UNCLASSIFIED

OAK RIDGE NATIONAL LABORATORY

Operated By

UNION CARBIDE NUCLEAR COMPANY

 POST OFFICE BOX P
 OAK RIDGE, TENNESSEE

EXTERNAL TRANSMITTAL AUTHORIZED

ORNL
CENTRAL FILES NUMBER

CF-56-4-4

COPY NO. //

DATE: April 10, 1956

SUBJECT: Calculation of Effects of Copper Catalyst in the HRT

TO: R. B. Korsmeyer

FROM: R. E. Aven and M. C. Lawrence

DISTRIBUTION

1. HRP Director's Office	30. W. R. Gall	59. M. I. Lundin	87. I. Spiewak
2. G. M. Adamson	31. H. E. Goeller	60. R. N. Lyon	88. R. W. Stoughton
3. R. E. Aven	32. J. L. Gory	61. J. L. Mathern	89. C. D. Susano
4. S. E. Beall	33. C. B. Graham	62. J. P. McBride	90. J. A. Swartout
5. A. M. Billings	34. A. T. Gresky	63. H. F. McDuffie	91. E. H. Taylor
6. E. G. Bohlmann	35. J. C. Griess	64. H. A. McLain	92. W. F. Taylor
7. R. E. Brooksbank	36. J. J. Hairston	65. R. A. McNees	93. D. G. Thomas
8. N. A. Brown	37. D. C. Hamilton	66. J. R. McWherter	94. T. H. Thomas
9. W. D. Burch	38. B. H. Hamling	67. O. Menis	95. P. F. Thomason
10. C. A. Burchsted	39. P. N. Haubenreich	68. C. Michelson	96. M. Tobias
11. F. R. Bruce	40. P. W. Hembree	69. E. C. Miller	97. D. S. Toomb
12. C. C. Cardwell	41. J. W. Hill	70. R. L. Moore	98. W. E. Unger
13. W. L. Carter	42. C. J. Hochanadel	71. R. C. Moren	99. R. Van Winkle
14. G. H. Cartledge	43. R. F. Hughes	72. C. W. Nestor	100. B. S. Weaver
15. R. H. Chapman	44. H. K. Jackson	73. E. O. Nurmi	101. A. M. Weinberg
16. H. C. Claiborne	45. G. H. Jenks	74. L. F. Parsly	102. H. E. Williamson
17. C. J. Claffey	46. R. W. Jurgensen	75. M. L. Pickelsimer	103. J. C. Wilson
18. E. L. Compere	47. S. I. Kaplan	76. L. R. Quarles	104. C. E. Winters
19. J. S. Culver	48. P. R. Kasten	77. R. C. Robertson	105. C. H. Wodtke
20. H. N. Culver	49. A. S. Kitzes	78. J. N. Robinson	106. W. C. Yee
21. N. W. Curtis	50. J. O. Kolb	79. A. M. Rom	107. F. C. Zapp
22. H. O. Day	51. R. B. Korsmeyer	80. M. W. Rosenthal	108. ORNL Doc. Ref.
23. W. K. Eister	52. U. Koskela	81. W. L. Ross	Lib. Y-12
24. J. R. Engel	53. K. A. Kraus	82. H. C. Savage	109. CR Library
25. K. E. Estes	54. J. E. Kuster	83. H. K. Search	110. REED Library
26. H. L. Falkenberry	55. J. A. Lane	84. C. H. Secoy	111. REED Library
27. D. E. Ferguson	56. M. C. Lawrence	85. C. L. Segaser	112. ORNL-RC Lab
28. W. J. Fretague	57. R. E. Leuze	86. E. M. Shank	Records
29. C. H. Gabbard	58. R. B. Lindauer		

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

UNCLASSIFIED

548 007

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

A study has been made of internal recombination of radiolytic gases in the HRT solutions using dissolved copper catalyst. Calculations have been made to determine the fraction of radiolytic gas production which is recombined internally as a function of copper concentration. This has been done for several power levels, operating temperatures, and pressures. The fraction of radiolytic gas recombined internally is shown (for several power levels) in Figures 1 and 2 as a function of copper concentration. The effect of power level on the copper concentration required is presented in Figures 3 and 4 for several fractions of gas recombined internally. The effects of overpressure and operating temperature are shown in Figures 5 and 6 respectively.

For the fuel solution of the HRT operating at 5 Mw (average temperature is 278°C and pressure is 2000 psia) the following copper concentrations are needed:

Percent Internal Recombination	Cu ⁺⁺ Concentration, $\frac{\text{gm-mols}^*}{\text{liter}}$
80	0.0019
90	0.0022
100	0.0025

If the operating pressure is lowered to 1700 psia (other conditions remaining the same) the copper required is

Percent Internal Recombination	Cu ⁺⁺ Concentration, $\frac{\text{gm-mols}^*}{\text{liter}}$
80	0.0032
90	0.0037
100	0.0042

* Cu⁺⁺ concentrations are given for the solution at 250°C temperature.

To get an indication of the copper requirements at a higher power level, Figure 13 was prepared in which the copper concentration is plotted versus the percent gas recombined internally in the HRT when it is operating at 10 Mw, at a pressure of 2000 psia and in the temperature range 210°C to 300°C.

Operation of the reactor at pressures other than the design pressure of 2000 psia will involve different concentrations of deuterium and quantities of gas in the let-down gas stream. The variation of these values has been estimated as a function of operating pressure. The results are presented in Figures 16 and 17. At 1700 psia operating pressure the volume flow rate (at STP) of gas for 14% let-down in the let-down stream is equivalent to the volume flow rate of gas for 20% let-down at 2000 psia operation. At the lower pressure, then, it may be advisable to use sufficient copper to recombine 86% of the radiolytic gas internally rather than the 80% recombination which is the design point for 2000 psia operation.

Calculations based on experimental data indicate that gamma-induced recombination of deuterium and oxygen in the D₂O blanket of the HRT is sufficient to prevent the formation of these gases. In this case no copper catalyst will be needed here. The presence of impurities (including Cu⁺⁺) tends to destroy the process by which γ -induced recombination takes place, so it may be advisable to design the blanket for copper catalyzed recombination until such time as sufficient data is obtained to place faith in the γ -induced process. The dissolved deuterium level is plotted versus copper concentration in Figure 7. If copper is used the recommended concentration is $1.6 \times 10^{-4} \frac{\text{gm-mols}}{\text{liter}}$. At this concentration the dissolved deuterium is ~0.0003 mol fraction which is low enough to prevent explosive concentrations in the blanket gas phase during a dumping operation.

548 093

An estimate of the copper requirements has been made for the HRT operating with a UO_2SO_4 blanket. The operating conditions for this case are:

Power: 5 Mw in Core

1 Mw in Blanket

Temperature: 210°C to 260°C in fuel solution

250°C to 260°C in blanket solution

Pressure: 1100 psia.

The fraction of gas recombined internally in the fuel solution is presented as a function of copper concentration in Figure 9. The dissolved deuterium level of the blanket is shown as a function of copper concentration in Figure 10.

548 004

INTRODUCTION

When the HRT is operating at a given power level, radiolytic gases ($D_2 + 1/2 O_2$) are generated at the following rates^[1]:

$$\text{Fuel solution:} \quad v = 3.5 \times 10^3 P_c \frac{\text{cc(STP)} D_2}{\text{sec.}} \quad (1)$$

$$D_2 O \text{ Blanket:} \quad v = 93 P_c \quad (2)$$

where P_c = core power in megawatts.

This gas is removed by catalytic recombination both internally and externally. The low pressure system of the HRT, including the external catalytic recombiner, is designed to handle a let-down gas stream corresponding to one megawatt operation at 2000 psia. Thus when the HRT is operating at 5 Mw total power at least 80% of the radiolytic gases should be recombined internally. At 10 Mw total power 90% of the radiolytic gases should be recombined internally. The internal catalyst used to effect this recombination is a copper compound dissolved in the reactor solutions. The purpose of this report is to estimate the copper concentration needed as a function of power level and fraction of gas recombined internally. The copper catalyst is very sensitive to temperature so this effect has been estimated. The recombination rate is a function of dissolved deuterium gas concentration as well as catalyst concentration. Since the concentration of dissolved gas in the liquid phase is directly proportional to its partial pressure in the gas phase, the effect of overpressure has been estimated.

All the estimated values for copper concentrations are for a circulation rate of 400 gpm in the core circulating system. The main circulating pump can be operated (in reverse) at lower circulating rates but this will occur for short periods of time only at pump start-up time.

Determination of Copper Concentration Required in Fuel Solution

The use of copper as an internal recombination catalyst in the HRT makes it possible to operate the reactor with a low pressure system designed to handle radiolytic gases from only one megawatt of power. While it is possible to use sufficient copper to recombine all radiolytic gas internally, some gas let-down is desirable in order to strip fission product gases such as xenon from the fuel solution. Also since copper has a thermal neutron cross section of about 3.6 barns it is important to keep its concentration at a minimum. In the calculations made to determine the amount of cupric ion needed in solution for various conditions in the HRT the following basic assumptions have been made:

1. Radiolytic gas is produced uniformly in the core, but not in the outside loop.
2. Deuterium or oxygen in the gas phase is not affected by the copper dissolved in the liquid phase, and that once deuterium or oxygen is in the gas phase it does not redissolve in the liquid.
3. Slug flow exists throughout the circulating loop.
4. Circulation rate of the core solution is 400 gpm.

The main circulation loop of the HRT consists of the core, gas separator, heat exchanger, pump and connecting piping as shown by the schematic diagram below:

548 006

If a small volume of fuel solution is considered as it moves around the circulating system, its position, its temperature and the neutron flux to which it is exposed can all be expressed as functions of time. The rate of change of deuterium concentration in the reactor solution is given by [3].

$$\frac{dy}{dt} = v - k_{cu} x y \quad (3)$$

where y = deuterium concentration in liquid phase, mol fraction.

t = time, seconds

v = deuterium production rate, $\frac{\text{lb. mols } D_2}{\text{lb. mol sol'n-sec.}}$

k_{cu} = recombination rate constant for copper catalyst, $\frac{\text{liters}}{\text{g mol } Cu^{++}\text{-sec.}}$

x = cupric ion concentration g mols/liter.

For a fuel solution circulating rate of 400 gpm the following average residence times were estimated from the volumes of the various loop components and piping:

Core vessel exit to heat exchanger = $t_2 - t_1 = t_{12} = 1.85$ sec.

Heat exchanger = $t_3 - t_2 = t_{23} = 2.12$ sec.

Heat exchanger to core entrance = $t_4 - t_3 = t_{34} = 3.21$ sec.

Core vessel = 11.11 sec.

Total time for one pass = 18.29 sec.

To determine the effects of overpressure, power level, and fraction of gas recombined the required copper concentration was calculated as a function of fraction of gas recombined internally for:

Case I - Reactor operating at 2000 psia and 278°C average temperature

and a) Power of 5 Mw.

b) Power of 4 Mw.

c) Power of 3 Mw.

Case II - Reactor operating at 1700 psia and 278°C average temperature

and a) Power of 5 Mw.

b) Power of 3 Mw.

Case III - Reactor operating at 1400 psia and 278°C average temperature

and a power of 5 Mw.

Case IV - Reactor operating at 2000 psia and 300°C fuel solution temperature

at core exit and a power of 10 Mw.

To determine the effect of operating temperature the minimum copper concentration required to give 100% internal recombination was calculated as a function of fuel temperature at the core exit for the reactor operating at 5 Mw. power.

The derivation of equations used in calculating the copper concentrations needed is given in the Appendix.

Minimum Copper Concentration Required for 100% Internal Recombination

For most cases under consideration here the minimum cupric ion concentration which will effect 100% internal recombination of the radiolytic gases, is that concentration which will allow the deuterium concentration in the fuel solution to become just saturated at the core exit (i.e. $y_1 = y_{sat}$ at the temperature of fuel leaving the core vessel). To determine the copper concentration required equation (13) of the Appendix is plotted for several power levels on Fig. 12. The minimum copper concentration for 100% recombination is found by setting y_1 equal to the saturation value for y at the core exit and reading the corresponding value of x (Cu^{++} concentration) from Fig. 12. Some values of

Cu^{++} concentration corresponding to 100% internal recombination are given in Table I.

It should be noted that if the operating temperature of the reactor is sufficiently low the saturation curve may be approached in the heat exchanger rather than at the core exit (See Fig. 8). In this event the minimum copper concentration which will represent 100% internal recombination is the value which corresponds to a fuel solution just saturated at the heat exchanger exit (i.e. $y_3 = y_{\text{sat}}$ at T_3).

Cu^{++} Concentration Determination When Some Gas is Removed by Let-down System

In order to determine the copper concentration as a function of percent deuterium recombined internally, equations (18), (22), (23) and (24) of the Appendix are used. The procedure is to first find γ_{sat} (time for the deuterium concentration to reach saturation) for a given copper concentration and gas production rate (i.e. power level). This is done by trial and error using equation (18). The amount of deuterium escaping to the gas phase in one pass through the circulating system is then found from equation (22). The fraction of gas in the let down stream and consequently the fraction recombined internally is found from equations (23) and (24) respectively.

Some values of cupric ion concentrations required for the four cases considered are listed in Table I. The percent deuterium recombined internally is plotted versus cupric ion concentration in Figs. 1 and 2 for operating pressures of 2000 psia and 1700 psia respectively.

TABLE I

COPPER CONCENTRATION REQUIRED FOR INTERNAL RECOMBINATION OF RADIOLYTIC GASES
 $\frac{\text{g mols. Cu}^{++}}{\text{liter}}$

Case	I-a	I-b	I-c	II-a	II-b	III	IV
Power, Mw	5	4	3	5	3	5	10
Operating Pressure psia	2000	2000	2000	1700	1700	1400	2000
Average Fuel Temperature, °C	278	278	278	278	278	278	255
100% Recombination	0.00250	0.00193	0.00144	0.00415	0.00215	0.0130	0.0082
90% Recombination	0.00222	0.00171	0.00128	0.00370	0.00194	0.0111	0.0072
80% Recombination	0.00194	0.00151	0.00113	0.00323	0.00173	0.0094	0.0063
70% Recombination	0.00167	0.00134	0.00099	0.00277	0.00152	0.0078	0.0054

Numerical values used in determining the various constants of equations

(13), (18), (22), (23) and (24) of the Appendix are listed in Table II.

SOME CONSTANTS USED IN EVALUATING THE Cu^{++} CONCENTRATION
IN THE HRT

Case	I-a	I-b	I-c	II-a	II-b	III	IV
D_2 Production rate, $\frac{\text{mols } D_2}{\text{mol sol'n-sec}}$	6.193×10^{-5}	4.96×10^{-5}	3.72×10^{-5}	6.193×10^{-5}	3.72×10^{-5}	6.19×10^{-5}	1.239×10^{-4}
$T_1, ^\circ\text{C}$	300	296	291	300	291	300	300
$T_4, ^\circ\text{C}$	256	260	265	256	265	256	210
k_{cu} at T_1 $\frac{\text{liter}}{\text{g-mol } \text{Cu}^{++} \text{ sec}}$	13.4	11.5	9.71	13.4	9.71	13.4	13.4
k_{cu} at T_4	2.29	2.79	3.36	2.29	3.36	2.29	0.284
γ_1	1.006×10^{-4}	7.81×10^{-5}	5.68×10^{-5}	1.006×10^{-4}	5.68×10^{-5}	1.006×10^{-4}	2.53×10^{-4}
γ_2	0.665	0.6212	0.585	0.655	0.585	0.655	0.851
γ_3	1.788×10^{-3}	1.796×10^{-3}	1.803×10^{-3}	1.788×10^{-3}	1.803×10^{-3}	1.788×10^{-3}	1.786×10^{-3}
$\sigma_1, ^\circ\text{C}^{-1}$	1.89×10^{-3}	1.87×10^{-3}	1.86×10^{-3}	1.89×10^{-3}	1.86×10^{-3}	1.89×10^{-3}	2.06×10^{-3}
$\sigma_2, (^\circ\text{C-sec})^{-1}$	1.305×10^{-5}	1.044×10^{-5}	7.83×10^{-6}	1.305×10^{-5}	7.83×10^{-6}	1.305×10^{-5}	2.85×10^{-5}
ϕ	14.42	21.88	35.17	14.42	35.17	14.42	0.821
$\left[\text{at}_{12} e^{-b/T_1} + \alpha_{23} + \text{at}_{34} e^{-b/T_4} \right]$	42.90	41.15	40.62	42.90	40.62	42.90	30.80
β_1 , mol fraction	3.69×10^{-3}	3.73×10^{-3}	3.46×10^{-3}	3.01×10^{-3}	2.724×10^{-3}	2.37×10^{-3}	5.04×10^{-3}
β_2 , (mol fract) sec^{-1}	1.035×10^{-4}	9.45×10^{-5}	5.94×10^{-5}	1.332×10^{-4}	7.876×10^{-5}	1.67×10^{-4}	2.25×10^{-4}

Effect of Reactor Power

By using the data of Table I and making cross plots of Figures 1 and 2, the effect of reactor power level on the amount of copper needed can be shown. In Figures 3 and 4 the copper concentration is plotted versus power level for operating pressures of 2000 psia and 1700 psia respectively.

Effect of Overpressure

For the previous calculations the assumption was made that the vapor pressure of D_2O in the core solution is variable and is equal to values given in the steam tables (Keenan and Keyes) for temperatures corresponding to the temperature of the fuel solution. The overpressure at any given point in the reactor is given by the difference between the total pressure and the partial pressure of water at this point. Since the concentration of deuterium in the liquid phase is directly proportional to the overpressure, it is important to note this assumption. If a chemical compound such as lithium sulfate (Li_2SO_4) is added to the fuel solution to suppress the vapor pressure of the water at a given temperature, the overpressure may be considerably different from those values calculated above. In this event a comparison of system overpressures (other operating conditions being equal) should be made to determine the amount of copper catalyst which is needed. (D_2 solubility may also be affected by Li_2SO_4).

The effect of over pressure can be shown by plotting the copper concentration needed for 100% internal recombination versus overpressure. This is done in Figure 5.

548 012

Effect of Operating Temperature

The recombination rate constant, k_{cu} , is not constant at all with temperature but varies exponentially according to [2].

$$k_{cu} = ae^{-\frac{b}{T}}$$

Where $a = \text{constant} = 2.37 \times 10^{10}$

$b = \text{constant} = 12,200$

$T = \text{temperature, } ^\circ\text{K}$

The effect of temperature can, therefore, be quite pronounced. To show this effect the copper concentration required to give a fuel solution just saturated with deuterium at the core exit was estimated for an exit fuel temperature of 250°C , 275°C and 300°C . The power level was 5 Mw and the overpressure at the core exit was held constant at 750 psi for the three temperatures. The copper concentration was calculated by setting y , equal to y_{sat} at the core exit and solving equation (13) of the Appendix for x . Copper concentration is shown as a function of operating temperature in Figure 6.

Because of the lower deuterium solubility at temperatures below 270°C (see Figure 8) it is possible for gas bubbles to appear first in the heat exchanger if the operating temperature is below this value. Values of Henry's Law Constant are based on experimental data [5] and if plotted versus temperature the negative slope of the curve in the temperature range 200°C to 270°C is significantly greater than the slope in the range 270°C to 300°C . Since the saturation value of deuterium varies inversely with the Henry's Law Constant the saturation curve passes through a maximum at some temperature near 270°C . The effect of varying overpressure in the system (at constant operating pressure) must also be considered. The procedure for the calculation of the

saturation curves of Figure 8 is given in the appendix.

HRT Operating at 10 Mw

An estimate of the copper concentration needed in the HRT when it is operating at 10 Mw power has also been made. In this case, however, the fuel temperature at the core exit was assumed to be 300°C. The average operating temperature is therefore lower than the 278°C assumed for operation at powers up to 5 Mw. Using equations (13), (18), (22), (23) and (24) of the appendix, the copper concentration was found as a function of fraction deuterium recombined internally and plotted on Figure 13.

Since the temperature of the fuel leaving the heat exchanger is low (compared to similar operation at 5 Mw power) there is the possibility of getting a gas phase in the heat exchanger. To show what might happen equation (12) of the appendix is written for 10 Mw as

$$y = e^{-0.821xe^{0.348\gamma}} \left\{ y_4 e^{0.821x} + 3.56 \times 10^{-4} \left[Ei(0.821xe^{0.348\gamma}) - Ei(0.821x) \right] \right\} \quad (12a)$$

The value of y calculated from equations (3), (7), (8) and (12) of the appendix is plotted for several values of x on Figure 14 to show the profile of the deuterium concentration in the fuel solution as it makes one pass through the main circulating loop. For comparison purposes the saturation curve is also drawn on Figure 14. As can be seen from Figure 14 for copper concentrations below 0.0055 $\frac{\text{gm-mols}}{\text{liter}}$ gas bubbles will form in the heat exchanger.

Deuterium Dissolved in Fuel Solution

When the reactor solutions are dumped, all dissolved gases come out of solution. As shown in CF 56-3-17, [8] if the deuterium concentration in the liquid phase is saturated when a dump is initiated, highly explosive concentrations of deuterium are likely to develop in the associated gas phase during part of the dumping period. If copper catalyst is used the entire fuel solution

will not be completely saturated with deuterium as assumed in CF 56-3-17, but will contain somewhat smaller concentrations depending on the amount of copper used. An estimate of the amount of dissolved deuterium present in the fuel solution of the HRT has been made as a function of copper concentration. The results are plotted on Figure 15.

Operation of Reactor at 1700 psia Total Pressure

The HRT is designed for an operating pressure of 2000 psia. It may be possible and desirable to operate the reactor at pressures lower than this. Some advantages of operating at lower pressures are:

- 1) Gas let-down stream is less explosive. See Figure 16.
- 2) Less pressure to contain.

Some disadvantages are:

- 1) More copper catalyst is needed to effect internal recombination.
- 2) Greater amounts of gas are let down due to the higher concentration of D_2O vapor in the let-down stream.
- 3) Stability of reactor is decreased.

If the HRT is operated at 1700 psia the deuterium concentration in the let-down stream is about 13.5% as compared to 20% at 2000 psia. This is usually non-explosive (i.e. with water vapor as diluent [9]). At 1700 psia the volume of gas (at STP) in the let-down stream corresponding to 20% let-down is 55 ft³/min as compared to 38 ft³/min for 20% let-down at 2000 psia (See Fig. 17). The low pressure system is designed to handle 20% gas let-down at 2000 psia. If the system pressure is lowered to 1700 psia it may be advisable to lower the percent gas let-down. Compared on a volume let-down basis 20% let-down at 2000 psia corresponds to about 14% let-down at 1700 psia. The comparative cupric ion concentrations required at 5 Mw reactor power are: (average operating temperature is 278°C).

20% let-down at 2000 psia $\Rightarrow$ 0.0019 gm-mols Cu^{++} /liter

14% let-down at 1700 psia $\Rightarrow$ 0.0035 gm-mols Cu^{++} /liter

Internal Recombination in D_2O Blanket

Radiolytic gases are being produced at a much smaller rate in the D_2O liquid of the blanket. The volume of the blanket is approximately 1560 liters ($\Rightarrow$ 2900 lbs D_2O) and at 5 Mw core power the temperature rise is 278°C to 282°C . The radiolytic gas production and energy absorption rates due to gamma absorption in the blanket for this power level are [1]:

$$v(\gamma\text{-abs}) = 300 \text{ cc } \text{D}_2(\text{STP})/\text{sec.}$$

$$E(\gamma\text{-abs}) = 1.77 \times 10^{24} \text{ ev/sec.}$$

Some D_2O is decomposed by energy absorbed in the blanket from the slowing down of fast neutrons. The fast neutron flux distribution in the D_2O blanket was calculated by members of the TBR design group in reviewing the design of the HRT reactor vessel. The fast neutron current entering the blanket from the core was estimated from this flux distribution. It is 0.71×10^{13} neutrons/(sec-cm²) at 5 Mw core power. Assuming that all the energy of the fast neutrons entering the blanket is absorbed by the blanket.

$$E(\text{f.neuts}) = (0.71 \times 10^{13}) (2 \times 10^6 \frac{\text{ev}}{\text{neuts}}) (2.08 \times 10^4 \text{ cm}^2) = 3 \times 10^{23} \frac{\text{ev}}{\text{sec}}$$

Assuming a G-value of 1.5 ($\frac{\text{molecules } \text{D}_2\text{O}}{100 \text{ ev}}$) for fast neutrons [6], the gas produced in the blanket by the slowing down of fast neutrons is

$$v(\text{f.n.}) = 160 \frac{\text{cc } \text{D}_2(\text{STP})}{\text{sec}} \quad (\text{at 5 Mw core power})$$

The total deuterium gas production in the blanket is then

$$v = 460 \frac{\text{cc } \text{D}_2(\text{STP})}{\text{sec}} \quad \text{at 5 Mw } \Rightarrow 93 \text{ P}_c \quad \frac{\text{cc } \text{D}_2(\text{STP})}{\text{sec}} \quad (2)$$

Assuming the temperature of the blanket constant at 280°C and no gas let-down, equation (1) of the appendix can be solved for steady state operation (i.e. $\frac{dy}{dt} = 0$)

$$y = \frac{v}{k_{Cu} x} \quad (4)$$

$$v = 93 P_c \frac{\text{cc } D_2(\text{STP})}{\text{sec}} = 3.16 \times 10^{-7} \frac{\text{moles } D_2}{\text{mole } D_2O - \text{sec.}}$$

$$k_{Cu} = 6.25 \text{ liters}/(\text{g.mol } Cu^{++} - \text{sec})$$

Equation (4) is plotted on Figure 7.

Gamma Radiation Induced Recombination in the D₂O Blanket

Recent investigations of gamma induced recombination of radiolytic gases by C. J. Hochanadel and G. H. Jenks have indicated the possibility of operating the heavy water blanket of the HRT with no internal catalyst. The gamma induced recombination process has a G. value of about 5 molecules of deuterium recombined per 100 ev. of gamma energy absorbed. The process is essentially independent of deuterium concentration and temperature. At the operating conditions of the blanket the overall reaction can be written [7]

The gamma induced reaction might be described by the following reactions [7]

Experiments by G. H. Jenks were made with pure water in a radiation field corresponding to the following energy absorption values

Energy from fast neutrons ≈ 4 watts/ml.

Energy from gammas ≈ 4 watts/ml.

There was no detectable change in pressure due to the build up of hydrogen and oxygen. In the D_2O blanket average energy absorption values are estimated to be

Energy from fast neutrons ≈ 31 watts/liter

Energy from gammas ≈ 180 watts/liter.

The estimated gamma induced recombination in the HRT blanket (assuming a G-value of 5 molecules D_2 /(100 ev γ 's absorbed)) is

$$1.77 \times 10^{24} (0.05) (3.717 \times 10^{-20}) = 3300 \frac{\text{cc D}_2 (\text{STP})}{\text{sec.}}$$

This is about seven times the recombination rate required in the blanket. In this case the deuterium concentration will be reduced to essentially zero in the blanket.

The gamma induced recombination process is very sensitive to impurities (including Cu^{++} , Br^- , etc.). These impurities react with the H and OH radicals and as a result break up the reaction chain. If such ions are present, little

or no recombination of radiolytic gas can be expected from the gammas. It may be possible to operate the D_2O blanket without copper if the D_2O is sufficiently pure. If copper is to be used at all in the blanket, it should be designed for copper recombination only with no aid expected from the gamma radiation.

HRT with UO₂ SO₄ Blanket

Fuel Solution

It is planned at some future date to operate the HRT as a converter with depleted uranium in the blanket. The blanket concentration will be about 300 gms U/liter. The reactor must therefore operate at lower temperatures to prevent phase separation in the blanket. Calculations of the required copper concentrations have been made for the following conditions:

Core: Power = 5000 kw
Operating Temperature = 210°C to 260°C
Operating Pressure = 1100 psia.

Blanket:	Power, a) From fission heat	= 700 kw
	b) From beta and gamma heat	= 300 kw (mostly γ 's)
	Operating temperature	= 250°C to 260°C
	Operating pressure	= 1100 psia
	Uranium concentration	= 300 $\frac{\text{gms}}{\text{liter}}$ at 260° (of 0.25% enriched U.)
	Volume	= 1740 liters.

The amount of copper catalyst needed for 100% internal recombination was calculated (using equation (13) of the appendix) as 0.0334 g-mols Cu^{++} /liter.

As can be seen from Figure 8, the saturation value for deuterium is essentially constant for operation in this temperature range and pressure. For this case equation (18) of the appendix reduces to

$$0.00105 \left[e^{1.32x e^{0.213 \tau_{\text{sat}}}} - e^{-6.25x} \right] = 2.90 \times 10^{-4} \left\{ \text{Ei}(1.32x e^{0.213 \tau_{\text{sat}}}) - \text{Ei}(1.32x) \right\} \quad \text{.....(11)}$$

For the copper concentration range in which gas bubbles are produced equation (15) of the appendix is used. For this case τ_1 must be computed from equation (16) of the appendix since its value may be less than $\tau_0 (= 11.1 \text{ seconds})$. The fractions of gas let-down and recombined internally were then estimated from equations (23) and (24) of the appendix. Results of these calculations have been plotted on Figure 9.

UO₂SO₄ Blanket

Considerable power is generated in the blanket for normal operating conditions. Radiolytic gas produced here can be estimated from the amount and type of radiation occurring in the blanket and from the G-values for these radiations [6]

$$G(\text{fission heat}) = 1.0 \frac{\text{molecules D}_2\text{O}}{100 \text{ ev}}$$

$$G(\gamma\text{'s}) = 0.10 \frac{\text{molecules D}_2\text{O}}{100 \text{ ev}}$$

Radiolytic gas production rates are (for 700 kw fission and 300 kw gamma heat)

$$v(\text{f.h}) = 1640 \frac{\text{cc D}_2(\text{STP})}{\text{sec.}}$$

548 320

$$v(\gamma's) = 70 \frac{\text{cc D}_2 (\text{STP})}{\text{sec.}}$$

$$v_{\text{Total}} = 1710 \frac{\text{cc D}_2 (\text{STP})}{\text{sec.}}$$

For this amount of γ -heat (300 kw) and assuming a gamma induced recombination rate value of G of 5 molecules D_2 /100 ev., the gamma induced recombination rate is $\sim 3500 \frac{\text{cc D}_2 (\text{STP})}{\text{sec.}}$. This is about twice the gas production rate and the possibility of operating without copper catalyst in the blanket, therefore, exists.

Again, however, the presence of impurities will tend to destroy the gamma induced recombination process. Since impurities will build up in the UO_2SO_4 blanket in the form of fission products, it may be advisable to design the blanket for copper recombination. Assuming the temperature constant at 255°C and no gas let-down equation (4) becomes (for this case)

$$y = \frac{5.27 \times 10^{-7}}{x} \quad (4a)$$

Equation (4a) is plotted on Figure 10.

APPENDIX

Derivation of Equations

The recombination rate of the radiolytic gases is proportional to the concentration of the gas in the liquid phase, the concentration of cupric ion, and the recombination rate constant which is dependent upon temperature.

Let y = concentration of deuterium dissolved in liquid phase, mol. fract.

x = concentration of Cu^{++} , g-mols/liter

$$k_{\text{Cu}} = ae^{-\frac{b}{T}} = \text{recombination rate constant, } \frac{\text{liters}}{\text{g mol Cu}^{++}\text{-sec.}}$$

(where a , b are constants)

The rate of change of concentration of deuterium in the liquid phase can be expressed by the differential equation [3]

$$\begin{aligned} \frac{dy}{dt} &= v - k_{\text{Cu}} x y \\ &= v - axye^{-\frac{b}{T}} \end{aligned} \quad (1)$$

Core to Heat Exchanger

For section 1-2 (see diagram page 5), which is the part of the circulating loop between the core exit and heat exchanger, the temperature is constant (i.e. $T = T_1 = T_2$) and v is zero.

Equation (1) becomes

$$\frac{dy}{dt} = -axye^{-\frac{b}{T_1}} \quad (2)$$

Considering x as a parameter equation (2) is written

$$\int_{y_1}^{y_2} \frac{dy}{y} = -axe^{-\frac{b}{T_1}} \int_{t_1}^{t_2} dt$$

Solving

$$y_2 = y_1 e^{-axe^{-\frac{b}{T_1}} t_{12}} \quad (3)$$

Heat Exchanger

In the heat exchanger the gas production rate is still zero, but the temperature is changing. By assuming a constant overall heat transfer coefficient and constant coolant temperature in the heat exchanger an expression can be derived relating temperature with time [3]

$$T = (T_2 - T_w) e^{-\epsilon(t-t_2)} + T_w \quad (4)$$

where

T_w = coolant temperature

ϵ = proportionality constant.

The constant ϵ can be determined from a knowledge of T_2 , T_3 , T_w and t_{23} .

If equation (4) is substituted for T in equation (1), the resulting equation is difficult to solve. To remedy this situation the temperature-time relationship (equation (4)) is approximated by [3]

$$\frac{1}{T} = \gamma_1 \ln(t + \gamma_2) + \gamma_3 \quad (5)$$

This approximation is very good as can be seen by reference to Figure 5 of CF 53-4-292 [3].

When equation (5) is substituted in equation (1) the resulting differential equation is easy to solve. The solution is [3]

$$y = y_2 \exp \left(\frac{-a e^{-b \gamma_3}}{1 - b \gamma_1} \left[(t - t_2 + \gamma_2)^{1 - \gamma_1 b} - \gamma_2^{1 - \gamma_1 b} \right] \right) \quad (6)$$

The concentration of deuterium at the exit of the heat exchanger is:

$$y_3 = y_2 e^{\alpha_{23} x} \quad (7)$$

$$\text{where } \alpha_{23} = \frac{-a e^{-b \gamma_3}}{1 - b \gamma_1} \left[(t_{23} + \gamma_2)^{1 - \gamma_1 b} - \gamma_2^{1 - \gamma_1 b} \right]$$

Heat Exchanger to Core

In the line from the heat exchanger to the core entrance the temperature is again constant ($T = T_3 = T_4$; neglecting any change that might occur in the pump) and the gas production rate is zero. In a manner analogous to the derivation of equation (3)

$$y_4 = y_3 e^{-a x e^{-\frac{b}{T_4}} t_{34}} \quad (8)$$

Outside Loop

The change in deuterium concentration in the outside loop is found as a function of cupric ion concentration by combining equations (3), (7) and (8).

$$y_4 = y_1 e^{-x} \left[at_{12} e^{-\frac{b}{T_1}} - \alpha_{23} + at_{34} e^{-\frac{b}{T_4}} \right] \quad (9)$$

Core Vessel

In the core vessel gas is being produced and the temperature is changing. The deuterium production rate (assumed constant) may be written

$$v = 1.239 \times 10^{-5} P_c \frac{\# \text{ mols } D_2}{\# \text{ mol sol'n-sec}}$$

Slug flow through the HRT core vessel is assumed. If uniform power density (i.e. uniform gas production) is also assumed the temperature-time relation will be approximately linear.

$$T = \psi_1 + \psi_2 \tau \quad (10)$$

where

$$\tau = t - t_4 = \text{time in core vessel, sec.}$$

$\psi_1, \psi_2 = \text{constants}$

If equation (10) is substituted in equation (1) the resulting equation is difficult to solve. Equation (10) may be approximated by a relation of the form

$$\frac{1}{T} = \sigma_1 - \sigma_2 \tau \quad (10a)$$

$\sigma_1, \sigma_2 = \text{constants}$

Values for σ_1 and σ_2 can be found from a knowledge of T_4 and T_1 .

548 025

A comparison of equations (10) and (10a) is given in Figure (11) for the reactor operating at 5 Mw and at 300°C at core exit.

Equation (10a) can be substituted in equation (1) to get

$$\frac{dy}{d\tau} = v - axye^{-b(\sigma_1 - \sigma_2\tau)} \quad (11)$$

This can be written

$$dy + axye^{-b(\sigma_1 - \sigma_2\tau)} d\tau = vd\tau$$

The integrating factor for this equation is

$$\int axe^{-b\sigma_1} e^{b\sigma_2\tau} d\tau = e^{\phi xe^{b\sigma_2\tau}}$$

$$\text{where } \phi = \frac{ae^{-b\sigma_1}}{b \cdot \sigma_2} = \text{constant}$$

Then

$$\int_{\substack{t=\tau \\ y=y_4 \\ \tau=0}}^{t=\tau} y = y(\tau) d \left\{ ye^{\phi xe^{b\sigma_2\tau}} \right\} = \int_0^{\tau} ve^{\phi xe^{b\sigma_2\tau}} d\tau$$

Upon integration

$$y_1 e^{\phi x e^{b \sigma_2 \tau}} - y_4 e^{\phi x} = \frac{v}{b \sigma_2} \left\{ \text{Ei}(\phi x e^{b \sigma_2 \tau}) - \text{Ei}(\phi x) \right\} \quad (12)$$

where Ei = refers to the exponential integral function which is tabulated [4].

Equation (12) refers to the concentration of deuterium in the liquid phase and is good as long as saturation conditions are not met. If y_1 , and τ_0 (= average residence time in core = 11.1 seconds at 400 gpm circulation rate) and equation (9) are substituted for y , τ , and y_4 respectively, equation (12) becomes

$$y_1 e^{\phi x e^{b \sigma_2 \tau_0}} - y_1 e^x \left[\phi - (a t_{12} e^{-\frac{b}{T_1}} - \alpha_{23} + a t_{34} e^{-\frac{b}{T_4}}) \right] = \frac{v}{b \sigma_2} \left\{ \text{Ei}(\phi x e^{b \sigma_2 \tau_0}) - \text{Ei}(\phi x) \right\}$$

Solving for y_1 ,

$$y_1 = \frac{\frac{v}{b \sigma_2} \left\{ \text{Ei}(\phi x e^{b \sigma_2 \tau_0}) - \text{Ei}(\phi x) \right\}}{e^{\phi x e^{b \sigma_2 \tau_0}} - e^x \left[\phi - (a t_{12} e^{-\frac{b}{T_1}} - \alpha_{23} + a t_{34} e^{-\frac{b}{T_4}}) \right]} \quad (13)$$

Equation (13) gives the deuterium concentration, y_1 , in the liquid solution at the core exit as a function of copper ion concentration.

Gas Let-Down

As long as saturation is not reached equations (9), (12) and (13) describe the relation between y and x fairly well. When saturation is exceeded, however, deuterium gas will come out of solution. If the saturation concentration of deuterium is constant throughout the system, the rate at which deuterium gas is evolved is given by

$$\frac{dL}{d\tau} = v - axy_{\text{sat}} e^{-\frac{b}{T}} \quad (14)$$

where L = loss of D_2 in bubbles $\frac{\text{lb mols } D_2}{\text{lb-mol sol'n}}$

y_{sat} = saturated concentration of D_2 in liquid phase

Equation (14) represents the rate of loss of deuterium from the liquid as long as the quantity $(v - axy_{\text{sat}} e^{-\frac{b}{T}}) \geq 0$. Since the temperature of a slug of fuel solution passing through the core is rising the quantity $axy_{\text{sat}} e^{-\frac{b}{T}}$ will increase. For some cupric ion concentrations, then, it is possible to reach saturation at some point in the core, produce bubbles for a while and then have the deuterium concentration fall below saturation again before the slug reaches the core exit.

For the case of constant y_{sat} the total loss of deuterium to the gas phase can be calculated by integrating equation (14) over the time interval

$\tau_{\text{sat}} \leq \tau \leq \tau_1$ where

τ_{sat} = time (after entering core) at which the slug of fuel solution becomes saturated.

τ_1 = time ($\geq \tau_{\text{sat}}$) at which either the deuterium concentration in the slug of fuel solution falls below saturation or the slug of liquid leaves the core, whichever is sooner (in the latter case

$\tau_1 = \tau_0 = 11.1 \text{ seconds}$)

548 028

$$\int_0^{L_c} dL = \int_{\tau_{sat}}^{\tau_1} v d\tau - a x y_{sat} \int_{\tau_{sat}}^{\tau_1} e^{-b(\sigma_1 - \sigma_2 \tau)} d\tau$$

Upon integration

$$L_c = v(\tau_1 - \tau_{sat}) - a x y_{sat} (e^{-b\sigma_2 \tau_1} - e^{-b\sigma_2 \tau_{sat}}) \quad (15)$$

where

L_c = total amount of deuterium escaping to the gas phase in one pass through the reactor, $\frac{1b \text{ mols } D_2}{1b \text{ mol sol'n}}$

For most cases the value of τ_1 of equation (15) is equal to the average residence time in the core (i. e. $\tau_1 = \tau_o = 11.1 \text{ sec.}$). For these cases the value of y_1 , is the saturation concentration of deuterium at the core exit.

In some cases, however, τ_1 may fall somewhere in the range $\tau_{sat} \leq \tau_1 \leq \tau_o$.

The time τ_1 represents the point in the reactor core at which the deuterium recombination rate equals or begins to exceed the deuterium production rate (i.e. when $\frac{dL}{d\tau} = 0$). At this time

$$v = a x y_{sat} e^{-b(\sigma_1 - \sigma_2 \tau_1)}$$

Solving for τ_1

$$\tau_1 = \frac{1}{\sigma_2} \left[\sigma_1 - \frac{1}{b} \ln \frac{a y_{sat} x}{v} \right] \quad (16)$$

In these instances y_1 will not be represented by the saturation value for deuterium at the core exit but is found by integrating equation (11) over the range $\tau_1 \leq \tau \leq \tau_0$ and $y_{\text{sat}} \leq y \leq y_1$, and solving for y_1

$$y_1 = e^{-\phi e^{b\sigma_2\tau_0}} \left\{ y_{\text{sat}} e^{\phi e^{b\sigma_2\tau_1}} + \frac{v}{b\sigma_2} \left[\text{Ei}(\phi e^{b\sigma_2\tau_0}) - \text{Ei}(\phi e^{b\sigma_2\tau_1}) \right] \right\} \quad \text{.....(17)}$$

The time at which saturation is reached in the fuel solution, τ_{sat} , is dependent upon the cupric ion concentration and the value of y_{sat} at this time. To determine the value of τ_{sat} equation (12) is written for the time range $0 \leq \tau \leq \tau_{\text{sat}}$

$$y_{\text{sat}} e^{\phi_{\text{xe}} b\sigma_2\tau_{\text{sat}}} - y_1 e^{x \left[\phi - (at_{12} e^{-\frac{b}{T_1}} - \alpha_{23} + at_{34} e^{-\frac{b}{T_4}}) \right]} = \frac{v}{b\sigma_2} \left\{ \text{Ei}(\phi_{\text{xe}} b\sigma_2\tau_{\text{sat}}) - \text{Ei}(\phi x) \right\} \quad \text{.....(18)}$$

Values for τ_{sat} may be found by trial and error from equation (18) and Figure 8.

When the HRT is operating in the temperature range 210°C to 260°C with a total pressure of 1100 psia the saturation value of deuterium is essentially constant (see Figure 8) and equations (15), (16) and (17) are useful in determining the fraction of gas let-down. For most of the cases considered in this report (operation at temperatures up to 300°C) the saturation value

for deuterium, y_{sat} , varies with temperature (and consequently with time γ). Since the recombination rate term $axy_{\text{sat}} e^{-\frac{b}{T}}$ is sensitive to the value of y_{sat} it is necessary to attempt to take this variation into consideration.

The value for y_{sat} can be estimated from Henry's Law

$$y_{\text{sat}} = \frac{p_{\text{D}_2}}{K_{\text{D}_2}} \quad (19)$$

where p_{D_2} = partial pressure of D_2 in gas phase, psi

K_{D_2} = Henry's Law Coefficient for D_2 , $\frac{\text{psi}}{\text{mol fraction}}$

The partial pressure of deuterium in the gas phase can be found by considering the overpressure on the system. The overpressure, p_g , is defined as

$$p_g = p_T - p_{\text{D}_2\text{O}}$$

where

p_T = total operating pressure, psi

$p_{\text{D}_2\text{O}}$ = partial pressure of water vapor at the fuel solution temperature, psi.

The partial pressure of deuterium is assumed 2/3 that of p_g ($2/3 \text{ D}_2$ and $1/3 \text{ O}_2$).

Some values of K are [5]

T, °C	K, $\frac{\text{psi}}{\text{mol. fract.}}$
300	1.98×10^5
280	2.30×10^5
260	2.66×10^5
240	3.60×10^5
220	4.73×10^5
200	6.21×10^5
180	7.25×10^5

Values for y_{sat} have been computed as a function of temperature for several total operating pressures. These are plotted on Figure 8.

From a knowledge of the average residence time and the temperature distribution in the core, it is possible to approximate the y_{sat} versus temperature curves of Figure 8 by straight line relations for the region near the core exit (i.e. $\sim 6 \text{ sec} < \tau \leq 11.1 \text{ sec.}$) of the form

$$y_{\text{sat}} = \beta_1 - \beta_2 \tau \quad (20)$$

where $\beta_1, \beta_2 = \text{constants}$

In this case equation (14) becomes

$$\frac{dL}{d\tau} = v + \beta_2 - ax y_{\text{sat}}(\tau) e^{-\frac{b}{T(\tau)}} \quad (21)$$

Substituting for $y_{\text{sat}}(\tau)$ and $T(\tau)$

$$\frac{dL}{d\tau} = v + \beta_2 - ax (\beta_1 - \beta_2 \tau) e^{-b(\frac{1}{\sigma_1} - \sigma_2 \tau)} \quad (21a)$$

For the cases considered in this paper where γ_{sat} is variable with time the value of γ_1 is equal to γ_0 (= 11.1 second). Equation (21a) can be integrated over the time interval $\gamma_{\text{sat}} \leq \gamma \leq \gamma_0$ to find the total loss of deuterium to the gas phase in one pass through the circulation loop

$$\int_0^{L_c} dL = \int_{\gamma_{\text{sat}}}^{\gamma_0} (v + \beta_2) d\gamma - ax \int_{\gamma_{\text{sat}}}^{\gamma_0} (\beta_1 - \beta_2 \gamma) e^{-b(\sigma_1 - \sigma_2 \gamma)} d\gamma$$

Solving for L_c

$$L_c = (\beta_2 + v)(\gamma_0 - \gamma_{\text{sat}}) - \frac{\phi x}{b \sigma_2} \left\{ \left[\beta_1 b \sigma_2 - \beta_2 (b \sigma_2 \gamma_0 - 1) \right] e^{b \sigma_2 \gamma_0} - \left[\beta_1 b \sigma_2 - \beta_2 (b \sigma_2 \gamma_{\text{sat}} - 1) \right] e^{b \sigma_2 \gamma_{\text{sat}}} \right\} \quad (22)$$

The fraction of deuterium (and oxygen) in the let-down stream is then given by

$$f_{\text{L.D.}} = \frac{L_c}{v \gamma_0} \approx 7265 \frac{L_c}{P_c} \quad (23)$$

where $f_{\text{L.D.}}$ = fraction of radiolytic gas in let-down stream.

The fraction, f , of radiolytic gas which is recombined internally is then

$$f = 1 - f_{\text{L.D.}} \quad (24)$$

Percent Radiolytic Gas Recombined Internally

FIG 2

FIG 3

FIG 4

FIG 5

MINIMUM Cu^{++} CONCENTRATION
VS
CORE EXIT TEMPERATURE
FOR 100% INTERNAL RECOMBINATION

Power = 5 Mw

Cu^{++} CONCENTRATION, gm-mols/liter

TEMPERATURE, °C (Core Exit)

overpressure constant at 150 psia
total operating pressure constant at 2000 psia

base 0.002 = 1

FIG 6

548 835

UNCLASSIFIED
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5
6
7
8
9
10
38

D₂ Concentration (liquid phase) in D₂O
Blanket VS Cu⁺⁺ Concentration
Core Power ~ 5 Mw, Ave Blanket Temp ~ 280°C

FIG 7

FIG 8

ORNL-IR-Dwg.-13961
UNCLASSIFIED

ORNL-LR-Dwg.-13962
UNCLASSIFIED

FIG 10

548 043

FIG 11

44

FIG 12

Percent Radiolytic Gas Recombined
Internally ~ Power 10 Mw

FIG 13

FIG 16

FIG 17

REFERENCES50

1. Aven, R. E. and Haubenreich, P. N. "Radiolytic Gas Generation Rates in the HRT" CF-55-8-77
2. McDuffie, H. F., Compere, E. L., Stone, H. H., Woo, L. F., Secoy, C. H., "The Radiation Chemistry of Aqueous Reactor Solutions", Reactor Science and Technology, June (1954) TID - 2013
3. Haubenreich, P. N., and Tobias, M., "Use of Copper as an Internal Recombination Catalyst in the ISHR" CF-53-4-292
4. "Tables of Sine, Cosine and Exponential Integrals" Vol. I, National Bureau of Standards.
5. Pray, H. A., Schweickert, C. E., and Minnich, B. H., "Solubility of Hydrogen, Oxygen, Nitrogen, and Helium in Water", Ind. Eng. Chem. p. 1146, 44, 1952.
6. Boyle, J. W., Ghormley, J. A., Hochanadel, C. J., Kieffer, W. F. and Sworski, T. J., "The Radiation Chemistry of Aqueous Reactor Solutions - Part I Radiation - Induced Decomposition", Reactor Science and Technology, March, 1953, TID-2008.
7. Hochanadel, C. J. "The Radiation Induced Reaction of Hydrogen and Oxygen at 25°C to 250°C. Session S.5, Paper No. 549, Geneva Conference.
8. Aven, R. E. "Survey of Gas Pressurization" CF-56-3-17
9. Pigford, T. H. "Explosion and Detonation Properties of Mixtures of H₂, O₂ and H₂O Vapor" ORNL 1322

548-051