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UNION CARBIDE NUCLEAR COMPANY
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MEMORANDUM

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November 13, 1957

TO: T.A. Gens and J.E. Savolainen
FROM: T.J. Carter, Jr., and R.A. Stone
SUBJECT: Zircex Kinetics and Uranium Loss Study

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INTRODUCTION

The Zircex process, a method of preparing fuel elements fabricated of nitric acid insoluble metals for aqueous reprocessing, is currently under development at ORNL (Figure 1). In the high temperature gas phase Zircex process, the zirconium bearing fuels are reacted with hydrogen chloride gas to form hydrogen, zirconium tetrachloride, and uranium trichloride. Zirconium tetrachloride is selectively removed from the hydrochlorination products by volatilization above 300°C. After sublimation uranium trichloride and a nitric acid insoluble residue remain in the hydrochlorinator. The uranium trichloride is dissolved in water and the chloride ion stripped from the solution by a nitric acid distillation prior to solvent extraction.

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ZIRCEX PROCESS
GAS-PHASE HYDROCHLORINATION

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FIG.
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A study made of the effects of temperature, impurities in the hydrogen chloride, flow rates and niobium content on both the reaction rates and insoluble uranium losses in the Zircex process is reported in this memorandum.

PROCEDURE

Details of experimental procedure are given in Appendix A. The following is a brief outline of the experiments performed:

Experiments With STR Type Fuel Element

- 1) Runs were made to determine the effect of moisture in the gas on uranium loss. Three different temperatures were used with each of three different percent moisture streams.
- 2) A run was made with a higher, approximately doubled, hydrogen chloride flow rate.
- 3) The flow of hydrogen chloride was reduced one half by the addition of 50% argon to the gas stream.
- 4) The effect of several carbon dioxide concentrations at 400°C and the effect of several temperatures at 20% carbon dioxide was studied.

Experiment With Zirconium

- 5) A run was made using a cylinder of zirconium to determine the reaction rate of zirconium.

Experiment With Navy Type Fuel Element

- 6) Partial runs were made with a niobium zirconium uranium alloy (10, 6, 84%) to determine comparative reaction rates.

RESULTS

Figure 2 is a plot of the volume of hydrogen evolved from the hydrochlorination as a function of time. Two curves are plotted, one for nearly 100% HCl and the second for 94% HCl and 6% CO₂. Figure 3 is a log-log plot of reaction rate with HCl flow rate. The volatile uranium losses are plotted versus reciprocal temperature in Figure 4.

The effect of temperature and of water content in the hydrogen chloride gas on insoluble uranium losses is presented in Figure 5. The logarithm of the uranium loss is plotted versus temperature with moisture content of the gas as the parameter. Figure 6 is a plot of the ratio of Zr to U in the residue versus the reciprocal of the reaction temperature.

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DISCUSSION OF RESULTS

Reaction Rates

In the work of Jansen and Birbara (2) reaction rates were reported to be chemical rate controlled and to have a reciprocal temperature dependence. At 400°C the maximum rate possible, as predicted from past work, would be the chemical reaction rate of 2 mg/min-cm², approximately one twelfth of the rate of 23.5 mg/min-cm² obtained in the present work. Reaction rates also did not show the expected temperature dependence for chemical rate controlling reaction. The rates of the present investigation were found to be a function of the HCl flow rate to approximately the 0.68 power.

A contradiction occurs in that a chemical rate controlling reaction indicates that mass transfer is great enough so that the process is that of chemical reaction. Two possible explanations are: (1) There must have been some subtle differences such as surfaces of the fuel elements used even though the compositions were comparable; (2) The platinum wire (used to determine if the organic gas impurities were being cracked at the reaction temperatures) is acting as a catalyst for a reaction which accelerates the hydrochlorination. Due to this contradiction a direct comparison cannot be made with past work.

The reaction rates were calculated from the rate of hydrogen evolved at the start of the reaction by assuming four moles of hydrogen chloride react to give two moles of hydrogen:

In past work the reacted weight was found by difference after a known hydrochlorination time. In both cases the initial area was assumed constant.

The general increase in reaction rate with increase in hydrogen chloride flow rate (Figure 3) suggests mass transfer rather than chemical reaction to be the controlling step. For slug flow of the reacting gas past the fuel element, reaction rate should decrease as the percent of hydrogen chloride reacted increases. Similarly, the addition of an inert gas to the feed stream should also reduce the rate of reaction. The results seem to be contradictory in that runs in which essentially complete hydrogen chloride usage was obtained have higher reaction rates than expected; while a run with 50 mole percent argon as a diluant in the gas feed gave a lower reaction rate. The unusual results obtained in this work are believed attributable to convection currents and backmixing resulting from the heating of the down-flowing cool feed gas.

The increase in temperature and decrease in average molecular weight of the gas, as a result of hydrogen chloride reacting exothermically to give hydrogen, made the reacted gas much less dense than the unreacted gas. With gas flow down past the fuel element the decrease in gas density undoubtedly set up convection currents and caused backmixing of the reacted gas with the unreacted gas. A similar effect was noted by Perona (6). Under these conditions the

controlling step of the reaction cannot easily be determined, as raising the reaction temperature would increase the magnitude of convection currents and degree of backmixing. If reaction rate were the rate controlling step, at the lower temperature, an increase in degree of backmixing could result in mass transfer becoming the controlling step. Similarly if mass transfer were the controlling step, at the lower temperature, an increase in the magnitude of the convection currents could result in an increase in mass transferred as a result of reduced film thickness.

Insoluble Uranium Losses

As seen from Figure 5, the uranium insoluble loss is directly proportional to the water content of the gas and the hydrochlorination temperature. Extrapolation of the line drawn for dry gas indicates that minimum losses are about 0.28% for a reaction carried out at 350°C. Lower reaction temperatures are impractical due to the non-volatility of the zirconium tetrachloride at the reduced temperatures.

The lost uranium in the form of an insoluble residue is believed to be zirconium dioxide and uranium dioxide in a solid solution complex (1). This solution may result from the reaction of water (4) and/or oxygen with zirconium and uranium at hydrochlorination temperatures. Losses due to oxygen from other sources will be more difficult to overcome as oxygen is soluble in the fuel elements.

The sample used in this study contained 0.065 weight percent oxygen (determined by vacuum fusion). The reaction of all the dissolved oxygen to form the insoluble residue would not account for the losses obtained. Another source of oxygen is the water gas shift:

Although the equilibria do not favor this reaction, rapid depletion of the moisture by its reaction with the metal would result in a mass action shift. The additional source of oxygen, from the small amount of carbon dioxide present in the hydrogen chloride gas (See Table II for the gas composition), and the dissolved oxygen is more than enough to form the insoluble residue (Appendix C). Heats of reaction for different possible reactions were compared with the calculated heat of reaction for the dry gas, 13 kcal/gmole (Appendix C). The water-gas reaction has a heat of reaction of 8.9 kcal/gmole, the value closest to the calculated value. Heats of reaction for other possible reactions are much too high.

Consequently, any contaminants inducing the oxidation of zirconium and uranium should be reduced to the minimum amounts consistent with the operation of the hydrochlorinator. The difficulties which would be encountered in removing the last vestiges of oxygen and its sources from a large quantity of hydrogen chloride would indicate that less than 0.28% uranium lost would be very difficult to obtain. However, if only the dissolved oxygen in the element were present to react, the percent loss would be 0.006%.

Insoluble Residue Composition

The insoluble residue undergoes a radical increase in UO_2 content at approximately 461°C . Although this composition shown by the curve (Figure 6) is not exactly that of the epsilon phase (11), it is within an order of magnitude of the epsilon phase composition.

Effect of CO_2 on the Reaction

As the amount of CO_2 increases, the reaction rate decreases; at 20% CO_2 the reaction is essentially stopped. After heating at various temperatures with a 20% CO_2 stream the sample had a very thin, hard black coating over the entire surface. The formation of this coating on the reacting surface passivates the reaction. After formation of the shell the reaction with hydrogen chloride will not occur unless the surface film is broken. The coating is probably ZrC , judging from the hardness and the large free energy of the possible reaction:

Volatile Losses

As the losses increase with temperature (Figure 4), a calculation was made to determine if the losses were due to the volatilization of uranium trichloride and/or uranium tetrachloride (Appendix D). Uranium trichloride was found to have too low a vapor pressure at the operating temperatures to explain the losses. The vapor pressure of uranium tetrachloride, at the higher temperatures, could account for the losses. At these temperatures the rate of formation of uranium trichloride in equilibrium with uranium tetrachloride is 1.47 times as great as for the formation of uranium tetrachloride (3). The most favorable condition for uranium tetrachloride formation is near the end of the reaction, when the partial pressure of hydrogen is low and the partial pressure of hydrogen chloride is correspondingly high. If the uranium tetrachloride is carried away from the surface by the turbulent gas stream as soon as it is formed, it would be possible though improbable for this to account for the losses at temperatures above 430°C .

From the slope of the curve in Figure 4 the energy of activation for a possible reaction was calculated and found to be 13 kcal (Appendix D). The slope of the curve corresponds to an exothermic reaction such as for the reaction of uranium trichloride to form uranium tetrachloride.

Losses from entrainment of the solid uranium trichloride by the extreme turbulence near the hydrochlorinator trap and the increased gas velocity resulting from expansion could be a contributing factor in the uranium losses. To reduce loss from this source a more complex trap would be needed or several desublimers in series. The losses from the source are a function of the equipment design.

CONCLUSIONS AND RECOMMENDATIONS

Exclusion of oxygen in any form is most desirable in reducing insoluble uranium loss. Uranium loss, which appears to be an epsilon phase solution, below 0.28% appears unlikely without very pure hydrogen chloride. Experimental tests should be performed with as pure hydrogen chloride as possible to determine the lowest percent uranium loss obtainable.

High reaction rates, 24 mg/min-cm², can be obtained with backmixing present. Reaction rates should be determined with an upflow system on material with different surfaces, area, and shape. Carbon dioxide can passivate the reaction at concentrations above 20%. Niobium in the fuel element reduces reaction rates by as much as 75%.

Work should be done to determine the uranium carried away by a gas stream passing over heated uranium trichloride at various temperatures.

LOCATION OF ORIGINAL DATA

The original data for this experiment are located in Secret Data Books No. 3028 on file at the M.I.T. Engineering Practice School, ORGDP, No. 5628 on file in the office of T.A. Gens, ORNL, and No. 5685 on file with Laboratory Records, ORNL, Union Carbide Nuclear Company, Oak Ridge.

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APPENDIXA. Description of Technique

The samples used in this study were cut from a single large bar of STR type fuel element to obtain, as near as possible, pieces of the same size and composition. After placing a zirconium alloy sample of known geometry and weight in the hydrochlorinator the system was evacuated with an oil pump to avoid undesirable and possibly hazardous reactions of air with both products and reactants in the hydrochlorinator. Prior to initiating the reaction by heating the sample, the reactant gas was allowed to enter and flush out the system.

Upstream of the flow meter (Figure 7) is a gas manifold where argon, carbon dioxide and hydrogen chloride were allowed to enter the system singly or in any desired combination. Initially a single gas was permitted to enter the manifold after evacuation. The entering gas built up the pressure in the system until it was slightly positive to atmospheric. When this pressure difference was reached as seen from a mercury manometer, the gas was vented to the atmosphere through the desublimator. If an additional gas were to be added, the hydrogen chloride flow rate was first adjusted and the flow of the additional gas into the manifold was then adjusted until the total flow rate desired was obtained.

The source of hydrogen chloride used in this experiment was a cylinder of commercial anhydrous hydrogen chloride (Table I for analysis). Since a Karl Fischer analysis on the gas indicated approximately 320 ppm (0.065 mole percent) water, it was used when a slightly wet source of hydrogen chloride was desired. To increase the water content of the gas a bubbler was inserted in the system between the manifold and the flow meter. Aqueous HCl was placed in the bubbler before passing hydrogen chloride gas through the system. The solution when saturated resulted in a constant water content in the gas of 0.33 mole percent.

TABLE IMASS SPECTROGRAPH REPORT ON ANHYDROUS HCl

<u>Impurity</u>	<u>Weight Percent</u>
CO ₂	0.62
N ₂	0.22
O ₂	0.02
A	0.003
H ₂	0.08
Benzene	<10 ppm
Chlorobenzene	<10 ppm
H ₂ O	Not determined (320 ppm by Karl Fischer Test)

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To obtain dry hydrogen chloride a coconut charcoal bed was inserted into the system instead of the bubbler. This was effective in adsorbing the water as noticed by the large amount of water evolved when the charcoal bed was evacuated at 100°C for desorption. Upon obtaining the gas of desired composition and flow rate the system was flushed to insure that the gas of the desired composition was in contact with the fuel element.

To initiate the run heat was added to the hydrochlorinator (Figure 8) from an electric coil jacket. A variac was placed in series with a Sim-Ply-Trol to decrease the fluctuations in temperature from the control set-point. This was not always accomplished as the Sim-Ply-Trol occasionally did not operate correctly. As a result the temperature was controlled primarily with the variac. Successful operation resulted in a temperature change of $\pm 5^\circ\text{C}$; however, $\pm 80^\circ\text{C}$ was encountered for a short time during some runs. The temperature was observed and recorded by a Brown Recorder. The thermocouple was placed next to the sample. During the run heat was continually added to replace the heat lost from the hydrochlorinator. When the temperature of the sample rose excessively, the amount of heat added was reduced by cutting back on the variac voltage setting.

When the reaction started as determined by the white zirconium tetrachloride vapor entering the desublimer, the off-gas was bubbled through a caustic solution to remove the excess (unreacted) hydrogen chloride. Work done by the Chemical Technology Division indicates that water alone is an effective scrubber. This was done to obtain the hydrogen evolution rate. The rate of hydrogen evolution was used to determine the completion of the run and the initial slope of the curve was used to determine the reaction rate.

Upon completion of the run the hydrochlorinator and desublimer were washed with water. The areas where zirconium tetrachloride collected were washed with water and the solution was digested in aqueous HCl. This solution also contained the volatile uranium losses since these deposited in the hydrochlorinator and the desublimer as well. The trap located near the sample was washed with water and the obtained solution digested in HNO_3 . The solutions were centrifuged and the insoluble residues combined. The HCl, HNO_3 solutions and the residue were analyzed for uranium and zirconium.

A summary of the runs and pertinent experimental data are included on Table II.

B. Estimation of Reaction Rate Controlled by Mass Transfer

From Perry's Handbook (8) the following expression is given for determining a diffusion coefficient:

$$D = 0.0043 \frac{T^{3/2}}{(V_A^{1/3} + V_B^{1/3})^2} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}} \text{ cm}^2/\text{sec}$$

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CLOSEUP OF HYDROCHLORINATOR

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Hydrochlorinator

Platinum Wire

Fuel Element

Desublimer

OAK RIDGE NATIONAL LABORATORY

INCHES

0 1 2 3 4 5 6 7 8

TABLE II
SUMMARY OF DATA

Run No. ^a	HCl Flow (cc/min)	Temp. (°C)	Feed Gas Composition (mole % of total gas)			Initial H ₂ Evolution (cc/min)	Initial HCl Utilization ^c	Reaction Rate (mg/min-cm ²)	Uranium Loss (% U in)		Fuel Element Reacted
			H ₂ O	CO ₂	A				Insoluble	Volatile	
3, ^b	78	425	0	0.50	0	27	1.4	15.5	0.7	2.4	STR
1	93	400	0	0.50	0	41	1.1	23.5	0.6	8.9	STR
5	108	550	0	0.50	0	30	1.8	17.2	3.5	26.8	STR
10	185	390	0	0.50	0	39	2.4	22.5	1.7	2.8	STR
3	59	430	0.064	0.50	0	26	1.1	14.5	1.3	5.3	STR
2	59	560	0.064	0.50	0	30	1.0	16.8	2.0	15.8	STR
16	69	590	0.064	0.50	0	-	-	-	3.1	-	STR
2, ^b	75	470	0.064	0.50	0	37	1.0	18.4	2.9	10.1	STR
6	57	410	0.30	0.50	0	19	1.5	11.0	-	-	STR
8	64	600	0.30	0.50	0	23	1.4	13.2	16.0	23.5	STR
4, ^b	88	430	0.30	0.50	0	27	1.6	15.5	2.2	1.2	STR
7	90	400	0.30	0.50	0	20	2.3	11.5	0.8	0.3	STR
15	85	410	0.064	6 - 10	0	22	1.9	12.4	2.9	-	STR
14	157	410	0.064	5.8	0	30	2.6	17.2	2.1	-	STR
9	60	400-600	0.064	20	0	0	∞	0	-	-	STR
13	34	605	0.064	0.50	50	10	1.7	5.8	6.5	21.0	STR
4	59	400	0.30	0.50	0	-	-	4.8	-	-	Navy
5	59	550	0	0.50	0	-	-	3.4	-	-	Navy
11	167	380	0.064	0.50	0	11	7.6	6.3	-	-	Zirconium

^a New reactor vessel used for Runs 4 through 16.

^b Runs 2', 3', and 4' were made by T.A. Gens.

^c Initial HCl utilization is the HCl flow divided by twice the initial H₂ evolution.

With a three component system the approximation that two constituents be taken as a single gas with proportional atomic volumes and molecular weights is made.

For HCl diffusing to the metal surface, H_2 and $ZrCl_4$ were combined using the following information:

	<u>At the Surface</u>	<u>In Main Stream</u>
p_{HCl}	0	1/2
p_{H_2}	2/3	1/2
p_{ZrCl_4}	1/3	0

Bulk Temperature = $500^\circ C$ ($773^\circ K$)
Total Pressure = 750 mm Hg

	<u>$V_{cc/gm\ atom}$</u>	<u>$M_{gm/gm\ mole}$</u>
HCl	25.3	36.5
H_2	7.15	2.0
$ZrCl_4$	129	233

V_{Zr} was determined by assuming the value was approximately equal to that for tin (8).

$$\begin{aligned}
 D &= \frac{0.0043 (773)^{3/2}}{(25.3^{1/3} + 55.8^{1/3})^2} \sqrt{\frac{1}{36.47} + \frac{1}{94.2}} \\
 &= \frac{(0.0043)(21500)}{46} (0.195) \\
 &= 0.392 \text{ cm}^2/\text{sec}
 \end{aligned}$$

The amount of HCl diffusing is:

$$N = \frac{D(p - p_1)}{RT \delta}$$

An expression for film thickness (δ) is:

$$\delta = \frac{k}{h}$$

k is assumed to be 0.1 Btu/hr-ft-°F; h is approximated by $h = 0.28\left(\frac{\Delta}{H}\right)^{1/4}$ (7).

With an assumed temperature difference (Δ) of 100°F and a plate height (H) of 0.033 ft,

$$h = 0.28\left(\frac{100}{0.033}\right)^{1/4} = 2.1 \text{ Btu/hr-ft}^2\text{-°F}$$

Therefore

$$\delta = \left(\frac{0.1}{2.1}\right)^{12(2.54)} = 1.45 \text{ cm}$$

and

$$N = \frac{0.392(1/2)}{(1.987)(773)(1.45)} = 2.14 \times 10^{-6} \text{ gm mole/cm}^2\text{-sec}$$

At a typical rate of 15 mg/min-cm², N_A is 3.4×10^{-7} gm mole/cm²-sec.

If ZrCl₄ diffusion away from the surface is controlling, N is calculated to be 1.75×10^{-6} gm mole/cm²-sec. The typical rate of 15 mg/min-cm² is equivalent to 0.086×10^{-6} gm mole/cm²-sec.

C. Insoluble Losses

1) Loss Due to Oxygen Dissolved in Cladding

At a ratio of 80 Zr/U in the insoluble product a total of 162 gram atoms of oxygen per gram atom of U is required if both Zr and U are in the dioxide form. The loss attributable to oxygen in the sample would be:

$$\left(\frac{W \times 0}{16 \times 100}\right)\left(\frac{1}{162}\right)\left(\frac{238}{W}\right) \times 10^2 = 5.9 \times 10^{-3}$$

2) A Calculation of a ΔH for the Reaction Leading to Insoluble Loss

If the equilibrium is assumed, then,

$$\frac{\partial \ln K}{\partial T} = \frac{\Delta H}{RT^2}$$

$$\frac{\ln K_2 - \ln K_1}{\frac{1}{T_1} - \frac{1}{T_2}} = \frac{\Delta H}{R}$$

$$\frac{\ln 0.5 - \ln 16}{1.145 \times 10^{-3} - 1.485 \times 10^{-3}} = \frac{\Delta H}{1.987}$$

$$\Delta H = 13 \text{ Kcal}$$

This calculated value may be compared to ΔH 's for the following postulated reactions:

3) Oxygen Available From the Water Gas Reaction

At a typical reaction time of 60 minutes and an HCl flow of 50 cc/min the total oxygen available would be:

$$\frac{50(60)(5 \times 10^{-3})}{22,400} = 6.7 \times 10^{-4} \text{ gm moles}$$

D. Volatile Uranium Loss

Losses due to either UCl_3 or UCl_4 vapor are estimated for a typical run with $\pi = 750 \text{ mm Hg}$, $T = 600^\circ\text{C}$, a feed gas rate of 50 cc/min, and 60 minutes reaction time. At these conditions $p_{\text{UCl}_3} = 1.6 \times 10^{-4} \text{ mm Hg}$ and $p_{\text{UCl}_4} = 30 \text{ mm Hg}$. The maximum loss attributable to UCl_3 vapor would be

$$\frac{60(50)}{22,400} \left(\frac{1.6 \times 10^{-4}}{750} \right) = 2.9 \times 10^{-8} \text{ gm moles}$$

while the maximum loss attributable to UCl_4 vapor would be

$$\frac{60(50)}{22,400} \left(\frac{30}{750} \right) = 5.4 \times 10^{-3} \text{ gm moles}$$

At a typical volatile loss of 20% at 600°C the actual gm moles uranium volatile losses are:

$$\left(\frac{1.85}{100} \right) \left(\frac{20}{100} \right) \frac{1}{238} = 1.6 \times 10^{-5} \text{ gm moles}$$

From the slope of the volatile loss an energy of activation can be calculated as follows:

$$\frac{\Delta E}{R} = \frac{\ln L_1 - \ln L_2}{\frac{1}{T_2} - \frac{1}{T_1}} \quad \text{where: } L = \text{percent lost}$$

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

$$\Delta E = \frac{(1.987)(\ln 40)10^3}{0.565} = 13 \text{ Kcal/gmole}$$

The slope of curve is correct for energy of activation for an exothermic reaction such as the equilibrium to UCl_4 .

E. Determination of Percent Water

π is approximately 750 mm Hg for most runs.

An aqueous HCl solution (41.3 m/o) will at 25°C have a particular partial pressure of water.

$$\begin{aligned}\pi &= P_{\text{HCl}} + P_{\text{H}_2\text{O}} \\ &= 745 + 2.45 = 747 \approx 750 \text{ mm Hg}\end{aligned}$$

As the $p_{\text{H}_2\text{O}}$ does not change much over a small range, the mole percent of H_2O is $2.45/747(10^2) = 0.33$.

From the gas analysis there is 320 ppm H_2O present in the HCl cylinder gas. Therefore the mole percent water is,

$$\frac{320/18}{10^6/36.5}(10^2) = 0.065$$

F. Determination of Reaction Rates

From H_2 evolution data at $t = 6$ minutes, $V'_{\text{gas}} = 100$ cc

and at $t = 25$ minutes, $V'_{\text{gas}} = 542$ cc

$$\frac{\Delta V'}{\Delta t} = \frac{542 - 100}{25 - 6} = 23.2 \text{ cc/min}$$

The inerts were 1.8 cc/min and the flow rate is approximately 22 cc/min. A correction must be made for the collection over caustic at 26°C.

$$p_{\text{H}_2\text{O}} \text{ over caustic} = 20 \text{ mm Hg}$$

$$\pi = 750 \text{ mm Hg}$$

$$\text{Therefore, } (21.4)\left(\frac{273}{299}\right)\left(\frac{730}{750}\right) = 19.0 \text{ cc/min}$$

Therefore the mg Zr reacted/min is,

$$\left(\frac{19.0}{22.4}\right)\left(\frac{1}{2}\right)(91.2) \times \frac{1000}{1000} = 38.7 \text{ mg/min}$$

As the initial surface area is $2(0.27 + 0.30 + 0.91) = 2.94$, the initial rate is 13.2 mg/min-cm².

G. Nomenclature

- D = diffusivity, cm^2/sec
- ΔE = activation energy, Kcal/gm mole
- H = length of fuel element, ft
- ΔH = heat of reaction, Kcal/gm mole
- ΔH_v = heat of vaporization, Kcal/gm mole
- K = equilibrium constant
- L = percent volatile uranium lost
- M = molecular weight, gm/gm mole
- N = rate of gas transfer, $\text{gm mole}/\text{sec-cm}^2$
- N_A = experimentally determined rate of gas transfer, $\text{gm mole}/\text{cm}^2\text{-sec}$
- O = weight percent oxygen in element
- P = pressure of gas in main stream, atm
- P_i = pressure of gas at surface, atm
- R = gas constant, $1.987 \text{ cal}/\text{gm mole-}^\circ\text{C}$
- T = temperature, $^\circ\text{K}$ or $^\circ\text{C}$
- V = atomic volumes, $\text{cc}/\text{gm atom}$
- V' = volume of off gas, cc
- W = weight of element, grams
- h = heat transfer coefficient, $\text{Btu}/\text{hr-sq ft-}^\circ\text{F}$
- k = thermal conductivity, $\text{Btu}/\text{hr-ft-}^\circ\text{F}$
- p = partial pressure
- t = time, minutes
- Δ = difference in temperature between gas and fuel element, $^\circ\text{F}$
- π = atmospheric pressure, mm Hg
- δ = film thickness, cm

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