TRITIUM MODULE FOR ITER/TIBER SYSTEM CODE

P. A. Finn
Argonne National Laboratory
9700 S. Cass Ave., Argonne, IL 60439

S. Willms
Los Alamos National Laboratory
Los Alamos, NM 87545

A. Busigin and K. M. Kalyanam
Ontario Hydro
Toronto, Ontario CANADA M5G 1X6

ABSTRACT

A tritium module was developed for the ITER/TIBER system code to provide information on capital costs, tritium inventory, power requirements, and building volumes for these systems. In the tritium module, the main tritium subsystems - plasma processing, atmospheric cleanup, water cleanup, blanket processing - are each represented.

INTRODUCTION

The ITER/TIBER reactor will provide a protypical fusion environment for testing leading candidates of nuclear components for power reactors. To aid in the design of ITER/TIBER, a system code was developed. The function of the code was to discover options which either reduce capital cost or result in significant improvements in performance for slight increases in capital cost. A tritium module was developed for the ITER/TIBER system code to provide information on capital cost, tritium inventory, power requirements and building volumes for tritium systems. In the tritium module, the main tritium subsystems - plasma processing, atmospheric cleanup, water cleanup, blanket processing - are each represented. The tritium module has a main module and two submodules. The two submodules provide detailed information on the plasma processing system and the water processing system. Two versions of the module were developed. One version was coupled to the ITER/TIBER code; the second version was a stand-alone module.

In the ITER/TIBER system code, the tritium module is interfaced to the plasma module for the fueling rate and its composition; to the vacuum module for the plasma exhaust rate; to the neutral beams for their input and output rates and composition, to the structural module for building volumes and leakage rates and to the blanket module for breeding ratio and type of blanket. Independent input are provided for atmospheric cleanup (cleanup time, tritium release rates to the environment), and for water cleanup (tritium concentration, flow rate). When decoupled from the ITER/TIBER system code, input must also be provided for plasma, vacuum, neutral beam, structure, and blanket parameters.

MAIN SECTION

The main section of the tritium module has six functions. First, it determines the tritium and deuterium feedrates for the plasma processing units as was done previously.(1) Second, it determines the tritium inventory and capital cost for blanket options other than the aqueous lithium salt solution - flibe, lithium lead, solid oxide, lithium. Third, it sums the tritium inventory in the tritium processing components and in all major units in the fusion plants; this includes tritium in storage. Tritium transport and migration for a limiter or divertor, handled in the plasma impurity control module of the ITER/TIBER code, is an input. Fourth, it determines the tritium supply need at startup and for each year. Fifth, it sums the total capital cost, operating cost, volume, and power requirements for all tritium systems, using information supplied by the two submodules. Sixth, it assesses the tritium loss to the environment as a function of cleanup time, and base tritium concentration. It also calculates the cost of needed atmospheric processing units.

Plasma - In the main section, the plasma processing feedrates include the exhaust from the vacuum pumping system, the fueler system and the blanket system. The fueler options are: a neutral beam system, a pellet fueler system, a combination of these two systems, or an alternate system. Each of these fuelers has a given fuel efficiency which is derived from the ratio between the amount of gas input into the fueler and the amount which is injected into the plasma. Since the magnitude of the plasma exhaust depends on the plasma fractional burn (ratio between the fuel burned and that fueled), an assessment of the relationship between tritium system capital cost, fractional burn and fueler efficiency is an assessment possible using the tritium module.

Blanket - The blanket options are: flibe, lithium lead, solid oxide, lithium, lithium salt/water. Generic algorithms and/or the output from a submodule were used to determine the tritium inventory in the breeding blanket, the tritium inventory in the blanket processing system, and the capital cost of the blanket processing system. The blanket inventory is a function of blanket mass for all blankets.

Inventory - The tritium inventory for plasma processing units or water processing units is calculated in the two submodules. Inventories for other areas are calculated and/or compiled in the main section of the module. A total inventory is provided.

Supply - The tritium supply needs are defined as a function of breeding ratio, processing losses during a year and decay losses for the on-site tritium inventory.

Losses - Tritium losses in four building areas are calculated as a function of cleanup time, in leakage rate, amount of tritium release and tritium base concentration.

Costs - The capital costs of the plasma processing system and the water processing system are determined in the two submodules. A multiplicative factor of four is used with specific plasma processing support equipment - monitors, inventory control instrumentation, secondary containment, etc, to account for needed equipment in the tritium area, in the hot cell, in the reactor hall, and in the fueler area (lasers, neutral beams, etc.). The tritium storage beds are sized and costed on the basis of the reserve storage needed for a 24 hour day of input to the plasma. A separate algorithm which is based on 142 m^3/minute units, (1) was used to determine the number of needed atmospheric processing systems in the four building areas. This algorithm, not that in the plasma processing module, was considered representative for large volumes.

Power - The power needs for plasma processing units or water processing units is calculated in the two submodules. Power needs for other areas are calculated and or compiled in the main section of the module.

Volume - The volume requirements for plasma processing units or water processing units are calculated in the two submodules. Power needs for other areas are calculated and or compiled in the main section of the module. The atmospheric tritium recovery units are larger than glove box cleanup systems, since they cleanup tritium releases in the reactor hall, etc., areas with volumes of 10^5 m^3.

The input variables are: burn time, dwell time, ramp time, fractional burn, fueler options, fuel cleanup option, cost of tritium, type of blanket, blanket mass, water processing option, cleanup time for four areas, inleakage rate for four areas, tritium release for four areas, tritium base concentration in four areas. The major assumptions/options/defaults are: 1) the reactor runs continuously or for one burn time/dwell time/ramp time combination; 2) the neutral beam efficiency is 0.07 to 0.3; 3) pellet fuelers use fuel at levels 1, 2 or 3 times the rate needed to maintain the plasma; 4) the pump regeneration times are < 2 hr; 5) the cost of tritium is <\$1 U.S./10^{10} Bq 6) the breeding ratio is 0-1.5; and 7) a day is a 24 hour operational day.

The output from the tritium module is capital cost, operating cost, tritium inventory, building volume for components, electrical and steam power requirements and unplanned tritium releases. The areas which have the greatest cost contribution are: 1) the blanket tritium systems; 2) the water cleanup system; and 3) the atmospheric tritium cleanup systems. Other tritium areas, monitors, plasma processing, etc., provide smaller differentials in capital cost if input parameters are varied an order of magnitude.

SUBMODULE - PLASMA PROCESSING

A submodule, developed at the Tritium Systems Test Assembly (TSTA), Los Alamos National Laboratory, contains algorithms for the plasma processing subsystem based on the tritium/deuterium plasma processing units at TSTA. The processing units included are a palladium diffuser or a molecular sieve unit for fuel cleanup, a cryogenic distillation unit, storage beds, gas analysis instrumentation, monitors, secondary containment units, a gas effluent unit, emergency air cleanup units, data acquisition units, a solid waste unit, and inventory control unit. The subroutine calculates the tritium inventory, power requirements, size and capital cost (1986 U.S.\$) of a given plasma processing unit as a power function of the tritium and deuterium feedrate. Installation costs were included in capital costs. Costs can be converted to current costs by using a current cost index.

The algorithms used to calculate equipment cost and tritium inventory are:

$$C = C_o\ (I/I_o)\ [(1 - x)\ (D/D_o)^p + x] \qquad (1)$$

$$T = T_o\ [(1 - x)\ (D/D_o)^p + x] \qquad (2)$$

where: C is the current cost, C_o is the original cost, T is the tritium inventory for the current design, T_o is the inventory for the original design, I is the current cost index, I_o is the original cost index, D is the current design value, D_o is the original design value, p is the exponent for the design ratio, and x is the fraction of C_o that is fixed cost. Cost indices used are the Marshall and Swift Equipment Cost Index and the Chemical Engineering Plant Cost Index.(2) The total capital cost is the sum of capital and installation costs. Two rules of thumb for p are: 1) in the process industry, p is about 0.6 (2) and 2) for very small installations or for processes employing extreme conditions of temperature or pressure, p is 0.3 to 0.5.(3). For certain fixed costs, p is 0.

The capital cost and installation cost of the subsystems at TSTA has been published(4); these costs are summarized in Table 1 as are values for p and x. The capital cost was increased for two subsystems: a 0.5 M$ mass spectrometer was added to the gas analysis system and a 0.12 M$ recombiner to the gas effluent system. Neither of these were included in the original TSTA capital costs. In Table 1 installation costs at TSTA are also shown. These installation costs are the costs incurred to insure that all subsystems were integrated. An operating cost for a facility the size of TSTA is also provided in this submodule. During startup when intensive checkout of all systems would be in progress, the operating cost would double.

The original tritium inventories at TSTA(5) are shown in Table 2 as are the exponents used in equation 2.

The input variables to the subroutine are: mass flowrate of tritium and deuterium, reactor hall volume and time to clean the reactor hall. The assumptions made are: 1) the building volume needed for the plasma processing equipment, if it is similar to that at TSTA, is an independent parameter; and 2) a storage bed holds 0.1 kg of tritium.

The ERC(emergency room cleanup) based on the unit at TSTA, has an upper building volume limit of 1 x 10^5 m^3. The flowrate through the ERC is greater than the inleakage rate so that a slight negative pressure is maintained. Cleanup time is less than 5 days; otherwise significant quantities of tritium will be adsorbed on surfaces, resulting in protracted cleanup times. The ERC decontamination factor is assumed to be greater than 10000 for which case cleanup times are independent of the inleakage rate. The target concentration in the area after decontamination is 7.4 x 10^5 Bq/m^3.

The volume of the plasma processing equipment and the ERC are given. These volumes do not include equipment such as the master data acquisition and control computer, emergency generator, uninterruptable power supply, compressors, power distribution panels, or extra storage beds for tritium reserve supply.

SUBROUTINE - AQUEOUS SALT BLANKET

The submodule developed at Ontario Hydro, contains algorithms for water processing and for processing the lithium salt aqueous blanket. This submodule, based on data from Ontario Hydro, calculates the capital cost, the tritium inventory, the building volumes, and the power requirements for a system which could be used to process the aqueous salt blanket or pure water.

This submodule has as options: 1) the type of water - light or heavy water; 2) light water pre-enrichment; 3) a flash unit to remove particulates or dissolved species; and 4) a water processing choice of either vapor phase catalytic exchange/cryogenic distillation or direct electrolysis/cryogenic distillation. System cost, size, and power consumption are calculated as a function of feed concentration and flowrate. Cost correlations were based on Ontario Hydro experience in the design and construction of tritium systems and other published data. No installation or building costs were included in this module's capital costs which were given in 1987 U.S.$.

The aqueous blanket concept is based on the use of near saturated solutions of lithium salts in either light or heavy water, serving as the coolant and the breeding medium. Tritium separation is effected by a system with either a vapor phase catalytic exchange (VPCE) or a direct electrolysis (DE) front end coupled to a cryogenic distillation back end. Two additional units are part of the front end: (a) separation of the tritiated water from the dissolved lithium by means of a flasher unit; and (b) water distillation pre-enrichment to reduce the size of the cryogenic distillation system. Ion exchange for removal of neutron activation products was not incorporated in this submodule. A recombiner to handle radiolytic products was also not incorporated.

Catalytic Exchange - In VPCE, tritium preferentially stays in the water phase. The gas to water vapor flow ratio therefore is 5:1 for H_2/HTO and 2:1 for D_2/DTO. Separation, therefore, occurs in the cryogenic unit. For an equivalent amount of material, D_2/DT separation requires a column more than twice the size as that for a H_2/HT separation.

Table 1: Summary of TSTA Subsystem Cost Data

Subsystem	Cost Capital $K	Cost Inst. $K	Year of Exp.	Design[a] Variable	p	x
Transfer Pumps	111	112	77	F	0.3	--
Fuel Cleanup	1000	70	80	F	0.3	--
Isotope Sep.	1237	63	78	F	0.3	--
Storage Beds	60	10	81	T	0.6	--
Gas Analysis	469	26	79	-	0.0	--
Tritium Monitor	193	33	78-82	V	0.3	0.8
Sec. Contain.	182	30	78-82	F	0.3	0.6
Gas Effl.Detrit.	443	60	80-81	F	0.6	--
Emerg. Cleanup	382	357	79-80	complex		
Data Acq/Control	1379	531	79-81	-	0.0	--
Unint. Power	95	44	80	complex		
Emerg. Gen.	100	168	80	complex		
Solid Waste	23	0	80	F	0.3	--
Inv. Control	25	13	--	-	0.0	--

[a] F is flowrate of 2.08×10^{-5} kg DT/s; T is inventory of 130 g.
V is test cell volume at TSTA, 3000 m^3.
D is room decontamination time, 86400 s.

Table 2: Summary of Tritium Inventory; I_o, for TSTA[a]

Subsystem	I_o, g	p	x
Isotope Sep.	100	0.6	0.44
Fuel Cleanup			
Diffuser	3	0.3	--
Mol. Sieve	30	0.3	--
Gas Effl.Detrit.	2	0.3	--
Other	1	0.3	--

[a] Flowrate is 2.08×10^{-5} kg DT/s. Diffuser is used with turbomolecular pumps.

The assumed number of VPCE stages is 5; this number achieves a detritiation factor of 10.0. The following parameters define the VPCE system: the feed rate of tritiated water (kg/s), the tritium concentration in the feed water (Ci/kg), the tritium concentration in return water (Ci/kg) and the return water flowrate (kg/s). Low pressure steam at 0.6 MPa is required for vaporizing the feed water and high pressure steam at 2.5 MPa for superheating the water vapor-gas mixture. For the same feed water rate, the gas flowrate for the H_2-HTO system is about 2.5 times that of the D_2-DTO system.

Direct Electrolysis - Electrolysis produces an H_2/HT or D_2/DT stream of the same molar flowrate and composition as the H_2O/HTO or D_2O/DTO feed. Thus, for the same separation, a cryogenic unit coupled to an electrolyser is significantly smaller than a cryogenic unit coupled to VPCE.

The electrolysis front end is assumed to be made up of 25 kA electrolytic cell modules. The parameters are the feed rate of tritiated water (kg/s) and the tritium concentration in feed water (Ci/kg). Since electrolytic cells are modular, the cost is directly proportional to scale. Above 70 Ci/kg, double containment of the electrolysis cells is recommended. The cost of the double containment is estimated to be equal to the electrolysis unit cost. This additional cost was not included in the submodule.

Cryogenic Distillation - The largest cost component is the first column in the cascade. The size of the first unit is determined by the feed flowrate to the column (mole/s) and the internal gas circulation rate. The flowrate depends on the feed concentration. The parameters are the feed rate to the cryogenic system (mole/s), and the tritium concentration in the feed (atom fraction T).

Lithium Salt Removal - Prior to tritium extraction, the solution is flashed to separate the water from the Li salt such that the remaining unflashed liquid would have a Li salt concentration not to exceed 90% of the solubility. The parameters for the flash unit are feed rate (kg/s), steam power requirement (w), Li concentration as fraction of solubility limit, tritium inventory of flash unit (Ci), and building volume for flash unit (m^3).

Pre-enrichment of Tritiated Water - Pre-enrichment of low concentration tritiated water can reduce the size of the downstream cryogenic distillation system. Water distillation (WD) is the recommended process; it can be used with either DE, VPCE or LPCE. It will reduce the size of the front end units and the cryogenic distillation unit. At concentrations above 100 Ci/kg, tritiated water begins to pose a life-threatening risk in case of accidental exposure and requires double containment of the WD unit. Double containment increases the cost and the difficulty of maintenance. Pre-enrichment to concentrations greater that 100 Ci/kg is considered undesirable and is not presently addressed by this module.

The tritium concentration in the overhead drawoff stream of the distillation tower (WD) is assumed to be less than 10% of the tritium feed concentration. The parameters for the WD are feed rate of tritiated water, (kg/s), feed tritium concentration,(Ci/kg), top drawoff tritium concentration, (Ci/kg), bottom drawoff tritium concentration,(Ci/kg), volatility of D_2O-DTO system (1.01222), and volatility of H_2O-HTO system (1.06324). For the H_2O-HTO system, an enrichment factor of 10,000 is possible. For D_2O-DTO an enrichment factor of 10 is possible. Therefore, distillation of D_2O is not included in the submodule. The maximum feed rate is 100 kg/h (0.028 kg/s). If higher enrichment or feed rates are specified, multiple columns would be required at additional cost.

The input variables to the Ontario Hydro subroutine include: tritiated water feed, tritium concentration in the feed, pre-enrichment choice, front end choice - vapor phase chemical exchange (VPCE) or direct electrolysis (DE), Li salt concentration as fraction of solubility limit, and mole fraction of light water. The major assumptions made are: 1) water distillation is only economic for light water cleanup; 2) water is either light water or heavy water(no intermediate mixtures); 3) separate correlations are used for light and heavy water; 4) lithium salt solutions are flashed to leave the lithium concentration in the remaining liquid at 90% of the lithium salt solubility limit; 5) in VPCE, 5 stages are used to achieve a detritiation factor of 10; 6) in DE, 25 kA electrolytic cell modules are used; 7) in an electrolysis cell, the tritium concentration in the electrolyte is 12 times higher than the feedwater concentration for H/T and 2 times higher for D/T; 8) above 70 Ci/kg, double containment of the electrolysis cells is recommended but not included in the cost correlation; 9) the largest cost component in cryogenic distillation (CD) is the first column and its cost is correlated to the cryogenic refrigeration requirement; 10) the CD contains a catalytic equilibrator to break up HT and DT; and 11) the water concentration prior to processing is between 0.01 and 34 Ci/L.

Correlations have been developed by Ontario Hydro for cost, power consumption, and cryogenic refrigeration load as a function of feed concentration and flow rate. The cost correlations are based on Ontario Hydro's experience, data on the CRNL Tritium Removal Plant(6), and data on the Tritium Systems Test Assembly (4). The costs include extensive engineering costs but do not include buildings, site services, installation, freight, duty, taxes or any indirect costs such as corporate overhead, etc. The cost equations are the capital equipment costs for procuring such a system from an engineering contractor. All costs are calculated by upgrading known costs to 1987 Canadian$ and then converting to 1987 U.S.$.

RESULTS FROM THE TRITIUM MODULE

A sample of the output from the tritium module is shown in Table 3 for different processing options for an aqueous salt solution blanket, a candidate blanket for an ITER type reactor. As can be seen in Table 3, use of a distillation unit prior to a VPCE unit not only results in a $7M capital cost savings, but also reduces the cryo duty (refrigeration equipment needed) and the volume of needed equipment.

Similar comparisons can be done for the use of direct electrolysis versus VPCE as the main tritium recovery unit or the implications of a low fractional burn on tritium inventory, as was done previously (7).

Table 3 - Different Processing Options for an Aqueous Salt Solution Blanket (18 g/d tritium recovered, 10 Ci/kg)

Salt Present	no	yes	yes	yes	yes
Solubility Limit	--	0.8	0.1	0.8	0.1
Distillation Factor	--	--	--	10	10
Water Flow -kg/s	0.2	2.	0.25	2.	0.25
Process Inv. - g	73	84	81	43	40
Steam - MW	3.6	4.5	4.5	9.7	9.7
Cryo Duty[a] - MW	0.12	0.13	0.13	0.01	0.01
Capital Cost[b] - $M	23	28	25	21	18
Volume[c] - 10^4 m^3	1.5	2.2	1.8	0.9	0.5

---

[a] If an advanced cryo system is used, electrical power needed is 16 times the cryo duty.

[b] This is 1987 U.S. $, no refrigeration equipment is included in the cost.

[c] The volume needed is valued at a minimum of $400/$m^3$. Thus, the use of distillation to concentrate the tritium in the water a factor of ten, results in >$5M capital cost savings.

FUTURE IMPROVEMENTS

Once engineering prototypes of individual blanket processing systems are developed, scaleable algorithms will be available for individual blanket tritium recovery systems to assess tritium inventory and capital cost. Each processing system can be developed as a separate submodule. Once data is acquired for operating systems, algorithms for a given system's reliability and algorithms for general tritium releases for a given system can be incorporated in the tritium module.

REFERENCES

1. Reid, R. L., et al; The Tokamak Systems Code; ORNL/FEDC-84/9, Oak Ridge National Laboratory, March 1985.

2. Peters, M.S. and K.D. Timmerhaus; Plant Design and Economics for Chemical Engineers; 3rd Edition, McGraw-Hill, New York, Chapter 5 (1980) and Chemical Engineering; McGraw-Hill, New York.

3. Aries, R.S. and R. D. Newton; Chemical Engineering Cost Estimation; McGraw-Hill, New York, p.7 (1955).

4. Bartlit, J.R., J.L. Anderson and V.G. Rexroth; Subsystem Cost Data for the Tritium Systems Test Assembly; Proceedings of the 10th Symposium on Fusion Engineering; Vol. 2, 1186 (1983).

5. Bartlit, J.R., W.H. Denton and R.H. Sherman; "Hydrogen Isotope Distillation for the Tritium Systems Test Assembly," Proceedings of the Third Topical Meeting on the Technology of Controlled Nuclear Fusion, May 9-11, 1978.

6. Dombra, A. H.; Estimates for the Recovery of Tritium from Li D_2O Breeder in a 1000 MW Fusion Reactor, Atomic Energy of Canada Ltd., CRNL, TTF-N-1, August 1986.

7. Finn, P.A., R.G. Clemmer, V.A. Maroni, C. Dillow; "Tritium Handling and Vacuum Considerations for the STARFIRE Commercial Tokamak Reactor," Proceedings of the 8th Symposium on Engineering Problems of Fusion Research; Vol. III, 1638-1642 (1979).