UNCLASSIFIED

OAK RIDGE NATIONAL LABORATORY
Operated By
CARBIDE AND CARBON CHEMICALS COMPANY

ORNL

POST OFFICE BOX P
OAK RIDGE, TENNESSEE

ORNL
CENTRAL FILES NUMBER

CF-54-11-1

DATE: November 1, 1954

SUBJECT: HRT Recombiner Condenser Design

TO: Distribution

FROM: R. E. Aven

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

Price \$ 0.40

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

UNCLASSIFIED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Summary

According to the present HRT design, it is expected that the CuSO_4 catalyst will bear the major gas recombination load when the reactor is operating at full power of 5 Mw (300°C and 2000 psia). This catalyst probably will be ineffective at lower temperatures. Since the reactor may operate with as much as 1.0 Mw of power at the lower temperatures, the low pressure system should be designed to handle the decomposition gases given off at these conditions. The original designs combined the condensing and recombining operations into one unit; however, the design presented here has separate units, one for recombination and one for condensation. (See drawings No. E-18228 and No. E-18226). Design basis for the recombiner-condenser units is:

Core power level	= 1200 kw (20 % factor of safety)
D_2 gas released in core	= 0.026 lb mols/min.
O_2 gas released in core	= 0.013 lb mols/min.
D_2O diluent added from D_2O evaporator	= 0.442 lb mols/min. (1 gpm evaporator rate)

The combustible gas mixture entering the recombiner is diluted well below the explosive limit. It is then passed through the catalyst bed which is packed with platinized alumina pellets, on which the D_2 and O_2 react. The temperature of the D_2O vapors leaving the recombiner is about 400°C . These vapors enter the condenser unit where the superheat is removed and the vapors condensed and cooled. These units are also used during a dumping operation to remove heat from the dumped fuel and blanket solutions. The actual times involved in this cooling operation depend on the rate at which the materials are allowed to dump. Estimates, however, are about 6 minutes for the core system with a 60 psia maximum pressure rise and for the blanket system, about 12 minutes with a 140 psia maximum pressure rise in the dump tanks.

UNCLASSIFIED

DECLASSIFIED

Introduction

At design conditions the decomposition gases constitute 8.1 mol percent of the gas mixture entering the recombiner. Assuming 100 percent recombination of the D_2 and O_2 , there is a $306^{\circ}C$ temperature rise across the recombiner. Under normal conditions the gas mixture enters the recombiner at $100^{\circ}C$; and, consequently, the exit temperature will be $406^{\circ}C$ ($763^{\circ}F$). The recombiner bed is $11\frac{1}{2}$ inches long (8 inches of the basket container is perforated) and $2\frac{1}{2}$ inches thick and is in the form of a cylindrical annulus with an inside diameter of 4 inches and an outside diameter of $9\frac{1}{2}$ inches. It is packed with $\frac{1}{8}$ " x $\frac{1}{8}$ " cylindrical pellets of 0.3 percent platinized alumina. The pressure drop across the recombiner bed is 0.2 psi for normal operation.

A reasonable design for the condensing unit has 62 U-tubes ($\frac{1}{2}$ inch-BWG 18) with an average effective length of about 13 feet. This gives an outside effective heat transfer surface of approximately 112 ft^2 . The tubes are housed in a 347 stainless steel shell of 12" inside diameter with 0.375" thick wall. The D_2O vapor is cooled and condensed on the shell side with the cooling water being sent through the tubes. The total cooling load for normal conditions is 740,000 Btu/hr which includes:

1. Cooling of the superheated gases (160,000 Btu/hr)
2. Condensation of the D_2O vapor (545,000 Btu/hr)
3. Cooling the condensate to $150^{\circ}F$ (35,000 Btu/hr)

About 55 percent of the cooling surface is employed in cooling the superheated gases to $100^{\circ}C$, the remainder being used to condense the vapors and cool the condensate.

During a dump of the fuel solution the recombiner condenser will be used to recombine decomposition gases which are normally dissolved in the

DECLASSIFIED

fuel solution and condense the vapors formed from the core material. About $1/3$ of the liquid D_2O in the fuel solution flashes to vapor during a dump. It is necessary to remove about 340,000 Btu from the core solution during a dumping operation to cool the material to liquid at $212^{\circ}F$ and atmospheric pressure. It is desirable to do this as fast as possible. Should all the material be dumped into the dump tanks instantaneously, the time required is 3 to 4 minutes. See Figure 2 for a plot of pressure versus time for an instantaneous dump. The actual time required to move the liquid from the core into the dump tanks will depend on the size of the dump line. For a $1/2$ inch schedule 80, dump line, the dumping time is approximately five minutes. As shown by Figure 2 the actual time required to cool the core solution to $212^{\circ}F$ and one atmosphere is about six minutes. The maximum pressure expected in the core low pressure system during an uncontrolled dump is about 60 psi.

The blanket system will have similar sized units for recombination and condensation. For a 1-inch schedule 80 blanket dump line, the time required to empty the high pressure blanket vessel is about 8 minutes. During a dump the cooling load on the condenser will be about 1,200,000 Btu. As shown by Figure 3 the time required to remove this amount of heat is about 12 minutes. The maximum pressure expected in the blanket low pressure system during an uncontrolled dump is about 140 psia.

When the condensate drain line is full to the condenser level, there will be a vertical head of liquid 12 feet above the check valve. This is equivalent to a pressure of 5.5 psi tending to open the check valve. During normal operation the total pressure drop across the entrainment separator, the recombiner, the condenser, and connecting piping and fittings is about $1/2$ psi and therefore flooding of the condenser does not appear to be a

problem. However, during a dumping operation the pressure drop across these items is of the order of 7-1/2 to 8-1/2 psi over the operating pressure range of 15 psia to 200 psia. This pressure tends to close the check valve preventing the return of condensate to the dump tanks. Hence, flooding of the condenser during a dumping operation, may be a considerable factor.

Recombiner Unit

Experimental data of Gaven, et al, [1] were used as a design basis for the recombiner. Most of the decomposition gases will be recombined in the core; however, a small amount of these gases are needed for such purposes as stripping out gaseous fission products. The gas mixture flowing to the recombiner at the design point is 0.48 lb mols/min. If a space velocity of $420,000 \text{ hr}^{-1}$ is assumed for 100 percent conversion, then the volume of catalyst required is

$$V_{\text{cat}} = 0.025 \text{ ft}^3$$

The volume of catalyst pellets in the recommended design is

$$V_{\text{act}} = 0.353 \text{ ft}^3$$

This is several times as much catalyst as the calculations indicate is needed. However, the bed thickness should be great enough to prevent channels from occurring through which the gas may pass without reacting. A thickness of 2-1/2 inches should be sufficient to insure good contact between the gas mixture and catalyst pellets. Also the pressure drop across the bed is a considerable factor since this is one of the major flow resistances in the low pressure system. These considerations, along with the realization that conditions in the HRT may not be the same as the conditions under which Gaven's group carried out experiments on hydrogen and oxygen recombination, led to the present design which has the large volume factor of safety.

DECLASSIFIED

The cylindrical annular type of bed was chosen because this geometrical form appears to have a lower pressure drop than beds with other geometrical shapes. To predict the pressure drop across the recombiner bed the following equation was used [2]

$$\Delta P = \frac{2.36 \mu^{0.15} L \rho^{0.85} V_o^{1.85} A_f}{D_p^{1.15}} \quad (1)$$

where ΔP = pressure drop, psf
 L = thickness of bed, ft
 μ = viscosity (0.919×10^{-5} lb/sec ft at 212°F or 1.69×10^{-5} lb/ft sec at 763°F)
 A_f = dimensionless wall factor ≈ 1.0 , [2]
 D_p = diameter of pellets = 0.01042 ft
 ρ = density (0.04146 lb/ft³ at 212°F or 0.02244 lb/ft³ at 763°F)
 V_o = superficial velocity of gas through bed, ft/sec.

Equation (1) may be written in a more convenient form for an annular type bed:

$$\frac{dP}{dr} = \frac{2.36 \mu^{0.15} \rho^{0.85} V_o^{1.85} A_f}{144 D_p^{1.15}} \quad (1a)$$

where $\frac{dP}{dr}$ = pressure drop, psi/ft
 r = radius of bed, ft

Under normal conditions the gas flow rate through the recombiner is 0.48 lb mols/min or 560 lb/hr. The physical properties are based on the physical properties of D_2O vapor as this is the case for the major part of the bed. Then solving equation (1a) for the cylindrical annular bed at normal conditions with gas leaving at 763°F :

$$\left(\frac{dP}{dr}\right)_{763^\circ\text{F}} = \frac{0.0609}{r^{1.85}}, \text{ psi/ft}$$

DECU... ..

And for conditions when only the vapor from the D_2O evaporator is flowing through the bed:

$$\left(\frac{dP}{dr} \right)_{212^{\circ}F} = \frac{0.03005}{r^{1.85}}, \text{ psi/ft}$$

Catalyst Bed for Recombiner

For the present design:

$$(\Delta P)_{763^{\circ}F} = 0.17 \text{ psi}$$

$$(\Delta P)_{212^{\circ}F} = 0.08 \text{ psi}$$

During a dump the pressure drop across the recombiner may be computed in terms of the velocity, v , through the gas inlet line and the density, ρ , of the D_2O vapor. The viscosity also varies with temperature and pressure, but not nearly so much as the density, and for these calculations the viscosity is assumed to be that of D_2O vapor at $212^{\circ}F$. The velocity, V_o ,

~~SECRET~~

DECLASSIFIED

~~SECRET~~

-8-

through the bed may be written in terms of the velocity, v , in the gas inlet pipe (3" Sch. 40).

$$V_o = \frac{0.0513 v}{2\pi r (8/12)} = \frac{0.01225 v}{r}$$

Substituting in (1a)

$$\frac{dP}{dr} = \frac{0.000159 \rho^{0.85} v^{1.85}}{r^{1.85}}$$

or

$$(\Delta P)_{\text{dump}} = 0.000446 \rho^{0.85} v^{1.85}, \text{ psi}$$

Pressure drop calculations were made on other geometrical basket forms to get a comparison on the basis of pressure drop. Some of the results are shown in Table I. Table I is calculated for equal thicknesses of pellet bed but not necessarily equal volumes of catalyst.

Table I

Comparison of Pressure Drop Across Different Basket Types

	<u>Disk</u>	<u>Spherical Annulus</u>	<u>Cylindrical Annulus</u>
$(\Delta P)_{212^\circ\text{F}}, \text{ psi}$	0.3	0.4	0.1
$(\Delta P)_{763^\circ\text{F}}, \text{ psi}$	0.6	0.9	0.2
$(\Delta P)_{\text{dump}}, \text{ psi}$	$0.0015 \rho^{0.85} v^{1.85}$	$0.002 \rho^{0.85} v^{1.85}$	$0.000446 \rho^{0.85} v^{1.85}$

Some question may arise concerning the temperatures which may be encountered in the recombiner bed. The pellets may be used at temperatures as high as 1200°C without loss of platinum and so no difficulty is expected here. Under normal design conditions the temperature of the gas mixture will not get higher than 406°C (763°F). With the maximum output of D₂O vapor from the 1 gpm D₂O evaporator about twice as much D₂ and O₂ gas can be recombined per minute without exceeding the explosive limits of the gas mixture. However,

~~SECRET~~

DECLASSIFIED

in this case, the temperature of the D_2O vapor leaving the recombiner is about $700^{\circ}C$ ($1290^{\circ}F$). The temperature rise in the gas stream across the recombiner is given by

$$\Delta t = \frac{N_{D_2} \Delta H}{W C_p} \quad (2)$$

where Δt = temperature rise, $^{\circ}F$
 ΔH = heat of recombination of D_2 and O_2 =
 $105,000 \text{ Btu/lb mol}$ [3]
 N_{D_2} = No. of lb-mols of D_2 per hour
 W = weight rate of flow, lb/hr
 C_p = heat capacity, Btu/lb $^{\circ}F$

Solving for (Δt) for design conditions

$$\Delta t = 551^{\circ}F$$

An estimate of the temperature profile of the catalyst pellets and gas passing through the recombiner is shown in Fig. 6. The estimated maximum pellet temperature is $870^{\circ}F$ and occurs about 0.2" inside the bed. See Appendix IV for the method of estimation of temperature profile.

A necessary condition that the catalyst function properly is that it must be dry. To insure that at least some of the pellets will be dry, a steam heater coil is placed in the bed. The reaction on the dry pellets around the steam coil will quickly dry the remaining pellets of the bed under start-up conditions.

The original design thinking was to place the recombiner basket inside the condenser shell, i.e., to have both recombining and condensing operations in one unit. This is desirable as it would eliminate some flanges and make the construction simpler and more compact. However, in the present horizontal condenser design, there was the possibility of condensate forming on the shell of the unit directly above the basket. This condensate could drip back into the catalyst bed, possibly keeping the pellets wet and destroying their catalytic activity. The condenser unit could not be placed

in a vertical position, because of cell limitations. Therefore, in order to prevent flooding of the catalyst, the recombiner and condenser are designed as separate units.

Condenser Unit

In calculating the surface area needed for desuperheating and condensing the D₂O vapors from the recombiner, the condenser was divided into two sections, a desuperheating section and a condensing section. The overall coefficient of heat transfer and the mean temperature difference based on 80 gpm of cooling water entering the condenser at 100°F are the following:

For desuperheating:

$$U = 9.0 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$
$$(\Delta t)_m = 300 \text{ } ^\circ\text{F}$$

For condensing:

$$U = 340 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$
$$(\Delta t)_m = 97 \text{ } ^\circ\text{F}$$

The calculations involved above are given in Appendix I. For normal conditions the area needed to desuperheat the vapor from the recombiner is

$$A_d = \frac{q}{U(\Delta t)_m} = \frac{160,000}{(9.0)(300)} = 61 \text{ ft}^2$$

and for the condensing section

$$A_c = \frac{545,000}{(340)(97)} = 16.5 \text{ ft}^2$$

The total area needed to cool and condense the D₂O vapor is 77-1/2 ft². It is desirable to subcool the condensate and the 112 ft² of effective surface area in the recommended design should provide sufficient cooling to the condensate.

~~SECRET~~

DECLASSIFIED

A cooling water flow rate of 80 gpm has been assumed and for this flow rate the pressure drop on the tube side is approximately 0.8 psi. During a dump the flow of cooling water may be increased to 150 gpm (particularly the blanket condenser). Since, at this time, the condenser is no longer desuperheating the vapor but condensing only, the capacity is greatly increased and this makes a larger flow rate of cooling water desirable. The pressure drop across the tubes for 150 gpm flow rate is about 2.4 psi, with a velocity in the tubes ~ 6 ft/sec.

The vapor is being condensed on the shell side mainly because this arrangement gives a better overall heat transfer coefficient ($U = 340$ Btu/hr ft² °F as compared to $U = 244$ Btu/hr ft² °F for D₂O condensing inside the tubes). Also, the present construction minimizes thermal stress problems. The pressure drop across the shell side of the condenser is fairly small. It was estimated using equations and charts in Kern [4]. The pressure drop across the shell side including entrance and exit losses and flow around baffles on 12" spacing, is ≤ 0.03 psi.

There may be a question as to whether the cooling water might boil at any point in the system. The outside tube wall temperature, t_w , may be determined from

$$U (t_g - t_c) = h_o (t_g - t_w) \quad (3)$$

where t_g = temperature of gas (At hottest point = 763°F)
 t_c = temperatures of cooling water at corresponding point (= 119°F)
 h_o = outside heat transfer coefficient = 10.7 Btu/hr ft² °F

Solving for t_w

$$t_w = 137^\circ \text{F}$$

~~SECRET~~

DECLASSIFIED

Therefore, there is little danger of the cooling water boiling during normal operation.

Condenser Performance During Dump

It is planned to utilize the core and blanket low pressure condensers to cool and condense the flashing D_2O solutions during a dumping operation. The advantages to using this method of removing heat at dump times are the following:

1. Since the condensers are needed for normal operation anyway, they may as well be utilized on a dump.
2. The release of dissolved D_2 and O_2 will cause little or no trouble as it will be well diluted by vapor from the flashing D_2O .
3. Even if dump line coolers are used, the condensers will be necessary during the dump to remove the heat of recombination of D_2 and O_2 dissolved in the solution.
4. There is no extra solution holdup required in the high pressure system.
5. All cooling and condensing take place at relatively low pressure.

The problem now is to determine the performance of the condensers at dump time. The quantities involved in the two systems are listed below:

	<u>Core System</u>	<u>Blanket System</u>
Volume of high pressure system, liters	480	1740
Volume of low pressure system, liters	1000(35.32 ft ³)	3000 (106 ft ³)
Average temperature before dump, °C	280 (536 °F)	280 (536 °F)
Weight of D_2O involved, lbs.	900	3220
Initial enthalpy of liquid [5] , Btu/lb	531.4	531.4
Total heat to be removed, Btu	340,000	1,200,000

If constant enthalpy is assumed for the systems during a dump then the fraction of liquid D₂O flashing to vapor may be found by trial and error from the equations

$$H_1 = h_{f2} + x h_{fg} \quad (4)$$

$$V_1 = v_{f2} + x v_{fg} \quad (5)$$

where h = enthalpy, Btu/lb

v = specific volume, ft³/lb

x = fraction of vapor

H = enthalpy of total mass of D₂O in system, Btu/lb

V = specific volume of total mass of D₂O in system, ft³/lb

Subscripts f = refers to properties of saturated liquid

1 = refers to initial conditions before dump

2 = refers to final conditions after dump

fg = refers to change by evaporation

Then if no cooling or condensation takes place the equilibrium condition after a dump will be:

	<u>Core System</u>	<u>Blanket System</u>
Pressure, psia	690	690
Temperature, °F	500	500
Vapor fraction	0.06	0.06

Should the solution be dumped instantaneously the initial conditions will be those listed above. Then as heat is removed from the system by condensation occurring in the condenser, the pressure of the gas is lowered and as a result the temperature is lowered. The pressure drop in the condenser is negligible and therefore the pressure and condensing temperature is constant with respect to the distance into the condenser. It is, however, a variable with respect

~~SECRET~~

DECLASSIFIED

to time during the dumping operation. If cooling water is available at 100°F and if it is allowed to rise to the boiling point (212°F) in the condenser, then the log mean temperature difference between the condensing steam and the cooling water may be computed as a function of pressure in the condenser. Since the blanket condenser handles several times as much condensate as the core condenser, the cooling water flow rate to the blanket condenser will be assumed 150 gpm instead of 80 gpm during a dump. Assuming that about 15 minutes will be required to remove the heat from the blanket solution, the average temperature rise of the cooling water is about 66°F. The log mean temperature difference, $(\Delta t)_m$, is given by

$$(\Delta t)_m = \frac{(\tau - t_1) - (\tau - t_2)}{\ln \frac{\tau - t_1}{\tau - t_2}} \quad (6)$$

where τ = condensing temperature of D₂O vapor, °F
 t_1 = temperature of cooling water into condenser, °F
 t_2 = temperature of cooling water from condenser, °F

Table II shows the variation of the log mean temperature difference with pressure and fraction of heat removed (See Figure 1). The values of $(\Delta t)_m$ computed for 150 gpm cooling water flow are based upon an average temperature rise of 66°F. This corresponds to an average heat flow rate of 4,900,000 Btu/hr or a $(\Delta t)_m$ of about 130°F. This $(\Delta t)_m$ occurs at a pressure of 40 psia. When the pressure is higher than this value the heat flow rate will be greater and consequently the temperature rise in the cooling water will be greater than 66°F. Hence the value of $(\Delta t)_m$ will be slightly smaller than that shown in Table II for 150 gpm, by an amount dependent upon the heat removal rate. Similarly for pressures less than 40 psia the values

~~SECRET~~

DECLASSIFIED

of $(\Delta t)_m$ will be slightly larger than the values given in Table II. In either case the correction is difficult to make and since its effect is small as compared to other uncertainties in the system, the deviation from the average values will be neglected.

TABLE II

Variation of Temperature Driving Force with Pressure

Pressure psi	Condensing Temperature °F	Fraction of heat removed	$\xleftarrow{\quad} \textcircled{(\Delta t)_m} \xrightarrow{\quad}$	
			$t_1=100^\circ\text{F}, t_2=212^\circ\text{F}$ (80 gpm coolant)	$t_1=100^\circ\text{F}, t_2=166^\circ\text{F}$ (150 gpm coolant)
690	500	0	342	367
600	486	0.073	328	353
500	467	0.151	308	333
400	445	0.238	285	311
300	417	0.339	257	283
200	382	0.465	221	247
100	328	0.645	166	193
80	312	0.696	149	177
60	293	0.758	129	158
40	267	0.833	101	131
20	228	0.953	53.7	91
15	213	0.997	50	75
14.7	212	1.000	50	74

The heat transfer equation may be written

$$q = - \frac{dQ}{d\theta} = U A (\Delta t)_m \quad (7)$$

where $-\frac{dQ}{d\theta}$ = rate of heat removal, Btu/hr.

The fraction of heat removed may be represented as

$$f = \frac{Q_o - Q}{Q_o - Q_1} \quad (8)$$

where subscripts "o" = refer to initial heat content.

"1" = refer to final heat content.

DECLASSIFIED

SECRET

Differentiating

$$df = \frac{1}{Q_0 - Q_1} (-dQ)$$

$$-dQ = (Q_0 - Q_1) df \quad (9)$$

Substituting equation (9) in equation (7)

$$(Q_0 - Q_1) \frac{df}{d\theta} = UA (\Delta t)_m \quad (10)$$

Solving for the time θ

$$\theta = \frac{Q_0 - Q_1}{UA} \int_0^f \frac{df}{(\Delta t)_m} \quad (11)$$

The value of the above integral is found by plotting $\frac{1}{(\Delta t)_m}$ versus f and integrating graphically. If the blanket solution is dumped instantaneously to the low pressure system, then a pressure versus time plot may be computed (using equation (11)) as the condenser reduces the heat content in the dumped solution. The time required for the condensers to reduce the dump tank temperature to 212°F and the pressure to atmospheric is approximately 4 minutes for the core system and 9-1/2 minutes for the blanket system. These represent the minimum times required to cool and condense the core and blanket solutions to atmospheric conditions, by this particular design (See Figures 2 and 3).

It will take some time, however, to dump the solution from the core and blanket to the respective dump tanks. This will change the pressure versus time curve considerably and will increase the time required to remove the heat from the dumped solution. Estimates of the times required to remove the solutions from the core and blanket into the low pressure systems were made from pressure versus weight and pressure versus time curves prepared by

~~SECRET~~

DECLASSIFIED

R. Van Winkle (See Figures 4 and 5). For an unthrottled dump about five minutes are required to empty the core through a 1/2" schedule 80 dump line, and about eight minutes to empty the blanket through a 1" schedule 80 dump line. Under these conditions the total times involved for the removal of heat is approximately six minutes for the core system and twelve minutes for the blanket system. The maximum pressure attained in the core dump tank is about 60 psia and occurs about 15 seconds after the beginning of a dump, while the maximum pressure built up in the blanket dump tank is approximately 140 psia and occurs about a minute after the dumping operation starts. See Appendix III for the method used in determining the pressure versus time plots of Figures 2 and 3.

Flooding During a Dumping Operation

The above figures were calculated assuming no flooding takes place in the condensers. Flooding may be a factor to consider during a dumping operation, since a relatively large pressure drop occurs between the dump tank and condenser at this time. This pressure difference tends to hold the check valve in the condensate drain closed. Then as soon as the condensate drain line is filled the condenser will begin to flood. When the condensate line is full the liquid leg above the check valve is about 12 ft high. This corresponds to a pressure of about 5.5 psi, tending to open the valve. When the pressure drop between the dump tank and condenser is greater than 5.5 psi, the check valve will be closed and the condenser will flood. The pressure drop is proportional to the flow rate between the dump tank and condenser. The flow rate depends on the capacity of the condenser, which is reduced when flooding occurs. When a sufficient number of condenser tubes are covered with water the flow rate falls to the point where the pressure drop is 5.5 psi or less

~~SECRET~~

DECLASSIFIED

and the check valve opens, returning condensate to the dump tank.

To estimate the pressure drop the items involved are the entrainment separator, the piping, the recombiner basket and the condenser tubes. Pressure drop across the entrainment separator was estimated from C. L. Segaser's report [6]. The pressure drop across the piping and recombiner basket is given by

$$(\Delta P)_{r+p} = \frac{G^2}{\rho} \left[\frac{0.000446}{G^{0.15}} + 0.000646 \right] \quad (12)$$

where G = mass flow rate, lb/sec, ft²

ΔP = pressure drop, psi

ρ = density of gas, lb/ft³

The pressure drop across the condenser is small and is neglected. Table III gives the pressure drop in the system as a function of condenser pressure and capacity (assuming full capacity at 150 gpm cooling water flow rate).

TABLE III

Pressure Drop in Low Pressure Core and Blanket Systems

Condenser Pressure P_c , psia	$q = UA(\Delta t)_m$ q , Btu/hr	Condensing rate $w = q/h_{fg}$ w = lb/hr	Pressure Drop, psi			
			Entrainment Separator $(\Delta P)_s$	Connecting Piping $(\Delta P)_p$	Recombiner Basket $(\Delta P)_r$	Total $(\Delta P)_{s+p+r}$
20	3,444,000	3590	1.06	4.41	1.96	7.43
40	4,919,000	5270	1.11	4.97	2.00	8.08
50	5,525,000	5980	1.13	5.19	2.13	8.45
70	6,357,000	7000	1.12	5.18	2.08	8.38
90	7,039,000	7870	1.10	5.17	2.03	8.30
100	7,341,000	8260	1.08	5.15	2.01	8.24
150	8,439,000	9770	0.99	4.91	1.86	7.76
180	9,006,000	10590	0.98	4.84	1.82	7.64
200	9,347,000	11090	0.95	4.79	1.79	7.53

As can be seen from Table III the pressure drop in the piping is the largest contributor to the total. If flooding is considered a real problem during a

DECLASSIFIED

~~SECRET~~

dump, then the pipe size may be increased to reduce the total pressure to the point where flooding is no longer a factor. See Appendix II for the method of calculating the pressure drop.

The maximum pressure drop would be expected at a pressure of 50 psia and would be 8.5 psi if the full capacity of the condenser were realized. This will be the case if sufficient holdup is provided in the condensate drain line. However, if the drain line is filled and the condenser floods, then the capacity will be reduced to a point where the flow rate will give a 5.5 psi pressure drop across the piping, entrainment separator, and re-combiner. This occurs at a mass flow rate of 26 lb/sec ft² and corresponds to a condenser capacity of 4,440,000 Btu/hr. The surface area being utilized at this time is given by

$$A = \frac{q}{U(\Delta t)_m}$$

where $q = 4,440,000 \text{ Btu/hr}$

$(\Delta t)_m \text{ at } 50 \text{ psia} = 146^\circ\text{F}$

$U = 340 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$

Solving for A

$$A = 90 \text{ ft}^2$$

This means that (112 - 90) or 22 ft² or 20 percent of the surface area has been flooded out. This will represent the lower 26 tubes in the condenser and since this is the worst flooding expected, indicates the maximum depth to which the condenser will be filled is about 2.7 inches. At this time the condenser shell will be holding about one cubic foot or 29 liters of condensate. When the condenser reaches this stage of flooding the pressure drop will be reduced to such a point that the check valve opens allowing condensate to drain back into the dump tanks. If this maximum rate of flooding occurs throughout

DECLASSIFIED

SECRET

the dumping operation, the time necessary to remove the heat from the dumped solutions will be increased by the ratio $\frac{A_{\text{actual}}}{A_{\text{effective}}}$. Under these conditions then the times expected are 7-1/2 minutes for the core solution and 15 minutes for the blanket solution.

Steam Blanketing of Tubes During Dump

Steam blanketing of the cooling water or tube side may be a problem to consider. As the pressure of the low pressure system increases during a dumping operation the condensing temperature increases causing a large temperature driving force across the condenser. From equation (3) the inside wall temperature of the tubes may be estimated as

$$t_w = \tau - \frac{U \left(\frac{D_o}{D_i} \right)}{h_i} (\tau - t_c)$$

$$= \tau - 0.423 (\tau - t_c)$$

Table IV lists some wall temperatures that may be expected at various condenser pressures.

TABLE IV

Inside Wall Temperatures at Various Condenser Pressures

Condenser Pressure P_c , psia	Condensing Temperature τ , °F	Wall Temperature, t_w , °F	
		At entrance ($t_c = 100$ F)	At exit ($t_c = 166$ °F)
20	228	174	202
50	281	204	232
70	303	217	245
80	312	222	250
100	328	232	260
140	353	246	274
150	358	249	277
200	382	263	291

As indicated by the above table there may be some boiling in the tubes during a dump. The boiling temperature will depend on the water pressure

DECLASSIFIED

SECRET

in the tubes. For water pressures above 20 psia there should be essentially no steam binding and for water pressures above 50 psia there should be little or no boiling.

Cooling Jackets for Dump Lines

Part of the heat content of the solutions can be removed by jacketing the dump lines and sending cooling water through the jackets. The problem here is to determine what fraction of the heat can be removed by this device. The temperature of the solution after it passes through the jacketed portion of the dump line is given by

$$\frac{t_1 - T_1}{t_2 - T_2} = \frac{e^{\left(1 - \frac{wC_p}{w'C_p'}\right) \frac{U_j A}{wC_p} - \frac{wC_p}{w'C_p'}}}{1 - \frac{wC_p}{w'C_p'}} \quad (13)$$

where t_1 = inlet temperature of cooling water = 100°F
 T_1 = inlet temperature of reactor solution, °F
 T_2 = outlet temperature of reactor solution, °F
 w = flow of reactor solution, lb/hr
 w' = flow of cooling water, lb/hr
 C_p = heat capacity of reactor solution, Btu/lb °F
 C_p' = heat capacity of cooling water, Btu/lb °F
 A = area of heat transfer, ft²
 U_j = overall heat transfer coefficient for jacket, Btu/hr ft² °F.

If the time of dump is assumed to be 5 minutes for the core system and 8 minutes for the blanket system, the following applies:

~~SECRET~~

-22-

	<u>Core System</u>	<u>Blanket System</u>
Dump line	1/2" Sch. 80 pipe	1" Sch. 80 pipe
Jacket annulus	1" Sch. 40 pipe	1-1/2" Sch. 40 pipe
Length of jacket, ft	15	15
T_1 , °F	536	536
w' , lb/hr	9600	21000
w , lb/hr	10800	24000
C_p , Btu/lb °F	1.00	1.00
C_p , Btu/lb °F	1.13	1.225
A , ft ²	3.3	5.2
U_j , Btu/hr ft ² °F	300	300

The final temperatures and amounts of heat removed by this method are as follows:

	<u>Core System</u>	<u>Blanket System</u>
Temperature at letdown valve, °F	500	515
Heat removal rate, Btu/hr	450,000	620,000
Fraction of heat removed	0.12	0.07

~~SECRET~~

DECLASSIFIED

APPENDIX I

Calculation of the overall heat transfer coefficient

The overall heat transfer coefficient is estimated from

$$\frac{1}{U} = \frac{1}{h_i(D_i/D_o)} + \frac{1}{h_{fi}(D_i/D_o)} + \frac{1}{h_w} + \frac{1}{h_o} + \frac{1}{h_{fo}} \quad (14)$$

where h = heat transfer coefficient

Subscript "f" = refers to fouling factor

c = refers to condensation film outside tubes

o = refers to outside

i = refers to inside

w = refers to tube wall

The tube size used in the condensers is 1/2" - BWG 18 stainless steel (No. 347).

The thermal conductivity of stainless steel at the temperatures involved

is 9.3 Btu/hr ft °F. From this h_w may be estimated as

$$h_w = \frac{k}{x_w} \frac{D_{avg}}{D_o} = 2054 \text{ Btu/hr ft}^2 \text{ °F}$$

To determine the outside coefficient in the condensing section for both normal operation and dump conditions, use the equation [4]

$$h_c \left(\frac{\mu_f^2}{k_f^3 \rho_f^2 g} \right)^{1/3} = 1.51 \left(\frac{4\bar{G}''}{\mu_f} \right)^{-1/3} \quad (15)$$

where $\bar{G}'' = \frac{W}{N_t L}$ = loading factor, lb/hr lin. ft.

The temperature range for condensing D_2O may be 260°C to 100°C. The following table can now be set up to determine the value of h_c over this range.

~~SECRET~~

DECLASSIFIED

TABLE V
Outside Film Coefficient for Heat Transfer
in Condensing Section

	← Dump Conditions →				Normal Conditions
	260°C	200°C	150°C	100°C	100°C
μ , lb/hr ft	0.275	0.365	0.490	0.750	0.750
k , Btu/hr ft °F	0.346	0.382	0.396	0.394	0.394
ρ , lb/ft ³	53.63	59.31	62.99	66.11	66.11
$\left(\frac{\mu_f^2}{k_f^3 \rho_f^2 g}\right)$	1.523×10^{-12}	1.592×10^{-12}	2.337×10^{-12}	5.047×10^{-12}	5.047×10^{-12}
$\left(\frac{\mu_f^2}{k_f^3 \rho_f^2 g}\right)^{1/3}$	1.152×10^{-4}	1.168×10^{-4}	1.328×10^{-4}	1.716×10^{-4}	1.716×10^{-4}
$\bar{G}' = \frac{W}{N_t L'} \frac{\text{lb}}{\text{hr lin. ft}}$	4.41	4.41	4.41	4.41	0.72
$\left(\frac{4\bar{G}'}{\mu_f}\right)^{-1/3}$	0.2499	0.2746	0.3030	0.3490	0.6383
h_c	3275	3550	3445	3070	5600

Assume h_c is constant over entire condensing range and equal to 3000 Btu/hr ft² °F.

The outside heat transfer coefficient, h_o , for the desuperheating section was calculated using Figure 28 in Kern [4]. The flow area across the tube bundle is given by

$$a_s = \frac{(ID) C' B}{144 P_T} \tag{16}$$

- where
- a_s = flow area, ft²
 - ID = inside diameter of shell = 11 inches
 - C' = clearance between adjacent tubes = 0.25 inch
 - B = baffle spacing = 12 inches
 - P_T = tube pitch = 0.75 inch.

Solving for a_s ,

$$a_s = 0.306 \text{ ft}^2$$

The modified Reynolds number, Re_s , is given by

$$Re_s = \frac{D_e \bar{G}_s}{\mu}$$

where D_e = equivalent diameter =
$$\frac{4 \left[(1/2 P_T)(0.86 P_T) - 1/2 \pi \frac{d_o^2}{4} \right]}{6 \pi d_o} =$$

$$D_e = 0.061 \text{ ft}$$

$$d_o = \text{outside diameter of tubes} = 0.5 \text{ inch.}$$

$$\bar{G}_s = \text{mass flow rate} = \frac{w}{a_s} = 1840 \text{ lb/hr ft}^2$$

$$w = \text{flow rate} = 562 \text{ lb/hr}$$

$$\mu = \text{viscosity of gas} = 0.047 \text{ lb/hr ft at } 480^\circ\text{F (average temperature)}$$

Solving for Re_s

$$Re_s = 2400$$

From Figure 28 (Kern)

$$j_H = 26$$

$$j_H = \frac{h_o D_e}{k} \left(\frac{C_p \mu}{k} \right)^{-1/3} \left(\frac{\mu}{\mu_w} \right)^{-0.14} \quad (17)$$

where h_o = outside heat transfer coefficient

k = thermal conductivity = $0.0205 \text{ Btu/hr ft } ^\circ\text{F}$

C_p = heat capacity = $0.5 \text{ Btu/lb } ^\circ\text{F}$

$$\left(\frac{\mu}{\mu_w} \right) = 1.0 \text{ (assumed)}$$

Solving for h_o ,

$$h_o = 9.2 \text{ Btu/hr ft}^2 ^\circ\text{F}$$

~~SECRET~~

DECLASSIFIED

The inside or cooling water coefficient of heat transfer, h_i , is estimated from Figure 25 in Kern [4]. Assuming 60 - 1/2" BWG, U-tubes through which cooling water flows at a rate of 80 gpm, the average velocity of the water is 3.37 ft/sec. Then from Figure 25 (Kern)

$$h_i = 960 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

A check using the Dittus-Boelter equation [7] was also made.

$$h_i = 0.0265 \frac{k}{D} \left(\frac{DG}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.3} \quad (18)$$

Solving for h_i and using physical properties of water at 100 $^\circ$ F

$$h_i = 1000 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

The two methods check closely and a value of 1000 Btu/hr ft 2 $^\circ$ F is used for h_i . The following fouling coefficients are assumed [8]

$$h_{if} = 2000 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

$$h_{of} = 4000 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

Solving equation (14) for U

$$U_d = 9.0 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F for desuperheating section}$$

$$U_c = 340 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F for condensing section}$$

The area, A, required for this unit is calculated from

$$A = \frac{q}{U(\Delta t)_m}$$

For the desuperheating section (assuming cooling water is available at 100 $^\circ$ F)

$$(\Delta t)_m = \frac{(763-111) - (212-107)}{\ln \frac{652}{105}} = 300^\circ\text{F}$$

and

$$A_d = 60.7 \text{ ft}^2$$

DECLASSIFIED

For the condensing section

$$(\Delta t)_m = \frac{(212-111) - (212-119)}{\ln \frac{(212-111)}{(212-119)}} = 97^\circ\text{F}$$

and

$$A_c = 16.5 \text{ ft}^2$$

As given in Kern [4], the weighted value of the overall coefficient of heat transfer is

$$U_{\text{weighted}} = \frac{U_c A_c + U_d A_d}{A_c + A_d} = 140 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$$

SECRET

DECLASSIFIED

APPENDIX II

Pressure Drop in Low Pressure System

In estimating the pressure drop across the entrainment separator use was made of C. L. Segaser's report [6] in which a plot was made relating flow rate in lb/min and pressure drop in inches of D₂O at 212°F. This chart assumes, however, that all gas flowing through the separator is at atmospheric pressure. To get the pressure drop when the low pressure system is under pressure, a conversion factor must be used. The pressure drop in psi is proportional to the (velocity)² x (density), i.e.,

$$\Delta P = k v^2 \rho = k \left(\frac{w}{A \rho} \right)^2 \rho = \frac{k}{A} \frac{w^2}{\rho} \quad (19)$$

where $k = \text{constant}$

Therefore, to convert from a reading at atmospheric pressure to a reading when another pressure is involved the atmospheric reading is multiplied by the ratio of gas density at one atmosphere to the gas density at the pressure in question. To convert from a (ΔZ) taken from Figure 2 of CF-54-7-122 to the pressure ΔP in psi, use the equation

$$(\Delta P)_g = \frac{(\Delta Z) 66.11}{(12)(144)} \frac{\rho_{atm}}{\rho} = 0.0383 \frac{\rho_{atm}}{\rho}$$

where $\Delta Z = \text{reading in inches of D}_2\text{O (from CF-54-7-122)}$

$\rho = \text{gas density at pressure of low pressure system.}$

Table III gives the pressure drop across the entrainment separator for several pressures for the present condenser design.

The pressure drop across the piping in the low pressure system may be estimated from the equation:

$$\Delta P = \frac{f v^2 \rho L_{eq}}{2 g_c D} \quad (20)$$

where f = Fanning friction factor

L_{eq} = equivalent length of piping

The piping is estimated to consist of 33 ft of 3" Sch. 40 pipe with 8 elbows, 1 enlargement into recombiner, one contraction into pellet basket and one contraction into the pipe. The total equivalent length is ~ 85 ft.

Solving equation (20) for normal conditions

$$\Delta P = 0.17 \text{ psi}$$

For the pressure drop during a dumping operation use

$$(\Delta P)_p = 0.000646 \rho v^2, \text{ psi} \quad (20a)$$

For the pressure drop across piping and recombiner basket

$$(\Delta P)_{r+p} = 0.000446 \rho^{0.85} v^{1.85} + 0.000646 \rho v^2$$

or

$$(\Delta P)_{r+p} = \frac{G^2}{\rho} \left[\frac{0.000446}{G^{0.15}} + 0.000646 \right] \quad (21)$$

To estimate the pressure drop across the condenser (shell side) use [4]

$$(\Delta P)_c = \frac{f G_s^2 D_s (N+1)}{2 g \rho D_e \phi_s} \quad (22)$$

where D_s = inside diameter of shell = 0.9166 ft

N = No. of baffles = 6

$N+1$ = No. of times gas crosses bundle from inlet to outlet = 7

$$\phi_s = \left(\frac{\mu}{\mu_w} \right)^{0.14} = 1.0 \text{ (assumed)}$$

f_s = friction factor read from Figure 29 in Kern

Solving for ΔP at 763°F and 212°F

$$(\Delta P)_c \text{ at } 763^\circ\text{F} = 0.055 \text{ psi}$$

$$(\Delta P)_c \text{ at } 212^\circ\text{F} = 0.027 \text{ psi}$$

SECRET

DECLASSIFIED

~~SECRET~~

-30-

The above pressure drop would be the case if the gas passed all the way through the condenser. As practically all the gas is D_2O vapor and is condensed the pressure drop will be much less than the above figures indicate and will probably be of the order of 0.01 psi. This is small in comparison with the pressure drop in other parts of the system and will be neglected in all calculations.

~~SECRET~~

DECLASSIFIED

APPENDIX III

Pressure Drop versus Time During Dump

The procedure for determining pressure versus time is essentially a trial and error process and is as follows:

1. Choose a time, measured from the beginning of a dumping operation, say 15 seconds.
2. Read from Figures 4 or 5 the weight of D_2O which will flow into the dump tanks in this time interval.
3. Calculate the total heat content added in the dump tank during this 1st interval. This includes the sensible heat of the solution, the heat of recombination of any dissolved D_2 and O_2 , and any heat added in the D_2O evaporator.
4. Assume a pressure in the condenser for this particular time.
5. Estimate an average $(\Delta t)_m$ from Figure 1 for the pressure interval between atmospheric pressure and the assumed pressure.
6. Compute from equation (7) the average rate of heat being transferred in the condenser and consequently the number of Btu removed from the dumped solution during the 1st time interval.
7. Compute the weight of D_2O present in the low pressure system at this time and divide into the total volume of the low pressure system to get the specific volume, V , ft^3/lb , after the 1st interval.
8. Subtract the number of Btu removed by the condenser from the total number of Btu present initially and divide by the total weight to get the specific heat content, H , Btu/lb, after the 1st interval.

~~SECRET~~

DECLASSIFIED

9. The fraction of vapor, x , which will flash from this solution is given by

$$x = \frac{H - h_f}{h_{fg}}$$

10. The fraction of vapor is also given by

$$x = \frac{V - v_f}{v_{fg}}$$

where h_f , v_f , h_{fg} , v_{fg} are values taken from the steam tables at the chosen pressure of step 4 plus $(\Delta P)_t$ from Table III.

11. By trial and error (using steam tables and making small corrections for D_2O) and correcting, H , for each new pressure assumed, find the pressure at which steps (9) and (10) will give the same value for x .

12. The pressure of step (11) is the dump tank pressure and the condenser pressure will be smaller by the amount $(\Delta P)_{total}$ from Table III.

13. Choose a new time say 30 seconds (next 15 seconds). Repeat the process making allowances for the different amount of solution present in the dump tank and for the heat already removed in the 1st time interval.

14. Repeat above process until enough points have been computed to draw the pressure versus time curve.

The pressure versus time curves shown in Figures 2 and 3 were calculated by the above procedure. After the solution is emptied from the high pressure systems, the curves fall off according to the plot drawn for an instantaneous dump.

APPENDIX IV

Temperature Profile in Catalyst Bed

An estimate of the temperature of the pellets as a function of catalyst bed radius is made using the simple relation (steady state operation):

$$\text{Heat input} = \text{Heat output}$$

The heat input to the catalyst pellets comes from the heat of reaction of D_2 and O_2 and is added at the rate of 105,000 Btu/lb-mol D_2 reacting. Heat is carried away (1) by the transfer of heat from the pellets to the main gas stream, (2) by thermal conduction through the pellets and (3) by the kinetic energy of the hot D_2O molecules which are formed on the pellet surface during the reaction. The thermal conductivity of alumina is small and the percentage of D_2O molecules involved in chemical reaction is small compared to the main gas stream. Therefore, the contribution to heat removal made by these methods is small (probably less than 20 percent) and so it is neglected from further computations. The pellets at the outside of the bed and the containing wall approach the temperature of the leaving gas and therefore little or no heat is transferred by radiation.

The rate of heat input in Btu/hr is given by

$$\text{Heat Input} = N_{D_2} \Delta H f(r)$$

where $f(r)$ = fraction of D_2 reacted at radius, r .

The rate of heat output in Btu/hr is given by

$$\text{Heat Output} = h_p A_p (T_p - T_g)$$

where h_p = heat transfer coefficient between pellets and gas stream.

A_p = heat transfer area involved.

T_p = temperature of pellet surface as a function of r .

T_g = temperature of gas stream as a function of r .

~~SECRET~~

DECLASSIFIED

The basic heat balance then is

$$N_{D_2} (\Delta H) f(r) = h_p A_p (T_p - T_g) \quad (23)$$

From the data of Gaven, et al [1], the following straight line equation may be assumed

$$(SV) = - 4.72 \times 10^6 f(r) + 5.14 \times 10^6 \quad (24)$$

where (SV) = space velocity

For the present case the space velocity is given by

$$(SV) = \frac{(0.468 \text{ lb mols/min})(60 \text{ min/hr})(359 \text{ ft}^3/\text{lb mol})}{V_c} = \frac{10.080 \text{ ft}^3/\text{hr}}{V_c} \quad (25)$$

where V_c = volume of catalyst as a function of r .

The catalyst volume, V_c is given by

$$V_c = \pi N (r^2 - r_1^2) = 2.0944 (r^2 - 0.031364) \quad (26)$$

where N = length of perforated area of bed container = 2/3 ft

r_1 = inside radius of basket

Combining equations (24), (25), and (26) and solving for $f(r)$:

$$f(r) = 1.0890 - \frac{0.001020}{(r^2 - 0.031364)} \quad (27)$$

The gas temperature is given as a function of $f(r)$

$$T_g = T_o + \frac{N_{D_2} \Delta H}{C_p w} f(r) \quad (28)$$

or

$$T_g = 212 + 551 \left\{ 1.0890 - \frac{0.001020}{(r^2 - 0.031364)} \right\}$$

where T_o = temperature of entering gas = 212°F

To estimate a value for h_p use the equation [9]

$$j_h = \frac{h_p}{C_p G} \left[\frac{C_p \mu}{k} \right]_f^{2/3} \quad (29)$$

$$j_h = 1.06 \left[\frac{D_p G}{\mu} \right]^{-0.41} \quad (30)$$

DECLASSIFIED

SECRET

Since most of the heat is transferred in the first 0.3" of the bed, the mass flow rate, $\dot{G}$, will be estimated on the basis of the inside flow area of the bed. A reasonable film temperature is assumed as $\sim 800^\circ\text{F}$.

Then at 800°F :

$$\begin{aligned}\mu &= 0.062 \text{ lb/hr ft} \\ k &= 0.029 \text{ Btu/hr ft } ^\circ\text{F} \\ C_p &= 0.5 \text{ Btu/lb } ^\circ\text{F} \\ \dot{G} &= 757 \text{ lb hr ft}^2 \\ D_p &= 0.01042 \text{ ft}\end{aligned}$$

Solving equation (30) for j_h

$$j_h = 0.1454$$

Substituting j_h in equation (29) and solving for h_p

$$h_p \cong 50 \text{ Btu/hr ft}^2 ^\circ\text{F}$$

The surface area for heat transfer is

$$A_p = V_c a$$

where $a = 346 \text{ ft}^2/\text{ft}^3$ for $1/8" \times 1/8"$ cylindrical pellets.

Equation (23) can now be written

$$N_{D_2}(\Delta H) f(r) = h_p a V_c (T_p - T_g)$$

Consider an elemental volume of bed $dV = 2\pi Nrdr$

Then

$$\lim_{\Delta r \rightarrow 0} \frac{N_{D_2}(\Delta H) [f(r+\Delta r) - f(r)]}{\Delta r} = \lim_{\Delta r \rightarrow 0} \frac{h_p a [V_c(r+\Delta r) - V_c(r)]}{\Delta r} (T_p - T_g)_{\text{avg}}(r)$$

$$\text{or} \quad N_{D_2}(\Delta H) \frac{df(r)}{dr} = h_p a \frac{dV_c}{dr} \tau(r) \quad (31)$$

where $\tau(r) = (T_p - T_g)$

~~SECRET~~

DECLASSIFIED

From equations (26) and (27):

$$\frac{d V_c}{dr} = 2(2.0944)r$$

$$\frac{df(r)}{dr} = \frac{0.002040 r}{(r^2-0.031364)^2}$$

Solving equation (31) for T_p (for present case):

$$T_p = T_g + \frac{0.004615}{(r^2-0.031364)^2} \quad (32)$$

Equation (32) indicates an infinite temperature on the inside face of the recombiner bed (i.e., the point where $r \rightarrow r_1$). To get an idea of the approximate temperature of the pellets in this area the maximum rate of recombination of stoichiometric hydrogen and oxygen is assumed to be $1.2 \frac{\text{ft}^3 \text{ H}_2 \text{ (STP)}}{\text{min cu. in. catalyst}}$. [10] [1] For the gas mixture entering the HRT recombiner (8.1 percent combustibles) the rate of heat input is

$$\frac{1.2 \text{ ft}^3 (105,000) \text{ Btu/lb mol} (1728 \text{ in/ft}^3) (60 \text{ min/hr}) (0.081)}{359 \text{ ft}^3/\text{lb mol in}^3 \text{ min}} = 2,950,000 \text{ Btu/hr ft}^3$$

Then

$$h_p (346 \text{ ft}^2/\text{ft}^3 \text{ cat.}) (T_p - T_g) = 2,950,000 \text{ Btu/hr ft}^3$$

$$\text{or} \quad (T_p - T_g) = \frac{2,950,000}{(50)(746)} = 171^\circ \text{F}$$

The maximum temperature difference between the pellets and the gas is then approximately 170°F . Table VI gives some of the calculated temperatures for the recombiner. These temperatures are plotted in Figure 6.

~~SECRET~~

DECLASSIFIED

TABLE VI

Pellet and Gas Temperatures in the Recombiner

r, in.	T_g , °F	T_p , °F
	Gas Temperature	Pellet Temperature
$r_i = 2.125$	212	383
2.150	212	383
2.180	472	643
2.210	593	764
2.250	664	835
2.300	708	867*
2.350	731	826*
2.400	747	805*
2.450	758	801*
2.500	763	795*

* Calculated from equation (32)

The values given in Table VI are based on equations which assume a homogeneous bed. Obviously the values are only approximate and are given only to get an order of magnitude idea of the temperatures involved in the bed.

SECRET

DECLASSIFIED

1. Gaven, J. V. et al., "Catalytic Recombination of Hydrogen and Oxygen ---II," KT-134.
2. Perry, J. H. ed., "Chemical Engineer's Handbook," Third Edition, McGraw-Hill (1950).
3. Zapp, F. C. and Aven, R. E., "HRT Design Data, Issue No. 2," CF-54-8-53.
4. Kern, D. Q., "Process Heat Transfer," McGraw-Hill (1950).
5. Keenan, J. H., and Keyes, F. G., "Thermodynamic Properties of Steam," Wiley (1950).
6. Segaser, C. L., "HRT Entrainment Separator Design Study," CF-54-7-122.
7. McAdams, W. H., "Heat Transmission," 2nd edition, McGraw-Hill (1942).
8. Segaser, C. L., "Heat Exchanger Design for the ISHR," CF-52-10-195.
9. Hougen, O.A. and Watson, K. M., "Chemical Process Principles, Part III," Wiley (1943).
10. Spiewak, I., and Aven, R. E., "Design of ISHR Catalytic Recombiner," CF-53-6-162.

UNCLASSIFIED
ORNL-LR-DWG 3809

Fig. 1. Variation of Temperature Driving Force with Pressure

DECLASSIFIED

Fig. 2. Variation of Pressure in Dump Tank with Time for Core System (Dumping Operation)

UNCLASSIFIED
ORNL-LR-DWG 3811

Fig. 3. Variation of Pressure in Dump Tank with Time for Blanket System (Dumping Operation)

DECLASSIFIED

Fig.4. Variation of Weight into Dump Tank vs. Time During Core Dump (Five Minute Dumping Time Assumed)

UNCLASSIFIED

UNCLASSIFIED
ORNL-LR-DWG 3813

Fig. 5. Variation of Weight into Dump Tank vs. Time During Blanket Dump (Eight Minute Dumping Time Assumed)

DECLASSIFIED

Fig.6. Temperature Profile of Catalyst Pellets and Gas in Recombiner

DECLASSIFIED