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LET-DOWN SYSTEM DESIGN FOR HOMOGENEOUS REACTORS

Summary

A study has been made to determine the feasibility of designing a gas let-down system for homogeneous reactors, in which the pressure is taken through a fairly long tube rather than across a throttling valve. A schematic design of such a system is shown in ~~Fig. 1~~ for the HRT in which the let-down stream passes through parallel tubes. Control is effected by the cutting in or out of tubes as is needed. Calculations indicate such a design is feasible. It is recommended that experimental work be done before the adoption of this design. The experimental work should be designed to

1. Demonstrate the ease of control
2. Determine the stability of the two phase flow in the system
3. Determine the operating characteristics throughout the pressure and temperature range expected.
4. Determine the effect of an orifice on flow stability.

Introduction

The radiolytic gas stream leaving the gas separator of a homogeneous reactor contains entrained liquid fuel solution. If a low-pressure recombination system is used, this gas stream must pass through a let-down system in which the pressure is reduced from operating pressure (2000 psia) to essentially atmospheric pressure. The present let-down system design for the HRT involves a throttling valve across which most of the pressure drop is taken. Since there is two-phase flow through the valve and the pressure drop is high, the throttling valve will probably have a short lifetime. It is desirable then to design a system in which the pressure drop is taken across the let-down line and an orifice on the low-pressure side if one is needed. The purpose of this study is to determine the feasibility of such a design.

Description of Design

In the design presented for the HRT (see Fig. 1), gases and entrained fuel solution from the gas separator enter a common header from which fifteen 3/16-in. (i.d., 0.072 in.) tubes are arranged in parallel. These tubes are 100 ft long and have on-off type valves at the high-pressure side.

The two-phase mixture passes through these tubes into a receiving container which is at atmospheric pressure. The radiolytic gases go to the recombiner-condenser from this receiving tank. Control of the let-down stream is maintained by cutting in or out tubes as needed. For the HRT operating at 5 Mw and recombining 75% of the radiolytic gas internally about 12 let-down lines will be needed, the extra three remaining available as spares.

Pressure Drop Calculations

The method of calculating the flow rates and pressure drops involved in designing the let-down system is based on equations outlined by S. Mirshak.⁽¹⁾ For the present case the upstream pressure is fixed (op. press.). Under normal operating conditions (2000 psia and 300°C) the pressure drop across the let-down line and the energy content of the two-phase mixture are high enough so that critical flow exists at the discharge end. Mirshak⁽¹⁾ gives a graph for steam-water mixtures in pipes in which the energy content of the flowing, flashing fluid is plotted versus the critical mass velocity with the maximum discharge or critical downstream pressure as a parameter. This critical pressure is assumed to be the pressure at the tube (or orifice) outlet, providing it is greater than the pressure into which the fluid discharges.

If an orifice is used on the downstream side, critical flow is assumed to exist in the orifice. The pressure drop across this orifice is

$$\Delta P = P_1 - P_c = \frac{P_c}{r} - P_c = 0.72 P_c \quad (1)$$

where

P_c = critical downstream pressure, psia

P_1 = pressure immediately upstream of the orifice

$r = \frac{P_c}{P_1}$ = critical pressure ratio = 0.58 (assumed same as that for saturated steam)⁽²⁾

In order to calculate the pressure drop across the tube, the two-phase mixture is assumed to be a single phase with average properties. The average viscosity, Z , is given by

$$\frac{1}{Z} = y\left(\frac{1}{Z_g}\right) + (1 - y)\left(\frac{1}{Z_f}\right) \quad (2)$$

where Z = viscosity in centipoises

y = weight fraction of gas in flashing mixture

subscripts

f = refer to liquid phase

g = refer to gas phase

The average specific volume, v , of the flashing mixture is given by

$$v = y v_g + (1 - y) v_f \quad (3)$$

The equation for pressure drop across the line is derived from application of the Bernoulli equation to small finite increments of length. This equation is

$$-\Delta P = \text{kinetic energy term} + \text{fractional work term} + \text{elevation term} \quad (4)$$

For the present design the elevation term has been neglected and thus equation (4) becomes

$$-\Delta P = M w^2 \Delta v + N w^{1.8} v_{\text{avg}} Z_{\text{avg}}^{0.2} \Delta L \quad (5)$$

where ΔP = pressure drop across length increment ΔL , psi

ΔL = increment of length, ft

$$M = \frac{1}{144 g_c A^2}$$

w = mass flow rate, lbs/sec

v_{avg} = arithmetic average of the specific volume, v , over pressure change, ΔP , ft^3/lb

Z_{avg} = arithmetic average of the viscosity, Z , over pressure change, centipoises

N = resistance factor

A = tube cross-sectional area available to flow, ft^2

g_c = conversion factor, 32.17 ft/sec^2

An expression for the resistance factor, N , is derived in Appendix A.

It is

$$N = \frac{0.000230}{g_c D^{4.8}} \quad (6)$$

where D = tube inside diameter, ft.

The schematic design presented in Fig. 1 is based on the following initial composition of the let-down stream for the HRT operating at 5 Mw. (3)

Composition at 300°C and 2000 psia

(D ₂ + 1/2 O ₂)	31.2 lbs/hr	3.7% (wt.)
D ₂ O vapor	110 lbs/hr	13.2%
UO ₂ SO ₄ -D ₂ O sol'n	693.8 lbs/hr	83.1%
	835 lbs/hr ⇌ 0.23 lbs/sec	100.0%

In order to compute the pressure drop in the let-down line as a function of flow rate, w , a relation is needed between the average specific volume, v , of the flashing mixture and pressure. To get such a relationship the following assumptions are made:

1. No heat is lost (or gained) to the air surrounding the let-down line
2. The entrained liquid is pure D₂O

Curve 2 of Fig. 2 shows the specific volume, v , plotted versus pressure for this initial let-down stream composition. The derivation of this curve is given in Appendix B.

A relation between the average viscosity of the two phase mixture and pressure is also needed in computing the pressure drop from equation (5). This relationship is given as curve 2 of Fig. 3. The derivation of this curve is given in Appendix C.

For ease of calculation equation (5) is written

$$\Delta L = \frac{-\Delta P - M \Delta v w^2}{N v_{\text{avg}} Z_{\text{avg}}^{0.2} w^{1.8}} \quad (7)$$

The pressure drop, $(\Delta P)_L$, can now be calculated as a function of flow rate, w , with length of line and size of line as parameters. This is done by the following procedure:

1. Divide the pressure range (0 - 2000 psia) into small finite increments. (At the higher pressures the change in v and Z with ΔP is small and therefore fairly large increments can be assumed without appreciable error.)
2. From Figs. 2 and 3 determine Δv , v_{avg} , and Z_{avg} for each pressure increment.

3. Assume a value for the flow rate, w .
4. Using equation (7) compute ΔL for each increment, ΔP .
5. Determine length along let-down line versus pressure for the flow rate assumed in step 3.
6. Repeat for other flow rates.
7. Plot length of let-down line versus pressure (and pressure drop) with flow rate as parameter. This is done in Fig. 4 for 3/16-in. (i.d. 0.072 in.) lines for a let-down stream of the composition assumed above.
8. From this plot, the pressure drop can be found as a function of flow rate for the desired length of line.

Several line sizes and lengths have been considered in this paper. Some of the data on line sizes are given in Table I.

Table I
Let-Down Line Data

Outside diameter in.	BWG Number	Inside diameter in.	Inside cross section A ft ²	M	N
3/16	16	0.058	0.00001835	640,000	930,000
3/16	17	.072	.0000283	270,000	330,000
1/4	16	.120	.0000785	35,000	28,000
3/8	16	.245	.000327	2,020	930
1/2	16	.370	.000747	390	130

Pressure drop is plotted versus flow rate for line lengths 90, 100 and 110 ft and line size as parameters in Fig. 5 for a let-down stream of the composition assumed above.

The critical pressure immediately downstream of the let-down line can be determined for the mass flow rate in the line. This was done for a let-down stream of the composition assumed above and plotted as curve 2 on Fig. 6. The curves of Fig. 6 are based on the graph of reference (1) for maximum discharge rates for steam-water mixture inside pipes. To use the chart in reference (1) a value for E , the energy content of the two-phase fluid, is needed. The value of this energy content for a mixture containing non-

condensable gases is assumed to be that energy which will give the same specific volume in a pure water-steam system.

From Fig. 6 then the final discharge pressure, P_c , is determined and $(2000 - P_c)$ is plotted versus flow rate on Fig. 5 for each line size. The intersection of the two curves for a particular line size and length determines the flow rate a single tube will handle. This value is 0.019 lbs/sec for 100 ft of 3/16-in. (i.d. 0.072 in.) line. Since the total flow rate from the HRT operating at 5 Mw is about 0.23 lb/sec, the number of parallel tubes of this size which is needed is $\frac{0.23}{0.019}$ or 12 tubes.

The amount of entrainment is by no means fixed at 83.1% as was assumed in the previous calculations. It is desirable then to know something of the operation of this type let-down system for different entrainment concentrations. Several entrainment concentrations have been considered in this study. (See Table II.)

Plots of specific volume versus pressure, viscosity versus pressure and critical discharge pressure versus mass flow rate for the compositions listed in Table II are given in Figs. 2, 3 and 6, respectively. Curves similar to Fig. 5 can be prepared also for compositions 1, 3, 4 and 5, to determine the capacity of each line under normal operating conditions (300°C and 2000 psia). These capacities have been determined and are presented in Table II and Fig. 7.

Table II
Line Capacities at Normal Operating Conditions

Liquid Composition at 300°C and 2000 psia (wt. %)	Equivalent Entrainment for HRT letdown stream (gpm)	Flow Rate, lbs/(sec-line)		
		3/16-in. (0.072 in. i.d.)	3/8-in. (0.245 in. i.d.)	1/2-in. (0.370 in. i.d.)
1. 100	--	0.036	0.90	2.64
2. 83.1	1.7	.019	.50	1.47
3. 77.0	1.2	.0173	.45	1.33
4. 89.6	3.0	.0221	.56	1.66
5. 0	0	.0097	--	--

Orifice at Discharge End of Line

The effect of an orifice at the discharge end of the let-down line has also been considered. In Fig. 8 the capacity of the let-down line is plotted versus orifice size, α . α is measured as the ratio of orifice area to the inside cross-sectional area of the line. The effect of using an orifice with the smaller lines, particularly the 3/16-in. line, is negligible. A curve of pressure drop versus flow rate is plotted on Fig. 5 for a 1/2-in. line with orifice at the discharge end. The effect of an orifice in the larger lines such as the 1/2-in. line is more pronounced, as can be seen in Figs. 5 and 8, and will provide some added measure of control. On this basis, an orifice is not recommended for the design presented in Fig. 1, but may be desirable for larger systems in which the larger size lines are used.

If a low-pressure recombination system is used for the TBR, then gases produced from about 150 Mw of reactor heat (assuming 2/3 of radiolytic gases are recombined internally) along with entrained fuel solution must be let down from 2000 psia to atmospheric pressure. The total flow rate, assuming 83.1% (wt.) of entrained liquid (composition 2), will be 28 lbs/sec. The number of let-down lines in parallel needed to handle this amount of flow is given in Table III for 3/8-in. and 1/2-in. tubes with and without orifices.

Table III
Number of Lines Needed for TBR Let-Down System

	<u>3/8 in. (i.d. 0.245 in.)</u>	<u>1/2-in. (i.d. 0.370 in.)</u>
With no orifice	56	19
With orifice of $\alpha = 0.5$	61	22
With orifice of $\alpha = 0.25$	70	26

The computation of line capacity when orifices are used is done using a trial and error procedure. This procedure is described in Appendix D.

Stability of Flow in Let-Down System

There may be a question as to whether the capacity of the lines might be affected by instability of the two-phase fluid flowing in the tubes. All preceding computations have assumed a homogeneous phase with average properties. To get an indication of the maximum effect for the HRT design, the total flow of 0.23/lb/sec is assumed to separate into two separate phases with the liquid and gas going through different tubes. The flow rates would be

Liquid (composition 1)	0.19 lb/sec
Gas (composition 5)	0.04 lb/sec

The number of tubes in parallel that will be required are

For the gas phase alone:	$\frac{0.04}{0.0097}$	or	4.1 tubes
For the liquid phase alone:	$\frac{0.19}{0.036}$	or	5.4 tubes

The total number of tubes needed for the flow in separate phases is 9-1/2, as compared to 12 tubes needed if the two phases are well mixed.

If the let-down system is operating with 12 tubes open and the let-down stream separates completely, by some means, into a gas and a liquid phase, where only 9-1/2 tubes are needed, then the extra tubes will transfer more liquid and the entrainment from the gas separator will be increased. The amount of increase will be about 0.8 gpm.

Stability of flow should be investigated experimentally before adoption of this type let-down system. From the calculations, however, it is expected to be a minor problem.

Operation at Lower than 2000 Psia Pressure

There are times, such as during start-up, that the reactor may be operating at pressures lower than 2000 psia. The line capacity can be found in a similar manner to that for 2000 psia operating pressure. The flow rates will vary slightly with the initial temperature of the let-down stream, but not nearly so much as the variations with initial pressure.

The line capacities of the HRT design for three operating pressures are (assuming let-down stream composition 2):

2000 psia	0.019 lb/sec-line (L = 100 ft)
1200 psia	0.0105 lb/sec-line (L = 100 ft)
600 psia	0.0047 lb/sec-line (L = 100 ft)

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APPENDIX A

RESISTANCE FACTOR

A general expression for the resistance factor, N , can be found by considering the equation⁽⁴⁾

$$\frac{dF}{dL} = \frac{6.49 f w^2}{2 g_c \rho^2 D^5} \quad (8)$$

or in terms of pressure drop

$$\Delta P = \frac{6.49 f L w^2}{2 (144) g_c \rho D^5} \quad (9)$$

where F = pressure head loss, ft of fluid

$\rho = \frac{1}{v}$ = fluid density, lb/ft³

f = fanning friction factor

For the range of Reynolds number between 5000 and 200,000 the value of f is given by⁽⁴⁾

$$f = \frac{0.046}{Re^{0.2}} = \frac{0.046}{\left(\frac{DG}{\mu}\right)^{0.2}} \quad (10)$$

where G = mass flow rate, lb/sec ft²

μ = viscosity, lb/sec ft

If the Reynolds number is expressed in terms of Z and w , equation (10) becomes

$$f = \frac{0.0102}{\left(\frac{w}{ZD}\right)^{0.2}} \quad (11)$$

Substituting equation (11) in equation (9)

$$\Delta P = \frac{0.000230 Z_{avg}^{0.2} v_{avg} \Delta L w^{1.8}}{g_c D^{4.8}} \quad (12)$$

Comparing equation (12) with the frictional work term of equation (5)

$$N = \frac{0.000230}{g_c D^{4.8}} \quad (16)$$

APPENDIX B

AVERAGE SPECIFIC VOLUME OF TWO-PHASE MIXTURE

If pure D_2O (composition 1) is let down in the let-down system, the curve for the specific volume versus pressure is relatively easy to determine. For the initial operating conditions of 2000 psia and $300^\circ C$ the enthalpy is given as

$$H = h_f (300^\circ C \text{ and } 2000 \text{ psia}) = 576.2 \text{ Btu/lb}$$

Assuming no heat is lost to the surroundings, the let-down stream will remain liquid until the pressure is reduced to 1250 psia (sat. pressure for $300^\circ C$). At this point the liquid will begin to flash and the weight fraction y of vapor is found from

$$y = \frac{H - h_f}{h_{fg}} \quad (13)$$

where H = initial enthalpy of fluid, Btu/lb

h = enthalpy of fluid at pressure, p

Subscript fg = refer to change by evaporation.

The average specific volume, v , is given by

$$v = v_f (D_2O) + y v_{fg} (D_2O) = \frac{18}{20} [\bar{v}_f (H_2O) + y v_{fg} (H_2O)] \quad (14)$$

Values for $v_f (H_2O)$, $v_{fg} (H_2O)$, h_f , and h_{fg} are found as functions of pressure in Keenan and Keyes Steam Tables. The specific volume versus pressure curve for pure D_2O is plotted as curve 1 on Fig. 2.

When non-condensable gases are present, as is the case for the actual let-down stream, the calculation of specific volume versus pressure is more involved. The initial partial pressure of D_2O (at 2000 psia and $300^\circ C$) is 1250 psi. The partial pressure of the radiolytic gases, $p(D_2 + O_2)$ is then 750 psi. The relation between the partial pressure of the non-condensable gases and the D_2O vapor is ⁽⁵⁾

$$p(D_2 + O_2) = \frac{\eta (D_2 + O_2) P_{D_2O}}{\eta_{D_2O} z} \quad (15)$$

where p = partial pressure

η = moles of material present

z = compressibility factor of D_2O vapor (assumed same as H_2O vapor and determined from Keenan and Keyes Steam Tables; compressibility factor for D_2 and O_2 is 1.0)

The initial enthalpy, H , for the two-phase mixture is

$$H = \gamma_{D_2O \text{ vapor}} h_g(1250 \text{ psia}) + \gamma_{D_2O \text{ liq.}} h_f(1250 \text{ psia}) + \gamma_{(D_2 + O_2)} C_p (D_2 + O_2)(572-32) \quad (16)$$

γ = wt. fraction of the initial mixture at 2000 psia and $300^\circ C$

C_p = heat capacity of $(D_2 + 1/2 O_2)$ gases = $0.532 \text{ Btu/lb-}^\circ F^{(7)}$

The initial enthalpy for each composition assumed is as follows:

Comp. 2	645.3 Btu/lb
Comp. 3	669.7 Btu/lb
Comp. 4	618.6 Btu/lb
Comp. 5	984.3 Btu/lb

Some of the energy of the fluid mixture is transferred to kinetic energy. This term becomes appreciable at the lower pressures when critical flow conditions are approached. The kinetic energy term is

$$K = \frac{1}{2 g_c (778)} \left(\frac{wv}{A} \right)^2, \text{ Btu/lb} \quad (17)$$

Equation (16) can now be written for any pressure below 2000 psia.

$$H - K = C_p (t-32) + (\gamma_{D_2O \text{ vap.}} + x) h_g + (\gamma_{D_2O \text{ liq.}} - x) h_f \quad (18)$$

where t = temperature, $^\circ F$ (sat. temp. at the partial pressure of the D_2O)

h = enthalpy at the partial pressure of the D_2O , Btu/lb

x = weight of liquid water which flashes to vapor, lbs/lb-mix.

Solving equation (18) for x

$$x = \frac{H - K - C_p (t-32) - \gamma_{D_2O \text{ vap.}} h_g - \gamma_{D_2O \text{ liq.}} h_f}{h_{fg}} \quad (19)$$

The procedure for determining specific volume versus pressure is:

1. Choose a partial pressure for the D_2O vapor. This determines t , h_f , h_g and h_{fg} in equation (19).
2. Assume a value for K .
3. Solve equation (19) for x . The fraction of D_2O vapor then is $(\gamma_{D_2O \text{ vap.}} + x)$ and the fraction of D_2O liquid is $(\gamma_{D_2O \text{ liq.}} - x)$
4. Compute number of moles of D_2O vapor.
5. Calculate partial pressure of $(D_2 + O_2)$ from equation (15).

This determines the total pressure $(p_{(D_2+O_2)} + p_{D_2O})$.

6. The specific volume is then found from the equation

$$v = \frac{18}{20} \left[v_g(\text{at } p_{D_2O \text{ vap.}}) (\gamma_{D_2O \text{ vap.}} + x) + v_f(\text{at } p_{\text{total}}) (\gamma_{D_2O \text{ liq.}} - x) \right] \quad (20)$$

7. Calculate the kinetic energy of stream from equation (17). This should equal that assumed in step 2. If an appreciable error exists here, a new value for K should be assumed and the process repeated.

8. Choose other values for the partial pressure of D_2O and calculate the respective specific volumes and total pressures. The specific volume is then plotted versus total pressure (see Fig. 2).

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APPENDIX C

VISCOSITY OF TWO-PHASE MIXTURE

The calculation of the viscosity versus pressure curves is based on equation (2)

$$\frac{1}{Z} = y \left(\frac{1}{Z_g} \right) + (1 - y) \frac{1}{Z_f} \quad (2)$$

The liquid phase is assumed to be D_2O and the viscosity is taken as that given by Henks et al. (6)

The viscosity of the gas phase, which is a mixture of gases, has been estimated by the method outlined in Hougen and Watson. (7) The values for the temperatures at various pressures is found from steps 1 and 5 of the procedure outlined in Appendix B. The weight fraction of gas phase in the mixture is found from

$$y = \gamma(D_2 + O_2) + \gamma(D_2O \text{ vap.}) + x \quad (21)$$

where γ = initial wt. fraction in let-down stream.

x = wt. of liquid phase vaporized, lb/lb mixture, (calculated in step 3 of procedure outlined in Appendix B)

Viscosity versus pressure is plotted in Fig. 3 for compositions 1, 2, 3 and 4.

APPENDIX D

ESTIMATION OF LINE CAPACITY WHEN ORIFICE IS USED ON LOW-PRESSURE END

In order to estimate a line capacity when an orifice is used, a trial and error calculation is made. The procedure used here is as follows.

1. Assume a flow rate, w lb/sec.
2. From the area of the orifice the mass flow rate can be computed, i.e., $G_c = \frac{w}{A_o}$.
3. From Fig. 6, read the discharge pressure, P_c , downstream of the orifice.
4. Using equation (1) calculate P_1 , the pressure immediately upstream of the orifice.
5. From Fig. 5 read the pressure drop, $(\Delta P)_L$, for the assumed value of w .
6. Add P_1 and $(\Delta P)_L$ to get the initial pressure in the line.
7. This initial pressure should equal 2000 psia. If it does not equal 2000 psia, then a new flow rate is assumed and the process repeated.

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*Schematic Design of Let-Down
System for HRT*

Figure 1

ORNL-LE-DWG-10073

Specific Volume vs Pressure

Initial Composition

Curve 1 - 100% liquid

2 - 83.1% "

3 - 77.0% "

4 - 89.6% "

5 - 0% "

Specific Volume, ft³/lb.

Pressure, psia

Figure 2

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Figure 3

CND-18-C-10075

Pressure Drop in Let-Down Lines

Figure 1

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*Discharge Pressure vs. Mass Flow Rate
in Let-Down Lines*

Figure 6

ORNL-IR-Dwg.-10078

Line Capacity vs. Amount of Entrainment

Figure 7

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ORNL-12-Dwg.-10079

Effect of Orifice on Line Capacity

Figure 5