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CRYOGENIC HYDROGEN ISOTOPE DISTILLATION FOR THE FUSION FUEL CYCLE

by

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ABSTRACT

Cryogenic distillation is an attractive method for the hydrogen isotopic separations required in fusion fuel cycles. The theoretical and practical aspects of designing and constructing such systems are well established. Practical considerations in the design of systems are presented and applied to the Isotope Separation System (ISS) at the Tritium Systems Test Assembly (TSTA), as well as systems of distillation columns that might be used for a reactor such as the Tokamak Fusion Core Experiment (TFCX) and the recovery of breeding blanket product.

INTRODUCTION

There are a number of different methods which may be used to separate the mixtures of D_2, DT, and T_2 (together with a small admixture of H_2, HD, and HT) which exit as unburned fuel from a fusion reactor chamber. Of the various methods, distillation is the oldest known to man and also probably the best understood. Other methods which have been used or proposed include thermal diffusion, palladium diffusion, gas chromatography, differential hydriding, and laser activated separation processes.

Distillation has several advantages over the other separation methods because the separation factors are relatively large, throughput is high, startup times are relatively short, and there is large design flexibility. A system of columns generally operates at a steady state and therefore control is relatively easy. Most instrumentation has been well developed and is available as off-the-shelf items. While there are large temperature gradients to the low temperature environment of the columns, during operation there is no temperature cycling, and hence fewer mechanical strains are set up in the system. Operating pressures are approximately one atmosphere and there are no large pressure gradients within the system. Several commercially constructed hydrogen isotope separation systems are already in operation, thus it is possible to utilize the existing commercial experience in the selection of column parameters and general design.

The major drawback to distillation as a technique of isotope separation is the relatively large inventory of tritium which is held up as surface film on the column packing and walls or as bulk liquid in the reboiler. Power requirements for the refrigerator necessary to

maintain the *ca.* 25 K temperatures are significant.

While the detailed simulation of a multicomponent distillation column is a complicated mathematical problem, present generation digital computers permit a rapid solution of the equations required to describe the system. Dynamical simulations are possible in addition to steady state solutions which are the basis of system design. Computer studies have also been made of the start-up conditions.[1]

The design concepts developed at the Tritium Systems Test Assembly (TSTA) have been applied to other fusion energy applications such as the separations required for the principal fuel streams at the Tokamak Fusion Core Experiment (TFCX), International Tokamak Reactor (INTOR), and the Technology Development Facility (TDF). Additionally, preliminary distillation system designs have been developed for several different tritium breeding blanket concepts to recover the tritium for use in the main fuel cycle. The earliest design studies were directed at the isotope separations needed at the Intense Neutron Source (INS), which was never constructed.

GENERAL PRINCIPLES

There are several basic principles to be considered in the design of an isotope separation system based on distillation.

1) The order of volatility of the hydrogenic molecules is H2, HD, HT, D2, DT, and T2, with H2 being the most volatile.
2) In general, a column can be designed to provide a specified separation between any two species, called the light and heavy key, which are usually adjacent to each other on the volatility scale. For preliminary design, species more volatile than the light key can be considered to be recovered 100% in the distillate (or top) product while species less volatile than the heavy key can be considered to be recovered 100% in the reboiler (or bottom) product.
3) A minimum of one column is required for each pure product.
4) Simple single columns can be used satisfactorily over a surprisingly wide range of operating conditions and a system of several individual columns may be reconfigured, should system parameters change. The marginal cost of adding an additional column to a system is of the order of 10% of the total cost.
5) While it is possible to remove additional streams at selected locations along a column, to do so will result in a column which is difficult to control and of a generally inflexible design.
6) Similarly, a column may have any number of feeds, but they are specified at the expense of system flexibility.
7) A height equivalent to a theoretical stage (HETP) of 5 cm may be used for columns packed with stainless steel packing such as "Heli-pak".[2] This is suitable

for columns from 1 cm i.d. to about 10 cm i.d.

8) A superficial vapor velocity of 3.5 to 5 in/sec will result in adequate flow without flooding of the packed section. This value is computed based on the unpacked area.

9) Holdup of liquid on the packing amounts to approximately 9.5% of the superficial volume.

10) Tritium has a heat of decay of 0.326 W/g. This manifests itself as a composition dependent heat leak to the column or reboiler.

11) The undesirable species, HT, may be removed by promoting the equilibrium

$$HT + D_2 \rightleftharpoons HD + DT \qquad \text{(Eq. 1)}$$

after which the HD may be removed as an innocuous distillate product and the DT recovered for recycling into the fuel stream.

TSTA

At TSTA, four cryogenic distillation columns have been designed, constructed, and installed to effect the separations required.[3,4] TSTA personnel were responsible for the process design and specifications. Arthur D. Little, Inc. (Cambridge, MA) was selected as the vendor responsible for the engineering design, process control, and construction. The columns are approximately 2.5 cm in diameter, 3-4 meters long, and filled with stainless steel packing. They are operated in two cascaded with no internal return paths. The nominal design feed is assumed to be an equilibrium mixture of 25% D_2, 50% DT, and 25% T_2 (with 1% protium) at a rate of approximately 363 gram-moles/day. The product streams of HD waste (containing only 2×10^{-7} mole fraction HT), 99.99+% D_2 for fueling neutral beams, DT for reactor fueling, and 98+% T_2 to fuel a tritium neutral beam (if one is used) or for experiments requiring pure tritium. In all likelihood, a column to produce pure T_2 would not be needed in an operating reactor, but at TSTA it is required in order to develop the design and operating expertise and to produce pure tritium for experiments.

Figure 1 is a flow schematic of the TSTA isotope separation system (ISS) and the principal design specifications are given in Table I. Column 1 was designed to provide a separation with D_2 as the light key and DT as the heavy key. The reboiler product stream is therefore ca. 67% DT and 33% T_2. This stream is used as the feed for Column 3 which operates as a two component column and provides a distillate stream of DT and a reboiler stream of T_2.

The operation of the system of Columns 2 and 4 is much more complex. These two columns must provide a stream of pure D_2 and a waste stream of HD to remove any protium which found its way into the reactor system. The molecule HT lies midway between HD and D_2 in volatility and is undesirable, yet half of any protium in the system ends up as HT. It cannot be discarded with the HD waste because it contains tritium which would constitute a hazard and there is too much to collect for storage or burial. Therefore, it should be treated as

the heavy key in Column 2. In Column 4, however, the separation is between D_2 which then is removed as the top or distillate stream and DT which is extracted as the reboiler stream. Any HT would necessarily appear in the distillate and contaminate the D_2 which is to be used for neutral beam injectors. Tritium in this stream is also highly undesirable. The solution to this dilemma is to promote the previously mentioned chemical reaction (1) which is one of several which occur when the three hydrogen isotopes are mixed. This reaction is catalyzed by small catalytic converters between Columns 1 and 2, and between Columns 2 and 4. The separation in Column 1 depletes DT in this loop. In addition, a large stream of D_2 is recirculated through the Column 2-4 loop. Both of these steps, together with the separation in Columns 2 and 4 tend to drive the equilibrium reaction to the right side of the equation. Thus the HT molecule is effectively removed from the system allowing the discard of H as HD and the retention of T as DT.

These columns have been operated successfully and several of the important design parameters verified by special experiments. Early experiments were carried out to establish the HETP which was found to be 5 cm. Several runs have been made with the system of columns which combined operator training with production of 50 m^3 of D-depleted H_2 (containing <3 ppm HD) and H-depleted D_2 (containing < 2 ppm HD) for research purposes. Measurements of liquid holdup on the packing and walls and of column pressure drop have been reported recently.[8]

At this time only preliminary results are available for feeds which include H, D, and T. The results are very encouraging and tend to verify that the multi-column system will perform as designed.

Several minor design errors were made in the ISS which, while not affecting overall performance, have proved to be inconvenient. To save a trivial cost, several intercolumn streams were not instrumented with flowmeters, but instead a calculated flow was indicated. This is fine for steady state conditions, however the actual flows are sorely missed during startup when condensation renders calculated flows meaningless. The missing flow transducers are now being installed. Column pressures are measured by MKS Baratron capacitance manometers. These normally work quite satisfactorily, however we chose to use one of the models without temperature compensation and as a result there is an electrical uncertainty of up to several torr mainly due to zero shifts and/or temperature effects. Since we are desirous of maintaining intercolumn pressure drops of the order of 30 torr this presents a control problem. The obvious solution would be to install the slightly more expensive, temperature controlled sensors.

Because there is a 1000-fold volume ratio between liquid H_2 and room temperature gas, it is necessary to have some sort of expansion volume in the system in case of a unexpected rapid warmup of the columns. A 0.37 m^3 was installed in the D_2 recirculation line which feeds into column H. This tank normally is filled only with essentially pure D_2 and hence does not contribute to the tritium inventory. However, in actual operation this tank is a serious operating inconvience. It is difficult to evacuate or purge and hence on startup presents a source of condensable impurities sufficient to freeze and

plug intercolumn flow lines. During operation, flow tends to be in and out of the surge volume rather than directly from one column to another if there are any pressure variations in the interconnected columns. The problem is being addressed by valving the tank out of the system with air-operated valves which will fail open, and a bypass valve. Each of the columns is individually provided with a rupture disk which exhausts into the surge volume. A bleed valve is being installed to allow the tank to be brought up to operating pressure gradually since if it were initially evacuated and then an on/off valve actuated the pressure swing would totally disrupt the operating distillation system.

As delivered, we had specified that there were to be no hard shutoff valves between columns. This has proved to be a great disadvantage when repairs or modifications were necessary because of the relatively large volume of the columns and their interconnection through long lines. With the installation of the individual rupture disks, we are also installing shutoff valves on the reboiler, feed, and distillate lines of each column. These hand-operated valves can be shut for maintenance and leak checking, but would normally remain open with the handles removed. In addition, a microswitch is attached to each valve, and all the switches are connected in series. Thus if any one valve is closed, a potentially unsafe condition is indicated in the control room.

The TSTA isotope separation system is a provides a good example of the flexibility inherent in a system designed with individual columns that are externally interconnected. The question arose of how to recover in case there were to be an accidental release of ca. 100 grams of tritium into the TSTA building. The Emergency Tritium Cleanup system (ETC) would be activated and ca. 85 grams of tritium would be recovered as HTO in various concentrations. With additional equipment the water could be electrolyzed to H_2, HD, and HT. After a replumbing of the four columns of the ISS, the system could be used to separate the HT, which could then be catalyzed according to the reaction

$$2HT == H_2 + T_2. \qquad \text{(Eq. 2)}$$

Another set of columns could then separate the T_2 for reuse in TSTA. While none of the columns would be optimally designed for the task, each would operate within a tolerance band sufficiently wide to permit the recovery operation without requiring an investment in a dedicated, completely separate system which might never be used.

TFCX

For the TFCX tritium processing system, we were requested to prepare a design for the isotope separation system. The feed composition specifications were quite similar to those of the TSTA ISS, except for a much lower flow rate of 4.9 moles/day. There were to be only two product streams, D_2 and T_2, as well as a waste stream of HD. As seen in Figure 2., this can be accomplished with a system of 3 cryogenic distillation columns.

Column 1 is designed, as in TSTA, to provide a principal separation between D_2 and DT. The distillate product, which is mostly D_2, is equilibrated to promote the HT dissociation reaction. Column 2 is designed to provide a separation between HD and HT, thus any ingrowth of protium into the TFCX system is discharged as innocuous HD waste as the distillate product. The reboiler product contains mostly D_2 as well as any HT and DT present in the column feed. The Column 2 reboiler stream is split into two streams with the bulk being recycled to the appropriate location in Column 1 as a principal feed.

The reboiler stream from Column 1 is mostly DT. To remove excess D_2 the stream is passed over a small room-temperature catalyst bed to establish isotopic equilibrium. This reactor is simply about 10 cm^3 of finely divided palladium supported on an inert ceramic substrate. This stream is the feed to Column 3, which separates DT and T_2. The distillate stream containing all of the D_2 and most of the DT is recirculated to same location as the external feed to Column 1, after an equilibration step to shift the species towards a larger fraction of T_2. The reboiler stream is combined with a small quantity of the reboiler stream from Column 2 to provide an essentially equimolar D-T mixture for reactor fueling.

Table II is a summary of the important design parameters for the TFCX ISS system. An important consideration was minimizing the total tritium inventory. At first glance it would seem that Column 1 might be unnecessary. However the recycle stream to Column 1 serves to increase the flows in the top section of Column 1 and thus increase the required diameter. Otherwise, the column would have a design diameter of only a few millimeters, clearly almost impossible to construct and control.

For this design, criteria for D_2 and T_2 product purity were set by personnel from the TFCX team at Princeton University. It is possible, however, to significantly reduce the complexity of the system and the inventory of tritium. If it is assumed that reasonably pure D_2 is still required for fueling neutral beams and that the actual goal is an approximately equimolar mixture of D and T in the torus, then a system of only two columns should suffice. Such a system is shown in Figure 3 and the design specifications are given in Table II. It is possible to prepare a wide range of torus fueling mixtures by varying the flows of the D_2 stream from the reboiler of Column 1 and the DT/T_2 stream from the reboiler of Column 3. By utilizing such a two-column isotope separation system rather than a three-column system, the tritium inventory would be reduced from ~70,000 Ci to only 27,000 Ci since the greatest portion of the inventory is in the lower portion of the packing and the reboiler of the third column.

BLANKET PRODUCT RECOVERY

System designers at the Argonne National Laboratory requested a preliminary design of a system to recover the tritium from breeding blanket. It was specified that tritium would be bred at the rate of 600 grams per day. An eluent of 40 kg/day of H_2 or D_2 would be passed over the blanket material into which tritium would diffuse. Also

present would be ^3He due to the decay of the tritium. The resultant feed stream would contain only a small amount of elemental tritium as most of the tritium would be in the form of HT or DT and hence a high degree of separation is necessary.

The first consideration was a choice of eluent gas. If the choice was D_2 then the species in the feed stream to the distillation system would be basically D_2 and DT along with ^3He, whereas if the eluent were H_2, then the species would be H_2 and HT together with ^3He. The relative volatility for the H_2/HT pair is significantly higher than that for the D_2/DT pair. Hence the decision to utilize normal hydrogen (protium) as the eluent.

A three column system was designed to effect the separations required. The system is shown schematically in Figure 4. The important parameters are given in Table III. The first column is designed with HD as the light key and HT as the heavy key. The small amount of HT in the distillate may be reduced by passing the gas over a small catalyst bed and then into Column 2. In the second column a small stream of *ca.* 1% is removed as the distillate. Because helium is only slightly soluble in liquid hydrogen and the withdrawl from the reboilers is from the liquid phase, any helium will be removed from the system through the top product stream. If there were no flow of hydrogen from the top of column 2, the helium concentration in the upper portion of the distillation column and the condenser would become very high and inhibit the separation. The bulk of the feed is removed as a reboiler product which is recycled to the blanket recovery system. Any HT is thus recirculated and never need appear as a waste product.

The reboiler product of Column 1 is enriched from *ca.* 1% HT to *ca.* 85% HT. At this point there is essentially no T_2. Therefore the stream is sent over a catalyst bed to effect the equilibrium reaction given previously by Equation 2. The feed to Column 3 then contains *ca.* 29% T_2. In column 3 the design separation is between DT and T_2. The D_2 and DT are recycled into Column 1 as the top product and the bottom product of 99.8% T_2 is recovered for introduction into the reactor fueling system.

COMPUTER SIMULATIONS

Several computer codes have been developed or modified to allow the steady state modeling of multicomponent distillation columns.[6,7,8] Features such as variation of enthalpy with species, phase, and composition rather than assuming equal molal heats and equal molal overflows; and nonideality of both the vapor and liquid phases have been incorporated into the codes.[9,10] Also included is the plate-by-plate release of energy due to the radioactive decay heat of tritium.

The separation factors for the separation of the liquid hydrogenic molecules are of the order of 1.1 to 1.5. The consequence is that approximately 60 to 80 stages are required in any one of the columns discussed here. To adequately solve the system of equations generated by the methods employed requires repeated inversions of matricies of dimension 60 x 60 (up to 200 x 200 using some techni-

ques). In some cases, band matricies may be used. However, the matricies are often ill-conditioned and unless the computer can retain a large number of significant figures, errors will creep into the calculations and propagate. While an 8-bit microprocessor with 64K of memory has been used for preliminary design studies which compute first approximations of flows and feed locations, a large mainframe computer such as a CDC-7600 or Cray-1 is necessary for the detailed plate-by-plate calculations of composition, flow, and temperature. Several studies have appeared which would indicate that a large number of small columns might be necessary for the separations required in the fusion energy processes. These studies were unrealistic in that they were limited by the size of computer memory available or the amount of computer time alloted.

SUMMARY

Currently available computer design simulations of multi-component distillation columns coupled with the body of commercial engineering design and fabrication expertise will permit the design and construction of efficient cryogenic distillation systems for the hydrogen isotopic separations which will be required for fusion energy reactor systems. Distillation systems designed with several simple columns provide a flexibility of configuration and operation to permit adaptation to altered feed or product specifications.

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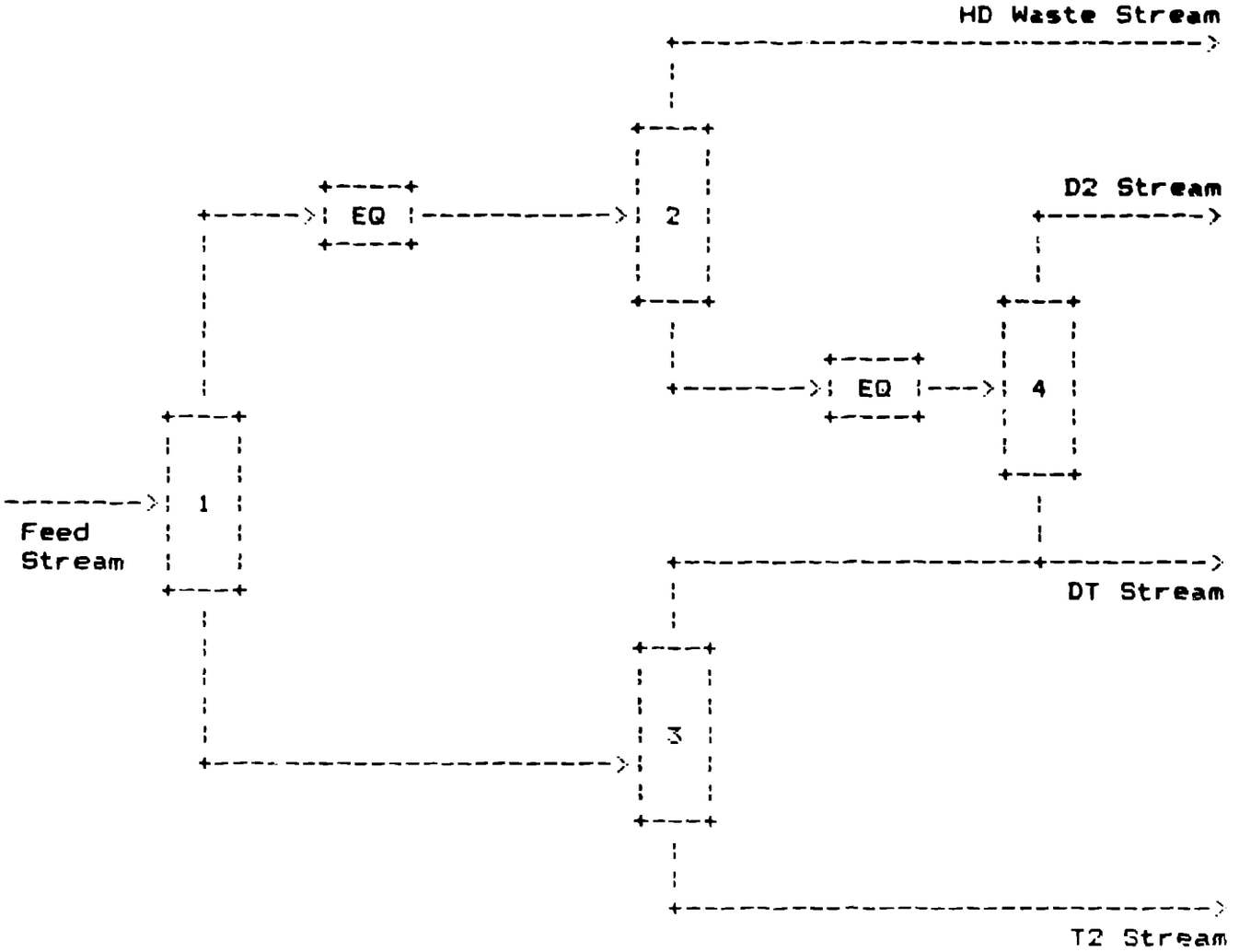

Figure 1.

ISOTOPE SEPARATION SYSTEM FOR TSTA

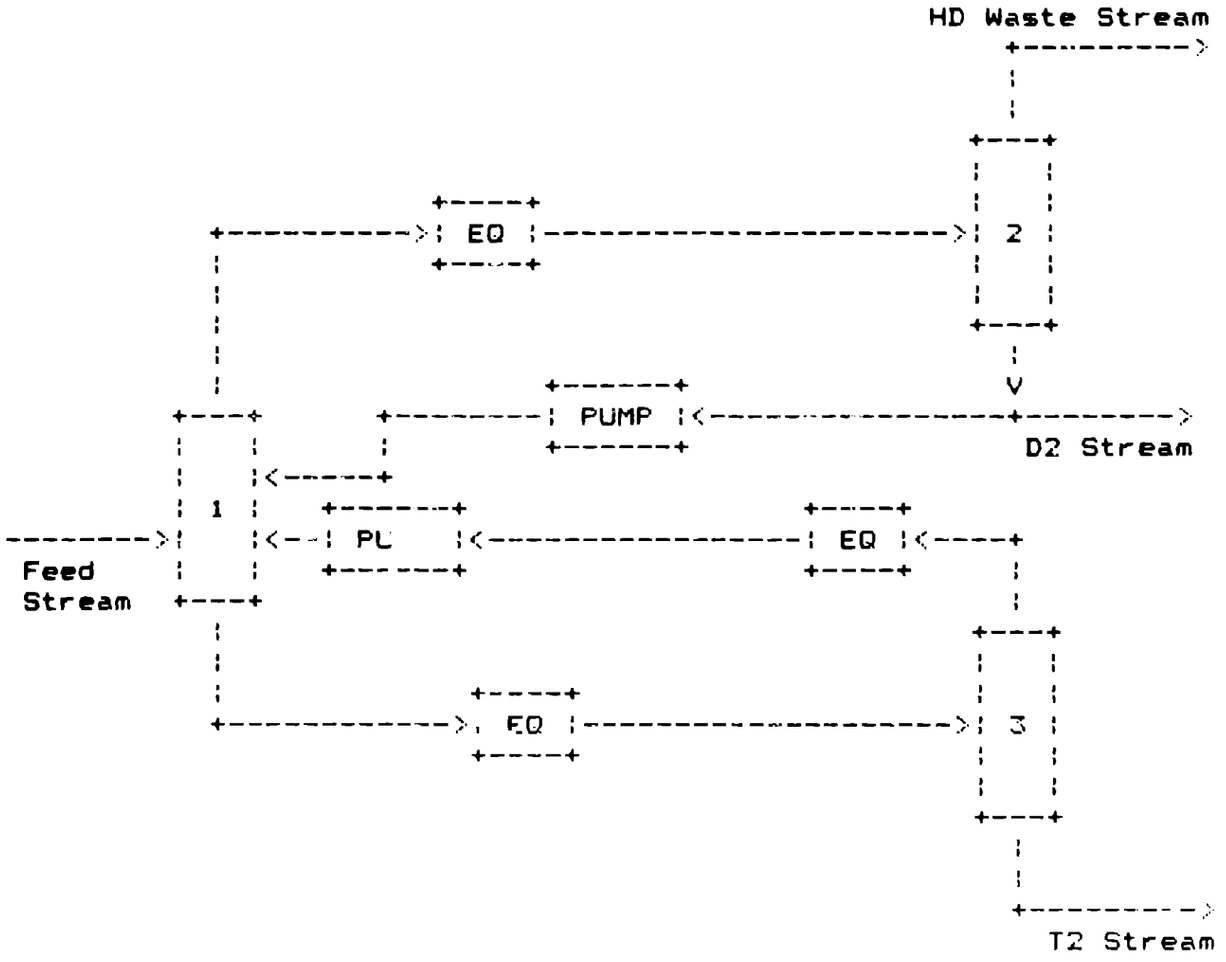

Figure 2.

ISOTOPE SEPARATION SYSTEM FOR TFCX

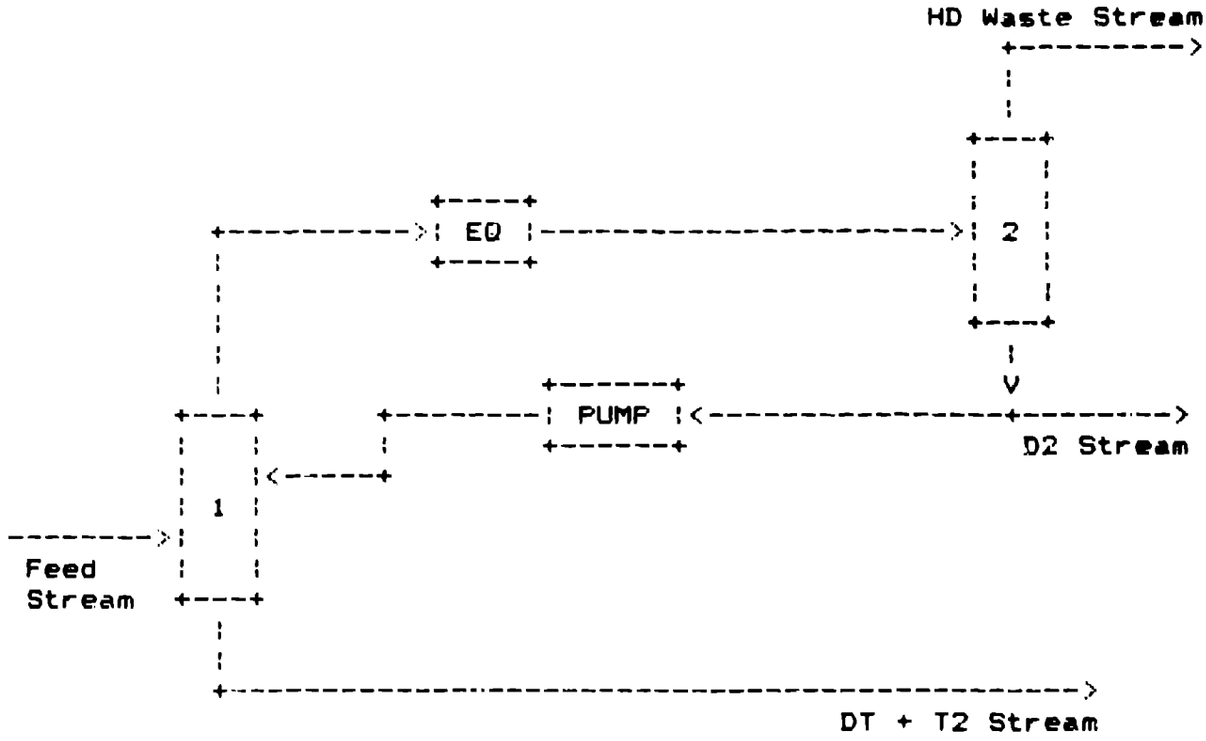

Figure 3.

ALTERNATE ISOTOPE SEPARATION SYSTEM FOR TFCX

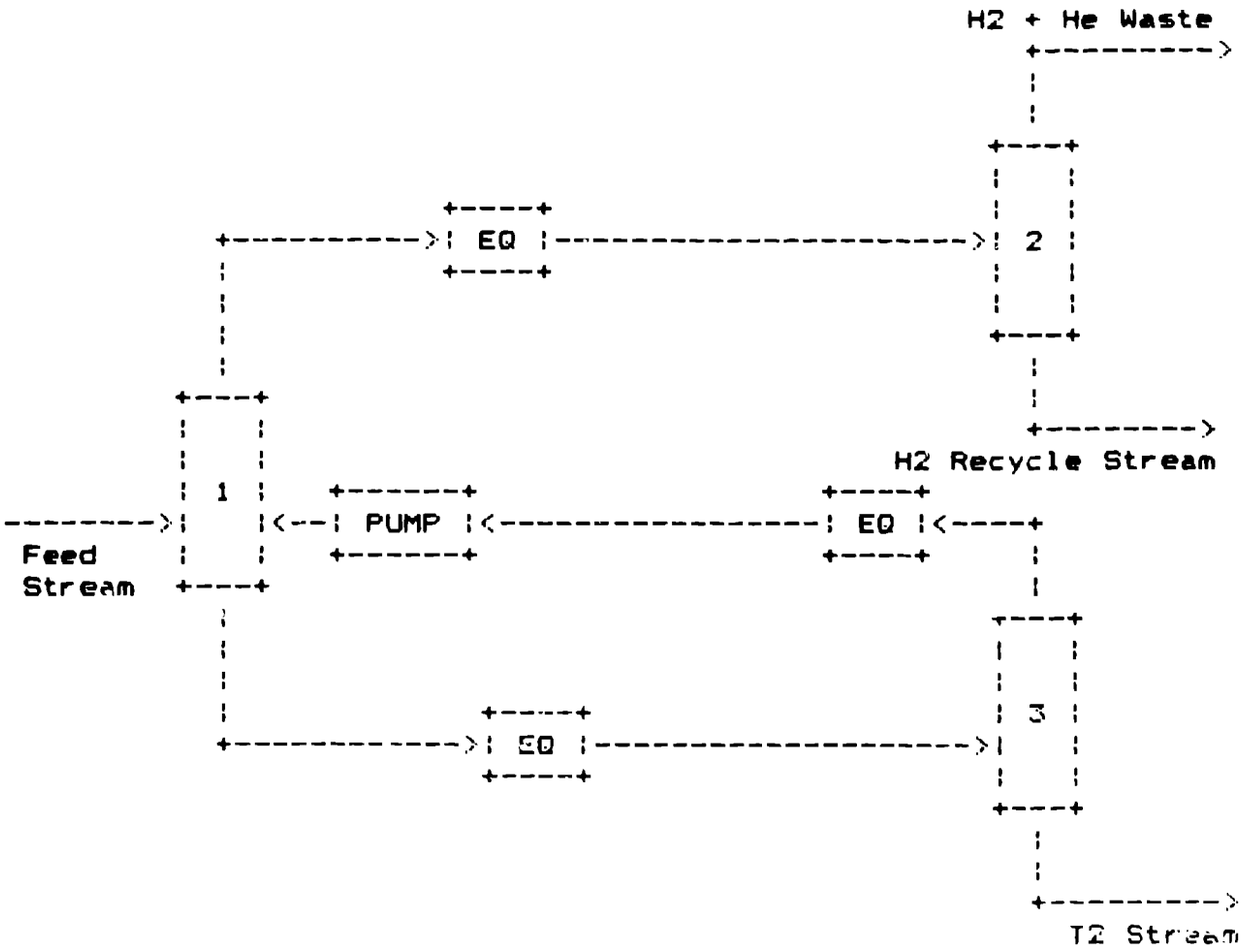

Figure 4.

ISOTOPE SEPARATION SYSTEM FOR ANL BLANKET PRODUCT RECOVERY

TABLE I

COLUMN PARAMETERS FOR TSTA ISOTOPE SEPARATION SYSTEM

	Column 1	Column 2	Column 3	Column 4
# of Stages, Packed Section	81	80	63	81
# of Rectifying Stages[a]	53	54	18	43
# of Intermediate Stages	0	0	0	0
# of Stripping Stages[b]	28	26	45	38
HETP, in.	2.0	2.0	2.0	2.0
Heli-pak Packing	#3008	#3008	#3008	#3008
Packed Length, feet	13.50	13.33	10.5	13.5
Inside Diameter, in.	1.12	0.759	0.975	1.495
Operating Pressure, Torr	860	830	800	800
Condenser Temperature, K	23.97	22.39	24.67	23.81
Reboiler Temperature, K	24.97	23.94	25.32	24.13
Condenser Duty, Watts out	27.26	18.18	27.68	49.09
Reboiler Duty, Watts in	28.05	17.98	30.49	49.62
Reflux Ratio[c]	20.96	192.0	9.76	9.66
Light Key Component	D2	HD	DT	D2
Heavy Key Component	DT	HT	T2	DT
Recovery Fraction Light Key[d]	0.95	0.99	0.995	0.9875
" " Heavy " "	0.0025	0.00005	0.1	0.005
Top Fraction	0.256419	0.019695	0.695520	0.976536
Feed:				
Flow Rate, moles/sec	4.4(-3)[e]	4.4(-3)	3.1(-3)[e]	4.3(-3)
H_2, mole fraction	1.4(-4)	1.2(-4)	[e]	2.9(-8)
HD, mole fraction	1.0(-2)	0.020	3.9(-9)	3.0(-4)
HT, mole fraction	9.3(-3)	1.0(-4)	1.3(-6)	1.5(-6)
D_2, mole fraction	0.248	0.969	0.017	0.989
DT, mole fraction	0.483	0.011	0.649	0.011
T_2, mole fraction	0.249	3.2(-5)	0.335	3.3(-5)
Distillate Products				
Flow rate, moles/sec	1.1(-3)	8.7(-5)	2.2(-3)	4.2(-3)
H_2, mole fraction	5.3(-4)	6.3(-3)		2.9(-8)
HD, mole fraction	0.041	0.994	5.2(-9)	3.1(-4)
HT, mole fraction	0.036	2.5(-7)	1.8(-6)	1.6(-6)
D_2, mole fraction	0.918	7.3(-8)	0.024	1.000
DT, mole fraction	4.7(-3)		0.928	5.7(-5)
T_2, mole fraction	6.1(-8)		0.048	
Reboiler Products				
Flow Rate, moles/sec	3.1(-3)	4.3(-3)	9.5(-4)	1.0(-4)
H_2, mole fraction				
HD, mole fraction	4.7(-9)	2.0(-4)		
HT, mole fraction	1.7(-6)	1.0(-4)		
D_2, mole fraction	0.017	0.989	2.4(-8)	0.527
DT, mole fraction	0.649	0.011	0.011	0.472
T_2, mole fraction	0.335	3.3(-5)	0.989	1.4(-3)
Inventories				
H_2, grams	0.166	3.39	0.000	0.011
D_2, grams	31.3	22.0	7.30	89.5
T_2, grams	24.4	0.10	41.0	5.33
Inventory Totals				
Total H_2, grams	3.57			
Total D_2, grams	153.05			

- Rectifying stages are located in the top section of the column
- Stripping stages are located in the bottom section of the column
- Molar ratio of liquid returning from condenser to material withdrawn as distillate
- Fraction of light key component recovered in the distillate
- Fraction of heavy key component recovered in the distillate
- The number in parentheses represents the exponent of 10, i.e., 1.1(-6) = 1.1×10^{-6}
- Entries left blank are $< 10^{-10}$

TABLE II

COLUMN PARAMETERS FOR A TFCX ISOTOPE SEPARATION SYSTEM

	Three Column System			Two Column System	
	Column 1	Column 2	Column 3	Column 1	Column 2
# of Stages, Packed Section	77	76	77	79	76
# of Rectifying Stages*	15	45	43	16	45
# of Intermediate Stages	55	0	0	48	0
# of Stripping Stages*	7	31	34	13	31
HETP, in.	2.0	2.0	2.0	2.0	2.0
Heli-pak Packing	#3012	#3012	#3012	#3012	#3012
Packed Length, feet	12.83	12.67	12.83	12.83	12.67
Inside Diameter, in.	0.375	0.307	0.307	0.375	0.307
Operating Pressure, Torr	830	800	800	830	800
Condenser Temperature, K	23.93	22.28	24.31	23.93	22.28
Reboiler Temperature, K	24.65	23.81	25.20	24.83	23.81
Condenser Duty, Watts Out	2.48	1.09	2.04	4.05	1.09
Reboiler Duty, Watts In	1.83	1.09	2.14	3.97	1.09
Reflux Ratio*	6.3	873.0	21.3	10.8	873.0
Light Key Component	D2	HD	DT	D2	HD
Heavy Key Component	DT	HT	T2	DT	HT
Recovery Fraction Light Key*	0.95	0.99	0.9945	0.995	0.99
" " Heavy " "	0.001	0.001	0.001	0.001	0.001
Top Fraction	0.761635	0.003473	0.721766	0.876971	0.003473
Feed:					
Flow Rate, moles/sec	5.7(-5)*	3.3(-4)	1.0(-4)	5.7(-5)	3.1(-4)
H_2, mole fraction	1.4(-4)	3.8(-6)	*	1.4(-4)	4.2(-6)
HD, mole fraction	0.011	3.5(-3)		1.1(-2)	3.7(-3)
HT, mole fraction	9.3(-3)	2.4(-6)		9.3(-3)	3.0(-6)
D_2, mole fraction	0.248	0.995	0.232	0.248	0.995
DT, mole fraction	0.484	1.5(-3)	0.492	0.484	1.8(-3)
T_2, mole fraction	0.248	6.0(-7)	0.276	0.248	8.3(-7)
Distillate Products					
Flow rate, moles/sec	3.3(-4)	1.1(-6)	7.5(-5)	3.1(-3)	1.1(-6)
H_2, mole fraction	1.0(-6)	1.1(-3)		2.5(-5)	1.1(-3)
HD, mole fraction	2.2(-3)	0.999		1.9(-3)	0.999
HT, mole fraction	1.3(-3)	6.9(-7)		1.7(-3)	6.9(-7)
D_2, mole fraction	0.996	1.0(-5)	0.322	0.996	1.0(-5)
DT, mole fraction	1.9(-4)		0.678	9.0(-5)	
T_2, mole fraction	3.2(-9)		3.8(-4)		
Reboiler Products					
Flow Rate, moles/sec	1.0(-4)	2.9(-5)	2.9(-5)*	4.4(-5)	1.2(-5)*
H_2, mole fraction					
HD, mole fraction	8.3(-6)	3.5(-5)		8.2(-8)	3.5(-5)
HT, mole fraction	4.7(-5)	2.4(-6)		2.5(-6)	2.4(-6)
D_2, mole fraction	0.168	0.998	1.3(-6)	0.036	0.998
DT, mole fraction	0.615	0.0015	9.7(-3)	0.641	0.0015
T_2, mole fraction	0.217	6.0(-7)	0.990	0.323	6.0(-7)
Inventories					
H_2, grams	0.002	0.57	0.000	0.002	0.57
D_2, grams	6.1	4.3	1.9	5.6	4.3
T_2, grams	1.5	0.003	5.7	2.1	0.003
Inventory Totals					
Total H_2, grams	0.57			0.57	
Total D_2, grams	12.28			9.93	
Total T_2, grams	7.22			2.08	

- Rectifying stages are located in the top section of the column
- Stripping stages are located in the bottom section of the column
- Molar ratio of liquid returning from condenser to material withdrawn as distillate
- Fraction of light key component recovered in the distillate
- Fraction of heavy key component recovered in the distillate
- The number in parentheses represents the exponent of 10, i.e., 1.1(-6) = 1.1×10^{-6}
- Entries left blank are $< 10^{-10}$

TABLE III

COLUMN PARAMETERS FOR AML BLANKET PRODUCT RECOVERY SYSTEM

	Column 1	Column 2	Column 3
# of Stages, Packed Section	38	11	38
# of Rectifying Stages[a]	17	10	14
# of Intermediate Stages	12	0	0
# of Stripping Stages[a]	9	1	24
HETP, in.	2.0	2.0	2.0
Heli-pak Packing	#3008	#3008	#3012
Packed Length, feet	6.33	1.83	6.33
Inside Diameter, in.	4.35	1.40	0.957
Operating Pressure, Torr	830	800	800
Condenser Temperature, K	20.69	20.56	22.33
Reboiler Temperature, K	23.13	20.56	25.22
Condenser Duty, Watts out	330.5	51.70	28.90
Reboiler Duty, Watts in	537.3	53.77	31.80
Reflux Ratio[a]	1.60	25.00	10.00
Light Key Component	H2	H2	HT
Heavy Key Component	HT	HT	T2
Recovery Fraction Light Key[a]	0.998897	0.0100000	0.999616
" " Heavy " [a]	0.007201	5.862(-6)	6.587(-5)[a]
Top Fraction	0.983209	0.0100000	0.767956
Feed:			
Flow Rate, moles/sec	0.233	.231	4.0(-3)
H_2, mole fraction	0.990	1.000	0.265
HD, mole fraction	2.0(-7)	1.3(-8)	1.0(-5)
HT, mole fraction	9.9(-3)	1.3(-6)	0.443
D_2, mole fraction	[a]		
DT, mole fraction	1.3(-9)		1.1(-5)
T_2 ,mole fraction	3.9(-5)		0.292
Distillate Products			
Flow rate, moles/sec	0.231	2.3(-3)	2.8(-3)
H_2, mole fraction	1.000	1.000	0.374
HD, mole fraction	2.6(-8)		1.4(-5)
HT, mole fraction	1.1(-4)	5.2(-8)	0.626
D_2, mole Fraction			
DT, mole Fraction			4.4(-8)
T_2, mole fraction			2.7(-5)
Reboiler Products			
Flow Rate, moles/sec	4.0(-3)	0.229	1.2(-3)
H_2, mole fraction	0.059	1.000	
HD, mole fraction	1.7(-5)	1.3(-8)	
HT, mole fraction	0.855	1.3(-6)	5.8(-4)
D_2, mole fraction			
DT, mole fraction	3.6(-6)		3.9(-5)
T_2 ,mole fraction	0.086		0.999
Inventories			
H_2, grams	588.2	64.9	2.2
D_2, grams	0.001	0.000	0.000
T_2, grams	74.3	0.001	13.1
Inventory Totals			
Total H_2, grams	655.5		
Total D_2, grams	0.001		
Total T_2, grams	87.4		

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[a] Rectifying stages are located in the top section of the column

[b] Stripping stages are located in the bottom section of the column

[c] Molar ratio of liquid returning from condenser to material withdrawn as distillate

[d] Fraction of light key component recovered in the distillate

[e] Fraction of heavy key component recovered in the distillate

[f] The number in parentheses represents the exponent of 10, i.e., 1.1(-6) = 1.1×10^{-6}

[g] Entries left blank are $< 10^{-10}$