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REPORT
on
PROCESS DESIGN STUDIES
of a
TRITIUM RECOVERY PROCESS
USING
DUAL TEMPERATURE EXCHANGE
WITH
METAL HYDRIDES
by

Robert F. Benenati

January 22, 1976

MASTER

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INFORMAL REPORT

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I. SUMMARY

Studies have been made of the process characteristics of a plant to decontaminate tritiated water using dual temperature exchange with vanadium hydride. Feed to the plant consists of 300 Kg/day of water containing one curie per kilogram of tritium. The recycle water ("pure water") contains only 1% of the tritium fed to the plant.

A reference design was developed based on a decontamination factor of 10^2 and 10 Kg/day of enriched product. This design requires a total of 48 ideal separation stages, 22 stages in the enriching section and 26 stages in the stripping section, with each stage operating between temperatures of 0°C and 60°C. Only low grade heat is required for the heating cycle and a relatively small (12 Ton) ice machine is required for the cooling cycle. Vanadium hydride was selected for the solid phase and a total plant inventory of approximately 10 tons is required. Based on an assumed price of 10 \$/#, a capital investment of around \$200,000 is required just for the vanadium. A unique mechanical design of the dual temperature stage complete with all heat transfer surfaces and flow diverters has been devised and modeled.

Assessing the complete capital cost of this reference plant has not yet been attempted. All that can be said at this time is that we see no single item of equipment which requires any technological development.

Various process conditions have been studied to appraise the effect of changing the decontamination factor, changing the split between enriched product and recycle water, and so on. There appears to be no reason to expect significant improvements in the process at design conditions different from those selected. The reference design described herein has been developed with

an eye toward minimizing the need for compressors and blowers since, if operating difficulties were to develop, it is expected they would develop in this area. Furthermore, it seems reasonable to associate such minimization with cost minimization even prior to obtaining a detailed cost estimate for the entire plant. It would appear that there is no reason to refine the reference design further until more is learned experimentally about the long-term life expectancy of the metal hydride's isotope effect under practical operating conditions.

No studies have yet been made of the dynamic response of the system. Such studies are important for two reasons: (1) to expose problems associated with control of the process if any exist, and (2) to determine the effect of temperature transients on product specifications. Since the essence of the process involves periodic swings in temperature from 0°C to 60°C and back, a substantial portion of the overall operation at any point in time is expected to be in unsteady state transition from one state to another. This may affect results which thus far have been based on ideal stages and equilibrium conditions, and is therefore important, but must wait for analysis until better kinetic data are available.

A two step experimental program has been presented. The first step consists of a single stage unit, i.e., one hot bed and one cold bed operating in a simple closed loop. This experiment is developed in some detail. The second step in the experimental program would consist of five stages operating as a small cascade.

II. INTRODUCTION

1. Description of a New Design of a Dual-Temperature Separation Stage

BNL studies to date have indicated that the separation factor for H-T exchange on vanadium dihydride follows the equation

$$\alpha = 1.9 - 0.0063T(^{\circ}\text{C})$$

Thus the separation factor $\frac{(T/H)_{\text{solid}}}{(T/H)_{\text{gas}}}$ is 1.9 at 0°C but only 1.52 at 60°C. Figure 1-A shows schematically how this difference in α might be used to effect a separation of tritium from hydrogen. Assume a gas stream at concentration A enters a cold bed of VH_2 which bed had previously been equilibrated while hit with feed gas of the same composition. At the start of such an operation the cold VH_2 will have a tritium concentration represented by point D whereas its equilibrium concentration will be that represented by point E. In moving from point D to point E, the solid phase will remove tritium from the gas phase causing its tritium concentration to fall to point F. At breakthrough, i.e., when most of the solid phase is at point E, the process must be terminated since no further change in concentration of the inlet gas is possible. If at this point, the bed of solid VH_2 is heated to the temperature represented by the curve (y vs x) hot, and flow of feed gas is continued, the feed gas will pick up tritium from the solid since the solid tritium concentration is in excess of the equilibrium value and will approach point G in concentration. The solid will be losing tritium and will return to the concentration at point D. The net effect of the passage of gas at concentration A through this dual temperature bed will be to separate part of it into a lean gas at concentration B and the remainder of it into a rich gas at concentration C.

Figure 1-A

Figure 1-B

Obviously the necessity to maintain concentration gradients in a real device restricts the gas and/or solid phases from achieving equilibrium concentrations. Figure 1-B indicates the relationship which can be expected to exist between actually achievable concentrations and the corresponding equilibrium values. It can be seen that the actual separation (C'B'), will be less than the ideal separation (C-B).

Returning to the idealized representation shown in Figure 1 and based on a concentration X_o at point A, the concentration of the solid at point D will be $X_o \alpha_{hot}$; that of the gas phase at points B or F will be $\frac{X_o \alpha_{hot}}{\alpha_{cold}}$; that of the solid at point E will be $X_o \alpha_{cold}$; and that of the gas at points C and G will be $\frac{X_o \alpha_{cold}}{\alpha_{hot}}$. The effective separation per stage represented as C/A is equal to the ratio $\alpha_{cold}/\alpha_{hot}$, whereas the effective separation represented as C/B is equal to $(\alpha_{cold}/\alpha_{hot})^2$. Assuming operation of the hot and cold beds at 60°C and 0°C, respectively, the effective α is 1.25. Clearly many of these dual-temperature stages will have to be assembled in a cascade to effect any significant concentration of tritium.

If the interstage gas flow is to be at the temperature of the cold bed, it will be necessary to heat a portion of the stage flow before it enters the hot bed and to cool it after it leaves the hot bed. Furthermore, it will be necessary to interrupt the flow periodically and to heat one bed and cool the other prior to readmitting the gas. This interruption in the gas flow would be extremely undesirable and could be avoided by having a second duplicate set of beds which would be valved off-line and be heating or cooling. At the end of a given cycle, the flow would be diverted from the active pair of beds to the pair being heated and cooled. While this second pair is active in H/T exchange, the first pair could be going through the heating-cooling cycle.

A practical stage design which accomplishes all of the above is shown in Figure 2. Half of the manifolding and valving required is also shown. The manifolding and valving required for the beds indicated as inactive and for the heat exchangers surrounding the beds indicated as active would be identical to that shown and would be oriented 90° to the plane of the drawing.

2. Detailed Description of Stage Operation

The complete cycle of operations for a single stage would be as follows:

Cycle 1 Bed

- A Cooling
- B Cold-Active
- C Heating
- D Hot Active

Cycle 2 Bed

- A Cold-Active
- B Heating
- C Hot-Active
- D Cooling

Cycle 3 Bed

- A Heating
- B Hot-Active
- C Cooling
- D Cold-Active

Cycle 4 Bed

- A Hot-Active
- B Cooling
- C Cold-Active
- D Heating

Figure 2 depicts the flows and valve settings for Cycles 1 and 3 in the above sequence. Cycle 1 is indicated by the dashed arrows while Cycle 3 is indicated by the solid red arrows. During Cycle 1, butterfly valve 1 is set to direct the stage inlet flow to the inner manifold while closing off the outer manifold.

MANIFOLDING ≠ VALVE DETAILS FOR HALF STAGE

Figure 2

The inlet gas divides, part flowing through Bed B, the remainder flowing through the heat exchanger surrounding inactive Bed C where it is heated to the hot bed temperature. Valve 3 is set to direct the effluent from Bed B to the next higher stage. Valves 2 and 4 are set to direct the effluent from the heat exchanger to active Bed D. Flow through this hot bed is in the direction counter to that which was taken when the bed was used at the cold temperature. Effluent gas from the hot bed is directed to the heat exchanger surrounding Bed A after which it passes on to the next lower stage.

At the conclusion of Cycle 1, the interstage flow piping (accented with heavy lines in Figure 2) is valved off while comparable piping connected to previously inactive beds of this stage is valved in thus permitting process gas to flow without interruption.

At the conclusion of Cycle 2, process gas flow is returned to Beds B and D but with valves 1 through 4 having been switched to their alternate positions. Part of the inlet flow passes through Bed D (which is now cold) to the next higher stage, while the remainder passes through the heat exchanger around Bed A, through Bed B, through the heat exchanger around Bed C to the interstage pipe to the next lower stage.

During Cycle 4 the temperature of Beds B and D are again switched thus completing the cycle.

III. PROCESS DESIGN

1. Overall Plant Flowsheet

This chapter summarizes efforts to date at developing a flowsheet for decontamination of tritiated water using dual temperature exchange with vanadium hydrides. Figure 3 shows an overview of the process for one set of conditions.

Feed to the plant was arbitrarily assumed to be 300 Kg/day of water containing one curie per kilogram of tritium (approximately 0.1% of the expected tritium released from power reactors in the next 20 years). Recycle water ("pure water") was to contain only 1% of the tritium fed to the plant. The remainder of the tritium was to be stored as a relatively stable metal hydride, or might serve as feed to another plant producing tritium to fuel fusion reactors.

As shown in Figure 3, feed water is electrolyzed to produce dry gaseous hydrogen which is fed to the dual temperature plant. (The usual procedure of building a hydrogen isotope separation plant as a parasite to a synthetic ammonia plant - to avoid the cost of the electrolysis step - is probably not applicable in the case of tritiated water.) The electrolytic cells required rank among the smaller units which are currently commercially available. The oxygen generated is indicated as going to waste. The purified hydrogen is also wasted by burning it to water and recycling it to the environment. Obvious process refinements such as recombining the oxygen and hydrogen in a fuel cell to produce electricity to reduce the outside electrical requirements of the electrolytic cells have not been examined, as being outside the range of the present study.

Figure 3. Tritium Concentration Process

Operation of the dual temperature isotope separation cascade requires that the vanadium hydride bed swing between two temperatures, chosen as 60°C and 0°C for this study. Therefore heat energy must be supplied to go from the lower to the upper temperature and refrigeration must be provided when going the other way. In addition mechanical energy must be provided to compress some of the gas which recycles from the cold stream to the hot stream as the tail end of the cascade is reached.

2. Detailed Flowsheet Dual Temperature Cascade

Processing details of the dual temperature cascade are shown in a number of figures and tables. The temperature and pressure levels around the dual temperature cascade are shown in Figure 4. The feed stream enters at the lower left. Approximately 10% of the feed is compressed to 198 psia and joins the hot stream at the entrance to the enriching section which contains 22 ideal stages. The remainder is expanded adiabatically to 6 psia and 0°C and joins the cold stream flowing into the stripping section which consists of 26 ideal stages. The enriched hydrogen stream leaves the left hand end of the cascade at 156 psia and 60°C. The lean hydrogen leaves the right hand end of the cascade at 0°C and 6 psia and therefore requires a booster compressor in order that this stream may leave the process at atmospheric pressure. The feed and booster compressors are both shown to have moderate power requirements.

Complete details of the flow to each of the stages are shown in Figures 5A & B and in Tables 1 and 2. Flows and tritium concentrations shown were determined from stage by stage calculations which were made with a specially written computer program.

Figure 4. Temperature & Pressure Levels Around Dual-Temperature Cascade

Figure 5A shows the enriching section of the cascade, and indicates how the net upflow (the enriched tritium stream) passes through the hot half of the stage. It should be remembered that whereas Figure 3A shows one half of each stage marked hot and the other half marked cold, in reality each half stage is hot for a while, then cold for a while, then hot again and so on. The actual pipe manifolding required to accomplish this alternate switching is not indicated on Figure 5A, but is as discussed in Chapter II. It should be noted that the mass flow for both the hot and cold streams is greatest at the feed tray and diminishes as flow proceeds toward the head end of the cascade. Flow reduction is accomplished by by-passing a small portion of the hot flow to the cold stream at each stage. The by-passed flow is expanded and cooled to the operating pressure and temperature of the cold stream as shown in the sketch below

TYPICAL FLOWS AROUND SINGLE
ENRICHING STAGE

HYDROGEN TO
HYDROGEN = 1.1 atm

Figure 5A. Enriching Section - Dual Temperature Tritium Separation Processes

The entire enriching section can be operated without pumps or compressors to circulate the hydrogen since all required pressure drops can be obtained through slight adjustments of the stage temperature. Table 1 shows the hot and cold side temperatures, pressures and flows for each stage of the enriching section. It also shows the stage cooler duty and the effective separation factor which, since it depends on the stage temperatures, is different for each stage. Figures in Table 1 are based on an assumed 2 psi pressure drop per stage on the hot side and 1 psi pressure drop on the cold side. It should be noted that whereas the temperatures change of less than 0.3°C per stage, it is not necessary to control these temperatures nor is it necessary to control the individual pressures. These temperatures and pressures all follow naturally once the temperatures and pressures at the ends of the cascade are controlled, in much the same manner as do the temperatures and pressures in the individual plates of a distillation column.

Figure 5B shows the stripping section of the cascade. Typical flows are as shown in the sketch below. Since in this portion of an ideal cascade some

TYPICAL FLOWS AROUND SINGLE STRIPPING STAGE

TABLE 1STAGE CHARACTERISTICS - ENRICHING SECTION

Stage No.	H O T S I D E			C O L D S I D E			Cooler Duty Btu/hr	Effective Separation Factor
	Temp. °C	Press. Psia	Flow SCFM	Temp. °C	Press. Psia	Flow SCFM		
21	60.0	156	0.30	24.40	27.4	0.36	44.7	1.316
20	60.27	158	0.66	23.73	26.4	0.78	52.5	1.325
19	60.50	160	1.08	23.10	25.4	1.27	61.5	1.334
18	60.84	162	1.58	22.30	24.4	1.86	72.7	1.346
17	61.12	164	2.16	21.55	23.4	2.54	85.1	1.357
16	61.40	166	2.84	20.77	22.4	3.35	100.3	1.367
15	61.68	168	3.65	19.96	21.4	4.29	117.7	1.378
14	61.95	170	4.59	19.11	20.4	5.40	138.2	1.390
13	62.23	172	5.70	18.23	19.4	6.71	162.7	1.402
12	62.49	174	7.01	17.31	18.4	8.24	191.0	1.414
11	62.79	176	8.54	16.34	17.4	10.04	224.5	1.426
10	62.02	178	10.34	15.32	16.4	12.16	263.9	1.44
9	63.28	180	12.47	14.24	15.4	14.65	310.2	1.454
8	63.54	182	14.96	13.10	14.4	17.58	364.2	1.469
7	63.80	184	17.88	11.89	13.4	21.01	428.2	1.484
6	64.05	186	21.32	10.60	12.4	25.06	503.3	1.5
5	64.30	188	25.34	9.21	11.4	29.80	591.5	1.518
4	64.55	190	30.11	7.70	10.4	35.39	695.2	1.538
3	64.80	192	35.69	6.07	9.4	41.95	815.9	1.558
2	65.04	194	42.25	4.27	8.4	49.65	960.1	1.580
1	65.28	196	49.96	2.27	7.4	58.71	1128.4	1.605
0	65.52	198	49.87	0.0	6.4	58.02	-	1.633

FROM
TO ENRICHING
SECTION

$X = 34.9$

Figure 5B. Stripping Section - Dual Temperature Tritium Separation Process

of the cold low pressure hydrogen should be added to the hot high pressure hydrogen at each stage, a compressor would be required at each stage. A heater is not required since the work of compression is more than enough to bring the gas temperature up from the cold side temperature to the hot side temperature.

Table 2 shows the process conditions at each stage of the stripping section determined from the aforementioned computer program. Also shown in this table are the horsepower requirements of the interstage compressors required in this section of the cascade. It should be noted that the flow variation from stage to stage shown in Table 2 is small in the vicinity of the feed stage and can be ignored with virtually no loss of efficiency in the overall process. Thus, instead of requiring an interstage compressor at every stage, it should be possible to hold a constant flow in stages -1 through -10 with a substantial savings in cost of compressors (though there would be no savings in the work of compression required). It should also be possible to hold flows constant for blocks of five or more stages with a further reduction of the number of compressors required. Maintaining flow constant over a group of stages will increase the cost of the vanadium inventory somewhat, thereby cutting into the compressor savings which might be realized. No attempt has yet been made to optimize this possibility nor to determine its exact effect on overall cascade costs.

3. Effect of Process Parameters

a. Product Split

The effect of changing the split between tritium enriched hydrogen and recycled hydrogen on some of the characteristics of the isotope separation

TABLE 2

STAGE CHARACTERISTICS - STRIPPING SECTION

Stage No.	H O T S I D E			C O L D S I D E			Interstage Recycle Compression Hp.	Effective Separator Factor
	Temp. °C	Press. Psia	Flow SCFM	Temp. °C	Press. Psia	Flow SCFM		
0	65.52	198	49.87	0.0	6.4	58.02	0.065	1.633
-1	65.76	200	49.17	26.68	31	57.89	0.012	1.359
-2	66.00	202	49.04	26.07	30	57.74	0.015	1.368
-3	66.23	204	48.90	25.44	29	57.57	0.018	1.377
-4	66.46	206	48.72	24.80	28	57.36	0.022	1.386
-5	66.69	208	48.51	24.14	27	57.12	0.026	1.395
-6	66.92	210	48.27	23.45	26	56.83	0.032	1.405
-7	67.15	212	47.98	22.74	25	56.49	0.039	1.415
-8	67.37	214	47.64	22.00	24	56.09	0.046	1.425
-9	67.60	216	47.25	21.24	23	55.63	0.057	1.436
-10	67.82	218	46.78	20.45	22	55.08	0.068	1.446
-11	68.04	220	46.23	19.62	21	54.43	0.083	1.458
-12	68.25	222	45.58	18.76	20	53.66	0.101	1.469
-13	68.47	224	44.81	17.86	19	52.76	0.123	1.481
-14	68.68	226	43.91	16.92	18	51.70	0.149	1.494
-15	68.90	228	42.95	15.93	17	50.45	0.181	1.507
-16	69.11	230	41.61	14.89	16	48.99	0.221	1.521
-17	69.32	232	40.14	13.79	15	47.26	0.269	1.535
-18	69.52	234	38.41	12.63	14	45.22	0.328	1.550
-19	69.73	236	36.37	11.38	13	42.82	0.402	1.567
-20	69.94	238	33.98	10.15	12	40.01	0.491	1.584

TABLE 2 (cont'd.)

STAGE CHARACTERISTICS - STRIPPING SECTION

Stage No.	H O T S I D E			C O L D S I D E			Interstage	Effective Separator Factor
	Temp. °C	Press. Psia	Flow SCFM	Temp. °C	Press. Psia	Flow SCFM	Recycle Compression Hp.	
-21	70.14	240	31.16	8.62	11	36.68	0.605	1.602
-22	70.34	242	27.83	7.07	10	32.77	0.774	1.622
-23	70.54	244	23.92	5.37	9	28.16	0.919	1.644
-24	70.74	246	19.32	3.50	8	22.75	1.138	1.667
-25	70.94	248	13.90	1.41	7	16.36	1.419	1.694
-26	71.13	250	7.51	-.97	6	8.85	1.862	1.724

cascade is shown in Figure 6. In developing this figure, the quantity of enriched product was varied from 1 to 50 Kg/day while holding the amount of tritium in this product stream to 99% of the tritium in the feed, i.e., a constant decontamination factor of 10^2 . Curve 1 shows the Kg/day of zirconium which would be required to store the enriched product as $ZrH_{1.9}$. It might be noted that this is independent of the assumed enrichment. Curve 2 shows the total number of ideal stages required. It should be noted that the decrease in required stages as we increase the quantity of enriched product occurs almost entirely in the enriching section. This is because the stage requirement of the stripping section is controlled by the concentration of tritium in the recycled hydrogen and this varies only slightly over the range shown in Figure 6.

b. Decontamination Factor

It is also interesting to note what happens to the cascade as the decontamination factor is changed up or down from that assumed above. Figure 7 shows the number of stages required as the decontamination factor is changed from 10^2 to 10^5 while holding the split constant. In this instance most of the variation in number of stages required occurs in the stripping section with the enriching section remaining essentially constant.

4. Process Control

On passing the gas stream through the metal hydride bed, it first emerges with a T/H ratio in approximate equilibrium with the T/H ratio in the solid phase at the operating temperature. Continued passage of gas through the bed results in a "front" across which there is a sharp change in concentration in the solid phase. This "front" moves through the bed and when it reaches the

Figure 6. Effect of Changing Split in Isotope Separation Cascade

Figure 7. Effect of Decontamination Factor on Stage Requirements for Fixed Split

discharge end, the bed temperatures must be switched along with the flow streams, and the alternate temperature cycle begun. The velocity of movement of this "front" through the bed is not fully understood at this time but is known to be dependent on gas velocity, temperature, prior history of the bed, etc. Dynamic studies must be made to appraise the merits of various policies of control of this cycle. For example, should individual stages in the cascade be cycled independent of the proximity to breakthrough in adjacent stages or should blocks of stages (or possibly the entire cascade) be cycled based on some measure of average conditions? Should a constant mass velocity be maintained through all stages in the cascade (the vanadium inventory was computed on this basis) or should the flow cross section of all stages (or blocks of stages) be held constant, thereby reducing design and construction costs (costs of spares, etc.)? Should all stages have the same flow length or should the flow length be a function of position of the stage in the cascade? These and similar questions need to be answered; however, the present state of knowledge concerning the performance characteristics of these metal hydrides is inadequate to permit the appropriate dynamic studies from being made.

5. Engineering Design of Dual Temperature Stage

A preliminary engineering design of a single stage incorporating both the hot and cold beds as well as a pair of beds in transition from one temperature to the other, heat exchange surface, flow manifolds, switching valves, etc. has been completed and a very preliminary model made. No potential problems in constructing such a separation stage have come to light. In fact, the entire construction technique follows very closely upon existing technology associated with the construction of compact heat exchanger types.

More detailed engineering analysis of this design concept need to be made. In addition, other concepts should be studied so that component design and process design can move ahead jointly.

IV. EXPERIMENTAL VERIFICATION

It is highly desirable to test the concept of the dual-temperature chromatographic separation stage described in this report under conditions approximating those which would obtain in a practical tritium removal plant. The stage calculations of Chapter III indicate that the flow rates which would exist at the head end of a tritium removal plant are such that prototype operation of the head end stage and a laboratory test of the basic concept could be accomplished in a single useful experiment.

1. Single Stage Experiment

The very small flow rates required at the head end of such a plant suggest that for experimental verification, design of laboratory stages might be simplified (i.e. built at lower cost) with no significant increase in operating costs. Specifically, the heat interchanges which were part of the original stage design might be eliminated and all heating and cooling done by external means (a few hundred BTU/Hr). Also, the hot water piping can be replaced by electrical heating coils resulting in a significant reduction in plumbing complexity. Finally, just half a stage need be constructed since intermittent operation between the separation phase and the heating/cooling phase will adequately simulate continuous operation of the complete stage.

The balance of this chapter presents the details of the proposed prototype.

Figure 8 is a flowsheet of the prototype installed in a closed loop, i.e. T-rich and T-poor streams are mixed and recycled to feed point. The recycled feed is shown entering on the left of the flowsheet where a pair of trim valves (manually set) will control the split between the hot unit and the cold unit.

Figure 8. Schematic of Proposed Prototype Experiment

The desired split is approximately 49% to the hot unit and 51% to the cold unit, however, this should probably be one of the parameters varied during prototype operation to study its effect on overall stage performance. The feed line to the hot unit is provided with an electrical heater to bring the gas temperature to approximately 60°C. Block valves 1, 2, 3, and 4 are solenoid operated so that each hydride bed in turn can serve as the hot unit while the other serves as the cold unit. With valves 1 and 4 open and 2 and 3 closed, the upper bed will be operating at the hot temperature and the lower bed will be operating at the cold temperature. Each hydride bed is provided with cooling water to its internal heat exchanger and electrical heating on its outer surface. The hot bed would have the electrical heater turned on and the cooling water turned off to maintain the bed temperature. Conversely the cold bed would have its cooling water turned on and its electrical heater turned off. The exit gas flow from each bed will pass through a rotometer for flow measurement after which a small sample will be removed (continuously) for tritium assay. A make-up stream at the feed composition will be added to the system continuously to maintain a constant feed flow rate. Output from the hot and cold unit plus the make-up stream will be passed through a mixing tank to insure that the feed composition remains constant throughout the experiment. A Sigma pump in a pressure tank will be used to recycle the fluid around the loop. (This pump should probably be located at the discharge of the mixing tank rather than where shown on the flow sheet).

Figure 9 shows the details of the two hydride bed units required for this experiment. The hydride particles are held in the annular space formed of a 1/2-in. stainless steel tube located concentrically within a 1-1/4-in. stainless steel tube. Perforated stainless steel plates serve to contain the hydride particles at either end of the unit. Six equally spaced copper fins

Figure 9. Details of Hydride Bed Unit

bridge the gap between the inner and outer tubes and serve to increase the heat transfer surface during the heating and cooling cycles. Cap assemblies with inlet and outlet connections for the gas flow are joined to a bolting ring at either end of the 1-1/4-in. tube. Suitable bushings are used with each cap to seal the place where the coolant tube passes through the cap. A thin layer of insulation outside the 1-1/4-in. tube and a wrapping of electrical heater wire completes the unit.

Operation of the experiment would be roughly as follows:

1. Preheat one hydride bed to 60°C using the electrical heater with cooling water flow shut off. Simultaneously cool the other bed to 0°C using the cooling water flow with electrical heater turned off.
2. Turn on Sigma pump with solenoid block valves appropriately set.
3. Adjust trim valves to achieve hot and cold flows desired.
4. Monitor heat input to hot unit and cooling water flow to cold unit to maintain desired gas temperature.
5. After a prescribed time interval (based initially on observed breakthrough times) shut off Sigma pump.
6. Use electrical heater and coolant flow to cool hot bed to 0°C and heat cold bed to 60°C.
7. Return to Step 2.

The primary objective of this experiment will be to prove the feasibility of the concept. Specifically, this will be achieved by noting separation achieved as well as the stability of this separation over an extended period of operation. Once the primary objective has been achieved and a "bench mark performance" noted, a number of interesting effects can be studied. There are the obvious parameters of absolute pressure level, temperature range between hot

and cold units, total flow rate, and flow split; all of which have practical significance. In addition there is the very important effect of cycle time on separation efficiency, i.e. how far can one climb up the breakthrough curve before separation efficiency is seriously impaired. Lastly, the entire hydride bed may be unbolted and replaced by one containing another material assuming more than one material are in serious contention when this prototype is operational.

2. Multi Stage Experiment

Assuming overall success of the experimental program described above, the next step would appear to be the testing of a group of stages which could represent a prototype of the head-end stages of a tritium removal plant.

As with the single stage unit, the very small flows involved suggest modifications in the cascade configuration which reduce the valves, pumps, heat exchangers, etc. that are required with (possibly) only a small loss of separation efficiency. The balance of this chapter describes a "unit cell" which might contain from 5 to 10 individual stages.

Figure 10 shows schematically what might be expected from a cell containing 5 stages. The gas concentration labeled (1) represents the upflow from the cell below while the gas concentrations labeled (-1) and (6) are respectively the downflow to the cell below and the upflow to the cell above. The remaining numbered points represent effluent gas concentrations from the individual stages. The points labeled by letter represent the concentration (T/H) of the hydride phase in each stage. As indicated on the insert sketch of typical stage concentrations, the concentration of the solid phase in the hot half of the stage moves from the higher letter to the lower letter whereas

Figure 10. Schematic of a 5-Stage Cell

that in the cold half of the stage moves from the lower letter to the higher letter.

Figure 11 shows the additional piping and valves required to operate a five-stage unit on a continuous basis with countercurrent flow through the hot and cold beds of each stage. During 1/2 cycle, the valves would be as indicated. During the other half cycle (when the bed temperatures would be opposite those shown) all valves marked C would be opened and those marked O would be closed. This valve manipulation at the end of each half cycle might be simplified and the number of valves reduced by a factor of 2 using special two-way plug cocks similar to those sketched below:

Not shown in Figure 11 is the piping, pumps, heat exchangers, etc. needed to close the loop. Stream C requires a pump to bring it up to the pressure level of stream B with which it is joined. A second pump brings the combined stream up to the pressure level of stream A, thus closing the loop. The heat transfer needs are essentially the same as those presented for a single stage in my May 8 memorandum.

Figure 11. Additional Process Piping Required to Operate Continuously (Hot & Cold)

V. CONCLUSIONS

Everything that has emerged from this study to date leads to the conclusion that dual temperature isotope exchange between a gaseous hydrogen stream and a solid bed of metal hydride is both possible and practical. Little is known concerning its economic feasibility. However, since nothing in the process is beyond the present limits of technology, and since the need for tritium in the future is expected to grow, it would appear that further work on this process, especially the experimental described in Chapters III and IV, should proceed with vigor.