964.6	927.1	889.6	874.0	1000.0	980	1016	1011	1047
13000	974.2	933.6	892.9	876.0	1012.5	991	1029	1025	1063
14000	983.7	940.0	896.2	878.0	1025.0	1002	1043	1038	1080
15000	993.3	946.4	899.5	880.0	1037.5	1013	1057	1052	1096
16000	1002.8	952.8	902.8	882.0	1050.0	1024	1071	1065	1112
17000	1012.4	959.3	906.1	884.0	1062.5	1035	1084	1079	1129
18000	1021.9	965.7	909.4	886.0	1075.0	1045	1098	1092	1145
19000	1031.5	972.1	912.7	888.0	1087.5	1056	1112	1106	1162
20000	1041.0	978.5	916.0	890.0	1100.0	1067	1126	1119	1178

[b] See Appendix B For Computer Program and Data Used.

the movement of the work through the bath and the various outside plate temperatures at the corresponding heat rate is shown in Col. 1 of Table 2. When the galvanizing plant is stopped, the convection coefficient H, becomes a conduction coefficient (404.4 BTU-IN/FT^2-HR-°F)[11] and the factor (1/H) becomes (2/404.4) where the "2" is the distance from the thermocouple in the molten zinc bath to the inside of the kettle plate in inches. The temperature under these conditions is shown in Col. 5 of the Table and note that the running temperature is 1002.8°F and the stopped temperature is

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[11] Chapman, <u>Heat Transfer</u>, p. 572.

1050.0°F, a difference of 47.2°F for a heat input of 16,000 BTU/SQ FT-HR. Col. 6 through Col. 9 shows the effects on temperature when the kettles are not operated or maintained properly and the zinc-iron alloy layer is allowed to build up to a .250 inch layer and then to a .500 inch layer. An inspection of Table 2 shows that when the kettle is stopped with a .500 inch layer build up the temperature goes up to 1112°F for a 16,000 BTU input. For a 20,000 BTU input it becomes 1178°F, a very dangerous condition because the kettle will become overheated as explained in the following paragraph.

Hot-rolling develops in the steel a pearlitic microstructure which consists of alternate plates of iron and iron carbide. If the steel is heated for an extended period of time in the temperature range of 1200-1300°F, this plate-like pearlitic structure will change to one that consists of small spheres of iron carbide in the steel matrix. This type of microstructure is called "spheroidized" and is of enlargening grain structure and a general weakening of the steel is experienced. It is not a good practice to allow the outside of the steel plate to exceed 1100°F for this reason. The prime cause of kettle overheating is the build-up of the kettle alloy layer and the accumulation of "dross" in the kettle. Dross is minute particles of zinc iron alloy formed by the constant alloying and eroding of the iron kettle by the molten zinc and also from the alloying action of the zinc on the iron pipe as it moves through the bath.

Therefore, minute particles of iron are constantly going into solution with the molten zinc and settling on the bottom and sides of the kettle. If the kettle is improperly operated by not removing this settlement (called dross), the alloy layer on the sides of the kettle increases in thickness and thereby increases the kettle plate temperature and shortens kettle life.

The temperature, T_r, gives the value of the temperature at the midpoint of the 2" plate or, if the plate had eroded down to a thickness of 1", this would be the temperature of the outside surface of the plate when it was 1" thick. This temperature, T_r, is also important in the derivation of the stress to rupture equation in Chapter V because the exponent in that equation is a function of this temperature. In other words, if this temperature, T_r, lies outside the range of the exponent derived, then that particular life calculation is invalid.

The temperature, T_m, is important in the calculation of the wear rate, since it is at this surface that the erosion of the kettle surface takes place. The temperature, T_1, is the temperature of the molten zinc at the surface of the zinc-iron alloy layer. These temperatures are very important in determining the range of the mechanical properties of the kettle steel and form the foundation for Chapter III.

In order to obtain a mental picture of Table 2, Figure 3 is plotted for a plate 2 inches thick, alloy layer .125 inches thick and a molten zinc temperature of 840°F

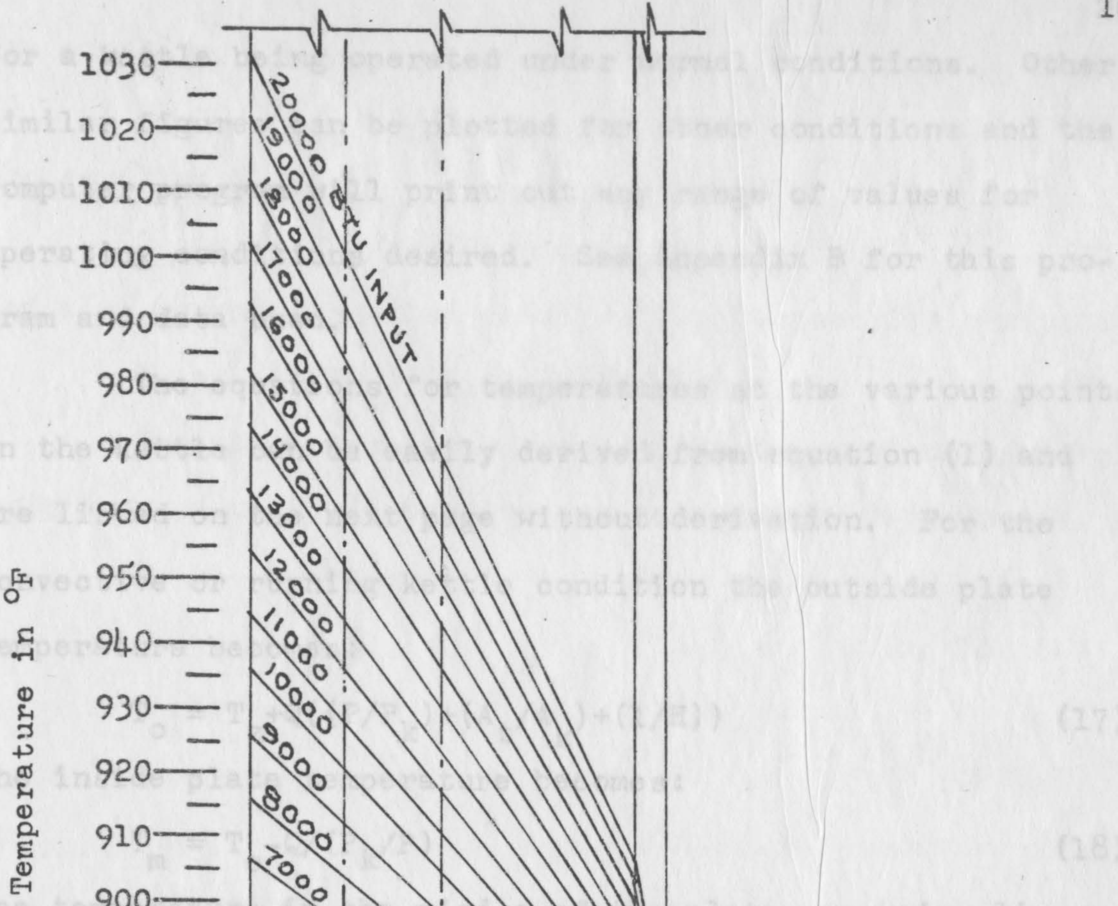

Fig. 3. Galvanize Kettle Temperature Distribution Across The Kettle Plate Wall Including Heat Rate At Various Temperatures With Kettle Zinc Temperature At 840°F.

for a kettle being operated under normal conditions. Other similar figures can be plotted for other conditions and the computer program will print out any range of values for operating conditions desired. See Appendix B for this program and data used.

The equations for temperatures at the various points in the kettle can be easily derived from equation (1) and are listed on the next page without derivation. For the convective or running kettle condition the outside plate temperature becomes:

$$T_o = T_z+Q((P/P_k)+(A_t/A_k)+(1/H)) \tag{17}$$

The inside plate temperature becomes:

$$T_m = T_o-Q/(P_k/P) \tag{18}$$

The temperature in the middle of the plate, assuming linear temperature gradient becomes:

$$T_r = (T_o+T_m)/2 \tag{19}$$

The temperature on the inside of the alloy layer becomes:

$$T_i = T_m-Q/(A_k/A_t) \tag{20}$$

Now as the kettle stops, equation (17) becomes:

$$T_o = T_z+Q((P/P_k)+(A_t/A_k)+(H_t/H')) \tag{21}$$

Where H_t is the distance from the plate to the thermocouple in the molten zinc and H' is the conductive heat transfer coefficient. If the heat rate for any equation is desired they become for equation (17):

$$Q = (T_o-T_z)/((P/P_k)+(A_t/A_k)+(1/H)) \tag{22}$$

For equation (18):

$$Q = (T_o-T_m)(P_k/P) \tag{23}$$

For equation (20):

$$Q = (T_m - T_i)(A_k/A_t) \tag{24}$$

For equation (21):

$$Q = (T_o - T_z)/((P/P_k)+(A_t/A_k)+(H_t/H')) \tag{25}$$

And also remembering that equation (2) becomes for conduction:

$$K = 1/((P/P_k)+(A_t/A_k)+(H_t/H')) \tag{26}$$

The above equations are used in the various computer programs and their derivation can be found in Reference 1.

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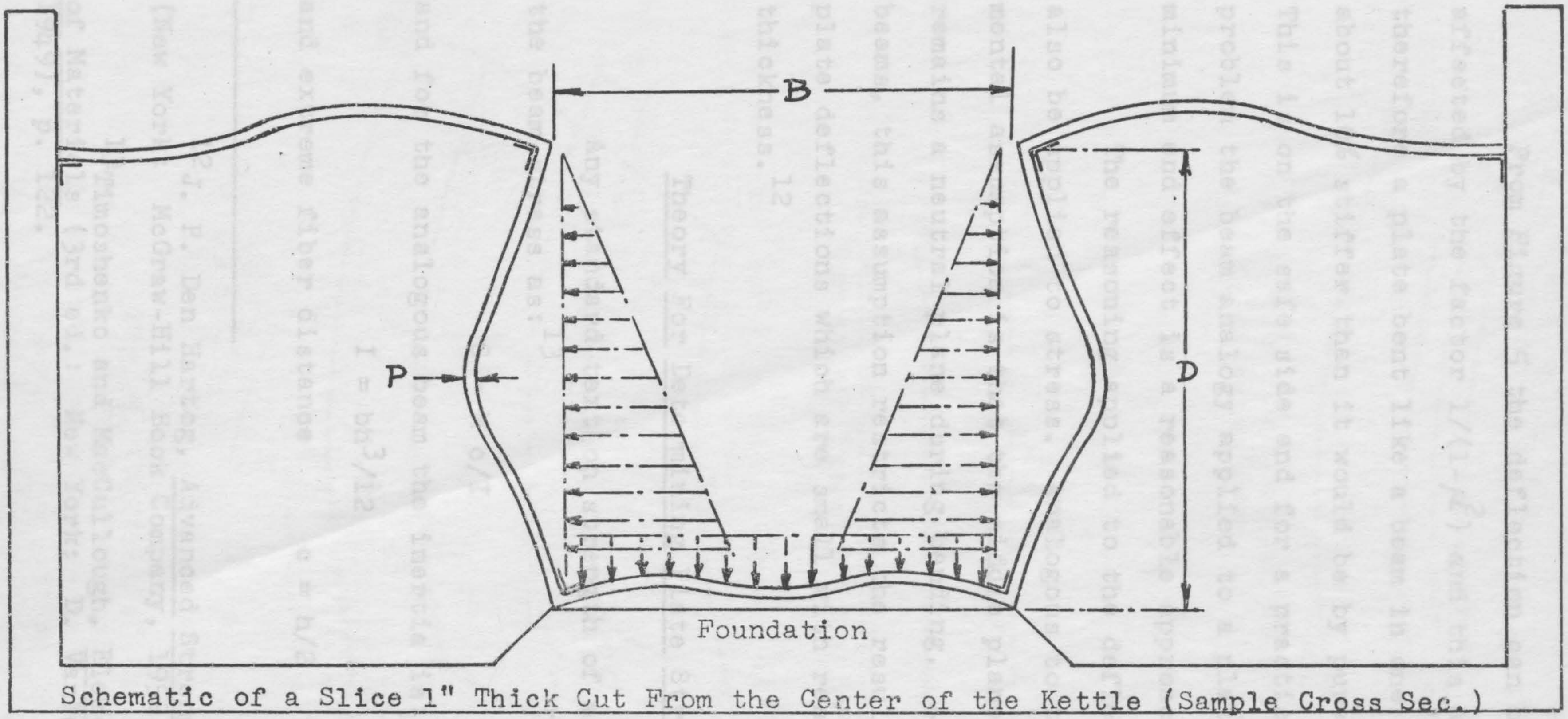
CHAPTER III

METHOD OF CALCULATING PLATE STRESS

Introduction

An important equation in the bending of straight beams states that the bending moment equals the stiffness (EI) times the curvature d^2y/dx^2 of the "Neutral Line" of that beam. Plates are a two dimensional generalization of beams and when the end effect (twist) of the plate becomes negligible in one dimension, the plate assumes the approximate curvature of a simple beam in the other dimension. For example, take a long, deep, galvanizing kettle with a length equal to four times its depth. If a one inch thick vertical slice is taken from the center of the kettle and the loading superimposed on the beam analogy as shown in Figure 4, the equations relating to simple beam theory reasonably relate to the beam analogy also. The deflections are exagerated for clarity in Figure 4.

The main reason for a slight difference is a stiffening effect on the deflection curve caused by the fact that the analogous beam section cut from the center section cannot escape the stress effect caused by the end restraint on the kettle and therefore the analogous beam cannot change its cross section antielastically like the beam which is free.



Schematic of a Slice 1" Thick Cut From the Center of the Kettle (Sample Cross Sec.)

Assumptions:
1). This 1" Slice Constitutes Our Worst Loading Condition.
2). Indeterminant Structural Analysis Applies To 1" Thick Slice.
3). Moments Determined By Hardy Cross Method Can Be Applied To Plate Stress Formulas. Plate & Shell Formulas Obtained By Timoshenko Are Valid and Can Be Reduced To Simple Beam Formulas.
4). The End Effects of the Kettle Are Negligible At the Kettles Midpoint.
5). Kettle is 4 Times As Long As It Is Deep and Is Deeper Than It Is Wide.

Fig. 4. Free Standing Kettle Analysis

From Figure 5 the deflection can be seen to be affected by the factor $1/(1-\mu^2)$ and this amounts to 1.10, therefore a plate bent like a beam in one plane only is about 10% stiffer than it would be by pure beam action. This is on the safe side and for a practical engineering problem the beam analogy applied to a plate at a point of minimum end effect is a reasonable approach.

The reasoning applied to the deflections above can also be applied to stress. Analogous to the beam, a fundamental assumption is that the middle plane of the plate remains a neutral plane during bending. As in the case of beams, this assumption restricts the results (in general) to plate deflections which are small with respect to the plate thickness.[12]

Theory For Determining Plate Stress

Any standard text on strength of materials derives the beam stress as:[13]

$$S = M\,c/I \tag{27}$$

and for the analogous beam the inertia is:

$$I = bh^3/12 \tag{28}$$

and extreme fiber distance $c = h/2$ (29)

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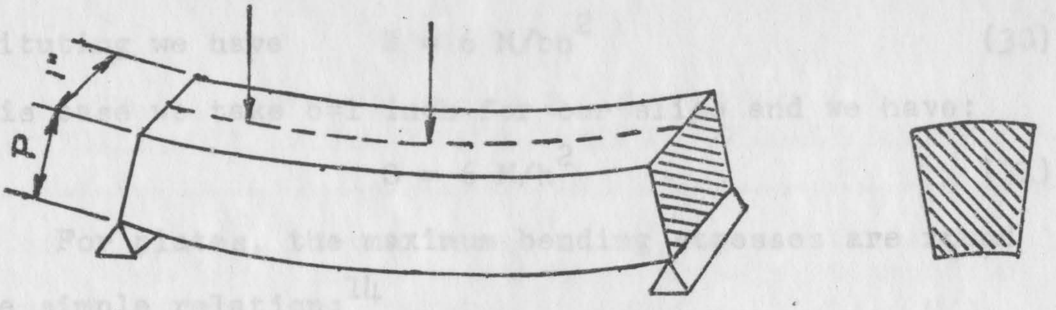
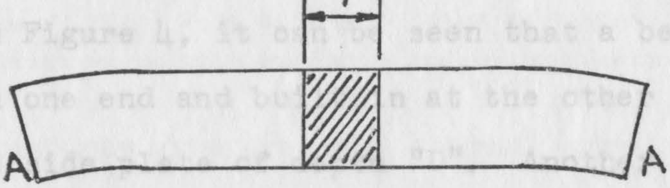
[12] J. P. Den Hartog, Advanced Strength of Materials (New York: McGraw-Hill Book Company, 1952), pp. 113-114.

[13] Timoshenko and MacCullough, Elements of Strength of Materials (3rd ed.: New York; D. VanNostrand Company, 1949), p. 122.



a). Vertical Section And Antielastic Curvature Of Analogous Beam.



b). Center Section With Restrained Antielastic Curvature (Except At The Ends).

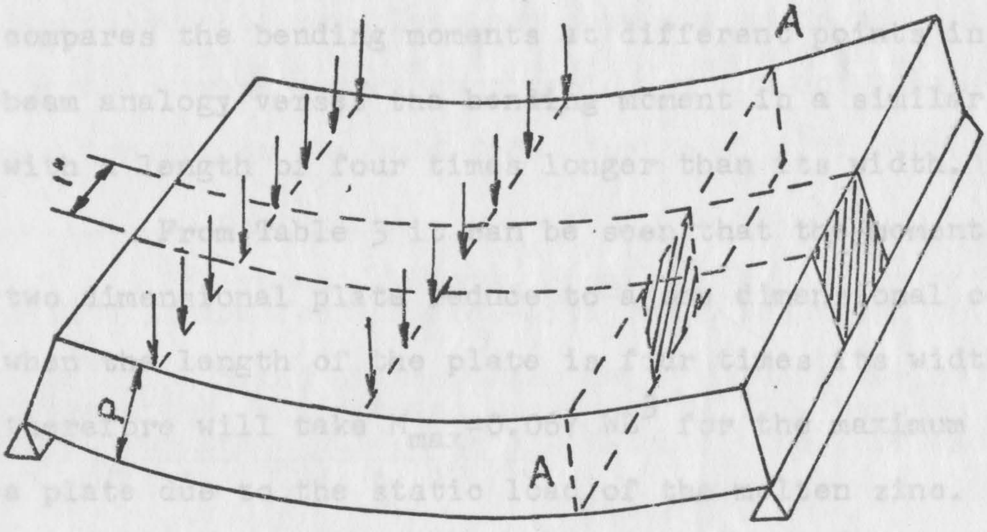


Fig. 5. A Beam "a" And A Unit Width Strip Of Plate "b" Under Identical Bending Loads. Because In Case "b" The Antielastic Curvature Is Prevented, The Stiffness "b" Is Greater Than The Stiffness "a" By A Factor Of $1/(1-\mu^2)$, Which Is About 10 Percent.

substituting we have $S = 6\ M/bh^2$ (30)

in this case we take b=1 inch for our slice and we have:

$$S = 6\ M/h^2 \tag{31}$$

For plates, the maximum bending stresses are found by the simple relation:[14]

$$S_{x(MAX)}=6\ M_{xMAX)}/P^2 \text{ and } S_{y(MAX)}=6\ M_{y(MAX)}/P^2 \tag{32}$$

where P is plate thickness. This can be seen to conform to the stress equation (31) for simple beams where h=P.

From Figure 4, it can be seen that a beam simply supported on one end and built in at the other would be an analogy to a side plate of depth "D". Another analogy would be a beam built in at both ends. The actual truth lies somewhere between the two analogies. Table 3 on the next page compares the bending moments at different points in the above beam analogy verses the bending moment in a similar plate with a length of four times longer than its width.

From Table 3 it can be seen that the moments in a two dimensional plate reduce to a one dimensional condition when the length of the plate is four times its width. We therefore will take $M_{max}=0.067\ WL^3$ for the maximum stress in a plate due to the static load of the molten zinc. This will insure that we are on the safe side with our moment, since the method of supporting the top edge of the plate will lie somewhere between a rigid support and a simple support under various design and installation conditions.

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[14] Den Hartog, Advanced Strength of Materials, p. 111.

TABLE 3

PLATE VS. BEAM BENDING MOMENT COMPARISON ONE END FIXED, ONE END SUPPORTED, HYDROSTATICALLY LOADED

Position From Simply Supported End	Beam[15] One End Fixed One End Supported	Plate, Three Edges Built In, Fourth Edge Simply Supported[16]	Plate, Three Edges Simply Supported Fourth Edge Built In[17]	Plates Clamped On All Four Edges[18]
X=0	M=0	M=0	M=0	$M=0.0333\ WL^3$
X=L/2	$M=.029WL^3$	$M=0.029\ WL^3$	$M=0.029\ WL^3$	$M=0.0208\ WL^3$
X=L	$M=.067WL^3$	$M=0.067\ WL^3$	$M=0.067\ WL^3$	$M=0.0500\ WL^3$

We must now consider the thermal stresses involved in heating one side of the plate. An analysis of the problem shows that the static zinc load will produce tension on the outside of the plate and compression on the inside. The thermal stress causes compression on the hot face (outside) and tension on the cold face (inside). [19]Timoshenko gives

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[15] Raymond J. Roark, *Formulas For Stress and Strain* (4th ed.: New York: McGraw-Hill Book Company, 1965), p. 110.

[16] United States Department of the Interior Bureau of Reclamation, Engineering Monograph No. 27, *Moments and Reactions For Rectangular Plates*, (Washington: Government Printing office, 1970), p. 19.

[17] Timoshenko, *Theory of Plates and Shells*, (2nd Ed.: New York: McGraw-Hill Book Company, 1959), p. 196.

[18] Timoshenko, *Theory of Plates and Shells*, pp. 202-204.

[19] Timoshenko, *Theory of Plates and Shells*, p. 50.

the maximum thermal stress as:

$$S_t = \alpha E(T_o - T_m)/2(1-\mu) \tag{33}$$

where the following constants are for a temperature range of 800 to 1100°F

α = Coeff. of Expansion = 0.798×10^{-5} @ 950°F
μ = Poissons Ratio = 0.3
E = Youngs Modulus = 16.3×10^6 psi @ 950°F
T_o = Temperature on hot face in °F
T_m = Temperature on cold face in °F

Regarding the stresses in a plate undergoing pure bending due to a linear temperature variation across its thickness; the plate would normally assume a spherical curvature and would produce no stresses provided the edges are free and deflections small in comparison to the thickness. If the edges are fixed, the plate will be held flat by uniform edge moments and the maximum resulting bending stress will be as given in equation (33) in two dimensions. This thesis however is limited to uniaxial stress, and the thermal stress is neglected in the horizontal direction. The justification for this assumption being that the plate is not so rigidly held at the ends of the kettle and the kettle is relatively free to move along its length; however, the top and bottom edge are more rigidly held and thermal stresses develop. A fixed plate uniformly held along all its edges is held in a biaxial stress state. The equation (32) also represents this condition of thermal stress and is given by:

$$S_{x(MAX)} = -6\, M_{x(MAX)}/P^2 \tag{34}$$

and

$$S_{y(MAX)} = -6\, M_{y(MAX)}/P^2 \tag{35}$$

where M_x and M_y are the moments of the biaxial thermal stress state and for plates uniformly clamped along all edges:

$$M_x = M_y = M = (T_o - T_m)(J)(1+\mu)/P \qquad (36)$$

where the plate stiffness is:

$$J = E\,P^3/12(1-\mu^2) \qquad (37)$$

If the principle stresses are of opposite sign, the maximum shearing stress acts in the plane bisecting the angle between the "xz" and "yz" planes and is equal to:

$$\text{Maximum shearing stress} = 1/2(S_{x(MAX)} - S_{y(MAX)}) \qquad (38)$$

If the principle stresses are of the same sign, the maximum shear acts in the plane bisecting the angle between the "xy" and "xz" planes or in that bisecting the angle between "xy" and "yz" planes and is equal to:

$$\text{Maximum shearing stress} = \tfrac{1}{2}\, S_{x(MAX)} \qquad (39)$$

or

$$\text{Maximum shearing stress} = \tfrac{1}{2}\, S_{y(MAX)} \qquad (40)$$

depending on which of the two principal stresses "$S_{x(MAX)}$" or "$S_{y(MAX)}$" is greater. By assuming uniaxial stress the inference is that:

$$S_1 > S_2 > S_3 \qquad (41)$$

and the governing equation is:

$$S_1 - S_2/2 = \text{Maximum shear stress} \qquad (42)$$

and that S_1 and S_2 are a composite of the static stress due to the zinc load and the thermal stress in the horizontal direction; S_2 being neglected and S_1 becomes:

$$S_1 = S - S_t \text{ (uniaxial stress)} \qquad (43)$$

It is readily apparent that the bending moment in the plate depends on the boundary conditions of the plate and that the stress condition varies from point to point on the plate. The boundary condition is affected by the designer, the fabricator, and the installer. The data which is set forth here is considered to be on the safe side in an attempt to cover all possible contingencies for kettles with a length to width ratio of 4. However, it is to be noted that any bracing of the free standing kettle will invalidate the uniaxial stress assumption of this thesis. In the final chapter a recommendation for future study is made in that the biaxial stress state be evaluated and compared to the uniaxial stress state and that the thermal stress effects be more fully investigated. The biaxial stress solution is given by equation (74).

An interesting field observation is that free standing non-braced kettles (properly designed) have better life than their braced counterparts. An explanation is that a free standing kettle is better able to stress relieve itself and also the open combustion chamber allows more uniform heat distribution across the kettle heating surface. Another consideration is the fact that no simple formula for the reactions necessary to hold the edges of square plates in the original plane is available.[20]

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[20] Roark, Formulas For Stress and Strain, p. 375.

The final factor to be considered is the steady state stress distribution due to creep. This is shown in Figure 6 below:

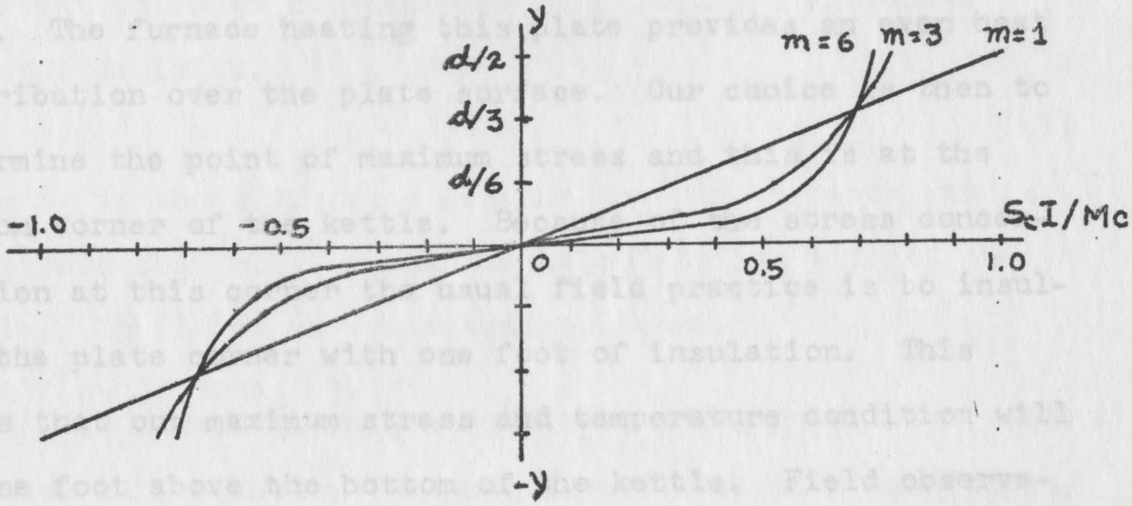

Fig. 6. Illustrates The Steady State Distributions of Stress For m=3 and m=6 Showing Comparison To the Elastic Case Where m=1. Note That a Maximum Creep Bending Stress Predicted On the Basis of the Elastic Bending Equation (S=Mc/I) Is a Conservative Value.

Equation (44) on the next page gives the factor (A_c) which modifies the elastic equation (S=Mc/I). Please refer to Reference 21 for its derivation.

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[21] Frank A. D'Isa, *Mechanics of Metals* (Reading, Massachusetts: Addison-Westly Co., 1968), pp. 266-268.

The following equation represents the lines of modification to the elastic curve shown in Figure 6.

$$S_c = (Mc/I)(A_c) = (Mc/I)(2y/d)^{1/m}(2m+1/3m) \qquad (44)$$

We now have all the factors on hand necessary to calculate the stress at any point. However, we are only interested in the maximum stress at the point of maximum temperature. The furnace heating this plate provides an even heat distribution over the plate surface. Our choice is then to determine the point of maximum stress and this is at the bottom corner of the kettle. Because of the stress concentration at this corner the usual field practice is to insulate the plate corner with one foot of insulation. This means that our maximum stress and temperature condition will be one foot above the bottom of the kettle. Field observations have shown no deterioration of the side plate in this area when the insulation is applied. However, the bottom plate is another problem and will be covered shortly. For the static stress one foot above the bottom of the kettle we shall assume the moment to be the same as at the bottom to be on the safe side. The stress equation is:

$$S = (6)(A)(W)(A_c)(D^3)/(P^2) \qquad (45)$$

where

A = Moment Factor = 0.067
W = Weight of Molten Zinc = 0.257 lb/in^3
A_c = Stress Relaxation Creep Function ($m=3$) = 0.778
D = Depth of Kettle (Plate Width) = L in Inches
P = Plate Thickness in Inches

Calculations for Stress

The program for calculating the above stress can be found in Appendix C. The fact that the thermal stress and static stress are working in such a manner so as to compliment one another extends the life of the kettle. This is important and must be accounted for. This is expressed mathematically as:

$$S_s = S - S_t \qquad (46)$$

where S_s is the difference between the two stresses and is the stress that will be used to calculate the life of the kettle. The total stress equation becomes:

$$S_s = (6)(.067)(.778)(D^3)/(P^2) - (.798 \times 10^{-5})(16.3 \times 10^6)(T_o - T_m)/2(1-.3) \qquad (47)$$

to solve this equation one must assume a certain heat input, Q, a plate thickness, P, and a kettle depth, D.

This equation (47) is simple, but tedious and a computer program for its solution is found in Appendix D. Table 4 summarizes some of the data. As can be seen from Table 4 on the next page the thicker the plate the greater the thermal stress, as the plate reduces in thickness the less the effect of the thermal stress and the greater the static stress.

The effect of temperature on the other mechanical properties of A-285-C firebox galvanizing quality semi-killed, hot rolled steel are listed in Table 5.

TABLE 4

PLATE THERMAL AND STRESS CONDITIONS FOR A GALVANIZING KETTLE 70 INCHES DEEP[c]

Outside Plate Temp. T_o	Mean Plate Temp. T_m	Static Stress S	Thermal Stress S_t	Actual Stress S_s	Plate Thk. P	Heat Rate Q
1102.8	902.8	1723.1	18571.4	-16848.3	4.0	16000
1077.8	902.8	2250.6	16250.0	-13999.4	3.5	16000
1052.8	902.8	3063.3	13928.6	-10865.3	3.0	16000
1027.8	902.8	4411.2	11607.1	- 7196.0	2.5	16000
1002.8	902.8	6892.4	9285.7	- 2393.3	2.0	16000
977.8	902.8	12253.2	6964.3	5288.9	1.5	16000
952.8	902.8	27569.7	4642.9	22926.9	1.0	16000
927.8	902.8	110278.8	2321.4	107957.4	0.5	16000
1110.7	904.5	1723.1	19151.8	-17428.7	4.0	16500
1085.0	904.5	2250.6	16757.8	-14507.2	3.5	16500
1059.2	904.5	3063.3	14363.8	-11300.5	3.0	16500
1033.4	904.5	4411.2	11969.9	- 7558.7	2.5	16500
1007.6	904.5	6892.4	9575.9	- 2683.5	2.0	16500
981.8	904.5	12253.2	7181.9	5071.3	1.5	16500
956.0	904.5	27569.7	4787.9	22781.8	1.0	16500
930.3	903.5	110278.8	2394.0	107884.8	0.5	16500
1118.6	906.1	1723.1	19732.1	-18009.0	4.0	17000
1092.1	906.1	2250.6	17265.6	-15015.1	3.5	17000
1065.5	906.1	3063.3	14799.1	-11735.8	3.0	17000
1038.9	906.1	4411.2	12332.6	- 7921.4	2.5	17000
1012.4	906.1	6892.4	9866.1	- 2973.6	2.0	17000
985.8	906.1	12253.2	7399.6	4853.6	1.5	17000
959.3	906.1	27569.7	4933.0	22636.7	1.0	17000
932.7	906.1	110278.8	2466.5	107812.3	0.5	17000
1134.4	909.4	1723.1	20892.9	-19169.8	4.0	18000
1106.3	909.4	2250.6	18281.3	-16030.7	3.5	18000
1078.2	909.4	3063.3	15669.7	-12606.4	3.0	18000
1050.1	909.4	4411.2	13058.0	- 8646.9	2.5	18000
1021.9	909.4	6892.4	10446.4	- 3554.0	2.0	18000
993.8	909.4	12253.2	7834.8	4418.4	1.5	18000
965.7	909.4	27569.7	5223.2	22346.5	1.0	18000
937.6	909.4	110278.8	2611.6	107667.2	0.5	18000
1150.2	912.7	1723.1	22053.6	-20330.5	4.0	19000
1120.6	912.7	2250.6	19296.9	-17046.3	3.5	19000
1090.9	912.7	3063.3	16540.2	-13476.9	3.0	19000
1061.2	912.7	4411.2	13783.5	- 9372.3	2.5	19000
1031.5	912.7	6892.4	11026.8	- 4134.4	2.0	19000
1001.8	912.7	12253.2	8270.1	3983.1	1.5	19000
972.1	912.7	27569.7	5513.4	22056.3	1.0	19000
942.4	912.7	110278.8	2756.7	107522.1	0.5	19000

[c] See Computer Program in Appendix D.

TABLE 5

SHORT TIME TENSILE PROPERTIES OF CARBON STEEL A-285-C PLATE

Test Temp. $^{\circ}$F	Yield Stress	Ult. Stress	Elong. %	Red. Area %	Youngs Modulus E	Coefficient of Expansion
75	30400	55500	37.5	65.0	30000000	.00000650
200	28700	56400	27.0	58.5	27500000	.00000650
400	26100	64700	23.0	56.5	24500000	- - - - -
500	25000	66900	25.0	53.2	23000000	- - - - -
600	24300	60300	35.0	62.0	21500000	- - - - -
800	21800	41400	50.0	79.0	18500000	.00000783
1000	15400	25800	56.0	85.0	15500000	.00000802

See Reference 22 and 23 for the above data in Table 5. TENMAX is another, very low carbon grade of steel for manufacturing galvanize kettles. See Reference 24 for this data. TENMAX steel is more resistant to zinc attack than firebox quality steel, but it is metallurgically softer and yields at a lower stress than firebox steel. The designer must choose on the basis of his design which steel to use. In this thesis we shall use firebox quality A-285-C.

Kettle Corner Stress Concentration

Returning to Figure 4 we can see that the bending moment in the side plate at the corner of the kettle equals

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[22] ASTM DS 11S1, An Evaluation of the Elevated Temperature Tensile and Creep Rupture Properties of Wrought Carbon Steel (Philadelphia: ASTM, 1970) p. 26.

[23] Samuel L. Hoyt, Metals and Alloys Data Book (New York: Reinhold Publishing Company, 1943), pp. 100-101.

[24] St. Joseph Lead Co., Proceedings of the Conference on Fracture Failure Analysis of Galvanizing Kettles (Monaca, Pa.: Zinc Melting Division of St. Joseph Lead Co., 1970) p. 14.

the bending moment in the bottom plate. The deflection diagram in Figure 4 is exagerated for clarity, but shows the basic deflection pattern. Traditionally, the kettle bottom plates were made less thick than kettle side plates because it was assumed that the kettle bottom plate was held to the foundation by the weight of zinc in the kettle. Catastrophic kettle failures have occured because of fracture failure of the bottom plate in the area adjacent to the side plate bottom weld and running parallel to the long axis of the kettle. The reason for failure is that the bottom of the kettle lifts completely off the foundation for long, deep, narrow kettles typical of pipe galvanizing and the thinner bottom plate is subjected to a higher stress than the side plate. A small crack is then initiated on the top side of the bottom plate as the plate reaches its ultimate stress. Once initiated the crack stress concentration propagates the catastrophic failure. It is therefore recommended that galvanize kettle bottom plates be the same thickness as the side plates. See Figure 7 and the calculations which follow.

If a long, uniformly loaded beam is supported by a horizontal rigid foundation as is shown in Figure 7,[25] the angle Θ_r of the rotation of the end which will be bent by the moment M_o applied at that end will lift the plate a

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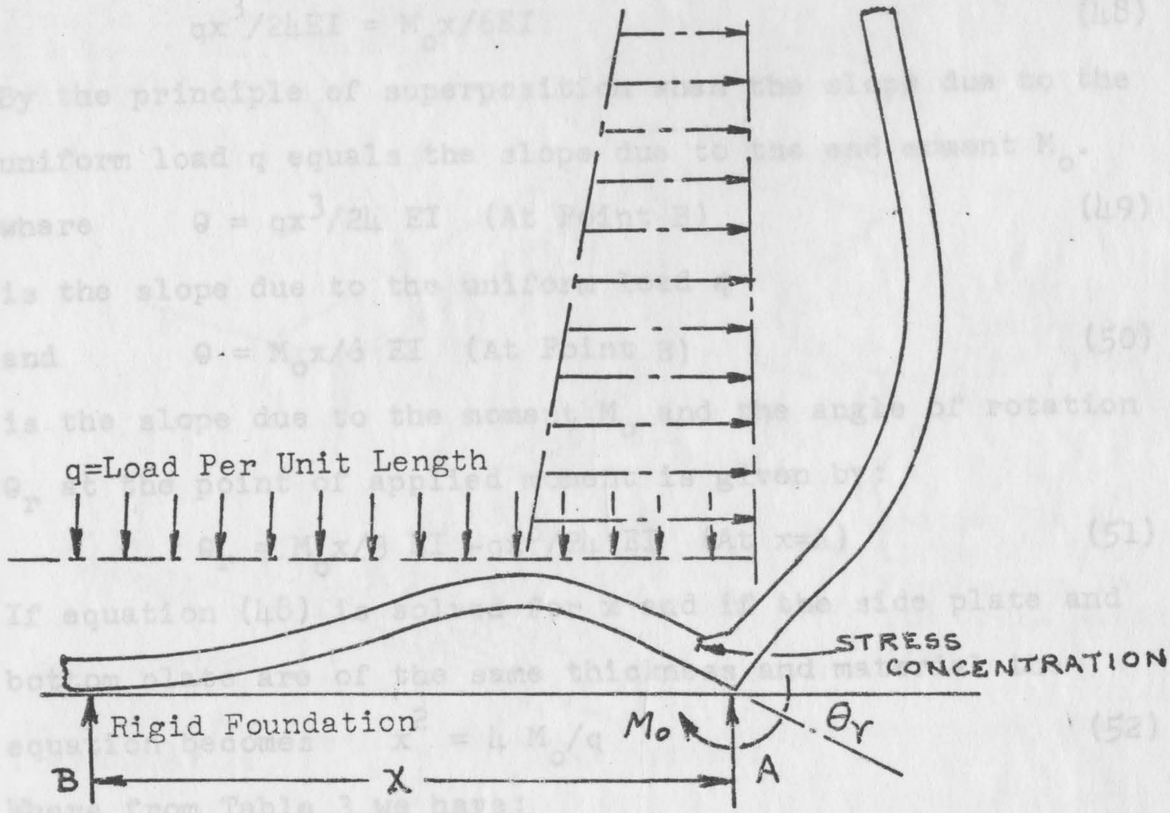
[25] S. Timoshenko, Strength of Materials (Part II, 3rd ed.: New York: D. VanNostrand Company, 1956), p. 74.



By The Principle of Superposition, When the Slope Due to the Uniform Load "q", Equals the Slope Due to the End Moment "M_o" Then:

$$qx^3/24\ EI = M_o x/6\ EI$$

Where: $\theta = qx^3/24\ EI$ @ Point B Is the Slope Due To the Uniform Load "q".

And: $\theta = M_o x/6\ EI$ @ Point B Is the Slope Due To the Moment "M_o".

$\theta_r = M_o s/3\ EI - qx^3/24\ EI$ Is the Angle of Rotation "θ_r" At Point A.

Fig. 7. Stress Analysis Of Kettle Corner Section.

distance x which is given by:

$$qx^3/24EI = M_o x/6EI \tag{48}$$

By the principle of superposition when the slope due to the uniform load q equals the slope due to the end moment M_o.

where $\theta = qx^3/24\ EI$ (At Point B) (49)

is the slope due to the uniform load q

and $\theta = M_o x/6\ EI$ (At Point B) (50)

is the slope due to the moment M_o and the angle of rotation θ_r at the point of applied moment is given by:

$$\theta_r = M_o x/3\ EI - qx^3/24\ EI \quad \text{(At x=A)} \tag{51}$$

If equation (48) is solved for x and if the side plate and bottom plate are of the same thickness and material the equation becomes $x^2 = 4\ M_o/q$ (52)

Where from Table 3 we have:

$$M_o = M = 0.067\ WD^3 \quad (L=D) \tag{53}$$

And for the uniform load on the bottom of the kettle:

$$q = WD \tag{54}$$

Or combining equations (52), (53), and (54):

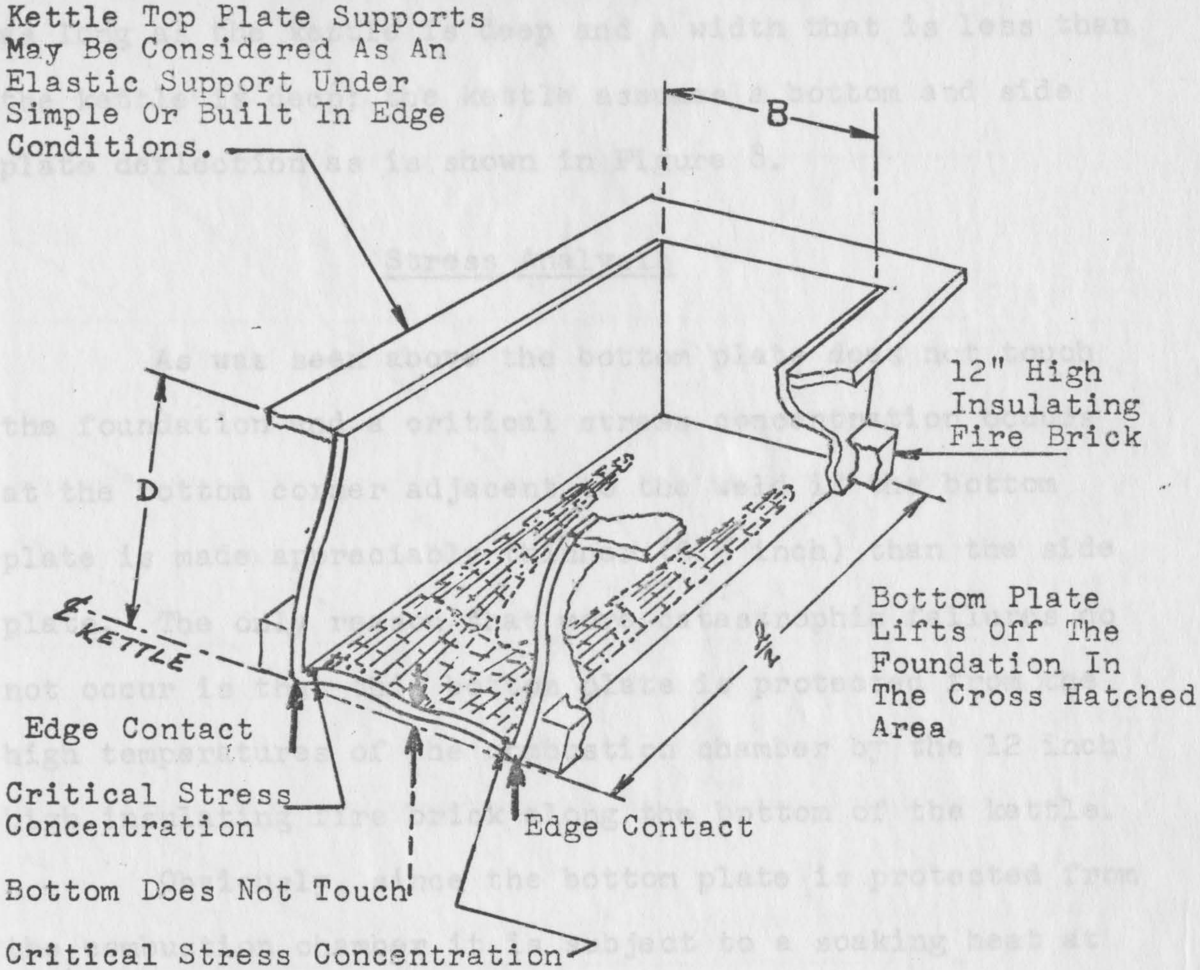
$$x^2=(4)(0.067)(W)(D^3)/(W)(D) \tag{55}$$

Clearing $x^2=(4)(0.067)(D^2)$ (56)

For a 70 inch deep kettle:

$$x = 36.24 \text{ inches} \tag{57}$$

This means that if we have a kettle 70 inches deep and up to 72.5 inches wide, the bottom of the kettle will not touch at the midpoint. In general it can be stated that for a free standing, unsupported kettle, with a length four times



For Long, Deep, Narrow Kettles The Bottom Plate Lifts Up Off The Foundation At The Center Of The Kettle For Point Contact At The Edges Only. The Bottom Of The Kettle Is Only Partially Supported.

Fig. 8. Free Standing Kettle Deflection Pattern.

as long as the kettle is deep and a width that is less than the kettle is deep; the kettle assumes a bottom and side plate deflection as is shown in Figure 8.

Stress Analysis

As was seen above the bottom plate does not touch the foundation and a critical stress concentration occurs at the bottom corner adjacent to the weld if the bottom plate is made appreciably thinner (0.5 inch) than the side plate. The only reason that more catastrophic failures do not occur is that this bottom plate is protected from the high temperatures of the combustion chamber by the 12 inch high insulating fire brick along the bottom of the kettle.

Obviously, since the bottom plate is protected from the combustion chamber it is subject to a soaking heat at least as hot as the molten zinc. Also, any thermal stress can be neglected for engineering purposes (pinching effect to be covered later) and the bottom plate is subject only to the moment caused by the side plate of the kettle. Assuming that the bottom plate is the same thickness as the side plate and the computer program in Appendix C gives the data graphed in Figure 9 which is valid for the maximum static stress in the side plate and bottom plate at the corner weld. We will assume that the maximum soaking temperature for the bottom plate lies between 800-1000°F and we find from Table 5 that our yield stress lies between 21,800 PSI and 15,400 PSI for A-285-C steel. Obviously any

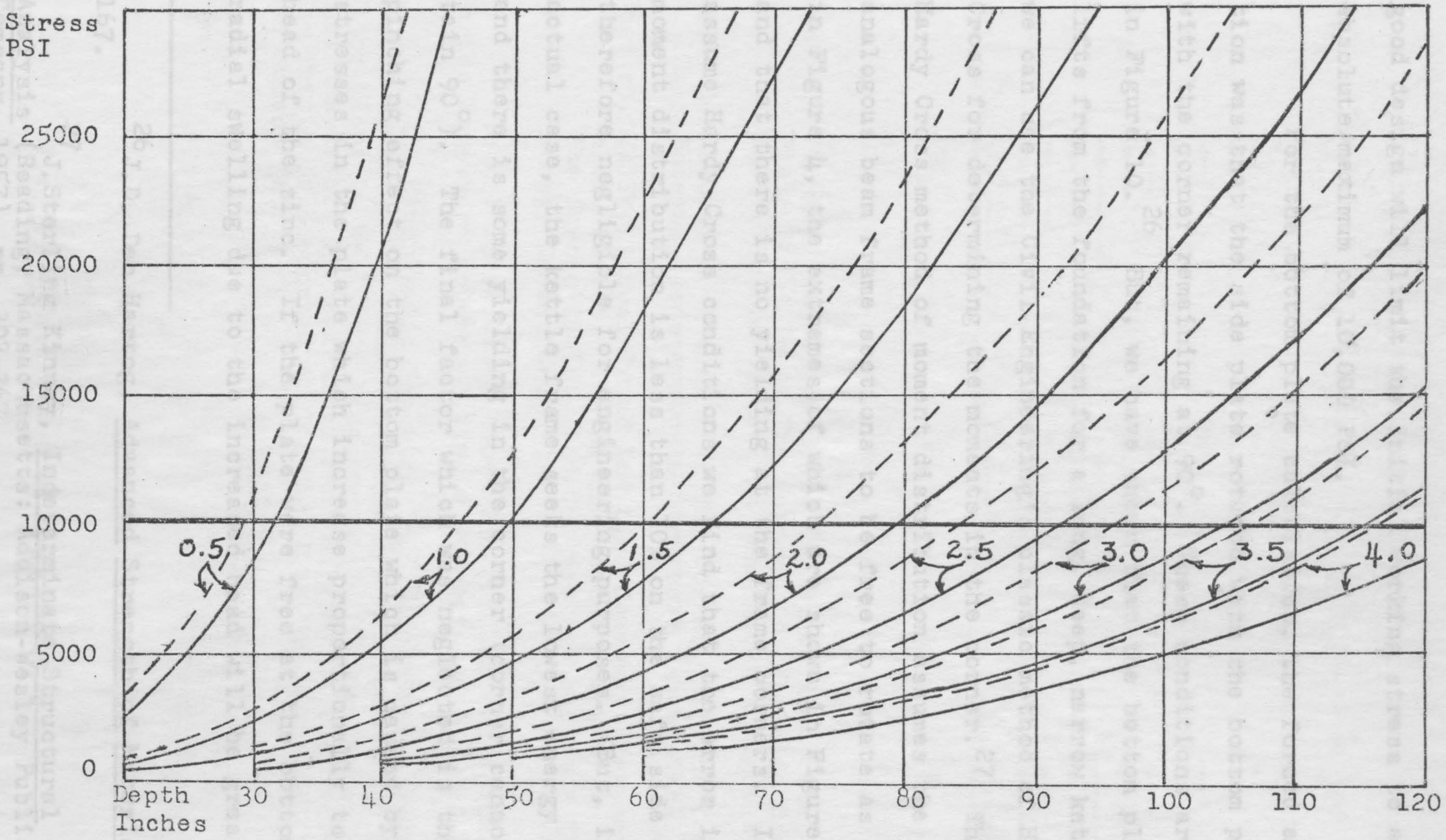


Fig. 9. Graph of Plate Stress in PSI Verses Plate Depth in Inches For Various Plate Thicknesses in Inches With a Stress Distribution of M=3 (Solid Lines) Compared to a Stress Distribution of M=1 (Dashed Lines) For a Maximum Working Stress of 10000 PSI @ 1000°F.

good design will limit the initial working stress to an absolute maximum of 10,000 PSI.

For the bottom plate calculation, the forced assumption was that the side plate rotated with the bottom plate with the corner remaining at 90°. These conditions are shown in Figure 10.[26] But, we have shown that the bottom plate lifts from the foundation for a long, deep, narrow kettle and we can use the Civil Engineering's classic method of Hardy Cross for determining the moments in the corner.[27] The Hardy Cross method of moment distribution assumes the kettle analogous beam frame sections to be free to rotate as shown in Figure 4, the extremes of which are shown in Figure 10, and that there is no yielding at the frame corners. If we assume Hardy Cross conditions we find that the error in moment distribution is less than 10% on the safe side and therefore negligible for engineering purposes. But, in the actual case, the kettle frame seeks the lowest energy level and there is some yielding in the corner (corner cannot maintain 90°). The final factor which was neglected is the pinching effect on the bottom plate which is caused by the stresses in the plate which increase proportionally to the head of the zinc. If the plate were free at the bottom the radial swelling due to the increased head will be greater

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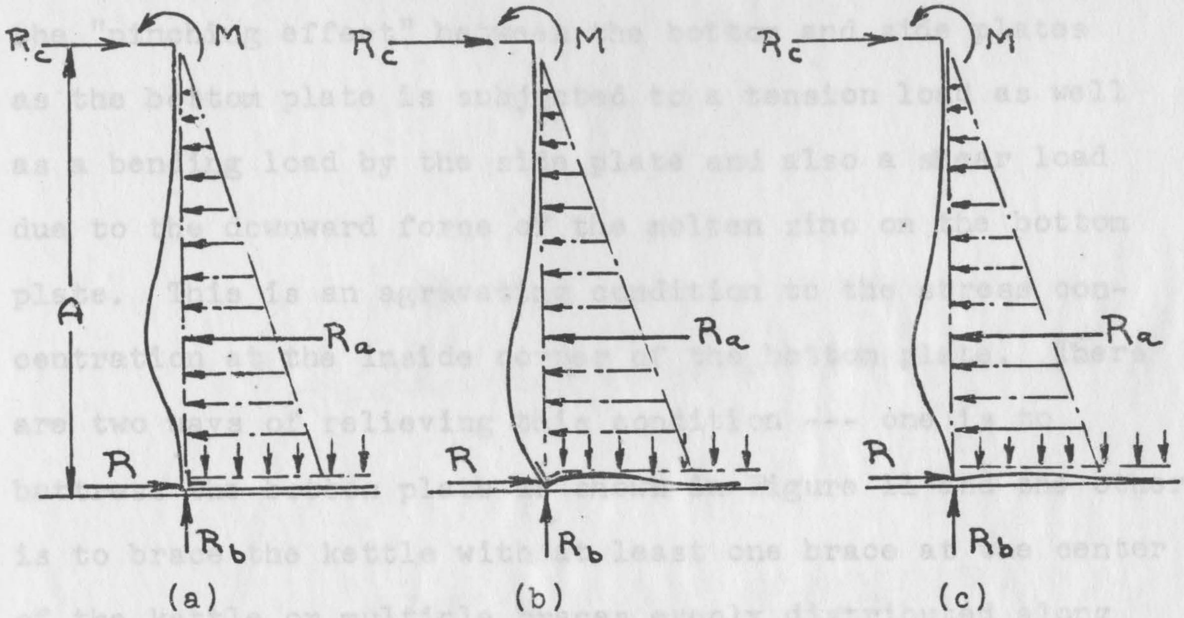
[26] J.D. Den Hartog, Advanced Strength of Materials, p. 167.

[27] J. Sterling Kinney, Indeterminate Structural Analysis (Reading, Massachusetts: Addison-Wesley Publishing Company, 1957), pp. 302-367.



Case a). Assumes The Bottom Plate To Remain Flat, The Side Plate Built In At The Bottom. No Yielding Occurs At The Bottom Corner, It Remains At A Right Angle.

Case b). Assumes No Yielding In The Corner, But The Corner Rotates (Indeterminate Structure Assumption).

Case c). Is The Actual Truth And Lies Somewhere Between Case a and Case b. The Kettle Bottom Plate Lifts And The Corner Yields, And The Kettle Assumes A Minimum Energy Condition.

In All Three Cases Above The Top Support Actually Varies Somewhere Between A Simple Support And A Rigid Support.

The Zinc Static Reaction "R_a" Necessitates A Concentrated Reaction "R_b" And A Lifting Off The Foundation Of The Floor Plate As Well As A Pinching Load "R" Due To The Fact That The Kettle Is Restrained From Bulging At The Bottom. The Kettle Is Supported At The Top With The Reaction "R_c" And Moment "M".

Fig. 10. Kettle Deflection Theory

than the compressive expansion of the bottom plate. Hence, the "pinching effect" between the bottom and side plates as the bottom plate is subjected to a tension load as well as a bending load by the side plate and also a shear load due to the downward force of the molten zinc on the bottom plate. This is an agravating condition to the stress concentration at the inside corner of the bottom plate. There are two ways of relieving this condition --- one is to buttress the bottom plate as shown in Figure 11 and the other is to brace the kettle with at least one brace at the center of the kettle or multiple braces evenly distributed along the kettle length. The first method is the simplest and least costly and does not change the assumptions of this thesis. The additional benefit is that it allows thinner plates to be used because the buttress raises the plate inertia and hence lowers the stress in the area of maximum critical stress. Caution is to be exercised to prevent any fin effects from the buttress which would raise the plate temperature in this area and thus weaken the plate. A double row of quality firebrick should be used to completely cover the buttress. This limits the maximum buttress height to approximately 12 inches. The alternate method is to brace the kettle plates from the furnace buckstays with brick as is a common practice. This is expensive, lengthens the time for a kettle change and forces the plate to be treated as two dimensional since in most cases the side plate length to

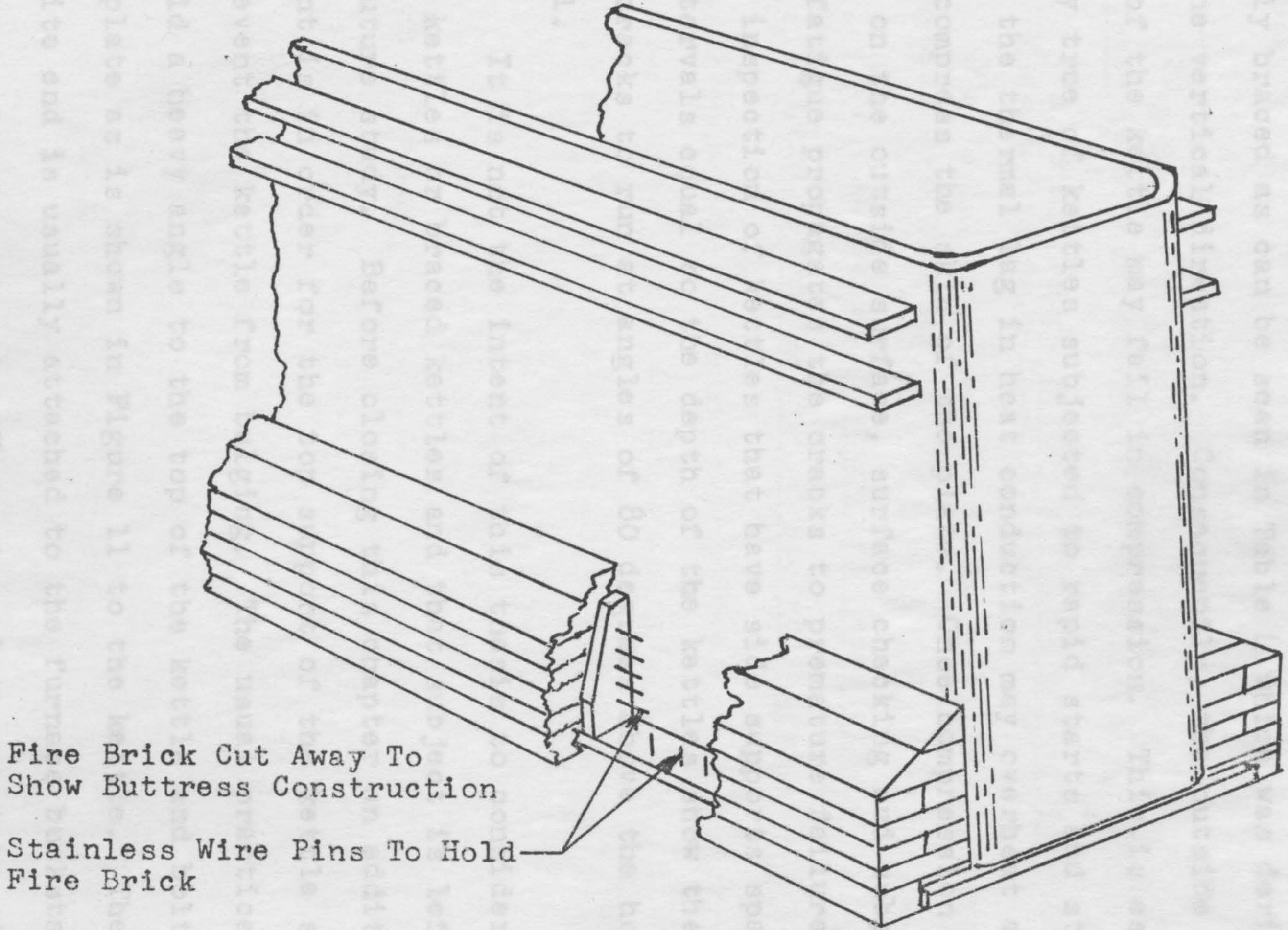


Fig. 11. Kettle Design Of Bottom Reinforcement

width ratio will be less than four. Under these conditions, the static stress considered in this thesis will be less; but, the stress in the horizontal direction will not be negligible and must be considered. This thermal stress in the horizontal direction is substantial if the kettle is rigidly braced as can be seen in Table 4 which was derived for the vertical direction. Consequently, the outside surface of the kettle may fail in compression. This is especially true of kettles subjected to rapid starts and stops since the thermal lag in heat conduction may overheat and over-compress the skin of the plate. Once compression cracks occur on the outside surface, surface checking and subsequent heat fatigue propagates the cracks to premature failure. Field inspection of kettles that have side supports spaced at intervals equal to the depth of the kettles show the primary cracks to run at angles of 80 degrees above the horizontal.

It is not the intent of this thesis to consider short kettles or braced kettles and that subject is left for future study. Before closing this chapter an additional comment is in order for the top support of the kettle so as to prevent the kettle from bulging. The usual practice is to weld a heavy angle to the top of the kettle and bolt a flat plate as is shown in Figure 11 to the kettle. The opposite end is usually attached to the furnace buckstays or other suitable support. These top plates must be of suitable strength to resist the bulging effect of the kettle top and adequately bolted to the heavy angle to resist the buckling effect of this force on the plate. Since the design of this top plate must fit individual conditions, no attempt is made here to design this top plate. However, the references 28, 29, 30, 31, and 32 should be adequate material for any design.

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[28] Friedrich Bleich, Buckling Strength of Metal Structures (New York: McGraw-Hill Book Company, 1952).

[29] S. Timoshenko, Theory of Elastic Stability (New York: McGraw-Hill Book Company, 1961).

[30] S. Timoshenko, Theory of Elasticity (New York: McGraw-Hill Book Company, 1958).

[31] S. Timoshenko, Strength of Materials.

[32] Roark, Formulas for Stress and Strain.

CHAPTER IV

METHOD OF CALCULATING KETTLE ATTRITION RATE

Introduction

In Chapter II great importance was attached to the temperature, T_m, at the interface between the zinc-iron alloy layer and its influence on the corrosive action of zinc on the kettle plate. The reactions between iron and zinc are the basis for all processes associated with hot dip galvanizing and they determine the structure and composition and the speed at which the steel is galvanized or attacked. Extensive research results are reported in the literature and various relationships have been derived as well as an insight into the kinetics of the reactions.[33] The variation of the rate of attack with temperature may be expressed according to the following equation.[34]

$$B_a = B_c e^{-U/R_g T_b} \qquad (58)$$

The symbols thereof are listed on the next page.

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[33] Zinc Development Association, Edited Proceedings of International Conferences on Hot Dip Galvanizing, Volumes 1-9, (London: Industrial Newspapers Limited, 1970).

[34] D. Horstmann and F. K. Peters, The Reactions Between Iron and Zinc (Edited Proceedings of 9th International Conference on Hot Dip Galvanizing at Dusseldorf in June, 1970: Edited by the Zinc Development Association, London: Industrial Newspapers Limited, 1971) p. 84.

Where B_a = Parabolic Rate Constant.
B_c = Constant Which is Characteristic of the Reaction.
U = Activation Energy.
R_g = The Gas Constant.
T_b = Absolute Temperature.

The rate of alloy formation is also affected by the heat transfer conditions in the molten zinc. The heat transfer coefficient, H, in Chapter II was treated as a pure convection coefficient in the operating or running stage and as pure conduction when the kettle was not operating or is stopped. However, this is not exactly true because this heat transfer is a complex phenomenon involving conduction and convection to various degrees in running or stopping the kettle. Some investigators hold to the theory that the formation of the hard zinc alloy layer provides protection against the diffusion process outlined above and maintain that bath agitation assists this hard alloy layer in reducing the diffusion phenomena. Investigators usually agree in principal on the laws which govern the rate of solution in zinc but they differ in their interpretations of the formation and growth of the intermetallic phases of the alloy layer and how the diffusion process takes place.

It is not the intent of this thesis to delve deeply into the reactions between iron and zinc nor to delve deeply into the complex interreaction of convection and conduction which takes place through an extremely thin layer of molten zinc which is in contact with the alloy layer. The intent is to arrive at some constants which represents the field conditions and fit the theoretical equations usually used in this work.

Calculation for Attrition Rate

The accepted equation expressing the rate of solution of iron in zinc may be expressed by:[35]

$$W_r = B_o (T_m)^n \tag{59}$$

Where W_r = Iron Attrition Rate in Inches Per 100 Hours.
B_o = Constant Which is Characteristic of the Reaction.
T_m = Temperature of the Surface in °F.
n = Attrition Rate Exponent.

It is worthwhile to note the similarity between equations (58) and (59). It is also worthwhile to note the similarity of this equation to the equations (66) and (69) developed in Chapter V for correlating high-temperature stress-rupture parameters. Table 6 is based on actual installations and shows the relationship of kettle life to the heat transfer in BTU/FT^2-HR.[36, 37]

Knowing the life in hours and thus the BTU rate we can calculate the temperature, T_m, and the wear rate, W_r, for the two points. We then have two equations and two

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[35] D. Horstmann, The Reactions Between Iron and Zinc p. 87.

[36] W.G. Imhoff, Heat Requirements For Hot Dip Galvanizing (Steel Magazine V 110 n 17 April 27, 1942) pp. 80-86.

[37] W.G. Imhoff, Heat Requirements for Hot Dip Galvanizing (Iron and Coal Trades Review V 145 n 3878 June 26, 1942) pp. 358-359.

TABLE 6

KETTLE LIFE IN MONTHS VERSES BTU/FT^2 HEATING AREA THROUGH KETTLE SIDE PER HOUR FOR ACTUAL FIELD INSTALLATIONS[d]

Life Months	BTU/FT^2-HR Transferred	Life Months	BTU/FT^2-HR Transferred	Life Months	BTU/FT^2-HR Transferred
0	30000	24	12000	51	8800
1	25000	27	11500	54	8600
4	20000	30	11000	57	8400
6	18000	33	10500	60	8200
9	16500	36	10000	63	8100
12	15000	39	9800	66	8000
15	14200	42	9500	69	7900
18	13300	45	9200	72	7800
21	12500	48	9000		

[d] Based On 500 Operating Hours Per Month.

unknowns expressed in the form of equation (59).

Thus W_r = Inches of Metal Lost/Life in Hours (60)

For example, if a kettle is 2 inches thick to start and the kettle fails when it is 1 inch thick after a life of 12 months at a heat transfer rate of 15,000 BTU/FT^2-HR, we have

$$W_r = (1/(12)(500)) = (B_o)(889.5)^n \qquad (61)$$

Where T_m is calculated from Chapter II and is found to be 889.5°F when the kettle is operated at an average 840°F. Another similar equation could be found and then the two equations with the two unknowns, B_o, and ,n, could be solved simultaneously. However, this proved to be an impractical approach because field data and life calculations in Chapter VI showed that similar kettles failed at approximately the same thickness no matter what heat transfer rate was used within the range of 8,000 to 20,000 BTU/FT^2-HR. The exact equation was finally derived in Chapter VI and is given below.

$$W_r = (T_m/948.90141) \text{ Exp } (1.0/1015078562) \qquad (62)$$

The computer program for determining this equation is listed in Appendix E and the printout from this program listed the following information in Table 7. Any attempt to understand this program should be reserved until the programs of the final chapters are understood. This program takes all the basic rough data for this thesis including stress, thermal conditions, life, etc., and searches for wear rate data that suits the field conditions for kettle life. The initial guesses for life at a corresponding heat rate were taken from Table 6. This data is plotted in Figure 12.

TABLE 7

FOR A 2 INCH THICK PLATE
WEAR RATE FOR TRIAL LIFE AND CORRESPONDING HEAT RATE[e]

Time Hours	Wear Per Time-In.	Calcul. Life-Hrs.	Estimated Life-Hrs	Estimated Heat Rate	Corres. (T_m) Temperature
100	0.0024	32400.0	33000.0	8000.0	866.42
100	0.0033	24000.0	24000.0	9000.0	869.72
100	0.0045	17900.0	18000.0	10000.0	873.02
100	0.0055	14800.0	15000.0	11000.0	876.32
100	0.0069	11900.0	12000.0	12000.0	879.62
100	0.0093	9000.0	9000.0	13300.0	883.92
100	0.0113	7500.0	7500.0	14200.0	886.89
100	0.0143	6000.0	6000.0	15000.0	889.53
100	0.0194	4500.0	4500.0	16500.0	894.48
100	0.0300	3000.0	3000.0	18000.0	899.44
100	0.0465	2000.0	2000.0	20000.0	906.04

[e] All Data Derived With Molten Zinc At 840°F.

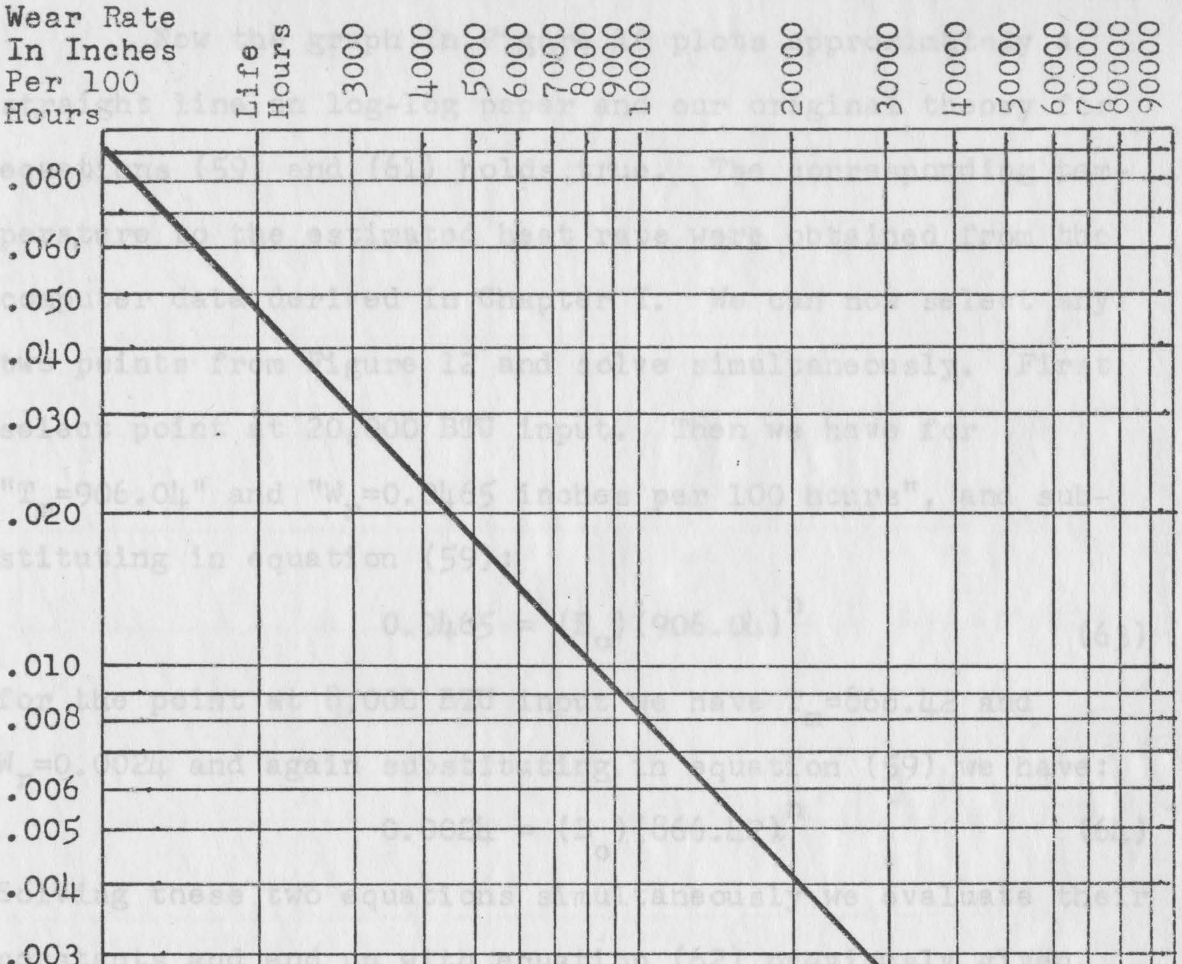

Fig. 12. Graph Of Wear Rate For A 2 Inch Thick Plate With Molten Zinc Temperature At 840°F At Various Heat Rates. Life In Hours Is From Field Data.

Now the graph in Figure 12 plots approximately a straight line on log-log paper and our original theory for equations (59) and (61) holds true. The corresponding temperature to the estimated heat rate were obtained from the computer data derived in Chapter I. We can now select any two points from Figure 12 and solve simultaneously. First select point at 20,000 BTU input. Then we have for "T_m=906.04" and "W_r=0.0465 inches per 100 hours", and substituting in equation (59):

$$0.0465 = (B_o)(906.04)^n \qquad (63)$$

for the point at 8,000 BTU input we have T_m=866.42 and W_r=0.0024 and again substituting in equation (59) we have:

$$0.0024 = (B_o)(866.42)^n \qquad (64)$$

Solving these two equations simultaneously we evaluate their constants and end up with equation (62) previously given. Equation (62) repeated:

$$W_r = \left(\frac{T_m}{948.90141}\right)^{\frac{1}{.015078562}} \qquad (65)$$

Attrition Rate Analysis

The computer program now evaluates the wear rate at different heat rates and the results are plotted in Figure 13. Some of the parameters already set are that the initial working stress due to the static load of the zinc should not exceed 10,000 PSI for any reason (Chapter III) in the side and bottom plates and the temperature at the plate outside, T_o, should not exceed 1,100°F for any reason (Chapter II).

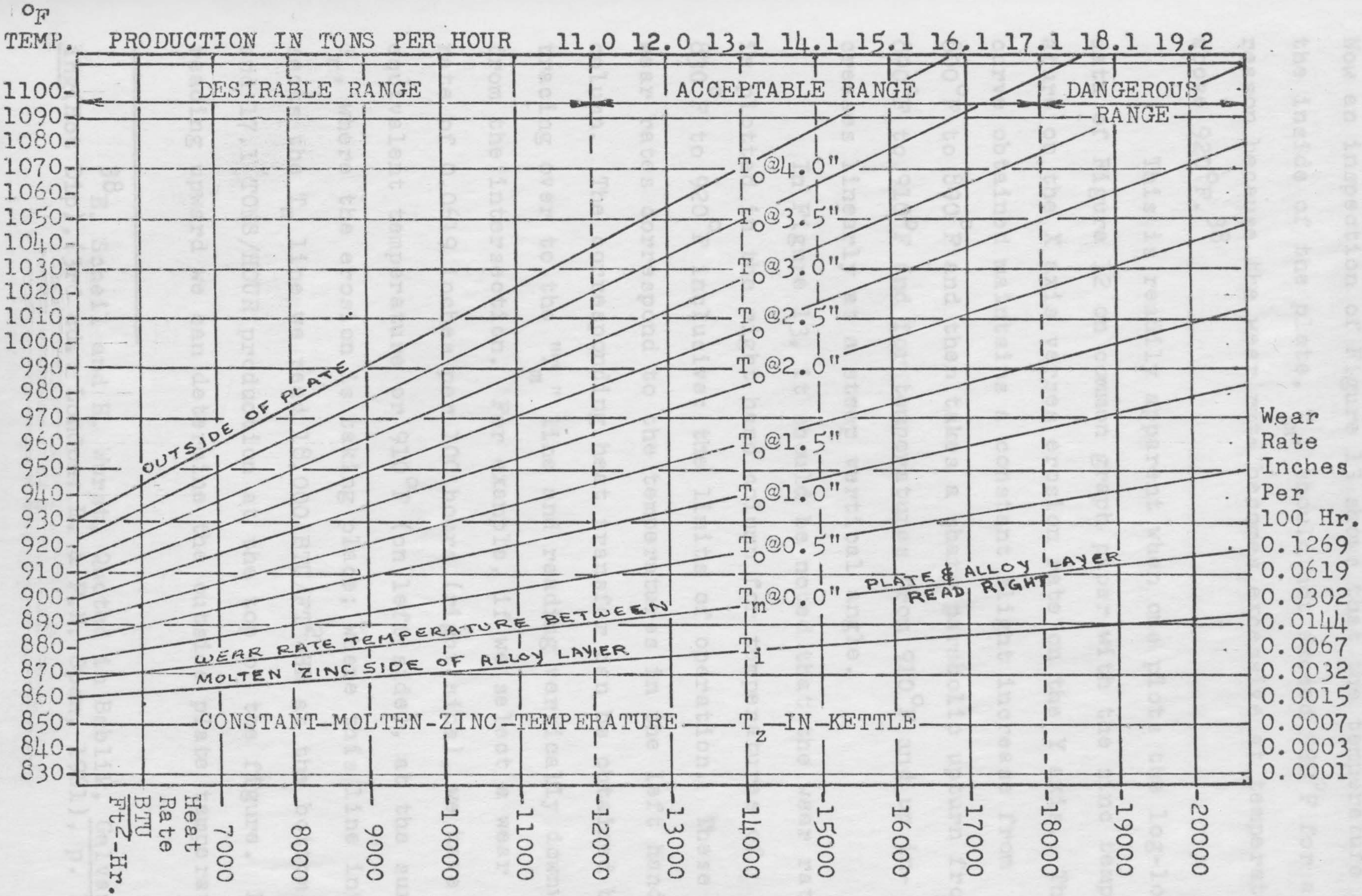

FIG. 13 GENERAL CONDITIONS FOR WEAR RATE AT 850°F MOLTEN ZINC TEMPERATURE

Now an inspection of Figure 13 shows that the temperature on the inside of the plate, T_m, should not exceed 920°F for any reason because the wear rate becomes excessive at temperatures above 920°F.[38]

This is readily apparent when one plots the log-log data of Figure 12 on common graph paper with the zinc temperature on the X axis verses erosion rate on the Y axis. The curve obtained maintains a constant slight increase from 800°F to 890°F and then takes a sharp parabolic upturn from 890°F to 910°F and for temperatures from 910°F and up increases linearly at a steep vertical angle.

In Figure 13, it should be noted that the wear rate is plotted in the right hand column for temperatures of 830°F to 920°F inclusive; the limits of operation. These wear rates correspond to the temperatures in the left hand column. The corresponding heat transfer can be obtained by tracing over to the "T_m" line and reading vertically downward from the intersection. For example, if we select a wear rate of 0.0619 inches per 100 hours (right side), we have an equivalent temperature or 910°F (on left side), at the surface, T_m, where the erosion is taking place; where this line intersects the T_m line we read 18,000 BTU/FT^2-HR at the bottom and 17.1 TONS/HOUR production at the top of the figure. By reading upward we can determine the outside plate temperature

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[38] E. Scheil and H. Wurst, Quoted in Bablik, Galvanizing(Hot Dip),(3rd ed.: London: E. & F.N. Spon, 1961), p. 180.

for this BTU input rate. At the intersection of the various plate thicknesses. For example, tracing vertically to the 2.5" plate line we read left from that intersection and find a temperature of 1050°F. Similar charts can be made for any kettle operating molten zinc temperature.

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CHAPTER V

METHOD OF DETERMINING STEADY STATE STRESS TO RUPTURE

Introduction

Creep may be broadly defined as plastic time-dependent deformation under load at elevated temperature. More specifically this means temperatures of about 1000 °F for carbon steel. In 1938,[39] creep was assumed to be a process that follows the same laws as chemical reactions, so that the rate of creep obeys the equation:

$$\text{Creep Rate} = B_d{}^{-U_a/R_gT_b} = B_b e^{-U_a/R_gT_b} \qquad (66)$$

Where B_b = A Constant, Independent of Temperature.
B_d = A Constant, Independent of Temperature.
U_a = Energy Change, Independent of Temperature.
R_g = The Gas Constant.
T_b = Absolute Temperature.

By assuming that the time to rupture varies inversely as the rate of creep, we have:

$$\text{Time To Rupture} = B_e/\text{Creep Rate} \qquad (67)$$

$$\text{Time To Rupture} = (B_e/B_b)e^{U_a/R_gT_b}$$

Or

$$\text{Time To Rupture} = B_f e^{U_a/R_gT_b} \qquad (68)$$

Where B_e = Constant Independent of Temperature.
AND B_f = Constant Independent of Temperature.

In this thesis we shall relate to mechanical properties and

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[39] J. J. Kanter, The Problem of the Temperature Coefficient of Tensile Creep Rate (American Institute of Mining and Metallurgical Engineers, Transactions of the Iron and Steel Division, Volume 131: Maple Press Co., York, Pa., 1938) pp. 385-418.

as was stated in Chapter IV, it is interesting to note the similarity between equation (68) and equation (58). Equation (59) was shown to represent a straight line plot on log-log graph paper. Similarly, if data from a high-temperature stress-rupture test plots a straight line on log-log paper that line can be represented by an equation similar to equation (59) or we have:

$$R_h = (B_g)(1/S_s)^{1/s} \qquad (69)$$

where R_h = Life in Hours.
B_g = Constant.
S_s = Uniform, Non-Varying Stress Level.
s = Exponent.

Predicting creep rupture under uniaxial or combined stresses is difficult. In Reference 40 the subject of static loading to rupture at ordinary temperatures is discussed and the following difficulties discussed.

1. Limitations of mathematics.
2. Anisotropic behavior which may develop with strain.
3. Change in stress distribution as strains become larger.
4. Increased stress, strain rate and temperature prior to failure.

Additional comments on the problem were discussed and reviewed on pages 279 and 280 of Reference 40. Reference 41 suggests that for a combined stress creep rupture criterion, the maximum shear stress theory would be worth consideration.

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[40] Frank A. D'Isa, Mechanics of Metals, pp. 229-280.

[41] J. Marin, Mechanical Behavior of Engineering Materials (Englewood Cliffs, New Jersey: Prentice Hall, 1962).

Assuming the maximum shear stress theory as the creep rupture criterion and it is known that $S_1 > S_2 > S_3$ so that the governing equation is:[42]

$$S_1 - S_2/2 = \text{Maximum Shear Stress} \tag{70}$$

A value for the maximum shear stress is obtained by introducing a relationship between rupture stress and rupture life in simple tension, such as:

$$\text{Rupture Stress} = (B_m)(R_h)^{-s} \tag{71}$$

where s is generally positive and less than unity. Recalling that the maximum shear stress in pure tension is equal to one-half of the axial stress, we may substitute:

$$\text{Rupture Stress}/2 = \text{Maximum Shear Stress} \tag{72}$$

and obtain $$S_1 - S_3 = (B_m)(R_h)^{-s} \tag{73}$$

or $$R_h = (B_m/S_1 - S_2)^{1/s} \tag{74}$$

as the equation which predicts rupture time and bears a resemblance to equation (66) and equation (68). If we assume uniaxial stress, equation (74) becomes:

$$R_h = (B_m/S_s)^{1/s} = B_n(1/S_s)^{1/s} \tag{75}$$

which is the equation for stress to rupture data which plots a straight line on log-log graph paper as in the case of equation (69). This equation also resembles equation (68) which relates creep to the same laws as chemical reactions.

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[42] Frank A. D'Isa, Mechanics of Metals, p. 280.

Method of Writing Equations

The existence of a correlation between the stress, S_s, temperature, T_r and time to failure, R_h, can be stated mathematically by the equation:[43]

$$f(S_s, T_r, R_h) = 0 \tag{76}$$

The existence of such a function is implicit in the conventional plots of log stress against log rupture life for lines of constant temperature, or any modifications, cross-plots, or extrapolations from such log-log plots. Equation (76) may be rewritten as:

$$R_h = g(S_s, T_r) \tag{77}$$

without any loss of generality. It is also conventional to express equation (77) in the form of logarithms, and thus:

$$\text{Log } R_h = \psi(\log S_s, T_r) \tag{78}$$

The form of equation (73) is deduced by equation (75) and conforms to the empirical forms of test data plotted on log-log paper. Francis J. Clauss,[44] classifies the above form of equation (78) as shown in Figure 14, 15, 16 and 17.

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[43] Francis J. Clauss, An Examination of High Temperature Stress-Rupture Correlating Parameters (Proceedings, American Society For Testing Metals, Vol. 60, 1960) p. 905.

[44] Grant and Mullendore, Deformation and Fracture At Elevated Temperatures (Cambridge, Massachusetts: MIT Press, 1965) pp. 67-89.

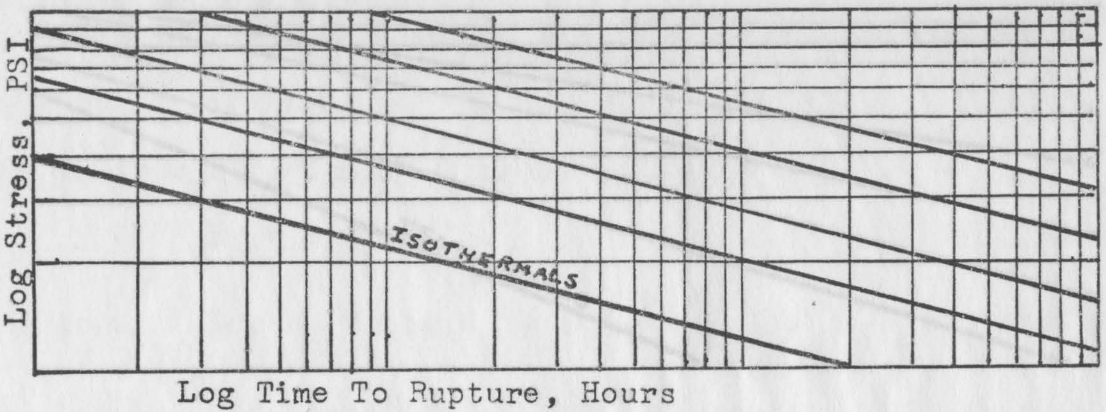

Fig. 14. Class I Stress Rupture Plot Represents A Family Of Straight Parallel Lines.

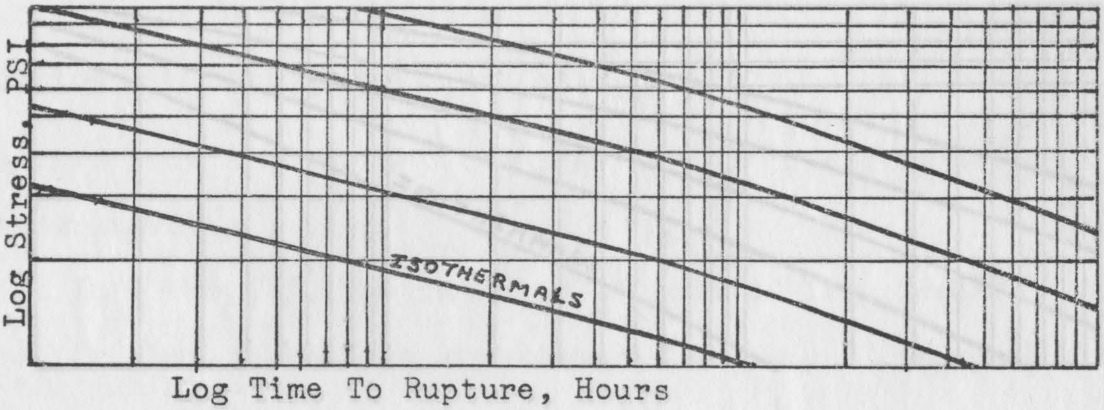

Fig. 15. Class II Stress Rupture Plot Represents A Family Of Curved Parallel Lines.

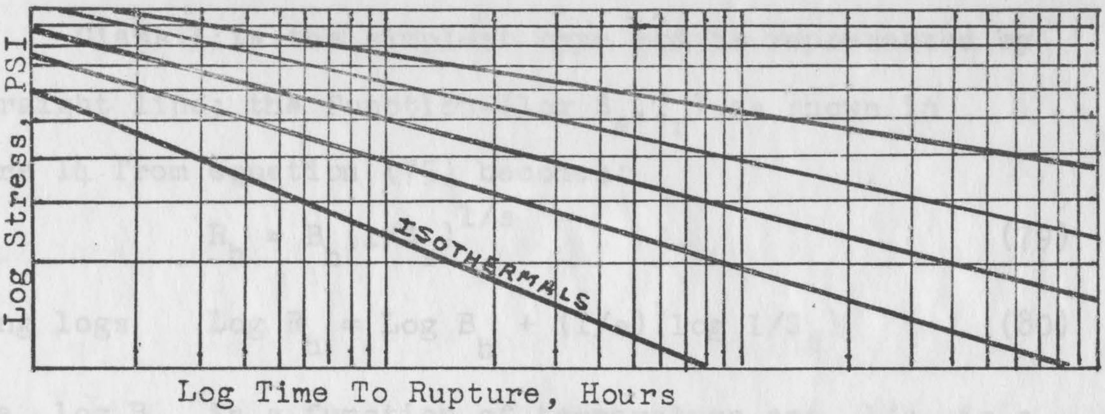

Fig. 16. Class III Stress Rupture Plot Represents Straight, Fan Shaped Family of Lines.

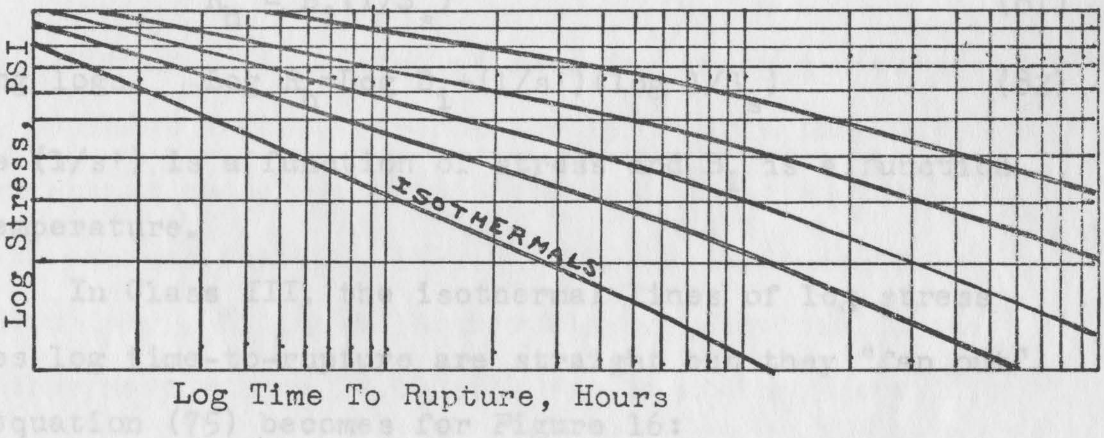

Fig. 17. Class IV Stress Rupture Plot Represents Curved, Fan Shaped Family Of Lines.

Class I is the simplest type and is represented by a straight line; the function $(\log S_s, T_r)$ as shown in Figure 14 from equation (75) becomes:

$$R_h = B_h(1/S_s)^{1/s} \qquad (79)$$

taking logs $\quad \text{Log } R_h = \text{Log } B_h + (1/s)(\log 1/S_s) \qquad (80)$

where, $\log B_h$, is a function of temperature and, $1/s$, is a constant and the slope of the isothermal lines. "B_h" is also a measure of the height between the isothermal lines.

A more complicated behavior is when the isothermal lines of log stress verses log time-to-rupture are curved rather than straight as shown in Figure 15 and equation (75) becomes for Class II:

$$R_h = B_i(1/S_s)^{1/s'} \qquad (81)$$

taking logs $\quad \text{Log } R_h = \text{Log } B_i + (1/s')(\log 1/S_s) \qquad (82)$

where $(1/s')$ is a function of stress and B_i is a function of temperature.

In Class III, the isothermal lines of log stress verses log time-to-rupture are straight but they "fan out" and equation (75) becomes for Figure 16:

$$R_h = B_j(1/S_s)^{1/s''} = (B_p/S_s)^{1/s''} \qquad (83)$$

taking logarithms

$$\text{Log } R_h = \text{Log } B_j + (1/s'')(\log 1/S_s) \qquad (84)$$

where the factors B_j and $(1/s')$ are both functions of temperature but not stress.

In Class IV, Figure 17, the isothermals are curved and fan out and equation (75) becomes:

$$R_h = B_k \; (1/S_s)^{1/s''} \qquad (85)$$

taking logs $$\text{Log } R_h = \text{Log } B_k + (1/s''')(\text{Log } 1/S_s) \qquad (86)$$

where (1/s''') is a function of both temperature and stress and "B_k" is a function of temperature only. If the coefficient (1/s''') is restricted to a constant value, Class I behavior is obtained (1/s); if (1/s''') is restricted to a function of stress only, Class II behavior is obtained (1/s'); if (1/s''') is restricted to a function of temperature only, Class III behavior is obtained (1/s").

Calculations for Static Life

Figure 18 is a plot of data for wrought carbon steel which includes A-285-C firebox steel.[45] Note that the data is fan shaped and corresponds to Class III type plots. We wish to express the 900, 950, and 1000°F isothermals in equation form. If these isothermals are extended to the left they meet at the 38,000 PSI stress and one hour life intercept. From Class III we have the general equation:

$$\text{Log } R_h = \text{Log } B_j + (1/s'')(\text{Log } 1/S_s) \qquad (87)$$

Selecting any two points on any line we can write the following equations from Figure 18 (logs to base 10).

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[45] ASTM DS 11S1, p. 90.

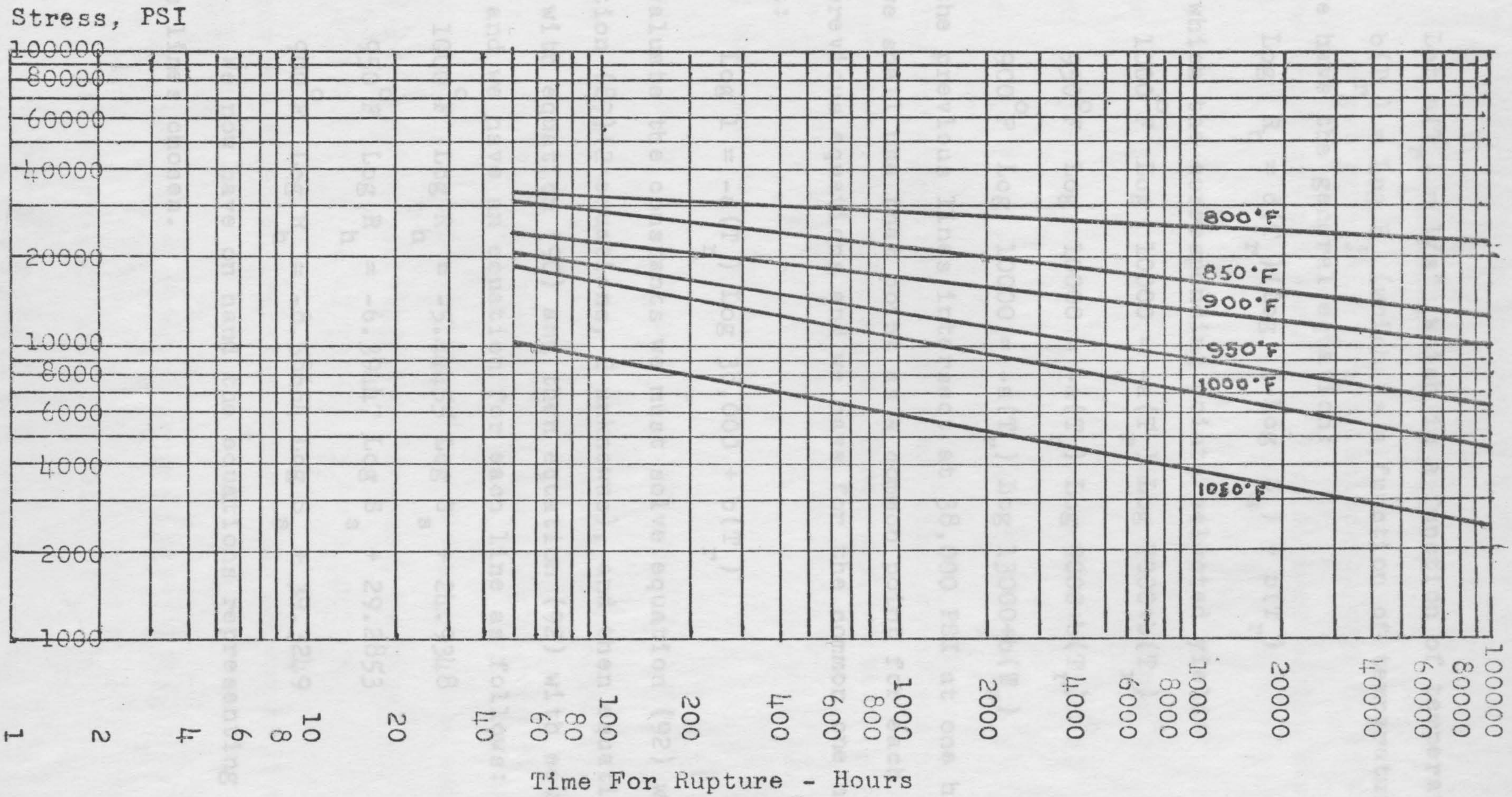

Fig. 18. Linear Regression Lines For Log-Log Scatter Bands Of Stress vs Rupture Time, Extended To 100,000 Hrs. Time Taken As Independent Variable.

NOTE: Let $a(T_r) = 1/s''$ (which is a function of temperature)

and $b(T_r) = \text{Log } B_j$ (which is a function of temperature)

and we have the general equation:

$$\text{Log } R_h = d(T_r)(\text{Log } 1 - \text{Log } S_s) + b(T_r) \qquad (88)$$

from which the corresponding points selected yield:

$$\text{for } 1000^{\circ}F \quad \text{Log } 10000 = -a(T_r)\,\text{Log } 7000 + b(T_r) \qquad (89)$$

$$\text{for } 950^{\circ}F \quad \text{Log } 10000 = -a(T_r)\,\text{Log } 9000 + b(T_r) \qquad (90)$$

$$\text{for } 900^{\circ}F \quad \text{Log } 10000 = -a(T_r)\,\text{Log } 13000 + b(T_r) \qquad (91)$$

All the previous lines intersect at 38,000 PSI at one hour and we shall use that point as a common point for each of the previous equations and we have for the common one hour point:

$$\text{Log } 1 = -a(T_r)\,\text{Log } 38{,}000 + b(T_r) \qquad (92)$$

To evaluate the constants we must solve equation (92) with equation (89)(2 equations, 2 unknowns), and then equation (92) with equation (90) and then equation (92) with equation (91) and we have an equation for each line as follows:

$$\text{for } 1000^{\circ}F \quad \text{Log } R_h = -5.44455\,\text{Log } S_s + 24.9348 \qquad (93)$$

$$\text{for } 950^{\circ}F \quad \text{Log } R_h = -6.39447\,\text{Log } S_s + 29.2853 \qquad (94)$$

$$\text{for } 900^{\circ}F \quad \text{Log } R_h = -8.58664\,\text{Log } S_s + 39.3249 \qquad (95)$$

We now have on hand the equations representing the three lines chosen.

Generalization of Equations

We can generalize the equations on page 67 by writing the constants $a(T_r)$ and $b(T_r)$ as a power series expansion:

for $a(T_r)$

for 1000°F $a_o+a_1T_r+a_2T_r^2+\ldots=5.44455 (T_r=1000^\circ F)$ (96)

for 950°F $a_o+a_1T_r+a_2T_r^2+\ldots=6.39447 (T_r= 950^\circ F)$ (97)

for 900°F $a_o+a_1T_r+a_2T_r^2+\ldots=8.58664 (T_r= 900^\circ F)$ (98)

Limiting our expansion to the above three equations and three unknowns and solving simultaneously, we have:

$a_o = 260.595$; $a_1 = -0.50375$; $a_2 = .0002486$ (99)

Doing the same for $b(T)$ we have:

for 1000°F $b_o+b_1T_r+b_2T_r^2+\ldots=24.9348 (T_r=1000^\circ F)$ (100)

for 950°F $b_o+b_1T_r+b_2T_r^2+\ldots=29.2853 (T_r= 950^\circ F)$ (101)

for 900°F $b_o+b_1T_r+b_2T_r^2+\ldots=39.3249 (T_r= 900^\circ F)$ (102)

Limiting our expansion to the above three equations and three unknowns and solving simultaneously we have:

$b_o = 1192.69$; $b_1 = -2.30555$; $b_2 = 0.0011378$ (103)

The general equation expressing the three isothermals then become:

$$\text{Log } R_h = -(260.595-0.50375(T_r)+0.0002486(T_r)^2)\text{Log } S_s + (1192.69-2.30555(T_r)+0.0011378(T_r)^2) \quad (104)$$

We shall now use the following form of the previous equation to develop the same constants:

$$R_h = (B_j/S_s)^{a(T_r)} \qquad (105)$$

Using the same points from Figure 18 for the 1000°F isothermal we have:

$$10000 = (B_j/7000)^{a(T_r)} \qquad (106)$$

$$\text{For } 950^{\circ}\text{F} \quad 10000 = (B_j/9000)^{a(T_r)} \qquad (107)$$

$$\text{For } 900^{\circ}\text{F} \quad 10000 = (B_j/13000)^{a(T_r)} \qquad (108)$$

and once again for all equations

$$1 = (B_j/38000)^{a(T_r)} \qquad (109)$$

Once again solving simultaneously we have:

$$\text{For } 1000^{\circ}\text{F} \quad R_h = (38000/S_s)^{5.44455} \qquad (110)$$

$$\text{For } 950^{\circ}\text{F} \quad R_h = (38000/S_s)^{6.39447} \qquad (111)$$

$$\text{For } 900^{\circ}\text{F} \quad R_h = (38000/S_s)^{8.58664} \qquad (112)$$

And if we express equation (110) in log form we have:

$$\text{Log } R_h = \text{Log } (38000/S_s)^{5.44455} \qquad (113)$$

$$\text{Log } R_h = 5.44455 \; (\log(38000/S_s)) \qquad (114)$$

$$\text{Log } R_h = 5.44455 \; (\log 38000 - \log S_s) \qquad (115)$$

$$\text{Log } R_h = (5.44455)(4.57979) - 5.44455 \text{ Log } S_s \qquad (116)$$

$$\text{Log } R_h = 24.9348 - 5.44455 \text{ Log } S_s \qquad (117)$$

Equation (116) is equivalent to equation (93) and we have thus shown the interchangeability and versatility of the geometric curve (exponent constant). Using the same procedure we can show the equivalency of equation (101) to equation (87) and equation (102) to equation (88). From our series expansion in equations (96) through (99) we expressed that exponent as a variable and can write the following exponential curve generalization.

$$R_h = (38000/S_s)^{Re} \qquad (118)$$

where $R_e = 260.595-0.50375(T_r)+0.0002486(T_r)^2$ (119)

The above power series could have been expressed as a representation of the natural log function (ln x) or as an exponential (e^x). Please note that equation (119) was not used in the final life calculation. The equation (129) developed in the next section was used.

Static Life Analysis

We have shown that from the maximum shear stress theory the following forms or variations thereof can be derived for stress-to-rupture data as derived in Statistics.

Exponential curve:

$$Y = ab^x \text{ or } \text{Log } Y = \text{Log } a+X(\text{Log } b) \qquad (120)$$

Geometric curve:

$$Y = aX^b \text{ or } \text{Log } Y = \text{Log } a+b(\text{Log } X) \qquad (121)$$

Gompertz curve:

$$Y = pq^{b^x} \text{ or } \text{Log } Y = \text{Log } p+b^x(\text{Log } q) \qquad (122)$$

where a, b, p, q are constants (equations 120, 121, 122 only). The exponent is then a function of stress and temperature (Class IV); a function of temperature (Class III); a function of stress (Class II); or a constant (Class I) and can be represented by a suitable power series expansion or its representation in the natural log function or exponential function.

The positions of the individual isothermal regression lines relative to one another in Figure 18 are not what one would normally expect and the conclusion was that this table was a composite of all data (pipe, tube, bar and plate) and therefore, the mixing of different populations caused the deviations. However, it is sufficiently accurate for our engineering analysis. After all the initial rough data was derived, a computer trace of the exponent (equations 118, 119) revealed that the exponent would reach a minimum value at about 1025°F and then would return upscale. The restriction on "T_r" was 900°F minimum and 1000°F maximum and the exponent performed within its range. However, as a check, the program in Appendix G was written and equations were written for the 1050°F and the 850°F isothermals (modified, see Figure 19). The five equations of the form below

$$a_o+850a_1+(850^2)a_2+(850^3)a_3+(850^4)a_4 = 12.0211 \qquad (123)$$

$$a_o+900a_1+(900^2)a_2+(900^3)a_3+(900^4)a_4 = 8.58664 \qquad (124)$$

$$a_o+950a_1+(950^2)a_2+(950^3)a_3+(950^4)a_4 = 6.39447 \qquad (125)$$

$$a_o+1000a_1+(1000^2)a_2+(1000^3)a_3+(1000^4)a_4 = 5.44455 \qquad (126)$$

$$a_o+1050a_1+(1050^2)a_2+(1050^3)a_3+(1000^4)a_4 = 4.10000 \qquad (127)$$

represent the 850, 900, 950, 1000 and 1050°F isothermals.

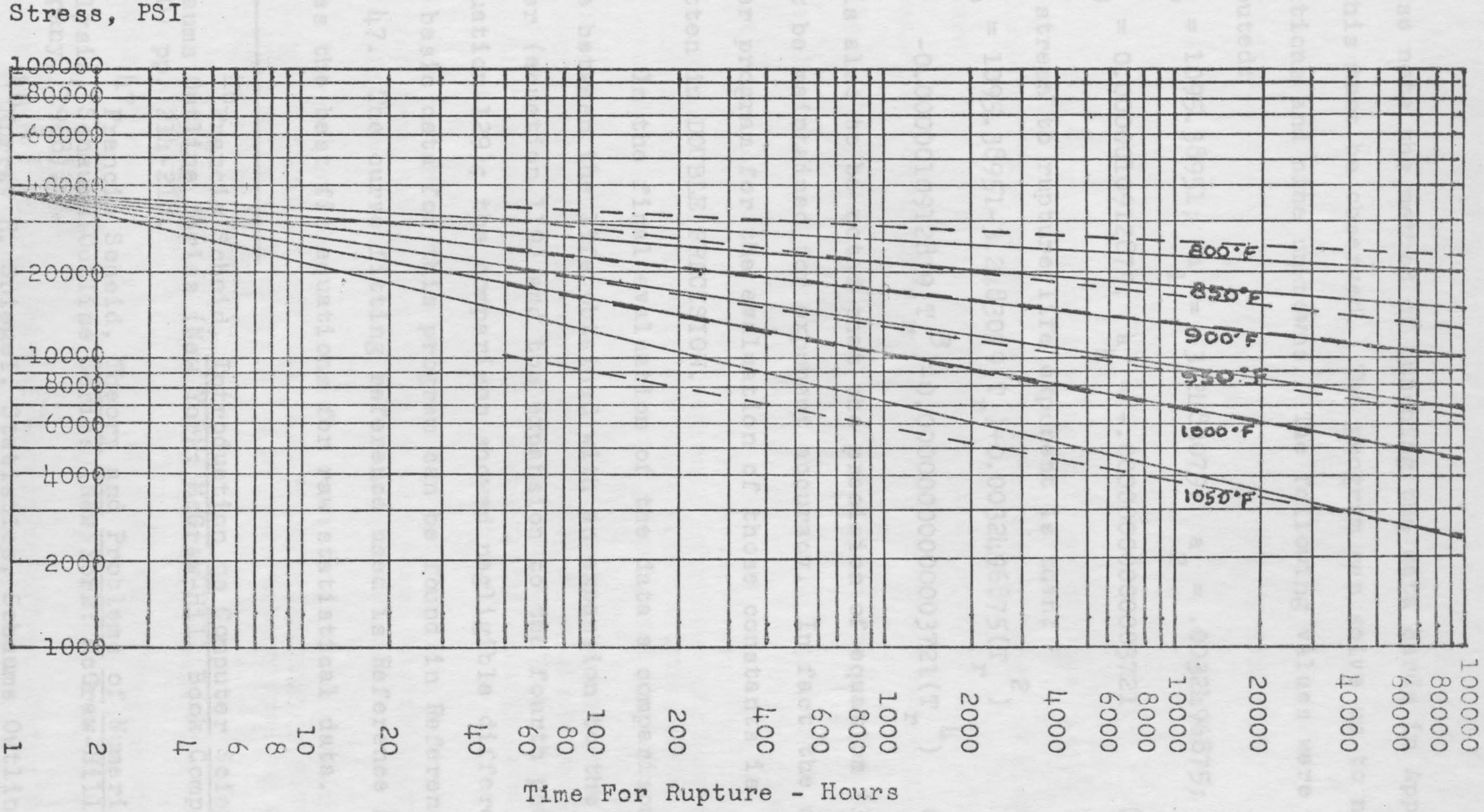

Fig. 19. Dotted Lines Show Original Regression Lines And Solid Lines Show Modified Regression Lines For Better Fit Of Exponential Data For Stress vs Rupture Time.

Please note the method of punching the data cards in Appendix G; this must be observed. The program can solve up to nine equations and nine unknowns. The following values were computed:

$$a_o = 1095.38951; \quad a_1 = -3.2483079; \quad a_2 = .0032496875;$$

$$a_3 = 0.0000010912879; \quad a_4 = -.0000000000003721 \qquad (128)$$

Our stress to rupture life exponent is then:

$$R_e = 1095.38951-3.2483079(T_r)+0.0032496875(T_r^2)$$
$$-0.0000010912879(T_r^3)-0.0000000000003721(T_r^4) \qquad (129)$$

It is also to be noted that the precision of equation (129) must be maintained for exponent accuracy. In fact the computer program for the evaluation of those constants is written in DOUBLE PRECISION.

In the final evaluation of the data a comparison was made between the life obtained with an expansion to the second power (equation 119) and the expansion to the fourth power (equation 129); the comparison showed negligible differences. The basic data for this program can be found in Reference 46 and 47. The curve fitting reference used is Reference 48 and gives the best fit equations for raw statistical data.

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[46] Francis Scheid, Introduction to Computer Science, Schaums Outline Series (New York: McGraw-Hill Book Company, 1970) pp. 214-218.

[47] Francis Scheid, Theory and Problems of Numerical Analysis, Schaums Outline Series (New York: McGraw-Hill Book Company, 1968).

[48] Murray R. Spiegel, Statistics, Schaums Outline Series (New York: McGraw-Hill Book Company, 1961) pp. 217-240.

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CHAPTER VI

STEADY STATE RUPTURE DATA RELATION TO GRADUALLY VARYING CONDITIONS

Introduction

The equations derived to this point have been dealing with steady state stress and temperature effects on time-to-rupture. The specific problem at hand requires that stress increase as temperature decreases due to the erosion of the kettle wall by the action of the zinc. In conjunction with these effects, high temperature introduces a number of complications. Included are:

1). Gaseous or liquid environments introduce surface reactions which interact strongly with fatigue cracks to accelerate crack initiation, growth, and failure.

2). Long hold-time periods between cycles introduce creep effects which interact with fatigue, often by changing the mode of crack propagation from the more ductile transgranular mode to the more brittle intergranular type.

3). The material may change its properties with long times at temperature due to aging and phase instability effects, or to creep damaging mechanisms.

4). Thermal cycling introduces complications regarding predictions of stresses and strains and uncertainty regarding the interaction of temperature cycling and strain cycling.

It is clear that many disciplines are involved here, including those of the surface chemist, metallurgist and mechanical engineer. In this thesis the above complications are considered in the overall averaging effect of the kettle's life. In other words, as the kettle cycles from full production to no production an average wear rate and life is considered for the total life of the kettle. That "average-life" is then reduced to a life on a 100 hour basis. For example, an average work week is considered as 125 hours with the remainder of the week, 43 hours, idle (major cycle). During this 125 hour work week the kettle operates for 2-1/3 hours, idles for 1/3 hour (minor cycle), operates for 2-1/3 hours, idles for 1/3 hour, etc., until the 125 work week hours are reached.

The operating month is then (4)(125) = 500 hours and the kettle life is measured as 500 hours per operating month. The wear rate over the week end idle period is considered as negligible, since only surface losses are being made up (major cycle). However, the wear rate on the minor cycle idle period is not considered negligible because relatively frequent start-ups and shutdowns cause initially higher temperatures and wear rates for a short period of time as compared to the running temperatures and wear rates. This is because of thermal lag and the molten zinc changing from convection to conduction conditions as the kettle cycles from run to stop and stop to run. Therefore, a monthly average of 500 operating hours was chosen and an average 100 operating hours for "average life" during this month. A kettle life on the computer printout of 2500 hours means that the kettle will last 5 months. This also means that the computer cycled through the series of calculations 25 times to arrive at the life or approximated an analytical solution in 25 steps. The analytical solution proved intractable mathematically and the computer solution was devised to approximate the mathematical solution by a series of steps. This series of steps varies widely under different conditions. See Figure 20 for the effects of simultaneous parameter variation and also Reference 48 for basic information for study. A sampling of data run at 10 hour increments had a negligible effect on the final life as compared to the 100 hour increment. The 100 hour increment took a full 10 computer minutes and it was deemed unnecessary to use (10)(10) = 100 computer minutes for a ten hour increment (to run the whole program).

We shall start with the life-fraction theory, then outline the analytical solution until the mathematics becomes intractable and then shift to the computer solution.

Life Fraction Theory

We shall attempt to take the preceding data developed for steady state stress-to-rupture and apply it to stress-to-rupture under non-steady temperatures and stresses. As already discussed, the behavior of a material subjected to a complex history of stress or temperature is governed by

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[48] John E. Dorn, Mechanical Behavior of Materials at Elevated Temperatures (New York: McGraw-Hill Book Company, 1961) pp. 419-454.

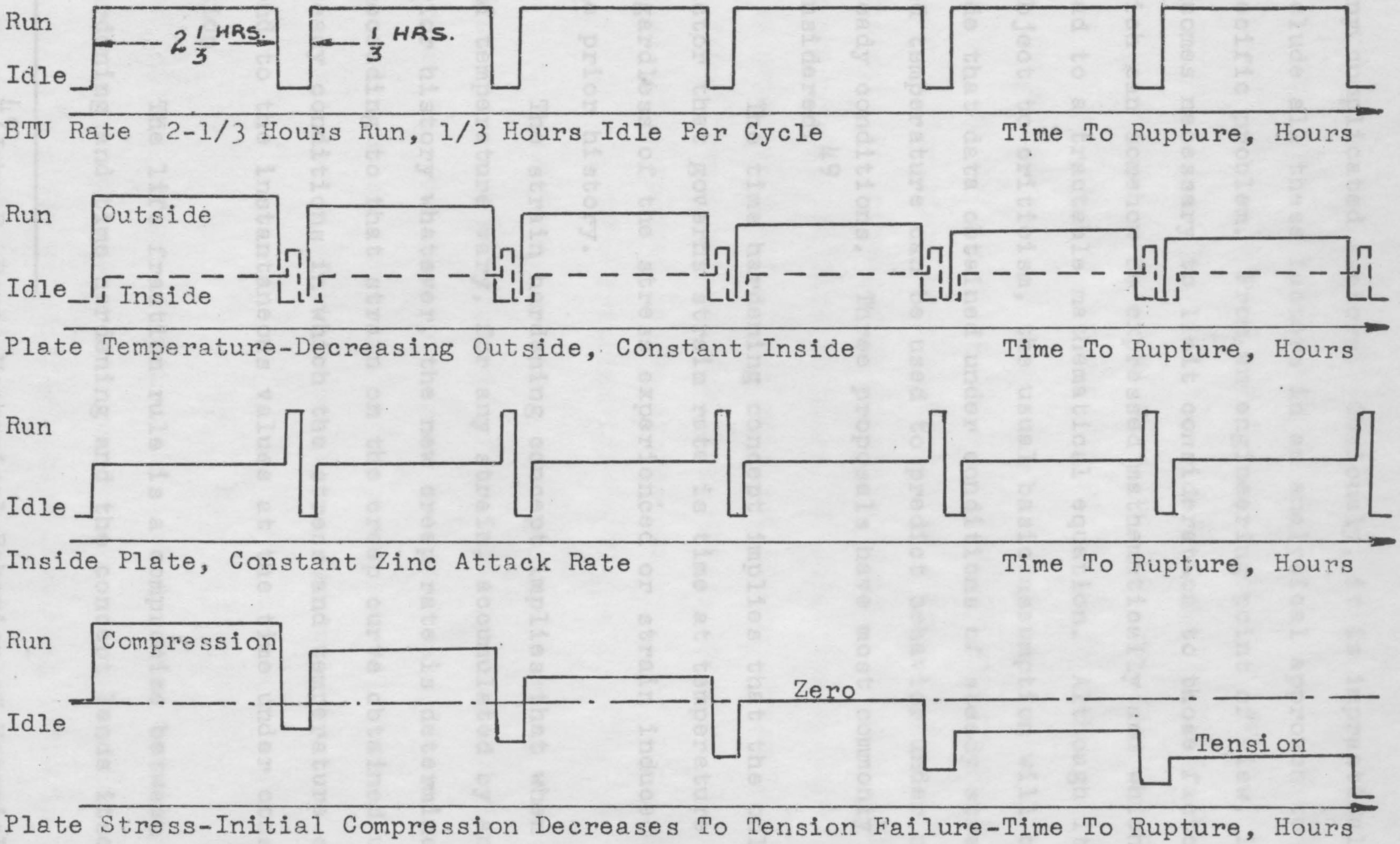

Fig. 20. Effect of Simultaneous Parameter Variation.

many complicated factors. Obviously, it is impractical to include all these factors in an analytical approach to a specific problem. From an engineering point of view, it becomes necessary to limit consideration to those factors which can somehow be expressed mathematically and which lead to a tractable mathematical equation. Although it is subject to criticism, the usual basic assumption will be made that data obtained under conditions of steady stress and temperature can be used to predict behavior under non-steady conditions. Three proposals have most commonly been considered.[49]

The time hardening concept implies that the only factor that governs strain rate is time at temperature regardless of the stress experienced or strain induced in the prior history.

The strain hardening concept implies that when stress and temperature vary, for any strain, accumulated by any prior history whatever, the new creep rate is determined by proceeding to that strain on the creep curve obtained under steady conditions in which the stress and temperature correspond to the instantaneous values at the time under consideration.

The life fraction rule is a compromise between strain hardening and time hardening and the concept lends itself

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[49] John E. Dorn, <u>Mechanical Behavior of Materials at Elevated Temperatures</u>, pp. 455-457.

well when stress and temperature both vary. The concept here is that if a material has a certain fraction of its life left at a given stress and temperature, then a change in stress and temperature will produce a new creep rate corresponding to the point at which the same percentage of life is left on the creep curve at the new (steady) stress and temperature.

We shall develop the life fraction rule to fit our theory. Consider the case where the stress alone (temperature constant) is increased in discrete steps. Using the life fraction rule the life in hours, R_h, that the specimen would have experienced if it had remained at one stress level can be found from our isothermal log stress, log time plot. The total life expended can be expressed:

$$F = \text{Fraction Life} = T/R_h = 1 \qquad (130)$$

Now if this specimen had only remained at this stress level and corresponding life fraction rupture time, R_{h_1}, for a time, T_1, and then the stress was increased, R_{h_2}, for time, T_2, and further increased in steps; the total fraction of life expended in a number of such steps would be:

$$F = \sum \frac{T}{R_h} = \frac{T_1}{R_{h_1}} + \frac{T_2}{R_{h_2}} + \ . \ . \ . = 1 \qquad (131)$$

and failure would occur when this sum is equal to unity according to the life fraction rule.

In other words, for a case involving variable temperature or stress, the life can be estimated by assuming that during any small interval of time the specimen loses some fraction of its life which is independent of the stress and temperature history. Conventional rupture data then can (in theory) be used to evaluate the fraction of life expended during each interval. Rupture occurs when the sum of these fractions is equal to unity.

In the case of continuously increasing stress, two methods of solution are possible. The stress verses time curve can be approximated by a number of finite steps, or an analytical solution can be applied. Consider conditions of stress varying linearly with time at constant temperature; an analytical approach is outlined below for those materials where the log-stress verses log-rupture time curve is linear in the range of times of interest.

Analytical Solution

First the summation

$$F = \sum T/R_h = T_1/R_{h_1} + T_2/R_{h_2} + --- \tag{132}$$

is replaced by the integral

$$F = \int_0^t dT/R_h \tag{133}$$

Also, as shown previously, the log-stress verses log-time to rupture curves can be represented analytically by

$$R_h = (b(T_r)/S_s)^{a(S_s,T_r)} \tag{134}$$

where $a(S_s,T_r)$ may be a constant or a function of stress and/or temperature depending on the type of log-stress verses log-time curve, as discussed in Equation (85).

To simplify the derivation we shall let:

$$r = (a(S_s, T_r)) \text{ and } C = (b(T_r)) \qquad (135)$$

and obtain

$$R_h = (C/S_s)^r \qquad (136)$$

where R_h = Rupture Life

S_s = Stress

T = Time

r = Life Exponent

The integral becomes:

$$F = \int_0^t dT/(C/S_s)^r = 1 \qquad (137)$$

If the stress starts at time zero, after a time, T, it will be equal to:

$$S_s = S_a T \qquad (138)$$

By combining equations (133), (136), and (138) we have by the life fraction rule (F=1) for stress starting at time zero:

$$1 = \int_0^t dT/(C/S_a T)^r \qquad (139)$$

$$1 = \int_0^t (S_a T)^r dT/(C)^r \qquad (140)$$

$$1 = (S_a/C)^r \int_0^t T^r \, dT \qquad (141)$$

$$1 = (S_a/C)^r \left| (1/r+1)(T^{r+1}) \right|_0^t \qquad (142)$$

$$1 = (S_a/C)^r \; (1/r+1)(t^{r+1}) \qquad (143)$$

$$t^{r+1} = (r+1)(C/S_a)^r \qquad (144)$$

$$t = ((r+1)(C/S_a)^r)^{1/r+1} \qquad (145)$$

Where, S_a, is the constant rate of stress increase with respect to time and remembering from previous work that, r, is a constant and, C, is a function of temperature. This applies to the simplest case, Class I, and varies linearly with time where, t, is the time to rupture under increasing stress.

If we go back to equation (139) when, r, is not a constant but is a function of temperature we have, for example, Class III at uniform stress and temperature when the exponent:

$$r = a_o + a_1 T_r + a_2 T_r^2 + ---$$

The life fraction equation (137) becomes:

$$1 = \int_o^t dT/(C/S_s)^{(a_o+a_1T_r+a_2T_r^2 + ---)} \qquad (146)$$

For the case where stress varies linearly with time and starts at zero stress

$$S_s = S_a T \quad \text{and} \quad T_r = T_t T \qquad (147)$$

Then $$1 = \int_o^t dT/(C/S_a T)^{(a_o+a_1(T_tT)+a_2(T_tT)^2+ ---)} \qquad (148)$$

This integration is complex. It may be simplified somewhat by assuming an approximation to the exponential series by an exponential (e^x) or a log function ($\ln x$). However, a solution is still not at hand even for this simple case where the stress starts at zero. Equations similar to the above equations (146) and (148) can be written for Class II and Class IV problems.

Most problems do not start with zero stress and for the simplest case where the stress starts at some point not equal to zero the stress becomes

$$S_s = S_i + S_a T \qquad (149)$$

Where S_i is the initial stress and combining equations (137) and (149) we have once again:

$$1 = \int_o^t dT/(C/S_i + S_a T)^r \qquad (150)$$

$$1 = \int_0^t (S_i + S_a T)^r \, dT/(C)^r \tag{151}$$

$$1 = (1/C^r) \left| (S_i + S_a T)^{r+1}/S_a(r+1) \right|_0^t \tag{152}$$

$$C^r = ((S_i + S_a t)^{r+1}/S_a(r+1)) - ((S_i)^{r+1}/(S_a)(r+1)) \tag{153}$$

$$(S_i + S_a t)^{r+1}/S_a(r+1) = C^r + (S_i)^{r+1}/S_a(r+1) \tag{154}$$

$$(S_i + S_a t)^{r+1} = ((C^r + (S_i)^{r+1}/S_a(r+1))(S_a(r+1)) \tag{155}$$

$$t = \frac{\left\{ \left(C^r + \dfrac{S_i^{\,r+1}}{S_a(r+1)} \right) \left(S_a(r+1) \right) \right\}^{1/r+1} - (S_i)}{S_a} \tag{156}$$

It is obvious that this integration is more complex than equation (145). As in the previous case, r, is a constant and C, is a function of temperature. As before, for example, for Case III at uniform stress and temperature which varies linearly with time and starts at some initial stress, S_i, and some initial temperature, T_c, we have:

$$S_s = S_i + S_a T \quad \text{and} \quad T_r = T_c - T_t T \tag{157}$$

$$\text{then } 1 = \int_0^t dT/(C/S_i + S_a T)^{a_0 + a_1(T_c - T_t T) + a_2(T_c - T_t T)^2 + ---} \tag{158}$$

This integration is more complex than equation (148) and is good for a stress varying linearly with time. Similar equations can be written for Class II and Class IV problem types. At this point an analytical solution was considered impractical and a computer solution was sought. See References 50 and 51 for similar viewpoints.

Computer Solution

In previous chapters general equations were derived for heat transfer, plate stress, attrition rate, stress-to-rupture and a life fraction rate. We shall now combine all the general equations developed in the preceding chapters into one computer program to solve the galvanize kettle life problem.

We will start with the life fraction theory equation (131) and we once again have:

$$F = \sum T/R_h = T_1/R_{h_1} + T_2/R_{h_2} + --- = 1 \text{ (Equation 131 repeated)}$$

Now we shall assume that each of the times, T_1, T_2, T_n, are each equal to 100 hours and assume that the rupture life, R_h, is calculated as "R_{h_1} = 6349 hours" for the first 100 hours; "R_{h_2} = 8694 hours: for the second 100 hours; "R_{h_3} = 7654 hours" for the third 100 hours; plus "T/R_{h_n}" etc., until the sum of "R_{h_n}" approximates one by the closest fraction over one. In

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[50] E.L. Robinson, Effect of Temperature Variation on the Long Time Rupture Life of Steels (Transactions of the ASME, Volume 74, 1952) pp. 253-259.

[51] G.H. Rowe and H.R. Meck, Stress Rupture of Metals Under Increasing Stress (Transactions of the ASME, Journal of Basic Engineering: December, 1965) pp. 875-877.

other words for some fictitious specimen:

$$F=100/6349+100/8694+100/7654+100/5199+\ldots+$$

$$100/3219+100/3674+100/2001 = 1.037 \qquad (159)$$

Therefore, the life of this specimen was approximated in "n" steps of 100 hours each to rupture and the fraction 1.037 is an indicator of the relative accuracy when considered with the number of steps.

For example, if 34 steps had been required to arrive at the fraction 1.037, then the total hours to rupture for that specimen would be (34)(100) or 3400 hours.

The fundamental statements in the life program in Appendix H are the statements:

RS=RS+T	Accumulates total number of hours stepwise.
FL=T/RH	Calculates life fraction.
FS=FS+FL	Accumulates total life fraction.
IF(FS-1.0000)	Stops the calculation when FS approximates 1.

This part of the program simulates the calculation of equation (159) and is the switch that continues the calculation for life or terminates it when "FS" approximates 1.

The most important equation is the life-to-rupture in hours from the program or:

```
RH=(38000./SS)**RE  Calculates Rupture Life
```

where "RE" is the exponent which is a function of temperature and "SS" is the actual stress as was shown in equation (118). The hand calculation of the exponent "RE" in equation (119) was the first approximation. The computer program for five equations and five unknowns generated "RE" from equation (129) and written in the program as shown on the following page.

```
RE=(+1095.38951-(3.2483079*TR)+(0.0032496875*(TR**2})-
1(0.0000010912879*(TR**3))-(0.0000000000000003721*(TR**4)))
```

where the "1" in the second line beside the parenthesis tells the computer that the second line is part of the first and must be read continuously with the first. "TR" is the temperature in the midpoint of the plate (usual design practice).

The temperatures on the outside of the plate is given by: `TO=TZ+(Q*((P/PK)+(AT/AK)+(HT/H)))` and is derived by equations (17) and (21). The temperature at the inside of the plate is given in the program by:

`TM=TO-(Q/(PK/P)`   (From Equation 18)

The temperature at the plate midpoint is given by:

`TR=(TO+TM)/2`   (From Equation 19)

and then this temperature "TR" is used in the exponent equation "RE".

The wear rate "WR" is then calculated at the inside of the plate where the zinc-iron diffusion is taking place at temperature "TM" and the statement below is derived from equation (65):

```
WR=(TM/948.9014078)**(1.0000000000/1015078562)
```

The static stress due to the zinc load is derived in equation (45) and appears as the statement below:

```
S = (6.*A*W*AC*(D**3))/(P**2)
```

The thermal stress due to the temperature gradient across the plate is derived in equation (33) and appears as the statement below:

```
ST = (130.0*(TO-TM))/1.40
```

The actual stress is the difference between the thermal stress and the static stress and is written in absolute value so as to simplify the life calculation (eliminate negative life).

```
SS=ABS(S-ST)
```

All of the above calculations must be made for each 100 hour increment of the program to satisfy the life to rupture. In other words, all of the design parameters must be read in (see statement 10 in program) and for records and checking convenience this data is printed in the output (write statement immediate after first read statement 10). The plate thickness (a unit thickness higher than desired) is initiated as the statement:

```
PL=3.5
```

where the initial plate thickness is taken as 3.5 inches. Statement 12 then subtracts a unit thickness (.5 inches):

```
PL=PL-0.5
```

which starts the calculation at 3 inches (thickness which we wanted to start with). The above two statements are necessary to force the program to loop through various plate thicknesses. The computer also prints out the plate thickness so the interpreter of the data will know what plate thickness the computer is working with. The computer then starts with a plate thickness of 3 inches, the design conditions in statement 10, initiates an initial kettle depth of 50 inches and calculates the life for heat inputs from 8,000 to 20,000 BTU/FT^2-HR. Each time the time increment occurs within a heat rate the wear rate is subtracted. The program then loops back and does the same for a kettle 60 inches deep, etc., until a maximum depth of 120 inches is reached; whereupon it loops back, subtracts .5 inch from the plate thickness and does the routine for a 2½ inch plate and then down to a ½ inch plate. The computer then reads another card of design data; if no card is available the program then stops. This program takes 10 computer minutes to run or 12 minutes complete execution time for 5 design data cards. It should be noted that each time the heat input "Q" is incremented the whole timing and accumulating mechanism of the program is reset.

The statement 28 prints out the following data:

```
28 Write(3,29)WR,TM,FS,TR,SS,P,Q,D,RS,RE
```

where WR is the final wear rate at failure
TM is the final inside plate temperature at failure
FS is the final fraction sum (measure of accuracy)
TR is the final plate midpoint temperature at failure
SS is the final actual plate stress at failure
P is the final plate thickness at failure
Q is the heat rate for which the life was calculated
D is the kettle depth for which life was calculated
RS is the life of the specimen in hours
RE is the exponent calculated for life at failure

The computer program is listed in Appendix H and a listing of data is reviewed in the next chapter.

Life Fraction Theory Analysis

The principal assumption of the life fraction theory is that the stress and temperature increase or decrease at a constant, non-interrupted rate. In this problem the stress or temperature rate was interrupted; but, for engineering purposes the assumption was also made that an "averaging effect" would make any errors negligible. Field data bears this out to be true. Any longer periods of down-time extend the kettle life and shorter down-time periods shorten life. However, the data arrived at is representative of field conditions and experiences. It is also to be noted that kettle deflection or creep strain was not considered in this program but a method for constructing the creep curve for any temperature at a given stress is given by Dorn.[52] Dorn also suggests the life fraction rule for cyclic temperature and stress conditions.[53] Further investigation and study of creep rates should prove interesting when correlated with stress to rupture data.

The computer program written above is very versatile and could be rewritten to include surface defects,[54] and metallurgical effects.[55] Analytical methods which have been developed to treat nonsteady load and temperature

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[52] John E. Dorn, Mechanical Behavior of Materials at Elevated Temperatures, pp. 458-459.

[53] John E. Dorn, Mechanical Behavior of Materials at Elevated Temperatures, pp. 459-463.

[54] ASTM STP 415, Fatigue Crack Propagation, (Philadelphia: ASTM, 1967).

[55] Lain Finnie and William Heller, Creep of Engineering Materials (New York: McGraw-Hill Book Company, 1959) pp. 64-88.

conditions neglect to a great extent many of the mechanical and metallurgical complications introduced by nonsteady conditions. Usually the methods are based on some simplifying assumption relating the behavior at any instantaneous value of stress and temperature with a corresponding behavior under steady conditions. Even in relatively simple physical cases and neglecting many metallurgical complications, the mathematics of the problem can become very difficult. Successive approximation methods then become very useful in determining numerical solutions in particular cases and the computer becomes an effective tool. Analytical techniques have also been attempted for the case of rapid heating and/or rapid loading and a similar approach as developed above could be effectively used.

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CHAPTER VII

CALCULATION FOR LIFE

Introduction

The data arrived at in the computer print-out must be analyzed so that data which is beyond the limits set in the previous chapters will be thrown out. Those limits are reviewed below:

T_o = Outside plate temperature must not exceed 1100°F to preserve the metallurgical properties of the material.

T_r = Plate middle point temperature must not exceed 1000°F. This is the same as limiting the exponent "R_e" to 5.4445.

R_h = Specimen life which is limited to a minimum of 2000 hours.

S_s = Actual stress must not exceed 10,000 PSI initially for a combination of thermal and static stress.

The selection of this data can be done in one of two ways. The first way is accomplished by the tedious task of reviewing all data from all programs; the second way is to write another program which automatically rejects data which is not acceptable. A program for this purpose is listed in Appendix I and a more sophisticated program with title blocks and printed identification appears in Appendix J. Either program will do the job. The data which the computer and a physical check shows as acceptable appears in the following table 8 through table 13 inclusive. Because of the complexity of the factors involved in the various equations used, any judgment on empirical factors or theoretical factors was always made in favor of the safe side of the factor and therefore the life listed in the tables for the various plates should be considered as a minimum life for kettles operated under the normal conditions assumed in this thesis. If this minimum life is not achieved then one should review the conditions of kettle design and/or operation of the underachieving kettle. The data tabulated is for a kettle which is being operated at 850°F. If a kettle is operated at 840°F then the life may be doubled, if a kettle is being operated at 860°F, then the life is one-half. For example, from Table 12, for a 2" thick kettle 70" deep being operated at a 16,000 BTU heat rate the minimum life to be expected is 2700.0 hours or 5.4 months (500 operating hours per month). If that same kettle was operated at 840°F under the same conditions and design, the life would be 5,400 hours or 10.8 months. On the other hand, if that same kettle was operated at 860°F, the life would be less than 1,300 hours or 2.6 months. It can be stated that for every 10°F increase in zinc temperature approximately half of the life of a kettle is lost. Table 14 summarizes this data for plates 4.0 inches thick to 1.5 inches thick inclusive.

In Tables 8 through 13 inclusive the first column gives the outside plate temperature when the kettle is new. As time goes on the kettle plate becomes thinner and thinner and column 3 gives the outside plate temperature at the final plate thickness (last column). This shows that for the same BTU heat transfer the outside plate temperature gets lower and the inside plate temperature (column 3) remains constant as long as the molten zinc temperature remains constant. The fourth column then gives the BTU heat rate equivalent to the above outside plate temperatures. Since the inside plate temperatures are constant under the above conditions the wear rate which is a function of this temperature is constant also (see column 13). The static stress is a function of plate depth and thickness; therefore, column 5 gives the stress when the kettle is new and column 6 gives the static stress due to the zinc when the kettle is ready to fail. The static stress due to the zinc causes tension on the outside of the plate and compression on the inside of the plate. The thermal stress is a function of temperature differential (indirectly plate thickness) and gets lower as the plate thins (static stress gets higher as plate thins). The thermal stress due to the heat load causes compression on the outside plate surface and tension on the inside plate surface. Column 7 gives the thermal stress when the plate is new and column 8 gives the thermal stress when the plate is eroded. It is interesting to note that the best life condition occurs when the static stress and the thermal stress balance each other in the proper proportion so as to minimize the actual stress (static & thermal) condition. The actual stress for a new kettle is given in column 9 and the actual stress at rupture is given in column 10. As was stated previously, Table 14 compares the life at zinc temperatures of 840°F and 860°F.

To use these tables one must determine the average zinc temperature the kettle is being run at (most kettles vary between 840°F and 860°F) and the average heat rate (most kettles run from 12,000 to 17,000 BTU/FT^2-HR and interpolate the tables for the kettle plate thickness and depth. Table 15 shows the range of acceptable zinc wear rates. From Tables 8 through 13 one can see that the life of a kettle is proportional to the wear rate for kettles of similar design. Table 16 lists the 4 inch plate conditions for a molten zinc temperature of 840°F and Table 17 lists the 4 inch plate conditions for a molten zinc temperature of 860°F. It is interesting to compare these tables with Table 8 which lists the 4 inch plate data for 850°F. One should note that the outside plate temperature increases or decreases at the same rate as the inside plate temperature. The final plate outside temperature corresponds to the final plate thickness and so does the final actual stress for similar kettle designs. Life factor and other data for kettles operated with zinc-iron alloy layers greater than 0.125 inch was not tabulated. Obviously, it is not worth tabulating data which shows short life due to poor kettle maintenance and operation. The increased zinc-iron layer causes a high inside plate temperature and high wear rates which gives short life. One should also note that the higher or lower zinc temperature allows appropriately more or less latitude in kettle design.

The blank spaces in Table 14 indicate that the life was not acceptable due to either high thermal stress or high static stress. Also, any life calculated that did not meet the specifications outlined in this thesis was rejected by the computer program and this rejected data is not included in any of the following tables.

TABLE 8

FOUR INCH THICK PLATE LIFE CONDITIONS FOR CONSTANT 850°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
1039.6	965.2	889.6	12000	5815	22884	13928	7021	-8113	15863	14500	105	.01387	4.0	2.016
1055.4	974.0	892.9	13000	5815	23357	15089	7529	-9273	15828	11500	105	.01773	4.0	1.995
1039.6	970.4	889.6	12000	6686	23034	13928	7504	-7242	15529	13500	110	.01387	4.0	2.155
1055.4	979.1	892.9	13000	6686	23802	15089	7997	-8402	15805	10800	110	.01773	4.0	2.120
1071.2	989.0	896.2	14000	6686	23809	16250	8611	-9563	15198	8500	110	.02265	4.0	2.119
1039.6	975.1	889.6	12000	7640	23516	13928	7939	-6288	15577	12600	115	.01387	4.0	2.279
1055.4	984.8	892.9	13000	7640	23893	15089	8532	-7449	15360	10000	115	.01773	4.0	2.261
1071.2	993.9	896.2	14000	7640	24516	16250	9071	-8609	15444	8000	115	.02265	4.0	2.233
1087.0	1003.0	899.5	15000	7640	25086	17410	9608	-9770	15447	6400	115	.02891	4.0	2.207
1039.6	980.3	889.6	12000	8680	23742	13928	8422	-5247	15320	11600	120	.01387	4.0	2.418
1055.4	989.9	892.9	13000	8680	24395	15089	9001	-6408	15394	9300	120	.01773	4.0	2.386
1071.2	998.9	896.2	14000	8680	25230	16250	9531	-7569	15698	7500	120	.02265	4.0	2.346
1087.0	1008.4	899.5	15000	8680	25735	17410	10111	-8729	15623	6000	120	.02891	4.0	2.323

TABLE 9

THREE AND ONE-HALF INCH PLATE LIFE CONDITIONS FOR CONSTANT 850°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
1020.9	950.1	889.6	12000	4783	22507	12187	5618	-7404	16888	13800	90	.01387	3.5	1.613
1035.1	958.0	892.9	13000	4783	22823	13203	6044	-8419	16778	10900	90	.01773	3.5	1.602
1049.4	966.1	896.2	14000	4783	22972	14218	6488	-9435	16484	8600	90	.02265	3.5	1.597
1020.9	955.3	889.6	12000	5625	22445	12187	6101	-6561	16343	12800	95	.01387	3.5	1.752
1035.1	963.1	892.9	13000	5625	23120	13203	6512	-7577	16607	10200	95	.01773	3.5	1.726
1049.4	971.1	896.2	14000	5625	23558	14218	6948	-8593	16609	8100	95	.02265	3.5	1.710
1063.6	979.6	899.5	15000	5625	23636	15234	7432	-9608	16204	6400	95	.02891	3.5	1.707
1020.9	960.0	889.6	12000	6561	22812	12187	6536	-5626	16276	11900	100	.01387	3.5	1.877
1035.1	968.1	892.9	13000	6561	23469	13203	6981	-6641	16488	9500	100	.01773	3.5	1.850
1049.4	976.0	896.2	14000	6561	24169	14218	7408	-7657	16761	7600	100	.02265	3.5	1.823
1063.6	985.0	899.5	15000	6561	24182	15234	7935	-8672	16246	6000	100	.02891	3.5	1.823
1077.8	993.0	902.8	16000	6561	24691	16250	8376	-9688	16314	4800	100	.03686	3.5	1.804
1020.9	965.2	889.6	12000	7595	22899	12187	7019	-4591	15879	10900	105	.01387	3.5	2.015
1035.1	973.2	892.9	13000	7595	23860	13203	7449	-5607	16411	8800	105	.01773	3.5	1.974
1049.4	982.0	896.2	14000	7595	24232	14218	7960	-6623	16271	7000	105	.02265	3.5	1.959
1063.6	990.4	899.5	15000	7595	24754	15234	8438	-7638	16315	5600	105	.02891	3.5	1.938
1077.8	998.6	902.8	16000	7595	25377	16250	8890	-8654	16486	4500	105	.03686	3.5	1.918
1092.1	1007.2	906.1	17000	7595	25686	17265	9389	-9669	16297	3600	105	.04696	3.5	1.903
1020.9	969.9	889.6	12000	8733	23347	12187	7454	-3454	15893	10000	110	.01387	3.5	2.140
1035.1	978.9	892.9	13000	8733	23879	13203	7984	-4469	15894	8000	110	.01773	3.5	2.116
1049.4	987.9	896.2	14000	8733	24364	14218	8512	-5485	15851	6400	110	.02265	3.5	2.095

TABLE 9 CONTINUED

PLATE OUTSIDE TEMPERATURE INIT.	PLATE OUTSIDE TEMPERATURE FINAL	IN-SIDE TEMP. INIT.	PLATE HEAT RATE INIT.	TENSION STATIC (+) STRESS INIT.	TENSION STATIC (+) STRESS FINAL	COMPRESSION THERMAL (-) STRESS INIT.	COMPRESSION THERMAL (-) STRESS FINAL	ACTUAL STRESS (TEN.-COMP.) INIT.	ACTUAL STRESS (TEN.-COMP.) FINAL	LIFE HOURS INIT.	PLATE DEPTH INIT.	WEAR RATE INIT.	PLATE THICKNESS INIT.	PLATE THICKNESS FINAL
1063.6	995.8	899.5	15000	8733	25347	15234	8942	-6501	16405	5200	110	.02891	3.5	2.054
1077.8	1004.1	902.8	16000	8733	26078	16250	9403	-7516	16674	4200	110	.03686	3.5	2.025
1092.1	1012.2	906.1	17000	8733	26820	17265	9852	-8532	16968	3400	110	.04696	3.5	1.997
1020.9	975.1	889.6	12000	9979	23529	12187	7937	-2208	15592	9000	115	.01387	3.5	2.279
1035.1	984.7	892.9	13000	9979	23965	13203	8519	-3224	15445	7200	115	.01773	3.5	2.258
1049.4	992.9	896.2	14000	9979	25058	14218	8973	-4239	16085	5900	115	.02265	3.5	2.208
1063.6	1002.6	899.5	15000	9979	25280	15234	9571	-5255	15709	4700	115	.02891	3.5	2.198
1077.8	1009.6	902.8	16000	9979	26792	16250	9917	-6270	16875	3900	115	.03686	3.5	2.136
1092.1	1019.7	906.1	17000	9979	26741	17265	10547	-7286	16193	3100	115	.04696	3.5	2.138
1020.9	980.3	889.6	12000	11338	23754	12187	8420	- 849	15334	8000	120	.01387	3.5	2.418
1035.1	989.7	892.9	13000	11338	24465	13203	8988	-1864	15477	6500	120	.01773	3.5	2.382
1049.4	998.8	896.2	14000	11338	25265	14218	9525	-2880	15740	5300	120	.02265	3.5	2.344
1063.6	1008.0	899.5	15000	11338	25924	15234	10074	-3896	15850	4300	120	.02891	3.5	2.314
1077.8	1017.0	902.8	16000	11338	26637	16250	10601	-4911	16035	3500	120	.03686	3.5	2.283
1092.1	1024.7	906.1	17000	11338	27879	17265	11010	-5927	16868	2900	120	.04696	3.5	2.232

TABLE 10

THREE INCH PLATE LIFE CONDITIONS FOR CONSTANT 850°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		IN- SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC(+) STRESS		COMPRESSION THERMAL(-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
1002.1	923.1	889.6	12000	1929	21841	10446	3104	-8517	18736	15400	60	.01387	3.0	.891
1014.8	929.1	892.9	13000	1929	21943	11317	3355	-9387	18588	12100	60	.01773	3.0	.889
1002.1	931.4	889.6	12000	3063	22135	10446	3877	-7383	18357	13800	70	.01387	3.0	1.113
1014.8	937.7	892.9	13000	3063	22689	11317	4158	-8253	18531	10900	70	.01773	3.0	1.102
1027.5	944.2	896.2	14000	3063	22906	12187	4456	-9124	18449	8600	70	.02265	3.0	1.097
1040.2	950.7	899.5	15000	3063	23126	13058	4752	-9994	18374	6800	70	.02891	3.0	1.091
1002.1	940.7	889.6	12000	4572	22145	10446	4746	-5873	17398	12000	80	.01387	3.0	1.363
1014.8	947.8	892.9	13000	4572	22560	11317	5094	-6744	17465	9500	80	.01773	3.0	1.350
1027.5	954.1	896.2	14000	4572	23490	12187	5377	-7614	18112	7600	80	.02265	3.0	1.323
1040.2	961.6	899.5	15000	4572	23507	13058	5759	-8485	17748	6000	80	.02891	3.0	1.323
1052.8	968.0	902.8	16000	4572	24193	13928	6055	-9355	18137	4800	80	.03686	3.0	1.304
1002.1	950.1	889.6	12000	6510	22524	10446	5616	-3935	16908	10200	90	.01387	3.0	1.612
1014.8	957.9	892.9	13000	6510	22920	11317	6031	-4806	16888	8100	90	.01773	3.0	1.590
1027.5	965.0	896.2	14000	6510	23687	12187	6389	-5676	17297	6500	90	.02265	3.0	1.572
1040.2	972.4	899.5	15000	6510	24250	13058	6765	-6547	17484	5200	90	.02891	3.0	1.554
1052.8	979.1	902.8	16000	6510	25181	13928	7082	-7417	18099	4200	90	.03686	3.0	1.525
1065.5	985.7	906.1	17000	6510	26139	14799	7385	-8288	18754	3400	90	.04696	3.0	1.497
1078.2	994.1	909.4	18000	6510	25848	15669	7864	-9159	17983	2700	90	.05977	3.0	1.505
1002.1	960.0	889.6	12000	8930	22828	10446	6534	-1515	16294	8300	100	.01387	3.0	1.876
1014.8	968.0	892.9	13000	8930	23556	11317	6968	-2386	16588	6700	100	.01773	3.0	1.847
1027.5	975.9	896.2	14000	8930	24212	12187	7401	-3256	16810	5400	100	.02265	3.0	1.822

TABLE 10 CONTINUED

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC(+) STRESS		COMPRESSION THERMAL(-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
1040.2	984.6	899.5	15000	8930	24409	13058	7898	-4127	16511	4300	100	.02891	3.0	1.814
1052.8	992.0	902.8	16000	8930	25269	13928	8280	-4997	16989	3500	100	.03686	3.0	1.783
1065.5	998.1	906.1	17000	8930	26793	14799	8544	-5856	18249	2900	100	.04696	3.0	1.732
1078.2	1007.6	909.4	18000	8930	26404	15669	9113	-6738	17291	2300	100	.05977	3.0	1.744
1002.1	969.9	889.6	12000	11887	23361	10446	7451	+1440	15909	6400	110	.01387	3.0	2.139
1014.8	978.8	892.9	13000	11887	23956	11317	7971	+ 570	15984	5200	110	.01773	3.0	2.113
1027.5	987.8	896.2	14000	11887	24402	12187	8506	- 300	15895	4200	110	.02265	3.0	2.093
1040.2	995.4	899.5	15000	11887	25558	13058	8905	-1171	16653	3500	110	.02891	3.0	2.045
1052.8	1004.9	902.8	16000	11887	25668	13928	9478	-2041	16190	2800	110	.03686	3.0	2.041
1065.5	1013.1	906.1	17000	11887	26380	14799	9934	-2912	16446	2300	110	.04696	3.0	2.041
1002.1	980.3	889.6	12000	15432	23767	10446	8417	+4986	15349	4400	120	.01387	3.0	2.417
1014.8	989.6	892.9	13000	15432	24535	11317	8975	+4115	15560	3700	120	.01773	3.0	2.379
1027.5	998.7	896.2	14000	15432	25300	12187	9518	+3245	15781	3100	120	.02265	3.0	2.343
1040.2	1007.6	899.5	15000	15432	26116	13058	0037	+2374	16078	2600	120	.02891	3.0	2.306
1052.8	1052.8	902.8	16000	15432	27128	13928	0505	+1504	16622	2200	120	.03686	3.0	2.262

TABLE 11

TWO AND ONE-HALF INCH PLATE LIFE CONDITIONS FOR CONSTANT 850°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
983.4	914.7	889.6	12000	1607	22448	8705	2329	-7097	20119	13400	50	.01387	2.5	0.669
994.5	920.3	892.9	13000	1607	22165	9430	2539	-7823	19626	10500	50	.01773	2.5	0.673
1005.6	925.3	896.2	14000	1607	22717	10156	2701	-8548	20015	8300	50	.02265	2.5	0.665
1016.7	930.0	899.5	15000	1607	23804	10881	2827	-9274	20976	6600	50	.02891	2.5	0.649
1027.8	935.7	902.8	16000	1607	23291	11607	3049	-9999	20241	5200	50	.03686	2.5	0.656
983.4	923.0	889.6	12000	2777	21872	8705	3102	-5927	18769	11800	60	.01387	2.5	0.890
994.5	928.9	892.9	13000	2777	22113	9430	3342	-6652	18770	9300	60	.01773	2.5	0.886
1005.6	934.2	896.2	14000	2777	22994	10156	3530	-7378	19464	7400	60	.02265	2.5	0.868
1016.7	939.5	899.5	15000	2777	23914	10881	3708	-8103	20206	5900	60	.02891	2.5	0.852
1027.8	944.9	902.8	16000	2777	24540	11607	3905	-8829	20635	4700	60	.03686	2.5	0.841
1038.9	951.6	906.1	17000	2777	23676	12332	4224	-9554	19452	3700	60	.04696	2.5	0.856
983.4	931.4	889.6	12000	4411	22260	8705	3875	-4294	18385	10200	70	.01387	2.5	1.112
994.5	937.6	892.9	13000	4411	22830	9430	4145	-5019	18685	8100	70	.01773	2.5	1.098
1005.6	944.2	896.2	14000	4411	22974	10156	4450	-5745	18523	6400	70	.02265	2.5	1.095
1016.7	950.3	899.5	15000	4411	23491	10881	4715	-6470	18775	5100	70	.02891	2.5	1.083
1027.8	955.9	902.8	16000	4411	24431	11607	4932	-7196	19499	4100	70	.03686	2.5	1.062
1038.9	961.6	906.1	17000	4411	25286	12332	5150	-7921	20135	3300	70	.04696	2.5	1.044
1050.1	969.4	909.4	18000	4411	24288	13058	5564	-8646	18723	2600	70	.05977	2.5	1.065
1061.2	975.4	912.7	19000	4411	24737	13783	5820	-9372	18917	2100	70	.07602	2.5	1.055
983.4	940.7	889.6	12000	6584	22166	8705	4744	-2120	17421	8400	80	.01387	2.5	1.362
994.5	947.7	892.9	13000	6584	22675	9430	5082	-2846	17593	6700	80	.01773	2.5	1.347

TABLE 11 CONTINUED

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
1005.6	954.1	896.2	14000	6584	23547	10156	5370	-3571	18176	5400	80	.02265	2.5	1.322
1016.7	961.2	899.5	15000	6584	23812	10881	5722	-4297	18090	4300	80	.02891	2.5	1.314
1027.8	967.0	902.8	16000	6584	24982	11607	5959	-5022	19023	3500	80	.03686	2.5	1.283
1038.9	974.1	906.1	17000	6584	25158	12332	6309	-5748	18849	2800	80	.04696	2.5	1.278
1050.1	979.5	909.4	18000	6584	26561	13058	6501	-6473	20060	2300	80	.05977	2.5	1.244
983.4	950.1	889.6	12000	9375	22542	8705	5614	+ 669	16928	6600	90	.01387	2.5	1.612
994.5	957.7	892.9	13000	9375	23018	9430	6018	- 55	16999	5300	90	.01773	2.5	1.595
1005.6	965.0	896.2	14000	9375	23736	10156	6383	- 780	17353	4300	90	.02265	2.5	1.571
1016.7	972.0	899.5	15000	9375	24518	10881	6728	-1506	17789	3500	90	.02891	2.5	1.545
1027.8	979.9	902.8	16000	9375	24658	11607	7157	-2231	17501	2800	90	.03686	2.5	1.541
1038.9	986.6	906.1	17000	9375	25570	12332	7467	-2957	18102	2300	90	.04696	2.5	1.513
983.4	960.0	889.6	12000	12860	22843	8705	6531	+4155	16311	4700	100	.01387	2.5	1.875
994.5	967.8	892.9	13000	12860	23643	9430	6955	+3429	16688	3900	100	.01773	2.5	1.843
1005.6	975.9	896.2	14000	12860	24255	10156	7395	+2704	16860	3200	100	.02265	2.5	1.820
1016.7	984.2	899.5	15000	12860	24640	10881	7861	+1978	16778	2600	100	.02891	2.5	1.806
1027.8	991.0	902.8	16000	12860	25868	11607	8184	+1253	17684	2200	100	.03686	2.5	1.762
983.4	969.9	889.6	12000	17117	23375	8705	7449	+8412	15925	2800	100	.01387	2.5	2.139
994.5	978.6	892.9	13000	17117	24034	9430	7958	+7686	16075	2400	100	.01773	2.5	2.109
1005.6	987.8	896.2	14000	17117	24439	10156	8499	+6961	15940	2000	100	.02265	2.5	2.092

TABLE 12

TWO INCH PLATE LIFE CONDITIONS FOR CONSTANT 850°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		INSIDE TEMP.	PLATE HEAT RATE	TENSION STATIC(+) STRESS		COMPRESSION THERMAL(-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
964.6	914.7	889.6	12000	2511	22491	6964	2327	-4452	20164	9800	50	.01387	2.0	0.668
974.2	920.1	892.9	13000	2511	22391	7544	2526	-5032	19864	7700	50	.01773	2.0	0.669
983.7	925.3	896.2	14000	2511	22827	8125	2695	-5613	20132	6100	50	.02265	2.0	0.663
993.3	929.6	899.5	15000	2511	24440	8705	2790	-6193	21649	4900	50	.02891	2.0	0.641
1002.8	934.6	902.8	16000	2511	24836	9285	2953	-6773	21833	3900	50	.03686	2.0	0.636
1012.4	940.0	906.1	17000	2511	24676	9866	3147	-7354	21528	3100	50	.04696	2.0	0.638
1021.9	944.6	909.4	18000	2511	25705	10446	3265	-7934	22440	2500	50	.05977	2.0	0.625
1031.5	950.2	912.7	19000	2511	25177	11026	3482	-8515	21694	2000	50	.07602	2.0	0.631
964.6	923.0	889.6	12000	4340	21903	6964	3100	-2623	18803	8200	60	.01387	2.0	0.890
974.2	928.8	892.9	13000	4340	22784	7544	3329	-3204	18954	6500	60	.01773	2.0	0.882
983.7	934.2	896.2	14000	4340	23080	8125	3523	-3484	19557	5200	60	.02265	2.0	0.867
993.3	940.4	899.5	15000	4340	22809	8705	3797	-4364	19011	4100	60	.02891	2.0	0.872
1002.8	945.7	902.8	16000	4340	23627	9285	3979	-4945	19647	3300	60	.03686	2.0	0.857
1012.4	950.0	906.1	17000	4340	25450	9866	4074	-5525	21376	2700	60	.04696	2.0	0.825
1021.9	954.7	909.4	18000	4340	26824	10446	4202	-6106	22622	2200	60	.05977	2.0	0.804
964.6	931.3	889.6	12000	6892	22286	6964	3873	- 71	18413	6600	70	.01387	2.0	1.112
974.2	938.2	892.9	13000	6892	22246	7544	4199	- 652	18047	5200	70	.01773	2.0	1.113
983.7	944.1	896.2	14000	6892	23042	8125	4443	-1232	18598	4200	70	.02265	2.0	1.093
993.3	949.9	899.5	15000	6892	23864	8705	4678	-1812	19186	3400	70	.02891	2.0	1.074
1002.8	956.8	902.8	16000	6892	23707	9285	5006	-2393	18700	2700	70	.03686	2.0	1.078
1012.4	962.5	906.1	17000	6892	24502	9866	5232	-2973	19269	2200	70	.04696	2.0	1.060
964.6	940.7	889.6	12000	10288	22187	6964	4742	+3324	17444	4800	80	.01387	2.0	1.361
974.2	947.5	892.9	13000	10288	22790	7544	5069	+2743	17720	3900	80	.01773	2.0	1.343

TABLE 12 CONTINUED

PLATE OUTSIDE TEMPERATURE		INSIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
983.7	954.0	896.2	14000	10288	23605	8125	5364	+2163	18241	3200	80	.02265	2.0	1.320
993.3	960.8	899.5	15000	10288	24123	8705	5685	+1583	18438	2600	80	.02891	2.0	1.306
1002.8	967.8	902.8	16000	10288	24367	9285	6033	+1002	18333	2100	80	.03686	2.0	1.299
964.6	950.1	899.6	12000	14648	22560	6964	5611	+7684	16948	3000	90	.01387	2.0	1.611
974.2	957.6	892.9	13000	14648	23117	7544	6005	+7104	17111	2500	90	.01773	2.0	1.592
983.7	964.9	896.2	14000	14648	23748	8125	6376	+6523	17408	2100	90	.02265	2.0	1.569

TABLE 13

ONE AND ONE-HALF INCH PLATE AND 1 INCH PLATE LIFE CONDITIONS FOR CONSTANT 850°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
FOR ONE AND ONE-HALF INCH THICK PLATE														
945.9	914.7	889.6	12000	4465	22534	5223	2325	- 757	20209	6200	50	.01387	1.5	0.667
953.9	920.0	892.9	13000	4465	22621	5658	2514	- 193	20107	4900	50	.01773	1.5	0.666
961.9	925.2	896.2	14000	4465	22939	6093	2688	-1628	20250	3900	50	.02265	1.5	0.661
969.8	930.5	899.5	15000	4465	22956	6529	2879	-2063	20076	3100	50	.02891	1.5	0.661
997.8	935.4	902.8	16000	4465	23625	6964	3027	-2498	20597	2500	50	.03686	1.5	0.652
985.8	940.9	906.1	17000	4465	23442	7399	3229	-2934	20202	2000	50	.04696	1.5	0.654
FOR ONE INCH THICK PLATE														
927.1	914.6	889.6	12000	10047	22577	3482	2322	+6565	20254	2600	50	.01387	1.0	0.667
933.6	919.9	892.9	13000	10047	22854	3772	2501	+6274	20353	2100	50	.01773	1.0	0.663

TABLE 14

ACCEPTABLE KETTLE LIFE IN HOURS AT VARIOUS MOLTEN ZINC TEMPERATURES, PLATE DEPTHS AND PLATE THICKNESSES.

KETTLE		840°F AND 860°F MOLTEN ZINC TEMPERATURE AND PLATE THICKNESS											
PLATE	HEAT	4.0		3.5		3.0		2.5		2.0		1.5	
DEPTH	RATE	840	860	840	860	840	860	840	860	840	860	840	860
50	12000						8200	27900	6500	20200	4800	12600	3100
	13000							21800	5200	15900	3800	10000	2500
	14000							17100	4100	12500	3100	7900	2000
	15000							13500	3300	9900	2500	6200	
	16000							10600	2600	7800	2000	5000	
	17000									6200		4000	
	18000									4900		3200	
	19000									3900		2500	
	20000									3100		2100	
60	12000						7500	24600	5800	16900		9300	
	13000					25200	6000	19300	4600	13300		7400	
	14000							15200	3700	10500		5900	
	15000							12000	3000	8300		4700	
	16000							9400	2400	6600		3800	
	17000							7500		5300		3000	
	18000									4200		2500	
	19000									3400		2000	
	20000									2700			
70	12000				8400	28600	6700	21000	5000	13400			
	13000					22500	5400	16600	4000	10600		4700	
	14000					17700	4300	13100	3200	8400		3800	
	15000					13900	3400	10300	2600	6700		3100	
	16000							8200	2100	5400		2500	
	17000							6500		4300		2100	
	18000							5200		3500			
	19000							4100		2800			
	20000									2300			

TABLE 14 CONTINUED

KETTLE PLATE DEPTH	KETTLE HEAT RATE	840°F AND 860°F MOLTEN ZINC TEMPERATURE AND PLATE THICKNESS 4.0 840	4.0 860	3.5 840	3.5 860	3.0 840	3.0 860	2.5 840	2.5 860	2.0 840	2.0 860	1.5 840	1.5 860
80	12000				7600	24900	5900	17200		9600		2100	
	13000			25300	6000	19600	4700	13700		7700			
	14000					15500	3800	10900		6200			
	15000					12200	3000	8600		5000			
	16000					9700	2500	6900		4000			
	17000							5500		3300			
	18000							4400		2700			
	19000							3500		2200			
	20000							2900					
90	12000			28600	6800	21000	5100	13300		5700			
	13000			22500	5400	16600	4100	10700		4700			
	14000			17700	4300	13200	3300	8500		3900			
	15000					10500	2700	6900		3200			
	16000					8400	2200	5500		2700			
	17000					6700		4500		2200			
	18000					5300		3600					
	19000							2900					
	20000							2400					
100	12000		7600	24500	5900	16900	4200	9300					
	13000			19400	4700	13500	3400	7600					
	14000			15400	3800	10800	2800	6200					
	15000			12200	3100	8700	2300	5000					
	16000			9600		7000		4100					
	17000					5600		3400					
	18000					4500		2800					
	19000					3600		2300					
	20000					2900							

TABLE 14 CONTINUED

KETTLE PLATE DEPTH	KETTLE HEAT RATE	840°F AND 860°F MOLTEN ZINC TEMPERATURE AND PLATE THICKNESS											
		4.0		3.5		3.0		2.5		2.0		1.5	
		840	860	840	860	840	860	840	860	840	860	840	860
110	12000	27900	6700	20400	5000	12700	3300	5100					
	13000	22100	5400	16300	4000	10300	2700	4400					
	14000	17300	4300	13000	3300	8400	2200	3700					
	15000			10400	2700	6800		3200					
	16000			8300		5500		2700					
	17000			6700		4500		2300					
	18000			5300		3700							
	19000					3000							
	20000					2400							
120	12000	23700	5800	16100	4000	8500	2300						
	13000	19000	4700	13000	3300	7100	2000						
	14000	15100	3800	10500	2700	5900							
	15000	12000		8500	2200	4900							
	16000	9400		6900		4100							
	17000			5600		3400							
	18000			4500		2800							
	19000					2300							
	20000												

TABLE 15

RANGE OF ACCEPTABLE WEAR RATE

PLATE TEMPERATURE	ZINC TEMPERATURE	WEAR RATE	HEAT RATE
879.6	840	0.00655	12000
882.9	840	0.00840	13000
886.2	840	0.01076	14000
889.5	840	0.01377	15000
889.6	850	0.01387	12000
892.8	840	0.01761	16000
892.9	850	0.01773	13000
896.1	840	0.02250	17000
896.2	850	0.02265	14000
899.4	840	0.02871	18000
899.5	850	0.02891	15000
899.6	860	0.02911	12000
902.7	840	0.03661	19000
902.8	850	0.03686	16000
902.9	860	0.03712	13000
906.0	840	0.04664	20000
906.1	850	0.04696	17000
906.2	860	0.04729	14000
909.4	850	0.05977	18000
909.5	860	0.06018	15000
912.7	850	0.07602	19000
912.8	860	0.07651	16000
916.0	850	0.09659	20000
916.1	860	0.09725	17000
919.4	860	0.12345	18000
922.7	860	0.15658	18000
926.0	860	0.19844	18000

TABLE 16

FOUR INCH PLATE LIFE CONDITIONS FOR CONSTANT 840°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
1029.6	956.4	879.6	12000	5815	22211	13928	7127	-8113	15084	30000	105	.00655	4.0	2.046
1045.4	965.9	882.9	13000	5815	22316	15089	7702	-9273	14613	23500	105	.00840	4.0	2.042
1029.6	961.5	879.6	12000	6686	22421	13928	7606	-7242	14815	27900	110	.00655	4.0	2.187
1045.4	970.7	882.9	13000	6686	22939	15089	8146	-8402	14792	22100	110	.00840	4.0	2.159
1061.2	980.7	886.2	14000	6686	22944	16250	8772	-9563	14172	17300	110	.01076	4.0	2.159
1029.6	966.5	879.6	12000	7640	22801	13928	8062	-6288	14738	25900	115	.00655	4.0	2.315
1045.4	975.6	882.9	13000	7640	23400	15089	8622	-7449	14778	20600	115	.00840	4.0	2.285
1061.2	985.4	886.2	14000	7640	23786	16250	9209	-8609	14577	16300	115	.01076	4.0	2.266
1077.0	995.7	889.5	15000	7640	23841	17410	9856	-9770	13985	12800	115	.01377	4.0	2.264
1029.6	971.9	879.6	12000	8680	22957	13928	8564	-5247	14392	23700	120	.00655	4.0	2.459
1045.4	981.2	882.9	13000	8680	23714	15089	9129	-6408	14585	19000	120	.00840	4.0	2.420
1061.2	991.1	886.2	14000	8680	24191	16250	9734	-7569	14456	15100	120	.01076	4.0	2.396
1077.0	995.7	889.5	15000	8680	24632	17410	10335	-8729	14297	12000	120	.01377	4.0	2.374
1092.8	1011.8	892.8	16000	8680	24525	18571	11048	-9890	13477	9400	120	.01761	4.0	2.379

TABLE 17

FOUR INCH PLATE LIFE CONDITIONS FOR CONSTANT 860°F MOLTEN ZINC TEMPERATURE. WHERE NO FINAL CONDITIONS ARE INDICATED THEY ARE THE SAME AS THE INITIAL CONDITIONS. WEAR RATE IS IN INCHES PER 100 HOURS.

PLATE OUTSIDE TEMPERATURE		IN-SIDE TEMP.	PLATE HEAT RATE	TENSION STATIC (+) STRESS		COMPRESSION THERMAL (-) STRESS		ACTUAL STRESS (TEN.-COMP.)		LIFE HOURS	PLATE DEPTH	WEAR RATE	PLATE THICKNESS	
INIT.	FINAL	INIT.	INIT.	INIT.	FINAL	INIT.	FINAL	INIT.	FINAL	INIT.	INIT.	INIT.	INIT.	FINAL
1049.6	964.5	899.6	12000	4307	23045	13928	6021	-9621	17023	8000	95	.02911	4.0	1.729
1049.6	968.8	899.6	12000	5023	23594	13928	6427	-8904	17167	7600	100	.02911	4.0	1.845
1049.6	974.3	899.6	12000	5815	23466	13928	6933	-8113	16532	7100	105	.02911	4.0	1.991
1065.4	982.5	902.9	13000	5815	24259	15089	7387	-9273	16871	5700	105	.03712	4.0	1.958
1049.6	978.7	899.6	12000	6686	24081	13928	7339	-7242	16742	6700	110	.02911	4.0	2.107
1065.4	987.0	902.9	13000	6686	24972	15089	7808	-8402	17164	5400	110	.03712	4.0	2.069
1081.2	996.4	906.2	14000	6686	25179	16250	8373	-9563	16805	4300	110	.04729	4.0	2.061
1049.6	984.1	899.6	12000	7640	24076	13928	7846	-6288	16230	6200	115	.02911	4.0	2.253
1065.4	993.0	902.9	13000	7640	24842	15089	8368	-7449	16474	5000	115	.03712	4.0	2.218
1081.2	1002.6	906.2	14000	7640	25185	16250	8950	-8609	16235	4000	115	.04729	4.0	2.203
1049.6	988.5	899.6	12000	8680	24733	13928	8251	-5247	16481	5800	120	.02911	4.0	2.369
1065.4	997.6	902.9	13000	8680	25591	15089	8788	-6408	16803	4700	120	.03712	4.0	2.329
1081.2	1006.8	906.2	14000	8680	26308	16250	9334	-7569	16973	3800	120	.04729	4.0	2.297

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CHAPTER VIII

SUMMARY

Findings

The tables in the previous chapters show that a kettle must not only be designed to suit static conditions but also must include thermal conditions. The static zinc load affects the deeper, thinner plates and the thermal stress affects the shorter, thicker plates. Table II shows this rather well in that 50" deep plates are limited to heat rates of 16,000 BTU; 60" deep plates are limited to 17,000 BTU; 70" deep plates limited to 19,000 BTU; 80" plates limited to 18,000 BTU; 90" plates to 17,000 BTU; 100" plates to 16,000 BTU and 110" plates to 14,000 BTU. For example, 2.5" plates above 110" deep are rejected by the computer as unsatisfactory. It is unreasonable that anyone would select a 2.5" plate, 100 inches deep because of the short life expected. The thickness of the plate at failure is also indicative of poor economy. The initial static stress of 17,117 PSI is too high and is the reason for the short life. A maximum of 10,000 PSI for an initial design condition for static stress is reasonable.

Also, in Table 11, the 50" deep plates show a higher actual initial stress condition. This results in higher compressive stress on the surface of highest temperature which drops the yield stress below the working stress. It is at this point that the surface can fail in compression; stress cracks open up and accelerated failure occurs. Other computer data (not listed) shows that the life drops sharply at smaller plate depths than 50" and heat loads above 14,000 BTU/FT^2-HR. The computer program did not take into account stress concentrations or metallurgical deterioration; therefore, it is sound judgment to stay away from short thick side plates so as to minimize the chances of a thermal stress failure even though the computer shows that excellent life is achieved. It is in this short, thick plate with high thermal stress that more study is needed to determine the effects of metallurgical and thermal stress deterioration.

Once again, it is repeated that the data derived in this thesis is applicable to the kettle it was derived for, but can serve as a guide or be adapted to other kettles with forethought and investigation. It is primarily because of furnace firing practice and kettle operating practice that this data cannot be directly applied to other kettles.

Some other findings of interest are that kettles of the same design fail at approximately the same thickness for heat inputs in the range of 6,000 to 19,000 BTU/FT^2-HR. The maximum heat rate allowed by the computer was 19,000 BTU/FT^2-HR. for certain designs. Any heat rate over 19,000 BTU/FT^2-HR. was rejected. The wear rate is constant for a constant molten zinc temperature because the inside plate temperature is constant under constant operating conditions and heat rates.

However, the outside plate temperature decreases as the kettle thins. The most astonishing finding is that half the kettle life is lost for every 10°F increase in molten zinc temperature and that life is proportional to the wear rate. This would imply that close temperature control is essential to maximize kettle life. Heat rates of less than 12,000 BTU/FT^2-HR were considered safe for the designs recommended below, therefore, they were not included in Tables 8 through 14.

Recommendations

The following kettle depths and plate thicknesses are recommended:

1.0 Inch thick plate for kettles from 0 to 45 inches deep
1.5 Inch thick plate for kettles from 45 to 60 inches deep
2.0 Inch thick plate for kettles from 60 to 73 inches deep
2.5 Inch thick plate for kettles from 73 to 85 inches deep
3.0 Inch thick plate for kettles from 85 to 96 inches deep
3.5 Inch thick plate for kettles from 96 to 106 inches deep
4.0 Inch thick plate for kettles from 106 to 116 inches deep

The maximum heat rate allowed for certain designs is 19,000 BTU/FT^2-HR and varies for different designs. It is not recommended that any kettle for any reason be operated at heat rates over 19,000 BTU/FT^2-HR or a molten zinc temperature above 860°F. It also should be noted that deeper, thicker kettle plates must be run at lower heat rates to minimize the outside plate temperatures. The average alloy thickness should be 1/8 inch maximum thickness and the maximum temperature on the inside of the plate should not exceed 920°F because the wear rate is logarithmic and very critical to kettle life. Other factors stated previously are that the outside plate temperature should never exceed 1100°F and that the temperature in the middle of the plate should never exceed 1000°F so as to preserve the metallurgical properties and prevent thermal stress failure. The actual initial stress must not exceed 10,000 PSI (tension or compression). Almost all premature failures of kettles are due to overheating the kettle.

Once again comes the often repeated warning against "blindly" plugging into "canned equations" without considering their basic assumptions. Each kettle design is individual and the design should be carefully checked to insure that the theoretical and empirical data is correct. The actual design should be reviewed according to the following recommendations.

The design of a kettle is based upon the size, shape and production requirements of the materials to be galvanized. Kettles should be fabricated with their vertical corners being round. Round corners tend to alleviate the washing effect of the zinc and thus lower the rate of corner erosion. No fins should be used to conduct heat. The result is a faster erosion rate around the fin. The product size and weight are factors in determining the kettle size and the wide variation in physical characteristics of products necessitates almost individual kettle design for economical production. The amount of start-ups and shutdowns should be minimized. Coupled with the above, one should note that

300 BTU are required per hour per pound of production which includes all heat losses. Kettles should be operated at as low a zinc temperature as possible. Kettle furnaces should be designed for even heat distribution and harsh thermal conditions avoided. The combustion chamber temperatures should be minimized, corrosive combustion atmospheres avoided and heat transferred to the kettle with a minimum temperature differential. Bottom plate thicknesses should be the same as the side plate thicknesses for free standing kettles and careful judgment should be used in the installation of side braces in non-free standing kettles so as to minimize the chances of compressive stress surface failure and resulting stress cracks. Kettles should be designed to minimize stress conditions. When the above design requirements have been ascertained, kettle plate specifications should be determined (metallurgical requirements, etc.). Kettles should be fabricated of plates having low carbon and silicon content, similar to galvanizing kettle quality "TENMAX" or A-285 galvanizing quality firebox steel. Plate material is to be of the quality specified, properly formed, welded and fabricated. The setting should be designed so that in the placement of the kettle its bottom is protected from heat with at least 12" of firebrick along the bottom. Also, direct flame impingement upon the sides of the kettle must be prevented. Remember, zinc dissolves iron in a high heat concentrated area. Startup time of a kettle should be

very slow and closely controlled. Expendable thermocouples attached to the kettle sides will prevent overheating. Slow startups are one of the most important practices or procedures which should be a must in all galvanizing operations. Overheating initiates surface failure in compression and causes many premature failures. A factor which effects the destruction of a galvanizing kettle is the alloying property of zinc; its degree of corroding and attraction for other metals. This action is a function of the temperature and varies with the temperature, that is, the higher the temperature the greater the alloying intensity and penetration power as discussed in this thesis.

Research has brought out the following facts regarding the formation of zinc-iron alloys in galvanizing pots with the consequent failure of the kettle:

1). Production on a weight basis determines the amount of heat which must be supplied to the kettle.

2). The speed of the work or production going through the pot vitally affects the heat intensity or time element.

3). The total metal capacity of the pot in relation to the production determines whether the pot will be overheated or not. If the metal capacity is large, there will be heat in reserve; if the metal capacity is small, the pot will be overheated continually. For example, whenever a kettle is stopped, the production is ceased before the kettle burners cut back and heat continues to be absorbed into the zinc. A larger kettle volume minimizes the temperature rise because of the greater heat sink.

4). The area heated in relation to the total surface area available for heating purposes is important. The larger the heating area, the better because a lower heat transfer rate results.

5). As stated previously, the alloying or destructive action of the molten zinc is a function of the temperature. The higher the temperature, the faster the alloying action takes place and the greater the penetrating power.

6). The quantity of work submerged at one time affects the pot life by directly affecting the total heat available in the bath. Violent temperature swings are sure to give a short life.

7). Pot failure and the formation of dross, which uses up a large percentage of good zinc, stress the importance of zinc-iron alloys and proper kettle maintenance.

8). Pot failure shows that the zinc-iron alloy takes the shape of spherules; gradually forming outlines which are hexagon in shape. These spherules are extremely brittle and show an iron content of about 8 per cent corresponding to the zinc-iron alloy $FeZn_{10}$.

9). Pot failure is a direct function of temperature and heat concentration and close temperature control is a must.

10). The mechanism of destruction includes the intense alloying action of zinc; the penetration into the steel forming first a zinc-iron alloy which gradually increases in depth until it forms spherules; when the heat intensity is sufficient, the alloying action penetrates deeply into the plate and the zinc-iron alloy formed increases the size of the particles and makes them brittle; the forces of expansion and currents set up by the heat, disintegrate and break up the zinc-alloy, which floats into the bath, exposing a new, deeper surface to the same action and continued alloying action and disintegration eventually brings about complete destruction of the pot as the stresses increase to failure.

The point is the fact that kettle design alone does not measure the life of a kettle. Operators share the responsibility.

Conclusions

Analytical solutions for this type of problem are applicable to simple cases and simple solutions. Complex problems are best handled by a computer. This method of problem solving has extensive application in the heat exchanger field. Basically, the galvanizing kettle is a heat exchanger and may be compared to the classical heat exchanger which is usually a bank of tubes either in a horizontal or vertical (or some angular) position through which and around which flows the heat exchange medium.

Any life expectency for heat exchangers was based on field data. The best design at least cost was a matter of conjecture. A more logical approach would be to determine the stress-to-rupture for different materials, generalize the equations for stress-to-rupture, write general equations for stress and temperature and combine the equations to some suitable life theory like the "life fraction rule" as is outlined in this thesis. A suitable computer program could then give the best design and life. Such a program could include intermittent loading and/or heating, metallurgical effects, fin effects, stress concentration, etc., and provide a better insight to the problem. Some other rules which predict non-steady state behavior from steady state behavior are the "time hardening" rule and the "strain hardening rule".

In this thesis, deflection was not considered a criteria of importance, except for justification of the uniaxial stress assumption. However, this approach is applicable to deflection analysis under varying stress and temperature.

Future Study

In this thesis the stresses were reduced to a uniaxial consideration for kettles whose length was four times its width. Although acknowledged to exist, the so-called kettle "hoop stress" was considered negligible at the center of the long side of the kettle. The extent of this "hoop stress" as the kettle is extended to greater length-to-width ratios and shortened to smaller length-to-width ratios should be a future study. The static and thermal stress interaction should be considered in the bi-axial state of stress.

The relationship of the stress-to-rupture equations to stress concentration and compression failure on the plate surface due to thermal stress should be investigated more fully. Field experience shows that the closer the kettle supports are spaced, the more severe the stress cracks.

Future study of the above can be accomplished by following the procedure of this thesis. As mentioned previously, other related problems are heat exchangers and these problems can be attacked with similar methods.

One more critical element remains---namely, which of the methods of transferring heat between the furnace and kettle is more efficient - radiation or convection or some combination of both? Also, what burner firing ratio cause the least surface damage - excess air, perfect combustion, or rich fuel mixtures. The argument over which is the most efficient heat exchange medium between the furnace and the kettle has yet to be settled.

This computerized approach developed from the maximum shear stress theory (which related to the log-log stress-to-rupture plots) and the life fraction rule (which relates the static conditions to the varying condition) can be adapted to a constant-temperature-constant-load condition which is interrupted by a reduction in load (keeping temperature constant). The general result is a reduction in creep rate and this situation can be simulated by a computer program. A program can also be written by increasing the temperature under constant load. The result will be an increased creep rate and this situation can be simulated by a suitable computer program. A single deviation of load or temperature does not generally have a significant effect on the shape of the creep curve (approximated by the computer solution). Repeated deviations or systematic cycling of load and/or temperature (or both) have an accelerating effect on creep and reduce time for fracture. A program could also be written to simulate these conditions and an almost endless variety of programs could be written for different problems. A master program could also be written with appropriate subroutines (derived from individual programs above) for the general solution of variable stress and temperature at different rates, cycles, recovery, hardening, annealing, etc. An interesting test of the above theory would be to obtain steady state data for various materials, write the appropriate program for each case using a theory such as the life fraction rule, and then obtain a life for a specimen that is simulated by the computer. The next step would be to test the specimen in the manner simulated by the computer and compare the results. It would be even more interesting to assume another theory (like time hardening or strain hardening) and compare the results of all.

As a final note for future study on galvanize kettle life, the Engineering Index found in any library reference room lists sources for practical galvanizing under the heading of "Galvanizing". Copies of these articles can be obtained from the Engineering Societies Library, Engineering Index Annual Photocopies Dept., 345 East 47th Street, New York, New York, 10017, for a nominal fee. Articles by W. G. Imhoff from the years 1940 through 1960 are of special interest. Another good source found in a library reference room is "Zinc Abstracts" and copies of articles from this reference can be obtained from the Zinc Abstracts Service, 14th Floor, 292 Madison Ave., New York, New York, 10017.

APPENDIX A

Computer Program For Production Rate Calculations

COMPUTER PROGRAM FOR PRODUCTION RATE CALCULATIONS

```
//C0014746  JOB  (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=A, TIME=1,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD  *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP.II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C FOR THE INITIAL CONDITIONS READ IN ON THE FIRST READ STATE-
C MENT THIS PROGRAM STARTS WITH A MOLTEN ZINC TEMPERATURE
C AND CALCULATES PRODUCTION RATE FOR EACH (Q) INPUT FROM
C 5000 TO 20000 BTU/SQ FT.HR, THE NEXT CARD IS READ FOR NEW
C CONDITIONS AND CYCLE REPEATS UNTIL NO CARDS ARE LEFT TO BE
C READ. THEN THE COMPUTER STOPS
C
C PRODUCTION RATE CALCULATIONS FOR A HEAT RATE AT ZINC TEMP.
C AA IS PLATE AREA EXPOSED TO HEAT TRANSFER IN SQUARE FEET
C AB IS ZINC SURFACE AREA IN SQUARE FEET
C AR IS ZINC SURFACE RADIATION LOSS IN BTU/SQ FT-HR
C PS IS MEAN SPECIFIC HEAT OF STEEL PIPE IN BTU/LB-DEG.F
C TZ IS MOLTEN ZINC TEMPERATURE IN KETTLE IN DEG.F
C TA IS PIPE TEMPERATURE AT AMBIENT CONDITIONS IN DEG.F
C  Q IS HEAT RATE INTO KETTLE THRU KETTLE PLATE BTU/SQ FT-HR
C PW IS PRODUCTION RATE IN POUNDS/HOUR
C
C READ IN AND PRINT OUT DATA
   10 READ (1,11)AA,AB,AR,PS,TZ,TA
   11 FORMAT(6F8.3)
      WRITE(3,11)AA,AB,AR,PS,TZ,TA
C THE DO LOOP ARRANGES FOR Q TO RUN THROUGH ITS VALUES
   23 DO25I=5000,20000,1000
      Q=I
C PRODUCTION RATE IS CALCULATED
      PW=(Q*AA-AR*AB)/(PS*(TZ-TA))
C PRINT REQUIRED ANSWERS
   25 WRITE(3,26)Q,PW,TZ
   26 FORMAT(3F8.1)
C GO BACK AND READ ANOTHER CARD,IF NO CARD IS AVAILABLE-STOP
   28 TO TO 10
   30 STOP
      END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *
```

```
 225.000 125.00 2000.000 000.140 840.000 060.000
 225.000 125.00 2100.000 000.140 850.000 060.000
 225.000 125.00 2200.000 000.140 860.000 060.000
 225.000 125.00 2300.000 000.140 870.000 060.000
/*
```

APPENDIX B

Computer Program For Thermal Layer Calculation

COMPUTER PROGRAM FOR THERMAL LAYER CALCULATION

```
//C0015171  JOB  (0,0,,,,,1,,0),
// SR200501.PENNELL,CLASS=A,TIME=1,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD  *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP.II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C FOR THE INITIAL CONDITION READ IN ON THE FIRST READ STATE-
C MENT THIS PROGRAM STARTS WITH A PLATE THICKNESS OF 4 INCHS
C AND CALCULATES TEMPERATURES TO,TM,TI,TR, FOR EACH HEAT (Q)
C INPUT FROM 5000 TO 20000 BTU/SQ FT-HR. THE PROGRAM THEN
C SUBTRACTS .5 INCH FROM PLATE AND RECOMPUTES TEMPERATURES
C AND CYCLES UNTIL 0.5 INCH PLATE THICKNESS IS REACHED. THE
C NEXT CARD IS READ FOR NEW INITIAL CONDITIONS AND CYCLE RE-
C STARTS UNTIL NO CARDS ARE LEFT TO BE READ-COMPUTOR STOPS.
C
C SIDE PLATE COMPOSITE LAYER TEMPERATURE CALCULATIONS
C PK-STEEL HEAT TRANSFER COEFF. BTU-IN/SQ FT-HR-DEG.F
C AT-ZINC-IRON ALLOY LAYER THICKNESS IN INCHES
C AK-ZINC-IRON ALLOY LAYER HEAT COEFF. BTU-IN/SQ FT-HR-DEG.F
C  H-MOLTEN ZINC CONVECTION COEFF. (DATA) BTU/SQ FT-HR-DEG.F
C  H-MOLTEN ZINC CONDUCTION COEFF.(DATA)BTU-IN/SQ FT-HR-DEG.F
C H & HT-CONVECTION ARE USED CONCURRENTLY FOR OPERATING BATH
C H & HT-CONDUCTION ARE USED CONCURRENTLY FOR IDLE ZINC BATH
C HT-UNITY FACTOR FOR MOLTEN ZINC BATH CONV(DATA) CONDITIONS
C HT-COND(DATA) DIST. TO THERMOCOUPLE FROM INSIDE KETTLE(IN)
C  P-PLATE THICKNESS IN INCHES
C  Q-IS HEAT RATE INTO KETTLE THRU KETTLE PLATE BTU/SQ FT-HR
C TO-TEMPERATURE AT OUTSIDE PLATE SURFACE IN DEG.F
C TM-TEMPERATURE AT STEEL AND ALLOY LAYER INTERFACE IN DEG.F
C TI-TEMPERATURE AT INSIDE PLATE SURFACE IN DEG.F
C TZ-TEMPERATURE OF MOLTEN ZINC AT THERMOCOUPLE IN DEG.F
C TR-AVERAGE TEMPERATURE OF PLATE BETWEEN TO AND TM
C
C READ DATE IN, INITIALIZE P, AND PRINT DATA
   10 READ(1,11)PK,AT,AK,H,HT,TZ
   11 FORMAT(7F8.3)
      P=4.0
      WRITE(3,11)PK,AT,AK,H,HT,TZ,P
C THE DO LOOP ARRANGES FOR Q TO RUN THROUGH ITS VALUES
   13 DO25I=5000,20000,1000
      Q=I
C CALCULATE TEMPERATURES AT LAYER INTERFACES
      TO=TZ+(Q*((P/PK)+(AT/AK)+(HT/H)))
      TM=TO-(Q/(PK/P))
      TI=TM-(Q/(AK/AT))
      TR=(TO+TM)/2
```

```
C PRINT REQUIRED ANSWERS
   25 WRITE(3,26)P,TO,TM,TI,Q,TR
   26 FORMAT(6F8.1)
C CONTINUE UNTIL P HAS BEEN REDUCED TO 0.5
      IF(P-0.5)10,10,27
C REDUCE P BY 0.5 INCHES AND RECALCULATE
   27 P=P-0.5
      GO TO 13
C WHEN ANSWERS ARE FINISHED, READ NEXT DATA CARD & CONTINUE
C WHEN ALL CARDS ARE READ-STOP
   30 STOP
      END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD *
 320.        .125 96.     500.0      1.      840.
 320.        .125 96.     500.0      1.      850.
 320.        .125 96.     500.0      1.      860.
 320.        .125 96.     500.0      1.      870.
/*
```

APPENDIX C

Computer Program For Static Plate Stress Calculations

COMPUTER PROGRAM FOR STATIC PLATE STRESS CALCULATIONS

```
//C0014716  JOB   (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=A,TIME=1,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD  *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C SIDE PLATE STRESS CALCULATIONS UNDER VARIOUS CONDITIONS
C  A IS A MOMENT FACTOR DEPENDENT ON PLATE EDGE CONDITIONS
C  W IS THE FLUID DENSITY IN LBS/CU IN
C AC IS STRESS DISTRIBUTION FACTOR DEPENDENT ON MATERIAL
C  P IS PLATE THICKNESS IN INCHES
C  D IS KETTLE DEPTH IN INCHES
C  S IS SIDE PLATE STRESS IN PSI
C
C READ DATA IN, INITIALIZE P, AND PRINT OUT DATA
   10 READ(1,11)A,W,AC
   11 FORMAT(4F8.3)
      P=4.0
   13 WRITE(3,11)A,W,AC,P
C THE DO LOOP ARRANGES FOR D TO RUN THROUGH ITS VALUES
      DO15I=10,120,10
      D=I
C STRESS IS CALCULATED
      S=(6.*A*W*AC*(D**3))/(P**2)
C PRINT REQUIRED ANSWERS
   15 WRITE(3,16)P,S,D
   16 FORMAT(3F8.1)
C CONTINUE UNTIL P HAS BEEN REDUCED TO 0.5
      IF(P-1.0)18,17,17
C REDUCE P BY 0.5 INCHES AND RECALCULATE
   17 P=P-0.5
      GO TO 13
C WHEN ANSWERS ARE FINISHED, READ NEXT DATA CARD & CONTINUE
   18 GO TO 10
C WHEN ALL CARDS ARE READ-STOP
   20 STOP
      END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *
 000.067 000.257 001.000
 000.067 000.257 000.778
 000.067 000.257 000.722
/*
```

APPENDIX D

Computer Program For Static And Thermal Stress

COMPUTER PROGRAM FOR STATIC AND THERMAL STRESS

```
//C0015896  JOB   (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=A,TIME=1,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM.
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C THIS PROGRAM COMPUTES VALUES FOR A HEAT TRANSFER RATE FOR
C VARIOUS PLATE THICKNESSES AND THEN REPEATS THE SAME FOR ANY
C NUMBER OF HEAT INPUT RATES
C
C SIDE PLATE STATIC AND THERMAL STRESS CALCULATIONS
C PK STEEL HEAT TRANSFER COEFF. BTU-IN/SQ FT-HR-DEG.F
C AT ZINC-IRON ALLOY LAYER THICKNESS IN INCHES
C AK ZONC-IRON ALLOY LAYER HEAT COEFF. BTU-IN/SQ FT-HR-DEG.F
C  H MOLTEN ZINC CONVECTION COEFF. BTU/SQ FT-HR-DEG.F
C  A DIMENSIONLESS MOMENT FACTOR FOR PLATES
C  W ZINC DENSITY IN LBS/CU.-IN
C  D DEPTH OF KETTLE IN INCHES
C HT UNITY FACTOR FOR MOLTEN ZINC BATH-CONVECTION CONDITIONS
C AC BENDING STRESS CORRECTION FACTOR FOR CREEP
C  P PLATE THICKNESS IN INCHES
C  Q IS HEAT RATE INTO KETTLE THRU KETTLE PLATE
C TO TEMPERATURE AT OUTSIDE PLATE SURFACE IN DEG.F
C TM TEMPERATURE AT STEEL AND ALLOY LAYER INTERFACE IN DEG.F
C ST THERMAL SIDE PLATE STRESS-IN-PSI
C Ss SIDE PLATE ACTUAL STRESS IN PSI
C  S STATIC SIDE PLATE STRESS IN PSI
C
C READ IN AND PRINT OUT INITIAL DATA
   10 READ(1,11)A,W,D,PK,AK,AT,H,TZ,HT,AC
   11 FORMAT(10F7.3)
      WRITE(3,11)A,W,D,PK,AK,AT,H,TZ,HT,AC
C READ IN AND WRITE VALUE FOR Q
   13 READ(1,14)Q
   14 FORMAT(F8.1)
      WRITE(3,14)Q
C INITIALIZE PLATE THICKNESS
      P=4.0
C CALCULATE TEMPERATURES AT LAYER INTERFACES
   20 TO=TZ+(Q*((P/PK)+(AT/AK)+(HT/H)))
      TM=TO-(Q/(PK/P))
C CALCULATE STATIC STRESS
      S=(6.*A*W*AC*(D**3))/(P**2)
C CALCULATE THERMAL STRESS
      ST=(130.0*(TO-TM))/1.40
C CALCULATE TRUE STRESS
```

```
         SS=S-ST
C PRINT OUT ANSWERS
      25 WRITE(3,26)TO,TM,S,ST,SS,P
      26 FORMAT(6F8.1)
C SUBTRACT 0.5 INCH FROM PLATE, CHECK THICKNESS, & RECALCULATE
         IF(P-0.5)13,13,27
C IF PLATE THICKNESS IS ZERO, READ ANOTHER CARD AND RECOMPUTE
      27 P=P-0.5
         GO TO 20
C IF NO CARD IS AVAILABLE-STOP
      30 STOP
         END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *
0.067 0.257 70.0 320.0 96.0 0.125 500.0 850.0 1.0 0.778
16000.0
16500.0
17000.0
18000.0
19000.0
/*
```

APPENDIX E

Computer Program For Estimating Wear Rate

COMPUTER PROGRAM FOR ESTIMATING WEAR RATE

```
//C0015899  JOB  (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=G,TIME=10,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM.
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C THIS PROGRAM SEARCHES FOR WEAR RATES WHICH SUIT OBSERVED
C FIELD CONDITIONS
C
C SIDE PLATE STATIC AND THERMAL STRESS CALCULATIONS
C PK STEEL HEAT TRANSFER COEFF. BTU-IN/SQ FT-HR-DEG.F
C AT ZINC-IRON ALLOY LAYER THICKNESS IN INCHES
C AK ZINC-IRON ALLOY LAYER HEAT COEFF. BTU-IN/SQ FT-HR-DEG.F
C  H MOLTEN ZINC CONVECTION COEFF. BTU/SQ FT-HR-DEG.F
C  A DIMENSIONLESS MOMENT FACTOR FOR PLATES
C  W ZINC DENSITY IN LBS/CU.-IN.
C  D DEPTH OF KETTLE IN INCHES
C HT UNITY FACTOR FOR MOLTEN ZINC BATH-CONVECTION CONDITIONS
C AC BENDING STRESS CORRECTION FACTOR FOR CREEP
C  P PLATE THICKNESS IN INCHES
C  Q IS HEAT RATE INTO KETTLE THRU KETTLE PLATE
C TO TEMPERATURE AT OUTSIDE PLATE SURFACE IN DEG.F
C TM TEMPERATURE AT STEEL AND ALLOY LAYER INTERFACE IN DEG.F
C ST THERMAL SIDE PLATE STRESS IN PSI
C SS SIDE PLATE ACTUAL STRESS IN PSI
C  S STATIC SIDE PLATE STRESS IN PSI
C TZ ZINC TEMPERATURE IN °F
C QT INITIAL GUESS FOR LIFE AT HEAT RATE Q
C RE LIFE EXPONENT
C RH LIFE HOURS
C RS HOUR SUMMATION
C FL FRACTION OF LIFE USED
C FS SUM OF FRACTIONS OF LIFE USED
C WR WEAR RATE IN INCHES PER 100 HOURS
C
C READ IN AND PRINT OUT INITIAL DATA
   10 READ(1,11)A,W,D,PK,AK,AT,H,TZ,HT,AC
   11 FORMAT(10F7.3)
      WRITE(3,11)A,W,D,PK,AK,AT,H,TZ,HT,AC
C READ IN HEAT RATE AND TRIAL LIFE ANTICIPATED FOR HEAT RATE
   13 READ(1,14)Q,QT
   14 FORMAT(2F8.1)
C SET TIME FOR EACH TIME INCREMENT (T)
      T=100.0
C SET LOWEST INITIAL WEAR RATE ANTICIPATED
```

```
      WR=0.00200
C INCREMENT WEAR RATE BY .0001 FOR EACH TIME INCREMENT
   15 WR=WR+0.0001
C SET FRACTION LIFE EQUAL TO ZERO
      FS=0.0000
C SET TOTAL TIME INCREMENTS EQUAL TO ZERO
      RS=0000000.0
C SET INITIAL PLATE THICKNESS FOR TRIAL
      P=2.00000
C CALCULATE LAYER TEMPERATURES
   20 TO=TZ+(Q*((P/PK)+(AT/AK)+(HT/H)))
      TM=TO-(Q/(PK/P))
      TR=(TO+TM)/2
C CALCULATE ACTUAL STRESS AT EACH INCREMENTED THICKNESS
      S=(6.*A*W*AC*(D**3))/(P**2)
      ST=(130.0*(TO-TM))/1.40
      SS=ABS(S-ST)
C CALCULATE RUPTURE LIFE EXPONENT
      RE=(+260.595-(0.503750*TR)+(0.000248600*(TR**2)))
C CALCULATE LIFE HOURS
      RH=(38000./SS)**RE
C ACCUMULATE TIME
      RS=RS+T
C CALCULATE LIFE FRACTION
      FL=T/RH
C CALCULATE LIFE FRACTION SUM
      FS=FS+FL
C IF LIFE FRACTION LESS THAN 1 SUBTRACT WEAR RATE AND RECOMPUTE
      IF(FS-1.0000)26,28,28
   26 P=P-WR
      GO TO 20
C IF LIFE FRACTION IS GREATER THAN 1 COMPARE TO TRIAL LIFE
   28 IF(RS-QT)30,30,15
C IF THE LIFE COMPUTED IS TOO GREAT-SEARCH FOR LESSER LIFE
   30 WRITE(3,31)WR,T,RS,FS,Q
C IF THE LIFE COMPUTED IS EQUAL TO THE TRIAL LIFE-PRINT WEAR RATE
   31 FORMAT(5F10.4)
      GO TO 13
C READ ANOTHER TRIAL LIFE AND ANOTHER HEAT INPUT-RECOMPUTE
   32 STOP
      END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *

0.067 0.257 72.0 320.0 96.0 0.125 500.0 840.0 1.0 0.778
  8000. 33000.
  9000. 24000.
 10000. 18000.
```

```
11000. 15000.
12000. 12000.
13300.  9000.
14200.  7500.
15000.  6000.
16500.  4500.
18000.  3000.
20000.  2000.
```

APPENDIX F

Computer Program For Wear Rate Verification Calculation

COMPUTER PROGRAM FOR WEAR RATE VERIFICATION CALCULATION

```
//C0018999  JOB  (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=D,TIME=3,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP. II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C FOR THE INITIAL CONDITION READ IN ON THE FIRST READ STATE-
C MENT THIS PROGRAM STARTS WITH A PLATE THICKNESS OF 4 INCHES
C AND CALCULATES TEMPERATURES TO, TM, TI, TR, FOR EACH HEAT (Q)
C INPUT FROM 5000 TO 20000 BTU/SQ FT-HR.  THE PROGRAM ALSO
C CALCULATES WEAR RATE AND THERMAL STRESS (WR AND ST) THEN
C SUBTRACTS .5 INCH FROM PLATE AND RECOMPUTES TEMPERATURES,
C ETC., AND CYCLES UNTIL 0.5 INCH PLATE THICKNESS IS REACHED.
C THE NEXT CARD IS READ FOR NEW INITIAL CONDITIONS AND CYCLE
C RESTARTS UNTIL NO CARDS ARE LEFT TO BE READ-COMPUTER STOPS.
C
C SIDE PLATE COMPOSITE LAYER TEMPERATURE CALCULATIONS
C PK-STEEL HEAT TRANSFER COEFF. BTU-IN/SQ FT-HR-DEG.F
C AT-ZINC-IRON ALLOY LAYER THICKNESS IN INCHES
C AK-ZINC-IRON ALLOY LAYER HEAT COEFF. BTU-IN/SQ FT-HR-DEG.F
C  H-MOLTEN ZINC CONVECTION COEFF. (DATA) BTU/SQ FT-HR-DEG.F
C  H-MOLTEN ZINC CONDUCTION COEFF. (DATA) BTU-IN/SQ FT-HR-DEG.F
C H & HT-CONVECTION ARE USED CONCURRENTLY FOR OPERATING BATH
C H & HT-CONDUCTION ARE USED CONCURRENTLY FOR IDLE ZINC BATH
C HT-UNITY FACTOR FOR MOLTEN ZINC BATH CONV.(DATA) CONDITIONS
C HT-COND.(DATA)DIST. TO THERMOCOUPLE FROM INSIDE KETTLE (IN)
C  P-PLATE THICKNESS IN INCHES
C  Q-IS HEAT RATE INTO KETTLE THRU KETTLE PLATE BTU/SQ FT-HR
C TO-TEMPERATURE AT OUTSIDE PLATE SURFACE IN DEG.F
C TM-TEMPERATURE AT STEEL AND ALLOY LAYER INTERFACE IN DEG.F
C TI-TEMPERATURE AT INSIDE PLATE SURFACE IN DEG.F
C TZ-TEMPERATURE OF MOLTEN ZINC AT THERMOCOUPLE IN DEG.F
C TR-AVERAGE TEMPERATURE OF PLATE BETWEEN TO AND TM
C WR-WEAR RATE
C ST-THERMAL STRESS
C
C READ DATE IN, INITIALIZE P, AND PRINT DATA
   10 READ(1,11)PK,AT,AK,H,HT,TZ
   11 FORMAT(7F8.3)
      P=4.0
      WRITE(3,11)PK,AT,AK,H,HT,TZ,P
C THE DO LOOP ARRANGES FOR Q TO RUN THROUGH ITS VALUES
   13 DO25I=805,1100,5
      TO=I
C CALCULATE TEMPERATURES AT LAYER INTERFACES
      Q=(TO-TZ)/((P/PK)+(AT/AK)+(HT/H))
```

```
      TM=TO-(Q/(PK/P))
      TI=TM-(Q/(AK/AT))
      TR=(TO+TM)/2
      WR=(TM/948.9014078)**(1,0000000000000/.015078562
      ST=(130.0*(TO-TM)/1.40
C PRINT REQUIRED ANSWERS
   25 WRITE(3,26)P,TO,TR,TM,TI,Q,WR,ST
   26 FORMAT(8F 13.6)
C CONTINUE UNTIL P HAS BEEN REDUCED TO 0.5
      IF(P-0.5)10,10,27
C REDUCE P BY 0.5 INCHES AND RECALCULATE
   27 P=P-0.5
      GO TO 13
C WHEN ANSWERS ARE FINISHED, READ NEXT DATA CARD & CONTINUE
C WHEN ALL CARDS ARE READ-STOP
   30 STOP
      END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *
 320.        .125 96.      500.0      1.        840.
 320.        .125 96.      500.0      1.        850.
 320.        .125 96.      500.0      1.        860.
 320.        .125 96.      500.0      1.        870.
/*
```

APPENDIX G

Computer Program For Solving For N Equations, N Unknowns

COMPUTER PROGRAM FOR SOLVING N EQUATIONS, N UNKNOWNS

```
//C0018742  JOB  (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=A,TIME=1,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD  *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP.II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C THIS PROGRAM SOLVES UP TO 9 EQUATIONS AND 9 UNKNOWNS OF FORM
C   A(1,1)X(1)+A(1,2)X(2)+---+A(1,N)X(N)=B(1)
C   A(2,1)X(1)+A(2,2)X(2)+---+A(2,N)X(N)=B(2)
C   ------------------------------------------
C   A(N,1)X(1)+A(N,2)X(2)+---+A(N,N)X(N)=B(N)
C BY THE GAUSS ELIMINATION METHOD
C
C IT REPLACES CERTAIN EQUATIONS OF THE SYSTEM BY COMBINATIONS
C OF OTHER EQUATIONS TO PRODUCE A TRIANGULAR SYSTEM SUCH AS
C   C(1,1)X(1)+C(1,2)X(2)+---+C(1,N)X(N)=D(1)
C              C(2,2)X(2)+---+C(2,N)X(N)=D(2)
C                          -------------------
C                             C(N,N)X(N)=D(N)
C THIS SYSTEM IS SOLVED BY "BACK SUBSTITUTION"
C THE LAST EQUATION YIELDS X(N) AT ONCE
C THE PRECEDING EQUATION THEN YIELDS X(N-1), AND SO ON
C
C THE DIMENSION (N) IS LEFT AS AN INPUT TO THE SUBROUTINE
C VARIABLE "ILL"SERVES AS AN INDICATOR OF EQUATION SOLVABILITY
C
C INPUT OF THE SYSTEM IN DOUBLE PRECISION
     DOUBLE PRECISION A,B,X
C EQUATION MATRIX MUST BE SQUARE ON LEFT SIDE
C COLUMN MATRIX ON RIGHT SIDE
     DIMENSION A(5,5),B(5),X(5)
C LEFT SIDE COEFFICIENTS ARE READ IN ROW BY ROW
C ONE ROW PER CARD
     READ(1,20)((A(I,J),J=1,5),I=1,5)
  20 FORMAT(5F16.0)
C COEFFICIENTS ARE PRINTED OUT AS THEY ARE READ IN
  21 WRITE(3,20)((A(I,J),J=1,5),I=1,5)
C READ IN RIGHT SIDE OF EQUATION
C START WITH FIRST NUMBER OF FIRST EQUATION
C ALL NUMBERS ON SINGLE CARD
     READ(1,23)(B(I),I=1,5)
  23 FORMAT(5F16.4)
C WRITE NUMBERS AS READ IN FOR RIGHT HAND SIDE
  22 WRITE(3,23)(B(I),I=1,5)
C CALL FOR THE SUBROUTINE
```

```
      CALL GAUSS(5,A,B,X,ILL)
C OUTPUT OF RESULTS
      IF (ILL-1) 11,9,11
    9 WRITE(3,10)
   10 FORMAT (18H NO SOLUTION FOUND)
C WRITE ANSWERS
   11 WRITE(3,12)(X(I),I=1,5)
   12 FORMAT(1X,5F25.17)
      STOP
      END
C
C GAUSSIAN ELIMINATION SUBROUTINE
      SUBROUTINE GAUSS (N,A,B,X,ILL)
      DOUBLE PRECISION A,B,X
      DIMENSION A(N,N),B(N),X(N)
      ILL=0
C THE CASE N EQUALS ONE
      IF (N-1)4,1,4
    1 IF (A(1,1))2,3,2
    2 X(1)=B(1)/A(1,1)
      RETURN
    3 ILL=1
      RETURN
C THE GENERAL CASE, FINDING THE PIVOT
    4 NLESS1=N-1
      DO 13 I=1,NLESS1
      BIG=DABS(A(I,I))
      L=I
      IPLUS1=I+1
      DO 6 J=IPLUS1,N
      IF (DABS(A(J,I))-BIG)6,6,5
    5 BIG=DABS(A(J,I))
      L=J
    6 CONTINUE
C INTERCHANGE IF NECESSARY
      IF (BIG) 8,7,8
    7 ILL=1
      RETURN
    8 IF (L-I) 9,11,9
    9 DO 10J=1,N
      TEMP=A(L,J)
      A(L,J)=A(I,J)
   10 A(I,J)=TEMP
      TEMP=B(L)
      B(L)=B(I)
      B(I)=TEMP
C REDUCE COEFFICIENTS TO ZERO
   11 DO 13J=IPLUS1,N
      QUOT=A(J,I)/A(I,1)
      DO 12K=IPLUS1,N
   12 A(J,K)=A(J,K)-QUOT*A(I,K)
```

```
  13 B(J)=B(J)-QUOT*B(I)
C THE BACK SUBSTITUTION STEP
     IF (A(N,N)) 15,14,15
  14 ILL=1
     RETURN
  15 X(N)=B(N)/A(N,N)
     I=N-1
  16 SUM=0
     IPLUS1=I+1
     DO 17J=IPLUS1,N
  17 SUM=SUM+A(I,J)*X(J)
     X(I)=(B(I)-SUM)/A(I,I)
     I=I-1
     IF (I) 18,18,16
  18 RETURN
     END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD *
     1.   850.   722500.   614125000.     522006250000.
     1.   900.   810000.   729000000.     656100000000.
     1.   950.   902500.   857375000.     814506250000.
     1.  1000.  1000000.  1000000000.    1000000000000.
     1.  1050.  1102500.  1157625000.    1215506250000.
12.0211 8.5866    6.3945       5.4445           4.1000
/*
```

APPENDIX H

Computer Program for Kettle Life (All Data)

COMPUTER PROGRAM FOR KETTLE LIFE (ALL DATA)

```
//C0018750  JOB  (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=G,TIME=10,MSGLEVEL=1
//   EXEC FORTGCLG
//FORT.SYSIN DD  *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C THIS PROGRAM COMPUTES KETTLE LIFE
C
C PK STEEL HEAT TRANSFER COEFF. BTU-IN/SQ FT-HR-DEG.F
C AT ZINC-IRON ALLOY LAYER THICKNESS IN INCHES
C AK ZINC-IRON ALLOY LAYER HEAT COEFF. BTU-IN/SQ FT-HR-DEG.F
C  H MOLTEN ZINC CONVECTION COEFF. BTU/SQ FT-HR-DEG.F
C  A DIMENSIONLESS MOMENT FACTOR FOR PLATES
C  W ZINC DENSITY IN LBS/CU.-IN.
C  D DEPTH OF KETTLE IN INCHES
C HT UNITY FACTOR FOR MOLTEN ZINC BATH-CONVECTION CONDITIONS
C AC BENDING STRESS CORRECTION FACTOR FOR CREEP
C PL=P PLATE THICKNESS IN INCHES
C  Q IS HEAT RATE INTO KETTLE THRU KETTLE PLATE
C TO TEMPERATURE AT OUTSIDE PLATE SURFACE IN DEG.F
C TM TEMPERATURE AT STEEL AND ALLOY LAYER INTERFACE IN DEG.F
C TI TEMPERATURE AT INSIDE PLATE SURFACE IN DEG.F
C TR AVERAGE TEMPERATURE OF PLATE BETWEEN TO AND TM
C ST THERMAL SIDE PLATE STRESS IN PSI
C SS SIDE PLATE ACTUAL STRESS IN PSI
C  S STATIC SIDE PLATE STRESS IN PSI
C TZ ZINC TEMPERATURE IN °F
C RE LIFE EXPONENT
C RH LIFE HOURS
C RS HOUR SUMMATION
C FL FRACTION OF LIFE USED
C FS SUM OF FRACTIONS OF LIFE USED
C WR WEAR RATE IN INCHES PER 100 HOURS
C  T IS TIME INCREMENT IN HOURS (100)
C
C READ IN INITIAL DESIGN DATA
   10 READ(1,11)A,W,PK,AK,AT,H,TZ,HT,AC
   11 FORMAT(9F7.3)
C PRINT OUT INITIAL DESIGN DATA
      WRITE(3,11)A,W,PK,AK,AT,H,TZ,HT,AC
C INITIALIZE PLATE THICKNESS(UNIT THICKNESS HIGHER THAN DESIRED)
      PL=3.5
C SUBTRACT A UNIT THICKNESS
   12 PL=PL-0.5
C PRINT OUT PLATE THICKNESS IN INCHES
      WRITE(3,13)PL
```

```
  13 FORMAT(F4.1)
C DETERMINE IF MINIMUM PLATE THICKNESS IS REACHED
      IF(PL-1.0)10,14,14
C INITIATE DEPTH IN INCHES
  14 D=50.0
C INITIATE HEAT RATE
  18 Q=8000.
C INITIATE TIME FOR EACH STEP IN HOURS
  19 T=100.
C EQUATE PLATE THICKNESS TO PREVENT PROGRAM CONFUSION
      P=PL
C INITIATE LIFE FRACTION
      FS=0.0000
C INITIATE LIFE HOUR ACCUMULATOR
      RS=0000000.0
C CALCULATE OUTSIDE PLATE TEMPERATURE
  20 TO=TZ+(Q*((P/PK)+(AT/AK)+(HT/H)))
C CALCULATE INSIDE PLATE TEMPERATURE
      TM=TO-(Q/(PK/P))
C CALCULATE TEMPERATURE IN MIDDLE OF PLATE
      TR=(TO+TM)/2
C CALCULATE WEAR RATE
      WR=(TM/948.9014078)**(1.0000000000/.015078562)
C CALCULATE STATIC STRESS
      S=(6.*A*W*AC*(D**3))/(P**2)
C CALCULATE THERMAL STRESS
      ST=(130.0*(TO-TM))/1.40
C CALCULATE ACTUAL STRESS
      SS=ABS(S-ST)
C CALCULATE LIFE EXPONENT
      RE=(+1095.38951-(3.2483079*TR)+(0.0032496875*(TR**2))-
     1(0.0000010912879*(TR**3))-(0.00000000000003721*(TR**4)))
C CALCULATE LIFE
      RH=(38000/SS)**RE
C ACCUMULATE TOTAL NUMBER OF HOURS STEPWISE
      RS=RS+T
C CALCULATE LIFE FRACTION
      FL=T/RH
C ACCUMULATE TOTAL LIFE FRACTION
      FS=FS+FL
C STOP CALCULATION WHEN FS APPROXIMATES 1
      IF(FS-1.0000)26,28,28
C SUBTRACT WEAR RATE
  26 P=P-WR
C LIFE HAS NOT BEEN APPROXIMATED-COMPUTE NEXT STEP
      GO TO 20
C LIFE APPROXIMATED-PRINT OUT DATA
  28 WRITE(3,29)WR,TM,FS,TR,SS,P,Q,D,RS,RE
  29 FORMAT(10F12.5)
C LOOP TO NEXT HEAT RATE AT THIS KETTLE DEPTH AND THICKNESS
      Q=Q+1000.
C CHECK HEAT RATE
```

```
      IF(Q-20000.)19,19,31
C MAXIMUM HEAT RATE NOT REACHED-COMPUTE NEXT RATE
C MAXIMUM HEAT RATE REACHED-GO TO NEXT KETTLE DEPTH
   31 D=D+10.
C CHECK KETTLE DEPTH
      IF(D-120.)18,18,12
C IF MAXIMUM DEPTH NOT REACHED-COMPUTE NEXT DEPTH
C IF MAXIMUM DEPTH REACHED-GO TO NEXT PLATE THICKNESS
C IF MINIMUM PLATE THICKNESS HAS BEEN REACHED-GO TO 12
C GO TO 12 SENDS COMPUTER TO READ THE NEXT CARD
   36 STOP
C IF NO MORE CARDS ARE AVAILABLE-STOP
      END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *
0.067 0.257 320.0 96.0 0.125 500.0 830.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 840.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 850.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 860.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 870.0 1.0 0.778
/*
```

APPENDIX I

Computer Program for Design Life (Select Data)

COMPUTER PROGRAM FOR DESIGN LIFE (SELECT DATA)

```
//C0019307  JOB  (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=G,TIME=10,MSGLEVEL=1
//   EXEC FORTGCLG
//FORT.SYSIN DD  *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C THIS PROGRAM COMPUTES KETTLE LIFE
C
C PK STEEL HEAT TRANSFER COEFF. BTU-IN/SQ FT-HR-DEG.F
C AT ZINC-IRON ALLOY LAYER THICKNESS IN INCHES
C AK ZINC-IRON ALLOY LAYER HEAT COEFF. BTU-IN/SQ FT-HR-DEG.F
C  H MOLTEN ZINC CONVECTION COEFF. BTU/SQ FT-HR-DEG.F
C  A DIMENSIONLESS MOMENT FACTOR FOR PLATES
C  W ZINC DENSITY IN LBS/CU.-IN.
C  D DEPTH OF KETTLE IN INCHES
C HT UNITY FACTOR FOR MOLTEN ZINC BATH-CONVECTION CONDITIONS
C AC BENDING STRESS CORRECTION FACTOR FOR CREEP
C PL=P PLATE THICKNESS IN INCHES
C  Q IS HEAT RATE INTO KETTLE THRU KETTLE PLATE
C TO TEMPERATURE AT OUTSIDE PLATE SURFACE IN DEG.F
C TM TEMPERATURE AT STEEL AND ALLOY LAYER INTERFACE IN DEG.F
C TI TEMPERATURE AT INSIDE PLATE SURFACE IN DEG.F
C TR AVERAGE TEMPERATURE OF PLATE BETWEEN TO AND TM
C ST THERMAL SIDE PLATE STRESS IN PSI
C SS SIDE PLATE ACTUAL STRESS IN PSI
C  S STATIC SIDE PLATE STRESS IN PSI
C TZ ZINC TEMPERATURE IN °F
C RE LIFE EXPONENT
C RH LIFE HOURS
C RS HOUR SUMMATION
C FL FRACTION OF LIFE USED
C FS SUM OF FRACTIONS OF LIFE USED
C WR WEAR RATE IN INCHES PER 100 HOURS
C  T IS TIME INCREMENT IN HOURS (100)
C SK INITIAL STRESS REJECT CHECK
C
C READ IN INITIAL DESIGN DATA
  10 READ(1,11)A,W,PK,AK,AT,H,TZ,HT,AC
  11 FORMAT(1X,9F7.3)
C PRINT OUT INITIAL DESIGN DATA
     WRITE(3,11)A,W,PK,AK,AT,H,TZ,HT,AC
C INITIALIZE PLATE THICKNESS(UNIT THICKNESS HIGHER THAN DESIRED)
     PL=4.5
C SUBTRACT A UNIT THICKNESS
  12 PL=PL-0.5
C PRINT OUT PLATE THICKNESS IN INCHES
     WRITE(3,13)PL
```

```
  13 FORMAT(1X,F4.1)
C DETERMINE IF MINIMUM PLATE THICKNESS IS REACHED
     IF(PL-1.0)10,14,14
C INITIATE DEPTH IN INCHES
  14 D=50.0
C INITIATE HEAT RATE
  18 Q=8000.
C INITIATE TIME FOR EACH STEP IN HOURS
  19 T=100.
C EQUATE PLATE THICKNESS TO PREVENT PROGRAM CONFUSION
     P=PL
C INITIATE LIFE FRACTION
     FS=0.0000
C INITIATE LIFE HOUR ACCUMULATOR
     RS=0000000.0
C CALCULATE OUTSIDE PLATE TEMPERATURE
  20 TO=TZ+(Q*((P/PK)+(AT/AK)+(HT/H)))
C CALCULATE INSIDE PLATE TEMPERATURE
     TM=TO-(Q/(PK/P))
C CALCULATE TEMPERATURE IN MIDDLE OF PLATE
     TR=(TO+TM)/2
C REJECT DATA IF TEMPERATURE "TR" IS TOO HIGH
     IF (TR-1000.0)21,21,31
C CALCULATE WEAR RATE
  21 WR=(TM/948.9014078)**(1.0000000000/.015078562)
C CALCULATE STATIC STRESS
     S=(6.*A*W*AC*(D**3))/(P**2)
C CALCULATE THERMAL STRESS
     ST=(130.0*(TO-TM))/1.40
C REJECT DATA IF INITIAL STRESS IS TOO HIGH
     SK=S-ST
     IF(SK+10000.0)31,22,22
C CALCULATE ACTUAL STRESS
  22 SS=ABS(S-ST)
C REJECT DATA IF ANY STRESS IS TOO HIGH
     IF(SS-25800)23,23,12
C CALCULATE LIFE EXPONENT
  23 RE=(+1095.38951-(3.2483079*TR)+(0.0032496875*(TR**2))-
  1(0.0000010912879*(TR**3))-(0.00000000000003721*(TR**4)))
C CALCULATE LIFE
     RH=(38000./SS)**RE
C ACCUMULATE TOTAL NUMBER OF HOURS STEPWISE
     RS=RS+T
C CALCULATE LIFE FRACTION
     FL=T/RH
C ACCUMULATE TOTAL LIFE FRACTION
     FS=FS+FL
C STOP CALCULATION WHEN FS APPROXIMATES 1
     IF(FS-1.0000)25,26,26
C SUBTRACT WEAR RATE
  25 P=P-WR
```

```
C LIFE HAS NOT BEEN APPROXIMATED-COMPUTE NEXT STEP
      GO TO 20
C REJECT ANY LIFE IF IT IS TOO LOW
   26 IF(RS-2000.0)30,27,27
C REJECT ANY LIFE IF IT IS TOO HIGH
   27 IF(RS-30000.0)28,28,30
C LIFE APPROXIMATED-PRINT OUT DATA
   28 WRITE(3,29)WR,TM,FS,TR,SS,P,Q,D,RS,RE
   29 FORMAT(1X,10F12.5)
C LOOP TO NEXT HEAT RATE AT THIS KETTLE DEPTH AND THICKNESS
   30 Q=Q+1000.
C CHECK HEAT RATE
      IF(Q-20000.)19,19,31
C MAXIMUM HEAT RATE NOT REACHED-COMPUTE NEXT RATE
C MAXIMUM HEAT RATE REACHED-GO TO NEXT KETTLE DEPTH
   31 D=D+5.
C CHECK KETTLE DEPTH
      IF(D-120.)18,18,12
C IF MAXIMUM DEPTH NOT REACHED-COMPUTE NEXT DEPTH
C IF MAXIMUM DEPTH REACHED-GO TO NEXT PLATE THICKNESS
C IF MINIMUM PLATE THICKNESS HAS BEEN REACHED-GO TO 12
C GO TO 12 SENDS COMPUTER TO READ THE NEXT CARD
   32 STOP
C IF NO MORE CARDS ARE AVAILABLE-STOP
      END
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *
0.067 0.257 320.0 96.0 0.125 500.0 830.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 840.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 850.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 860.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 870.0 1.0 0.778
/*
```

APPENDIX J

Computer Program for Design Life of Kettle With Title Blocks (Select Data)

SELECT DATA
COMPUTER PROGRAM FOR DESIGN LIFE OF KETTLE WITH TITLE BLOCKS

```
//C0019750  JOB  (0,0,,,,,1,,0),
// SR200501,PENNELL,CLASS=G,TIME=10,MSGLEVEL=1
//    EXEC FORTGCLG
//FORT.SYSIN DD  *
C
C THIS PROGRAM WRITTEN IN FORTRAN IV G LEVEL 20 IBM HASP II
C FORTRAN SYSTEM HAS BEEN CALLED-BEGIN PROGRAM
C DATA CARDS MUST PLACE IN PROPER SEQUENCE AT END OF DECK
C
C THIS PROGRAM COMPUTES KETTLE LIFE WITH TITLE BLOCKS
C
C PK STEEL HEAT TRANSFER COEFF. BTU-IN/SQ FT-HR-DEG.F
C AT ZINC-IRON ALLOY LAYER THICKNESS IN INCHES
C AK ZINC-IRON ALLOY LAYER HEAT COEFF. BTU-IN/SQ FT-HR-DEG.F
C  H MOLTEN ZINC CONVECTION COEFF. BTU/SQ FT-HR-DEG.F
C  A DIMENSIONLESS MOMENT FACTOR FOR PLATES
C  W ZINC DENSITY IN LBS/CU.-IN.
C  D DEPTH OF KETTLE IN INCHES
C HT UNITY FACTOR FOR MOLTEN ZINC BATH-CONVECTION CONDITIONS
C AC BENDING STRESS CORRECTION FACTOR FOR CREEP
C PL=P PLATE THICKNESS IN INCHES
C  Q IS HEAT RATE INTO KETTLE THRU KETTLE PLATE
C TO TEMPERATURE AT OUTSIDE PLATE SURFACE IN DEG.F
C TM TEMPERATURE AT STEEL AND ALLOY LAYER INTERFACE IN DEG.F
C TI TEMPERATURE AT INSIDE PLATE SURFACE IN DEG.F
C TR AVERAGE TEMPERATURE OF PLATE BETWEEN TO AND TM
C ST THERMAL SIDE PLATE STRESS IN PSI
C SS SIDE PLATE ACTUAL STRESS IN PSI
C  S STATIC SIDE PLATE STRESS IN PSI
C TZ ZINC TEMPERATURE IN °F
C RE LIFE EXPONENT
C RH LIFE HOURS
C RS HOUR SUMMATION
C FL FRACTION OF LIFE USED
C FS SUM OF FRACTIONS OF LIFE USED
C WR WEAR RATE IN INCHES PER 100 HOURS
C  T IS TIME INCREMENT IN HOURS (100)
C SK INITIAL STRESS REJECT CHEEK
C
C READ IN INITIAL DESIGN DATA
   10 READ(1,11)A,W,PK,AK,AT,H,TZ,HT,AC
   11 FORMAT(10F7.3)
C PRINT OUT INITIAL DESIGN DATA
      WRITE(3,9)
    9 FORMAT(131H   A      W        PK       AK       AT       H
     6TZ    HT     AC
     7INPUT DATA)
      WRITE(3,11)A,W,PK,AK,AT,H,TZ,HT,AC
C INITIALIZE PLATE THICKNESS(UNIT THICKNESS HIGHER THAN DESIRED)
```

```
      PL=4.5
C SUBTRACT A UNIT THICKNESS
   12 PL=PL-0.5
C PRINT OUT PLATE THICKNESS IN INCHES
      WRITE(3,13)PL
   13 FORMAT(F4.1)
C DETERMINE IF MINIMUM PLATE THICKNESS IS REACHED
      IF(PL-1.0)10,14,14
C INITIATE DEPTH IN INCHES
   14 D=50.0
C INITIATE HEAT RATE
   18 Q=8000.
C INITIATE TIME FOR EACH STEP IN HOURS
   19 T=100.
C EQUATE PLATE THICKNESS TO PREVENT PROGRAM CONFUSION
      P=PL
C INITIATE LIFE FRACTION
      FS=0.0000
C INITIATE LIFE HOUR ACCUMULATOR
      RS=0000000.0
C CALCULATE OUTSIDE PLATE TEMPERATURE
   20 TO=TZ+(Q*((P/PK)+(AT/AK)+(HT/H)))
C CALCULATE INSIDE PLATE TEMPERATURE
      TM=TO-(Q/(PK/P))
C CALCULATE TEMPERATURE IN MIDDLE OF PLATE
      TR=(TO+TM)/2
C REJECT DATA IF TEMPERATURE "TR" IS TOO HIGH
      IF (TR-1000.0)21,21,31
C CALCULATE WEAR RATE
   21 WR=(TM/948.9014078)**(1.0000000000/.015078562)
C CALCULATE STATIC STRESS
      S =(6.*A*W*AC*(D**3))/(P**2)
C CALCULATE THERMAL STRESS
      ST=(130.0*(TO-TM))/1.40
C REJECT DATA IF INITIAL STRESS IS TOO HIGH
      SK=S-ST
      IF(SK+10000.0)31,22,22
C CALCULATE ACTUAL STRESS
   22 SS=ABS(S-ST)
C REJECT DATA IF ANY STRESS IS TOO HIGH
      IF(SS-25800)23,23,12
C CALCULATE LIFE EXPONENT
   23 RE=(+1095.38951-(3.2483079*TR)+(0.0032496875*(TR**2))-
   1(0.0000010912879*(TR**3))-(0.0000000000003721*(TR**4)))
C CALCULATE LIFE
      RH=(38000./SS)**RE
C ACCUMULATE TOTAL NUMBER OF HOURS STEPWISE
      RS=RS+T
C CALCULATE LIFE FRACTION
      FL=T/RH
C ACCUMULATE TOTAL LIFE FRACTION
      FS=FS+FL
```

```
C STOP CALCULATION WHEN RS EQUALS 100
      IF(RS-100.0)50,50,24
C STOP CALCULATION WHEN FS APPROXIMATES 1
   24 IF(FS-1.0000)26,28,28
C SUBTRACT WEAR RATE
   25 P=P-WR
C LIFE HAS NOT BEEN APPROXIMATED-COMPUTE NEXT STEP
      GO TO 20
C REJECT ANY LIFE IF IT IS TOO LOW
   26 IF(RS-2000.0)30,27,27
C REJECT ANY LIFE IF IT IS TOO HIGH
   27 IF(RS-30000.0)28,28,30
C LIFE APPROXIMATED-PRINT OUT DATA
   28 WRITE(3,41)
   41 FORMAT(131H    TO    TR    TM    TI    Q    S
     2   ST    SK    RH    RS    D                    FINAL
     3CONDITIONS)
      WRITE(3,29)TO,TR,TM,TI,Q,S,ST,SK,RH,RS,D
   29 FORMAT(1X,12F9.1)
      WRITE(3,42)
   42 FORMAT(66H    WR    RE    FL    FS    P         FINAL
     8CONDITIONS)
      WRITE(3,40)WR,RE,FL,FS,P
   40 FORMAT(1X,5F10.5)
C LOOP TO NEXT HEAT RATE AT THIS KETTLE DEPTH AND THICKNESS
   30 Q=Q+1000.
C CHECK HEAT RATE
      IF(Q-20000.)19,19,31
C MAXIMUM HEAT RATE NOT REACHED-COMPUTE NEXT RATE
C MAXIMUM HEAT RATE REACHED-GO TO NEXT KETTLE DEPTH
   31 D=D+5
C CHECK KETTLE DEPTH
      IF(D-120.)18,18,12
C IF MAXIMUM DEPTH NOT REACHED-COMPUTE NEXT DEPTH
C IF MAXIMUM DEPTH REACHED-GO TO NEXT PLATE THICKNESS
C IF MINIMUM PLATE THICKNESS HAS BEEN REACHED-GO TO 12
C GO TO 12 SENDS COMPUTER TO READ THE NEXT CARD
   50 WRITE(3,47)
   47 FORMAT(48H               INITIAL AND FINAL CONDITIONS)
   48 WRITE(3,49)
   49 FORMAT(131H    TO    TR    TM    TI    Q    S
     4    ST    SK    RH    RS    D    P            INITIAL
     5CONDITIONS)
      WRITE(3,51)TO,TR,TM,TI,Q,S,ST,SK,RH,RS,D,P
   51 FORMAT(1X,12F9.1)
      WRITE(3,52)
   52 FORMAT(55H    WR    RE    FL    FS INITIAL CONDITIONS)
      WRITE(3,53)WR,RE,FL,FS
   53 FORMAT(1X,4F10.5)
      GO TO 20
   55 STOP
C IF NO MORE CARDS ARE AVAILABLE-STOP
      END
```

```
/*
//LKED.SYSPRINT DD SYSOUT=A
//GO.FT03F001 DD SYSOUT=A,DCB=RECFM=A
//GO.FT06F001 DD SYSOUT=A
//GO.FT01F001 DD  *
0.067 0.257 320.0 96.0 0.125 500.0 830.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 840.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 850.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 860.0 1.0 0.778
0.067 0.257 320.0 96.0 0.125 500.0 870.0 1.0 0.778
/*
```

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