X-17403

UNCLASSIFIED

CF-54-3-57

Subject Category: ENGINEERING

UNITED STATES ATOMIC ENERGY COMMISSION

HEAT TRANSFER AND PRESSURE LOSS IN PROPOSED ORR FUEL ASSEMBLIES

By
J. P. Sanders

March 11, 1954

Oak Ridge National Laboratory
Oak Ridge, Tennessee

Technical Information Service, Oak Ridge, Tennessee

UNCLASSIFIED

Date Declassified: December 16, 1955.

Printed in USA, Price 30 cents. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

CF-54-3-57

HEAT TRANSFER AND PRESSURE LOSS IN PROPOSED ORR FUEL ASSEMBLIES

By

J. P. Sanders

March 11, 1954

Work performed under Contract No. W-7405-Eng-26

OAK RIDGE NATIONAL LABORATORY
Operated By
Carbide and Carbon Chemicals Company
Oak Ridge, Tennessee

ABSTRACT:

In an investigation of the cooling system for the ORNL Research Reactor, calculations have been made to relate the pressure loss in the assemblies with the flow rate. In addition an expression was developed and evaluated to give the maximum temperature of the surface in contact with the water as a function of flow rate, inlet water temperature, and maximum heat flux. After this maximum heat flux has been determined and a maximum permissible surface temperature selected, the corresponding minimum flow rate and its associated pressure loss can be found for any inlet water temperature by the methods illustrated in this report. Examples of such results are shown in Table V.

As a by-product of the pressure loss calculations, certain recommendations have been made pursuant to the reduction of pressure loss in the assemblies. This recommendation is that the inlet and exit flow areas be made rectangular in cross section, thereby increasing the flow area and eliminating any sudden change from circular to rectangular cross section.

TABLE OF CONTENTS

APPENDIX II (Cont.)

APPENDIX III

INDEX OF TABLES

HEAT TRANSFER AND PRESSURE LOSS IN PROPOSED ORR FUEL ASSEMBLIES

INTRODUCTION

In order to design the most efficient cooling system for the ORNL Research Reactor, it is necessary to know the relationships between flow rate through the fuel assemblies, the pressure loss, and the maximum surface temperature at various operating powers. Since no flow tests have been made for the proposed ORR fuel assemblies, the pressure loss as a function of flow rate must be calculated from empirical flow relationships. The maximum surface temperature can be calculated from a simple heat balance if the assumption is made that no heat is conducted linearly along the fuel plate.

CALCULATION OF PRESSURE LOSS:

Description of the Assembly-

Essentially, the assembly is similar to a standard MTR fuel assembly with the exception that round adapters are used on both ends so that the element may be inverted for more complete burn up. The assembly is described in ORNL Drawing D-15898 with the exception that two modifications have been made. These changes are (1) it was assumed that entrance and exit straight sections shown as 2.000 inches I. D. could be opened to 2.250 inches I. D. and (2) the recent changes described in ORNL CF 53-12-119* in the MTR fuel and side plates are incorporated in this design. These changes include making the fuel plates 50 mils thick which include a 20 mil plate of uranium-aluminum alloy clad on both sides with 15 mil aluminum sheets. The side plates are reduced in thickness from 3/16 inch to 1/8 inch.

---

* Cunningham, J. E., 'Information Paper on MTR Fuel Elements," ORNL CF 53-12-119, December 21, 1953.

In reducing the fuel plate thickness from the original design of 60 mils, the overall cross sectional dimensions of 2.996 inches and 3.069 inches are maintained. If the original number of plates, 18, is maintained, this increases the gap width between plates to 0.1276 inches from the original 0.117 inches. If an additional plate is added, the gap width becomes 0.1177 inches, practically the original dimension..

Since there was some doubt as to the advantages of adding this nineteenth fuel plate, calculations have been made using both configurations in the pressure loss calculations.

Empirical Relationships Used to Determine Pressure Loss-

The losses due to sudden contractions were calculated according to Equation (31) in Badger and McCabe.* Changing this relationship from head loss to pressure loss in pounds per square inch, it becomes

$$\Delta p = \frac{K_c u^2 \rho}{2(144)\, g_c} \qquad (1)$$

The constant, K_c, is evaluated according to Figure 15 of this reference.** The significance of the remaining terms is found in Appendix I of this report. The losses due to a gradual contraction are neglected.***

The losses due to sudden expansions were calculated from Equation (30) in Badger and McCabe**** which is identical with Equation (102) in Vennard.*****

* Badger, W. L. and McCabe, W. L., Elements of Chemical Engineering, Second Edition, McGraw-Hill Book Co., Inc., New York, 1936, p. 40.

** Ibid. p. 40.

*** Vennard, J. K., Elementary Fluid Mechanics, Second Edition, John Wiley and Sons, Inc., New York, 1948. p. 178.

**** Badger, W. L., and McCabe, W. L., op. cit., p. 39.

***** Vennard, J. K., op. cit., p. 174.

Again changing to pressure loss in pounds per square inch, the equation is

$$\Delta p = \frac{(u_H - u_L)^2 \rho}{2(144)\, g_c}$$

In the case of a more gradual expansion, the formula is modified according to Equation (103) in Vennard.*

$$\Delta p = \frac{K_e(u_H - u_L)^2 \rho}{2(144)\, g_c}$$

The constant, K_e, was evaluated according to Figure 84 of this reference.**

The losses due to friction in straight lengths of constant cross sectional area were calculated according to the Fanning friction equation shown in McAdams.*** The integrated form of Equation (8_a) of this text, converted to pressure loss in pounds per square inch, is

$$\Delta p = \frac{2\ f\ u^2 \rho L}{(144)\ g_c\ D_e}$$

The Fanning friction factor, f, is found by computing the Reynolds number, then applying the relationship expressed graphically in Figure 51 of McAdams.**** A line drawn proportionately one-fourth the distance from line A to G on the plot was found to best relate the friction loss in the flow between the fuel plates.

In applying the friction equation and in determining the Reynolds number for flow in channels other than circular, and eouivalent hydraulic diameter was calculated according to the suggestion in Badger and McCabe.***** The equivalent diameter is given as four times the cross-sectional area of the channel divided by the wetted perimeter of the channel.

---

* Ibid, p. 175.

** Ibid, p. 176.

*** McAdams, W. H., Heat Transmission, Second Edition, McGraw-Hill Book Co., Inc., New York, (1942), p. 119.

**** Ibid, p. 118.

***** Badger, W.L., and McCabe, W. L., op. cit., p. 44.

Method of Calculation-

In the calculation of the pressure loss through the fuel assembly, the velocity between the fuel plates was assigned the value, V. By calculating the relative flow areas throughout the assembly, the velocities at other points could be determined in terms of this symbol. The pressure loss over each section was then calculated, also in terms of this symbol. In order that the pressure loss calculated might compare with the pressure loss which might be determined in an experimental apparatus, the effect of changes in velocity head was calculated. The net change in velocity head over the entire assembly was zero since it was assumed that velocities were the same above and below the assembly support grids.

Calculations were made, as was stated previously, both for 18- and 19-fuel plate assemblies. These calculations were made assuming that the average water temperature was 100°F. For the 19-fuel plate assembly, additional calculations were made assuming an average water temperature of 160°F. The viscosity of water at these temperatures was determined from the nomograph, Appendix II, in Badger and McCabe.* The density of water at these temperatures was determined as the reciprocal of the specific volume given in Keenan and Keys.**

An example of these calculations is shown in Appendix II of this report.

---

* Ibid., p. 632.

** Keenan, J. H., and Keys, F. G., Thermodynamic Properties of Steam, First Edition, John Wiley and Sons, Inc., New York, (1948), p. 29-30.

Validity of these Relationships-

In order to check the validity of the application of the formulae to the situation, a calculation of the pressure loss in a standard MTR fuel assembly was made and compared to experimentally determined results. The pressure loss was calculated for an average linear water velocity of thirty feet per second between the fuel plates at an average temperature of 80°F. These were compared with experimental data given in ORNL-CF-50-6-102.* The results are shown in Table I.

TABLE I

COMPARISON OF CALCULATED AND EXPERIMENTAL PRESSURE LOSS IN MTR FUEL ASSEMBLIES FOR A WATER VELOCITY OF 30 FT/SEC

	Calculated (psi)	Experimental (psi)
Upper End Box	14.1	13
Fuel Plate Section	17.1	18
Lower End Box	9.0	6
Total	40.2	37

* Kasper, S., "Water Flow in Materials Testing Reactor," ORNL CF 50-6-102, June 15, 1950, p. 6.

Results of Pressure Loss Calculations-

The relationship giving the pressure loss through the assembly as a function of velocity through the fuel plate is given in the following expressions.

In the 18-plate assembly at 100°F,

Upper end box	Δp	$= 0.00925\ V^2 + 0.00109\ V^{1.79}$
Fuel plates	Δp	$= 0.00387\ V^2 + 0.0272\ V^{1.79}$
Lower end box	Δp	$= 0.01012\ V^2 + 0.00195\ V^{1.79}$
Total Assembly	Δp	$= 0.02324\ V^2 + 0.0302\ V^{1.79}$

In the 19-plate assembly at 100°F,

Upper end box	Δp	$= 0.00857\ V^2 + 0.00104\ V^{1.79}$
Fuel plates	Δp	$= 0.00394\ V^2 + 0.0291\ V^{1.79}$
Lower end box	Δp	$= 0.00960\ V^2 + 0.00186\ V^{1.79}$
Total Assembly	Δp	$= 0.0221\ V^2 + 0.0320\ V^{1.79}$

In the 19-plate assembly at 160°F,

Upper end box	Δp	$= 0.00844\ V^2 + 0.00098\ V^{1.79}$
Fuel plates	Δp	$= 0.00388\ V^2 + 0.0276\ V^{1.79}$
Lower end box	Δp	$= 0.00944\ V^2 + 0.00175\ V^{1.79}$
Total Assembly	Δp	$= 0.0218\ V^2 + 0.0303\ V^{1.79}$

The velocity, V, is given in feet per second, and the pressure loss is in pounds per square inch. Table II gives values for the pressure loss at various velocities. Figure 1 shows this relationship graphically. Examination of this plot indicates that the variation in total pressure loss between these three situations does not differ significantly.

TABLE II
PRESSURE LOSS IN ORR FUEL ASSEMBLIES
with 18- and 19- plates
as a function of
Velocity between the Plates

Velocity V (ft/sec)	Pressure Loss in 19-plate Assemblies at 100°F (psi)	Pressure Loss in 18-plate Assemblies at 100°F (psi)	Pressure Loss in 19-plate Assemblies at 160°F (psi)
1	0.05	0.05	0.05
2	0.20	0.20	0.19
4	0.77	0.77	0.14
8	2.74	2.74	2.65
10	4.19	4.19	4.05
15	9.06	9.06	8.77
20	15.69	15.76	15.10
25	24.03	24.16	23.28
30	34.0	34.3	34.0
35	45.7	46.0	44.3

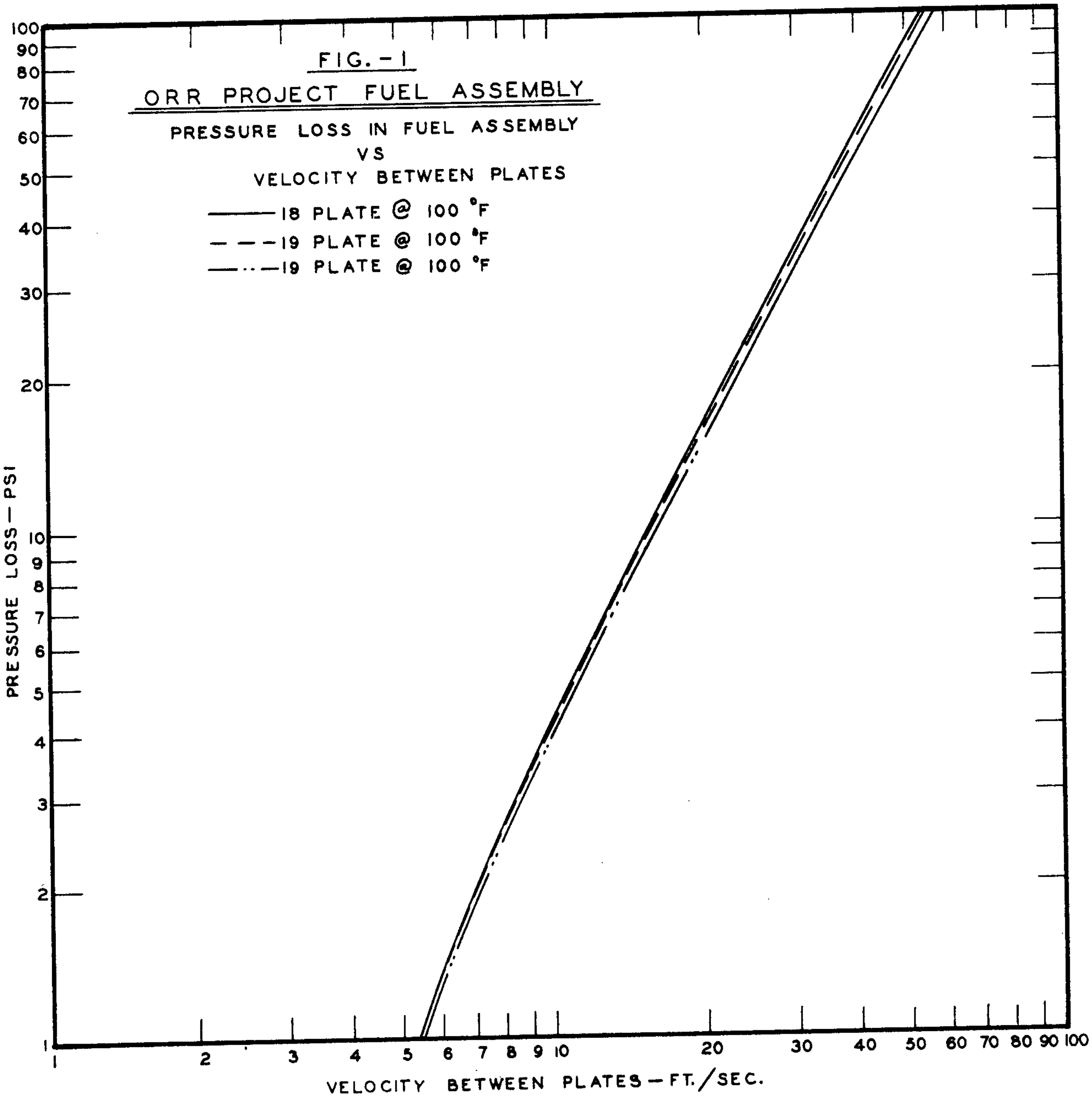
FIG. - 1
ORR PROJECT FUEL ASSEMBLY
PRESSURE LOSS IN FUEL ASSEMBLY
VS
VELOCITY BETWEEN PLATES
18 PLATE @ 100 °F
19 PLATE @ 100 °F
19 PLATE @ 100 °F
PRESSURE LOSS — PSI
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
VELOCITY BETWEEN PLATES — FT./SEC.

CALCULATION OF MAXIMUM SURFACE TEMPERATURE:

Development of Equations-

In calculating the maximum surface temperatures, the assumption was made that the neutron flux, and consequently the heat flux, was distributed, as in the MTR, according to a cosine curve which dropped to 0.4 times its maximum at the end and the plates. Thus, if Q_o represents the maximum heat flux at the center of the length of the fuel plate, $0.4Q_o$ represents the flux at the end of the fuel plate. In addition, it was assumed that no heat was conducted linearly along the fuel plate.

The heat flux in the fuel plate can now be expressed as

$$Q = Q_o \sin \pi x/L \qquad (5)$$

where L is the extrapolated length of the fuel plate that has zero flux at the ends. L is related to the actual length of the plate, a, by

$$L = a/\left[1 - (2)(0.4116)/\pi\right] \qquad (6)$$

$$= a/0.7380$$

Designating the temperature of water as T_w and that of the surface as T_m, the water flow rate in pounds per foot of width of plate per second as G; a heat balance from the entrance (designated sub 1) and any point, x, along the plate is

$$3600\ G\ C_p\ (T_w - T_{w_1}) = 2\int_{\frac{0.4116\ L}{\pi}}^{x} Q_o \sin \pi x/L\ dx \qquad (7)$$

Integrating this expression

$$T_w = T_{w_1} + \frac{2\ Q_o L}{3600\ \pi\ C_p\ G}\ (0.9165 - \cos \pi x/L) \qquad (8)$$

Since it is assumed that all the heat generated in the plate is transferred directly into the water, the following relationship is valid at any point, x.

$$h(T_m - T_w) = Q_o \sin \pi x/L \tag{9}$$

$$T_m = T_w + (Q_o/h)(\sin \pi x/L) \tag{10}$$

Substituting the value of T_w in equation (8) into equation (10), the surface temperature may be expressed

$$T_m = T_{w1} + \frac{2\ Q_o L}{3600\ \pi\ C_p\ G} \left(0.9165 - \cos \frac{\pi x}{L}\right) + \frac{Q_o}{h} \sin \frac{\pi x}{L} \tag{11}$$

In order to find the point at which the maximum value of T_m occurs

$$\frac{dT_m}{dx} = \frac{2\ Q_o}{3600\ \pi\ C_p\ G} \sin \frac{\pi x}{L} + \frac{Q_o}{h} \frac{\pi}{L} \cos \frac{\pi x}{L} = 0 \tag{12}$$

or

$$\tan \frac{\pi x}{L} = - \frac{3600\ \pi\ C_p\ G}{2\ h\ L} \tag{13}$$

The value of the heat transfer coefficient, h, was obtained from an empirical equation given in McAdams.* The equation is

$$h = 5.6\ (1 + 0.011t)(G')^{0.8}/(D')^{0.2} \tag{14}$$

where t is the bulk temperature of the fluid in degrees Fahrenheit, G' is the pounds of fluid flowing per second-square foot of cross section and D' is the hydraulic diameter in inches. The diameter was taken as twice the gap width which is approximately equal to the value obtained by dividing four times the area by the perimeter.

---

*McAdams, W. H., op. cit., p. 183, Equation (9).

In order to evaluate this heat transfer coefficient and also the heat capacity, and density, it is necessary to know the average bulk temperature of the liquid. This is taken as the arithmetic average between the inlet and exit water temperatures.

The total heat, H, removed from a foot width of plate in one second is

$$H = \frac{2}{3600} \int_{0.4116\ L/\pi}^{2.730\ L/\pi} Q_o \sin \frac{\pi x}{L}\, dx \qquad (15)$$

Integrating

$$H = 3.24 \times 10^{-4}\ Q_o\ L \ \ \text{Btu/ft.-sec.} \qquad (16)$$

The temperature rise of the water in flowing by the plate is found

$$\Delta T = H/G\ C_p \qquad (17)$$

As a first estimate, the value of C_p may be taken as 1.00 Btu per pound-degree Fahrenheit; L is 2.781 feet. The temperature rise, in terms of the maximum heat flux and flow rate is

$$\Delta T = 9.02 \times 10^{-4}\ Q_o/G \qquad (18)$$

The average bulk water temperature is then found

$$t = \frac{T_{w_1} + (T_{w_1} + \Delta T)}{2} \qquad (19)$$

Method of Calculation-

A value for the maximum heat flux, Q_o , was selected; and for a series of values for the mass flow rate, G, in pounds per foot of width-second, the rise in water temperature, ΔT, was calculated from equation (18). Next, an entrance water temperature was selected and the average bulk water temperature, t, was calculated from equation (19).

At this temperature, the values for the density was obtained as the reciprocal of the specific volume given in Keenan and Keyes* and the heat capacity was obtained from Figure 12-8 in ORNL-156*

For the known gap width and the determined density, it is now possible to calculate the mass flow rate, G', and the linear velocity, V for each assumed value of G. Sufficient values are now known to calculate the film heat transfer coefficient, h, from equation(14).

In order to locate the point of maximum surface temperature, the values of tan $\pi x/L$ are calculated from equation(13), and the corresponding values of sin $\pi x/L$ and cos $\pi x/L$ are read from tables. Since these are the only values needed in determining the maximum surface temperature, it is unnecessary to solve for the quantity x.

The values obtained are substituted in equation (11) to obtain the maximum surface temperature.

An example of these calculations is shown in Appendix III.

Results of the Calculations-

For a preliminary group of calculations, an average bulk water temperature of 130°F was assumed for all conditions, and a density, heat capacity, and heat transfer coefficient were determined, based upon this assumption.

---

*Keenan, J. H., and Keys, F. G., op. cit., p. 29-30

**Harrison, W. B., Physical Properties of Water and Water Vapor, ORNL-156, Part 12, April 7, 1949.

The quantity, maximum surface temperature minus inlet water temperature ($T_m - T_{w1}$), was calculated for various mass flow rates. For each of the proposed variations in fuel assemblies, the corresponding linear velocity is calculated. This information for various values of maximum heat flux is given in Table III and shown graphically in Figure 2.

More exact calculations according to the plan outlined in the previous section were made for the 19-plate assembly at a maximum heat flux of 6×10^5 Btu per square foot-hour and inlet water temperatures of 100, 120, 140, and 160°F. In the MTR this value of maximum heat flux corresponded approximately to a total power of 30 megawatts. The results of these calculations are shown in Table IV and are presented graphically in Figure 3.

A calculation was made to determine the effect of changing to an 18-plate assembly, maintaining the same linear velocity between the plates and increasing the heat flux proportionately. The overall effect was to increase the maximum surface temperature in a direct relationship to the increased flux. This amounted to from 3° to 5°F in the range of velocities from 20 to 40 feet per second, 5 to 7°F in the range 15 to 20 feet per second and 7° to 10°F in the range 10 to 15 feet per second. This effect is shown in Figure 4.

In calculating these values of maximum surface temperature, the stipulation is made that boiling does not occur in the water film. Since this is the desired operating condition in the reactor, these results are applicable. If the flux in one of the fuel assemblies is distorted by the presence of a shim rod, resulting in a peaking of the heat flux, a conservative estimate of the maximum surface temperature is found merely by substituting this maximum heat flux in the derived formulae.

TABLE III

MAXIMUM SURFACE TEMPERATURE MINUS INLET WATER TEMPERATURE
AS A FUNCTION OF WATER FLOW RATE FOR
VARIOUS MAXIMUM HEAT FLUXES

Mass Flow Rate (/ft-hr)	Velocity in 0.1177" gap (ft/sec)	Velocity in 0.1276" gap (ft/sec)	$T_m - T_{w_1}$ in °F for Maximum Heat Fluxes of					
			1×10^5 (Btu/ft^2-hr	2×10^5 (Btu/ft^2-hr)	4×10^5 (Btu/ft^2-hr)	6×10^5 (Btu/ft^2-hr)	8×10^5 (Btu/ft^2-hr	1×10^6 (Btu/ft^2-hr)
5,000	2.3	2.1	133.3	266.6	533.2	799.8	1066.4	1333.0
10,000	4.6	4.2	73.3	146.5	293.0	439.5	586.0	732.5
15,000	6.9	6.4	51.6	103.3	206.6	309.8	413.1	516.4
20,000	9.2	8.5	40.4	80.8	161.6	242.4	323.2	404.0
25,000	11.5	10.6	33.4	66.7	133.5	200.2	267.0	333.7
30,000	13.8	12.7	28.7	57.3	114.7	172.0	229.4	286.7
34,000	15.7	14.4	25.8	51.7	103.3	155.0	206.6	258.3
40,000	18.4	17.0	22.5	45.0	90.1	135.1	180.2	225.2
44,000	20.3	18.7	20.7	41.5	82.9	124.4	165.8	207.3
50,000	23.0	21.2	18.6	37.2	74.4	111.5	148.7	185.9
55,000	25.3	23.3	17.2	34.3	68.6	102.9	137.2	171.5
60,000	27.6	25.5	15.9	31.8	63.6	95.4	127.2	159.0
65,000	29.9	27.6	14.9	30.0	59.5	89.3	119.0	148.8
70,000	32.2	29.7	14.0	28.0	56.0	83.9	111.9	139.9
75,000	34.5	31.8	13.2	26.4	52.8	79.3	105.7	132.1

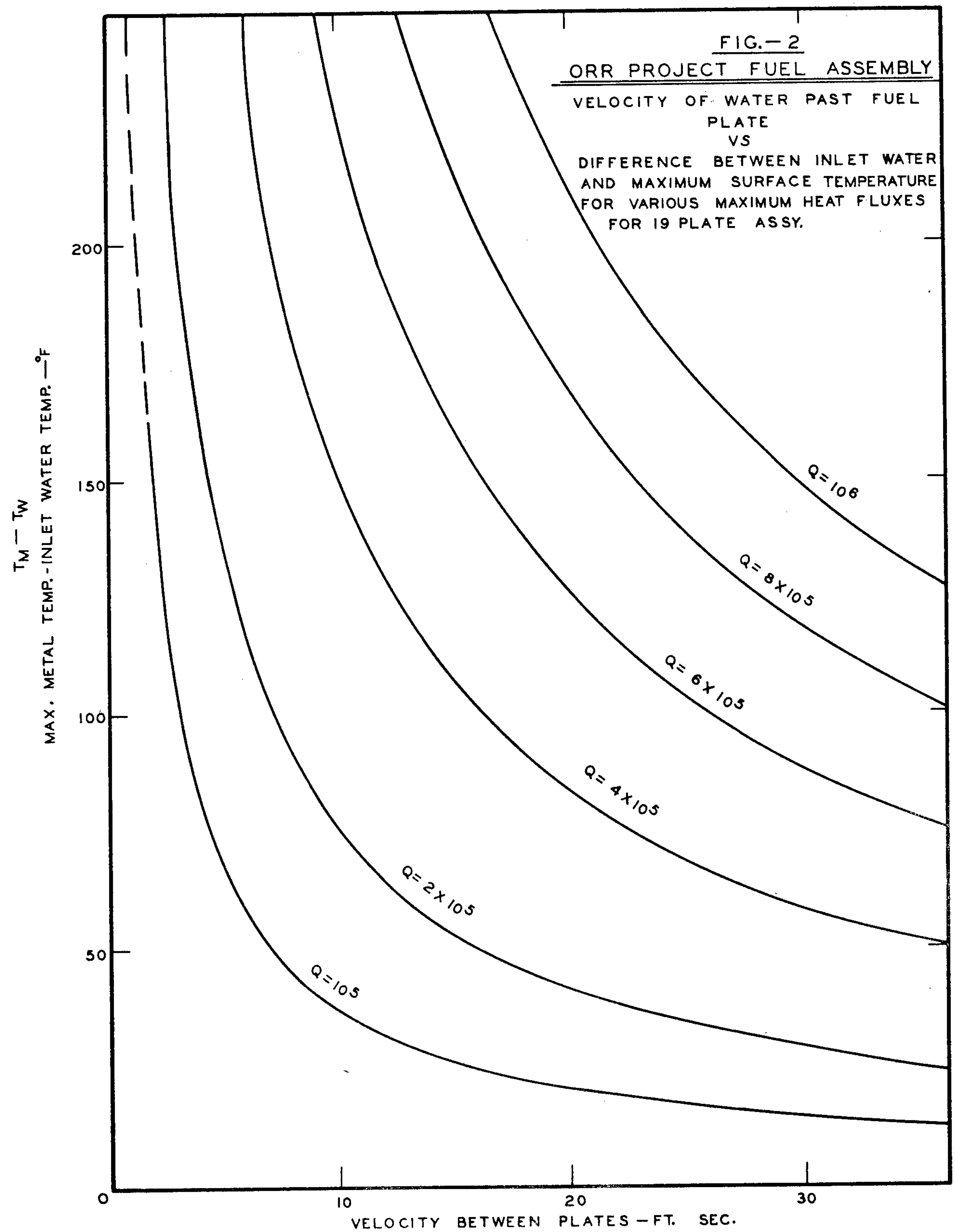
FIG. — 2
ORR PROJECT FUEL ASSEMBLY
VELOCITY OF WATER PAST FUEL PLATE
VS
DIFFERENCE BETWEEN INLET WATER AND MAXIMUM SURFACE TEMPERATURE FOR VARIOUS MAXIMUM HEAT FLUXES FOR 19 PLATE ASSY.
Q= 106
Q= 8X105
Q= 6X105
Q= 4X105
Q= 2X105
Q=105
200
150
100
50
0
10
20
30
TM — TW
MAX. METAL TEMP.-INLET WATER TEMP. —°F
VELOCITY BETWEEN PLATES — FT. SEC.

TABLE IV

MAXIMUM SURFACE TEMPERATURES*
FOR MAXIMUM HEAT FLUX, Q_o, OF 6×10^5 BTU/FT^2-HR
AND VARIOUS INLET WATER TEMPERATURES

Inlet Water Temperature	100°F		120°F		140°F		160°F	
Mass Flow Rate (#/ft-sec)	Velocity in 0.1177" gap (ft/sec)	Max. Surface Temperature (°F)	Velocity in 0.1177" gap (ft/sec)	Max. Surface Temperature (°F)	Velocity in 0.1177" gap (ft/sec)	Max. Surface Temperature (°F)	Velocity in 0.1177" gap (ft/sec)	Max. Surface Temperature (°F)
6	9.20	311	10.05	319	10.12	329	10.20	341
8	12.2	271	13.35	281	13.44	292	13.54	305
10	15.3	245	16.66	256	16.76	268	16.88	281
12	18.3	226	19.96	238	20.1	251	20.23	265
14	21.3	212	23.3	225	23.4	240	23.6	253
16	24.3	201	26.6	214	26.7	228	26.9	243
18	27.4	192	29.9	206	30.0	220	30.3	236
20	30.4	185	33.2	199	33.4	214	33.6	230
22	33.5	179	36.5	193	36.7	208	36.9	224

* These temperatures are applicable only if boiling does not occur.

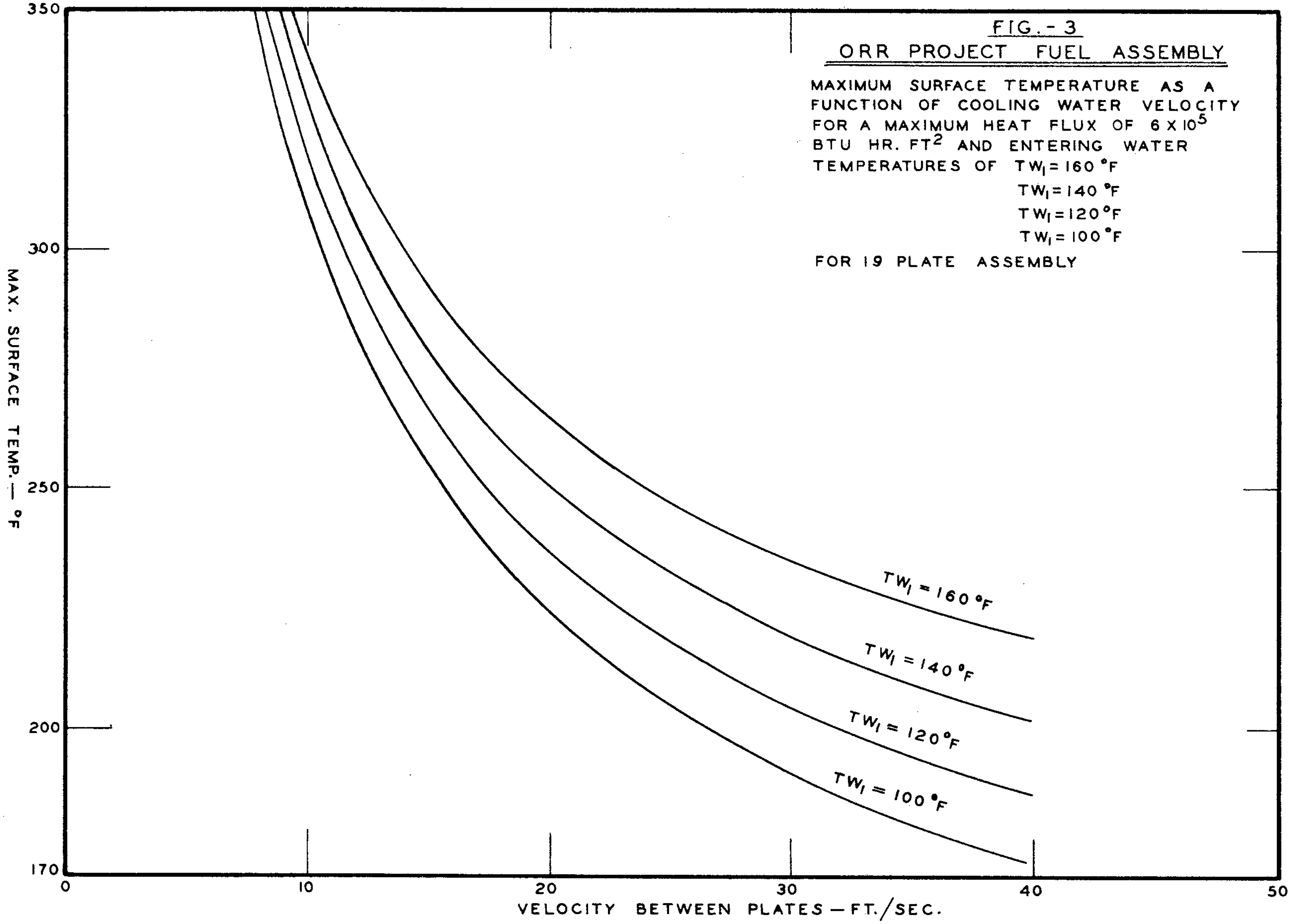

FIG. - 3

ORR PROJECT FUEL ASSEMBLY

MAXIMUM SURFACE TEMPERATURE AS A FUNCTION OF COOLING WATER VELOCITY FOR A MAXIMUM HEAT FLUX OF 6×10^5 BTU HR. FT^2 AND ENTERING WATER TEMPERATURES OF $TW_1 = 160\,°F$

$TW_1 = 140\,°F$

$TW_1 = 120\,°F$

$TW_1 = 100\,°F$

FOR 19 PLATE ASSEMBLY

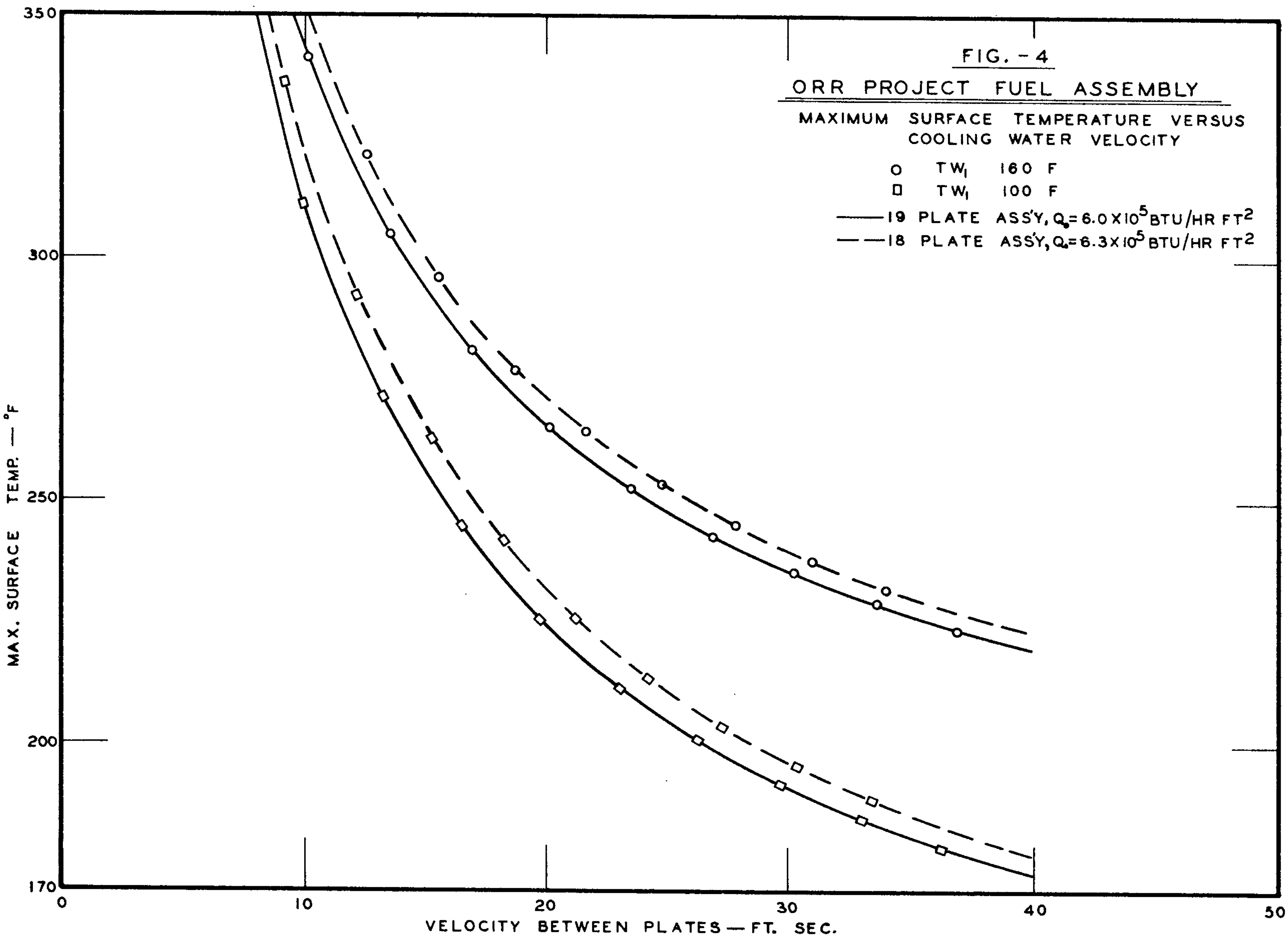
FIG. - 4
ORR PROJECT FUEL ASSEMBLY
MAXIMUM SURFACE TEMPERATURE VERSUS COOLING WATER VELOCITY
○ TW_1 160 F
□ TW_1 100 F
—— 19 PLATE ASS'Y, Q_o = 6.0×10^5 BTU/HR FT^2
– – 18 PLATE ASS'Y, Q_o = 6.3×10^5 BTU/HR FT^2
MAX. SURFACE TEMP. — °F
350
300
250
200
170
0
10
20
30
40
50
VELOCITY BETWEEN PLATES — FT. SEC.

OPERATING CONDITIONS FOR VARIOUS LIMITING SURFACE TEMPERATURES:

Depending upon the static pressure in the reactor, various maximum surface temperatures may be allowed without incurring the risk of film boiling. For any temperature the minimum allowable water velocity corresponding to any of the four inlet water temperatures can be read from Figure 3 of this report. For these flow rates the pressure drop across the fuel assembly can be read from Figure 2. A series of these values are given in Table V for the 19-plate assembly.

RECOMMENDED CHANGES IN FUEL ASSEMBLIES:

From the calculations of overall pressure loss in the assembly, it is possible to isolate the individual pressure losses across the various components. This study illustrates how changes might be made to reduce the pumping power.

For the 19-plate assembly with a linear velocity of 30 feet per second through the plate section, the exit loss from the lower end box comprises approximately 25% of the total pressure loss in the assembly. By changing this exit cross section to a 2.250 by 2.250 inch rectangular opening, this exit loss is lowered to 12.5% of the total. Altering the upper end box to a rectangular cross section would restore the ability to invert the element and produce a further reduction in pressure drop. Eliminating the sudden change from circular to rectangular cross section produces an additional 6% reduction in pressure loss.

TABLE V
OPERATING CONDITIONS FOR
VARIOUS ALLOWABLE SURFACE TEMPERATURES FOR
19-PLATE ASSEMBLY

Allowable Surface Temperature (°F)	Inlet Water Temperature (°F)	Velocity Between Fuel Plates (ft/sec)	Pressure Drop Across Fuel Assembly (psi)
210	100	23.7	21.8
	120	28.2	30.4
	140	35.1	46.3
215	100	22.3	19.4
	120	26.4	27.0
	140	32.5	39.8
220	100	21.1	17.5
	120	24.7	28.8
	140	30.1	34.6
	160	40.2	59.8
225	100	20.1	15.9
	120	23.2	21.3
	140	28.0	29.8
	160	36.4	48.9
230	100	19.0	14.4
	120	21.8	18.7
	140	26.1	26.3
	160	33.1	41.3
235	100	18.0	13.0
	120	20.6	16.5
	140	24.5	23.4
	160	30.6	36.8

A summation for the pressure loss in the assembly, with and without these modifications is found in Table VI

TABLE VI

PRESSURE LOSS IN 19-PLATE ASSEMBLY
FOR VELOCITY OF 30 FT/SEC
THROUGH PLATES

Section	Component	Pressure Loss Without Modifications (psi)	Pressure Loss With Modifications (psi)
Upper End Box	Entrance Loss	3.86	2.38
	Pipe Friction	0.48	0.48
	Expansion Friction	0.14	0.14
	Velocity Head	2.88	2.88
	Expansion from Round	0.84	--
Fuel Plates	Entrance Loss	3.02	3.02
	Friction	12.61	12.61
	Exit Loss	0.60	0.60
	Velocity Head	0.00	0.00
Lower End Box	Sudden Contraction	1.39	--
	Friction in Pipe	0.86	0.86
	Exit Loss	10.92	6.44
	Velocity Head	2.88	2.88
Total		34.72	26.53

APPENDIX I

NOMENCLATURE

A Length of fuel plate, feet

C_p Specific heat, Btu/pound-^oF

D' Hydraulic diameter, inches

D_e Equivalent hydraulic diameter, feet

f Fanning friction factor

g_c Gravity constant, 32.2 feet/second^2

G Water flow rate, pounds/foot of width-second

G' Water flow rate, pounds/foot^2-second

h Film heat transfer coefficient, Btu/foot^2-hour-^oF

H Total heat generated, Btu/foot of width-second

K_c Constant relating head losses due to sudden contraction to flow rate

K_e Constant relating head loss due to expansion to flow rate

L Lenght, feet

Δp Pressure loss, pounds/inch^2

Q Heat flux, Btu/foot^2-hour

Q_o Maximum heat flux, Btu/foot^2-hour

S Specific volume, foot^3/pound

t Average bulk water temperature, ^oF

T_m Surface temperature, ^oF

ΔT Temperature change in water flowing past fuel plate, ^oF

T_w Water temperature, ^oF

u Flow rate, feet/second

u_H Flow rate in smaller cross section, feet/second

u_L Flow rate in larger cross section, feet/second

V Velocity between fuel plates, feet/second

ρ Density, pounds/foot^3

μ Viscosity, pounds/foot-second

APPENDIX II

CALCULATION OF PRESSURE LOSS

Calculation of Pressure Loss in 19-Plate Assembly

For T = 100°F

μ = 0.72 C. P. = 0.000484 /ft-sec

ρ = 62.0 /ft^3

V = velocity between plates in ft/sec

Flow Areas:

In fuel plate section	0.0404 ft^2
In 2.250" I. D. pipe	0.0276 ft^2
In 2.625" I. D. pipe	0.0376 ft^2
In 3.019" x 2.746" area..........................	0.0576 ft^2

Velocity:

In fuel plate section	V ft/sec
In 2.250" I. D. pipe	1.464 V ft/sec
In 2.625" I. D. pipe	1.074 V ft/sec
In 3.019 x 2.746" area	0.701 V ft/sec
Above and below assembly	0.117 V ft.sec

Pressure Loss

In upper end box-

Entrance loss,

$$p = \frac{K_c\, u^2 \rho}{2(144)\, g_c}$$

$$= \frac{(0.3)(1.464\ V)^2(62.0)}{2(144)(32.2)} = 0.00430\ V^2$$

Friction in 2.250" I. D. pipe,

$$Re = \frac{D_e u \rho}{\mu}$$

$$= \frac{(2.25/12)(1.464\ V)(62.0)}{(0.000484)} = 3.52 \times 10^4\ V$$

$$\Delta p = \frac{2f\ u^2 \rho\ L}{144\ D\ g_c}$$

$$= \frac{2f\ (1.464\ V)^2 (62.0)(7/12)}{(2.250/12)(32.2)(144)} = 0.1783\ V^2\ f$$

V	f	p
1	0.0060	0.00107
5	0.0045	0.0200
10	0.0036	0.0642
20	0.0033	0.235
30	0.0030	0.481

V was plotted against Δp on log-log graph paper, and the resulting straight line was found to be of the form

$$\Delta p = 0.00104\ V^{1.79}$$

Friction in 5.50" long expander,

$$\Delta p = \frac{K_e(u_H - u_L)^2}{2\ g_c\ (144)}$$

$$\Delta p = \frac{(0.15)(1.464\ V - 1.074\ V)^2\ (62.0)}{2(32.2)(144)} = 0.000153\ V^2$$

Expansion from round section:

$$\Delta p = \frac{(u_H - u_L)^2 \rho}{2\ g_c\ (144)}$$

$$= \frac{(1.074\ V - 0.701\ V)^2\ (62.0)}{2\ (32.2)(144)} \text{ -----------} 0.00093\ V^2$$

Total head loss, upper box ---------------- $0.00538\ V^2 + 0.00104\ V^{1.79}$

Velocity head change

$$\Delta p = \frac{(u_H - u_L^2) \rho}{2\ g_c\ (144)}$$

$$= \frac{\left[(0.701\ V)^2 - (0.117\ V)^2\right] \left[62.0\right]}{2(32.2)(144)} \text{ ------ } 0.00319\ V^2$$

Net pressure loss, upper end box ------------- $0.00857\ V^2 + 0.00104\ V^{179}$

In Fuel Plate Section-

Entrance loss,

$$\Delta p = \frac{K\ u^2\ \rho}{2\ g_c\ (144)}$$

$$\Delta p = \frac{(0.5)(V)^2(62.0)}{2(32.2)(144)} \text{ ----------------- } 0.00334\ V^2$$

Friction in plates,

$$Re = \frac{D\,u\,\rho}{\mu}$$

$$= \frac{(0.235)(V)(62.0)}{(12)(0.000484)} = 2.509 \times 10^3\ V$$

$$p = \frac{2f\ u^2 \rho\ L}{g_c\ D\ (144)}$$

$$= \frac{2f\ V^2\ (62.0)(2.052)(12)}{(32.2)(0.235)(144)} = 2.802\ f\ V^2$$

V	f	Δp
1	0.0100	0.0280
5	0.0075	0.525
10	0.0064	1.793
20	0.0055	6.164
30	0.0051	12.861

Again this relationship is found to be Δp = -------------- $0.0291\ V^{1.79}$

Exit Loss,

$$\Delta p = \frac{(u_H - u_L)^2 \rho}{2\ g_c (144)}$$

$$\Delta p = \frac{(V - 0.701\ V)^2 (62.0)}{2\ (32.2)\ (144)}$$ --------------- $0.000598\ V^2$

Total head loss, fuel plates ---------- $0.00394\ V^2 + 0.0291\ V^{1.79}$

Velocity head ------------------------ 0

Net pressure loss, fuel plates -------------- $0.00394\ V^2 + 0.0291\ V^{1.79}$

In lower end box-

Sudden contraction,

$$\Delta p = \frac{K\, u^2 \rho}{2\, g_c (144)}$$

$$= \frac{(0.20)(0.701\ V)^2\ (62.0)}{2(32.2)\ (144)} \text{ --------------- } 0.000657\ V^2$$

Neglect gradual contraction.

Friction Drop, taking same Re as in upper end box.

$$\Delta p = \frac{2f\ u^2 \rho L}{g_c\ D(144)}$$

$$= \frac{2f\ V^2\ (1.464)^2 (62.0)(12.5)(12)}{(2.25)(32.2)(144)(12)} = 0.318\ V^2\ f$$

V	f	p
1	0.0060	0.00191
5	0.0045	0.0357
10	0.0036	0.1147
20	0.0033	0.420
30	0.0030	0.859

This is found to be $\Delta p =$ ---------------------- $0.00186\ V^{1.79}$

Exit loss,

$$\Delta p = \frac{(u_H - u_L)^2 \rho}{2\ g_c (144)}$$

$$= \frac{(1.464\ V - 0.117\ V)^2 (62.0)}{2(32.2)(144)} \text{ ----------- } 0.01213\ V^2$$

Total head loss, lower end box --------- $0.01279\ V^2 + 0.00186\ V^{1.79}$

Velocity head (negative of upper) ---------- $-\ 0.00319\ V^2$

Net pressure loss, lower end box ------- $0.0096\ V^2 + 0.00186\ V^{1.79}$

Summary of pressure losses:

In upper end box ---------------	$0.00857\ V^2 + 0.00104\ V^{1.79}$
In fuel plates -----------------	$0.00394\ V^2 + 0.0291\ V^{1.79}$
In lower end box ---------------	$0.00960\ V^2 + 0.00186\ V^{1.79}$
Total ---------------	$0.02211\ V^2 + 0.0320\ V^{1.79}$

APPENDIX II

CALCULATION OF MAXIMUM SURFACE TEMPERATURE

For a maximum heat flux of 6×10^5 Btu/ft^2-hr, the total heat transferred from a foot-wide strip of fuel plate is

$$H = 3.241 \times 10^{-4} Q_o L$$
$$= (3.241 \times 10^{-4})(6 \times 10^5)(2.781)$$
$$= 540.7 \text{ Btu/ft-sec}$$

For a heat capacity of 1.00 Btu/#^oF, the rise in the temperature of water in flowing past the fuel plate is

$$\Delta T = H/G.C_p$$
$$= 540.7/G$$

G is the mass flow rate of water past a foot-wide strip of plate. This value may be related to the mass flow, G', per square foot of flow area by:

for gap width of 0.1177" = 0.009808'

$$G' = G/0.009808 = 102.0\ G$$

The average bulk water temperature, t, is found

$$t = \frac{T_{w_1} + (T_{w_1} + \Delta T)}{2}$$

The inlet water temperature is 100^oF. The film heat transfer coefficient, h is found by

$$h = 5.6\ (1 + 0.011\ t)(G')^{0.8}/D^{0.2}$$

The following quantities may now be tabulated:

G (#/ft-sec)	ΔT (^oF)	G (#/ft^2-sec)	t (^oF)	h (Btu/hr-ft^2-^oF)
6	90.1	612.0	145	3788
8	67.6	816.0	134	4531
10	54.1	1020.0	127	5261
12	45.1	1224.0	123	5961
14	38.6	1428.	119	6633
16	33.8	1632.	117	7301
18	30.0	1836	115	7948
20	27.0	2040	114	8566
22	24.6	2244	112	9206

The point of maximum surface temperature is now investigated. The values are determined for

$$\tan \frac{\pi x}{L} = - \frac{2033\ G}{h}$$

G (#/ft-sec)	Tan $\frac{\pi x}{L}$	Sin $\frac{\pi x}{L}$	Cos $\frac{\pi x}{L}$
6	-3.2202	0.9550	-0.2966
8	-3.5895	0.9633	-0.2684
10	-3.8643	0.9681	-0.2505
12	-4.0933	0.9714	-0.2373
14	-4.2907	0.9739	-0.2270
16	-4.4556	0.9757	-0.2190
18	-4.6037	0.9772	-0.2123
20	-4.7467	0.9785	-0.2061
22	-4.8588	0.9795	-0.2016

Now the maximum surface temperature may be found from

$$T_m = T_{w1} + \frac{2Q_o\ L}{3600\ G\ C_p\ \pi} \left(0.9165 - \cos \frac{x\pi}{L}\right) + \frac{Q_o}{h} \sin \frac{\pi x}{L}$$

$$= 100 + 6 \times 10^5 \left[\frac{(0.9165) - \cos \frac{\pi x}{L})}{2033.4\ G} + \frac{1}{h} \sin \frac{\pi x}{L} \right]$$

The inner velocity can be found from the mass flow rate and density (reciprocal of specific volumes)

$$V = \frac{G'}{\rho} = 102.0\ G\ S$$

These are found to be

G (#/ft-sec)	T_m (°F)	S (ft^3/#)	V (ft/sec)
6	311	0.01632	10.0
8	271	0.01626	13.3
10	245	0.01623	16.6
12	226	0.01622	19.9
14	212	0.01620	23.1
16	201	0.01619	26.4
18	192	0.01618	29.7
20	185	0.01618	33.0
22	179	0.01618	36.3

☆ U. S. GOVERNMENT PRINTING OFFICE: 1956 O—372826