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TCODE--A COMPUTER CODE FOR ANALYSIS OF TRITIUM AND VACUUM SYSTEMS FOR TOKAMAK FUSION REACTORS

by

Robert G. Clemmer

FUSION POWER PROGRAM

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

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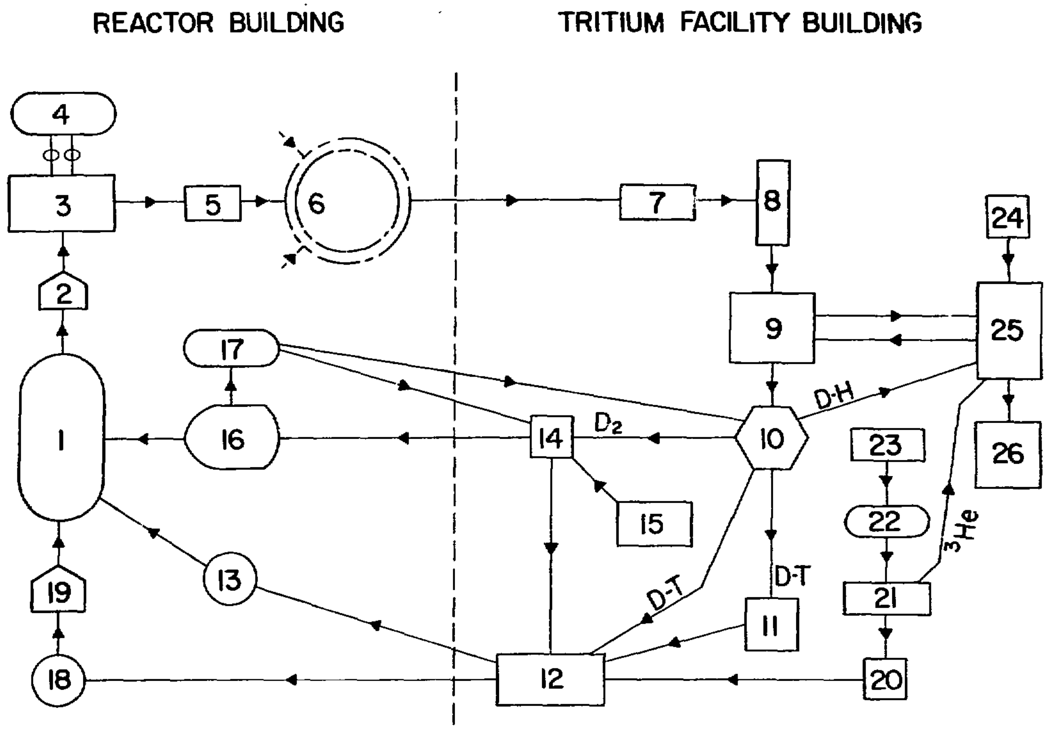
1 Introduction

The Argonne National Laboratory (ANL) systems code[1] was recently upgraded to include a comprehensive package (TCODE) that performs detailed parametric analyses of tritium and vacuum systems. This report is a description of that package. The TCODE was originally developed as a design tool for the analysis of tritium and vacuum systems for the near-term tokamak fusion reactors EPR[2] and TNS.[3] The TCODE was used to carry out parametric trade studies for these near term reactors.[4,5] Detailed design information for the code was also obtained from the Tritium Systems Assembly (TSTA),[6] from a TSTF proposal,[7] and from analyses carried out at ANL and elsewhere.[8-14] The detailed reference points used to develop TCODE all include a complete fuel cycle and they therefore rather closely resemble tritium processing systems for a commercial reactor.[8] Recently, TCODE was revised to include models for commercial reactors. Provisions for the option of a divertor vacuum system were added, so that the code can either simulate systems that evacuate the torus between burn cycles or can simulate divertor vacuum systems, which operate during the burn. The code also includes models for some of the breeding blanket and tritium recovery systems. The code is now an integral part of the ANL systems code, but it can be run independently and as such is a powerful tool for analysis of tritium and vacuum systems.

2. Fuel Cycle Scenario

The fuel cycle scenario that was developed for TNS[3] and EPR[2] is shown in Figure 1. Major features of the fuel cycle will be discussed below (for details, see References 2 and 3). All the portions of the fuel cycle for a commercial reactor are shown except those related to tritium recovery from the blanket. Following Figure 1, the spent DT fuel is exhausted from the torus either through vacuum ducts or divertor slots to the main vacuum pumps, assumed to be compound cryopumps with separate DT cryocondensation pumping backed by He cryosorption panels.[14] From this point, the fuel is passed to the tritium facility for chemical purification, isotopic separation, and preparation for refueling as cold gas or pellets. Also shown is the neutral beam injector system, which is assumed to input deuterium atoms. There are auxiliary systems that include tritium recovery, shipment-receiving, storage, waste processing, and safety systems.



1. TORUS
2. DEBRIS SEPARATOR
3. VACUUM PUMPS
4. SAFETY SURGE TANK
5. REGENERATION PUMPS
6. CONSOLIDATION MANIFOLD
7. TRANSFER PUMPS
8. COMPRESSOR
9. IMPURITY REMOVAL
10. ISOTOPIC ENRICHMENT
11. D-T STORAGE
12. FUEL BLENDER
13. COLD FUEL INJECTOR
14. D_2 STORAGE
15. D_2 SUPPLY
16. NEUTRAL BEAM INJECTOR
17. BEAM PUMPING SYSTEM
18. FUEL LIQUIFIER
19. PELLET INJECTOR
20. T_2 RECEIVER/STORAGE
21. HELIUM REMOVAL
22. HOLDING TANK
23. T_2 SUPPLY HOOKUP
24. PURGE/EFFLUENT PROCESSING
25. WASTE CONSOLIDATION
26. WASTE DISPOSAL

Figure 1. Fuel cycle scenario for a tokamak reactor.

3. Development of Computational Algorithms

3.1 Plasma and D-T Mass Balance

The sizes and costs of the components of the tritium and vacuum system are functions of the throughput rates. Therefore, it is necessary to determine D, T, He and impurity mass flow rates throughout the cycle (Figure 1). This is done by first obtaining a mass balance for all components in the plasma chamber, then each component is followed throughout the cycle. The inputs to the TCODE that determine flow rates in the plasma e.g., fusion power (P_{th}), burn time (t_B), and fractional burnup (F_b), are calculated in plasma physics routines external to TCODE. The inputs are then used to calculate input, burnup, and exhaust rates. The amount of tritium burned per cycle B_c is given by:

$$B_c = \frac{P_{th} \cdot t_B \cdot 10^6 \cdot 3.0}{E_F \cdot 10^{-12} \cdot 6.02 \times 10^{23}} = 4.99 \times 10^{-6} \cdot P_{th} \cdot t_B / E_F \quad (1)$$

where P_{th} = thermal power (MW), t_B = burn time (s), and E_F = energy per fusion (pJ). From this, the tritium input F_c and exhaust T_{exc} per cycle are then calculated, using the fractional burnup F_b.

$$F_c = B_c / F_b \quad (2)$$

$$T_{exc} = F_c - B_c \quad (3)$$

Just prior to startup, cold DT gas is loaded into the torus and the amount of tritium in grams (T_i) is

$$T_i = n_i \cdot \tfrac{1}{2} \cdot V_p \cdot 3.0 / 6.02 \times 10^{23} \quad (4)$$

where n_i = DT ion density (ions/m^3) and V_p = plasma volume (m^3). The amount of tritium fueled (probably as pellets) per cycle (T_{Fc}) is simply

$$T_{Fc} = F_c - T_i \quad (5)$$

The amount of deuterium exhausted per cycle is simply 2/3 of T_{exc}. The neutral beams, however, supply deuterium to the plasma at the rate of $\dot{D}°$ (g/cycle) which is given by

$$\dot{D}° = \frac{P_B \cdot 10^6 \cdot t_{NB} \cdot 2.0}{U_B \cdot 10^3 \cdot 1.6 \times 10^{-19} \cdot 6.02 \times 10^{23}} = 0.02075 \cdot P_B \cdot t_{NB}/U_B \quad (6)$$

or, on a daily basis,

$$\dot{D} = \frac{\dot{D}° \cdot 3600 \cdot 24}{t_B + t_D} \text{ g/day} \quad (7)$$

where P_B = neutral beam power (MW), t_{NB} = neutral beam duration(s), U_B = neutral beam energy (keV), t_B = burn time(s) and t_D = dwell period between burn(s). Then the amount of deuterium input per cycle is (D_{inc}) is given by

$$D_{inc} = (F_c \cdot 2/3) - \dot{D}° \quad (8)$$

This amount is then rationed to determine the amount of deuterium fueled as pellets and cold gas.

The eight equations and derived relationships discussed above set the mass flow rates of D and T with respect to the plasma chamber. Further, the flow rates of other species (e.g., ^1H, He) can be calculated or estimated. The helium ash in the plasma exhaust is simply 4/3 the amount of tritium burned. The other impurity levels in the plasma exhaust are scaled from estimates previously described.[3] The flow rates of the individual species can now be followed throughout the system.

Tritium inventories generally scale with mass flow rates. The pump inventory is set by the regeneration time, which is likely to be about four hours, allowing time for cooldown. Since the tritium processing system including the cryogenic distillation unit operates at a constant flow, it is necessary to provide surge tanks. The other rather small inventories in the fuel processing system are scaled from TNS and EPR values. The fuel preparation inventory is based upon an estimate of liquid DT necessary for the pellet maker. The storage is assumed to be 30 days burn. The decay losses from the inventories, TDPY are then calculated. The annual tritium consumption (T_{AN}) rate is calculated, including losses from burnup and production from breeding. A negative consumption value ($T_{AN} < 0$) implies net tritium production.

3.2 Torus Evacuation System

If there is no divertor, the vacuum pumps are assumed to operate between burns, and the required overall pumping speed (S_{tot}) is

$$S_{tot} = V_T \cdot \ln(P/P_o)/t \tag{9}$$

where V_T = torus volume (m^3), P = postburn gas pressure (Pa), P_o = preburn pressure (Pa), and t = portion of the dwell period (t_D) available for pumping = $t_D - t_L$. It should be noted S_{tot} is a strong function of P_o and t. It is difficult to operate with t less than about 20 s. Analyses have suggested[2,3] that P_o should be about 4×10^{-3} Pa. The required DT pump speed S_p is computed by solving the duct conductance equations:

$$S = S_{tot}/N \tag{10}$$

$$C_{en} = 0.059 \cdot D^2 \cdot 39.37^2 \cdot 0.86 \cdot 0.31 \cdot \sqrt{(T_G/\overline{A})} \tag{11}$$

$$C_d = 0.079 \cdot 39.37^3 \cdot D^3 \cdot [0.86/(39.37 \cdot L)] \cdot 0.31 \cdot \sqrt{(\overline{T}/\overline{A})} \tag{12}$$

$$C_{ef} = [(1/C_d) + (1/C_{en})]^{-1} \tag{13}$$

$$S_p = [(1/S) - (1/C_{ef})]^{-1} \tag{14}$$

where N = number of vacuum ducts, C_{en} = conductance at entrance to duct (m^3/s), C_d = duct conductance (m^3/s), C_{ef} = effective duct conductance (m^3/s), T_G = postburn gas temperature (K), $\overline{T}$ = beam duct temperature (K), $\overline{A}$ = average molecular weight, D = duct diameter (m), and L - duct length (m). The duct conductance is strongly dependent on the duct diameter, being a function of D^2 and D^3. There is also an optimization routine in the program which calculates the minimum duct diameter for a given pump speed.

In the program the required speed for He is calculated independently of that for DT, in the manner described above. The required helium speed then determines the area of cryosorption surface required per pump. The cryosorption surface is assumed to have a pumping speed of 50 m^3/s per square meter.

The required pump capacity is simply the product of the cycle averaged gas load rate and the loading time, which is equal to the regeneration time (4 hours).

If the system has a divertor, the pump speed is then the gas load rate divided by the pressure maintained at the pump ($\sim$ 0.01 Pa). Again the pumps are assumed to be compound cryopumps and the required He and DT speeds are calculated independently.

3.3 Neutral Beam Vacuum System

The required pump speed in the neutral beam injector is the gas load rate divided by the pressure maintained (10^{-2} Pa). The pumps are assumed to be Zr-Al getter pumps. The required surface areas are calculated, assuming a speed of 46 m^3/s per m^2 of surface area. The gas loads also determine the amount of deuterium in the neutral beam recycle, which will contain some impurities and will require some purification and isotopic enrichment. The tritium backstreaming into the neutral beams (T_B) can be estimated by:

$$T_B = \frac{2.5 \times 10^{-24} \cdot n_i \cdot V_p \cdot t_{NB} \cdot A_{BD} \cdot Z_i \cdot N_B}{A_T \cdot \tau_p^{\circ}} \qquad (15)$$

where n_i = ion density of plasma (ions/m^3), V_p = plasma volume (m^3), t_{NB} = neutral beam duration(s), A_{BD} = surface area of neutral beam port at first wall, Z_i = number of neutral beam injectors, N_B = number of burn cycles per day, A_T = torus surface area, and τ_p° = particle confinement time at startup.

3.4 Emergency Air Detritiation System (EDS)

The processing rate R_{EDS} (m^3/s) for the EDS is calculated by:

$$R_{EDS} = \frac{V_{Bldg}}{\varepsilon \cdot t_{EDS} \cdot 3600} \ln (T'/T^{\circ}) \qquad (16)$$

where V = building volume (m^3), ε = efficiency, t_{EDS} = allowable time for air detritiation operation, T' = initial tritium concentration after maximum credible release, and T° = tritium level at which EDS is shut off and building air is exhausted to the stack. The maximum credible release is taken to be the maximum tritium inventory in the reactor building including the cryopumps, the tritium recovery systems and the pellet fueling systems. The tritium storage is in a barricaded vault and the fuel processing units are located in the tritium facility building. Both volumes associated with these items are small and they require, therefore, smaller EDS processing rates. Experimental and computer modeling studies carried out at ANL[17] have suggested that the cleanup time should be no longer than 48 hours.

3.5 Capital Cost Algorithms

3.5.1 Torus Vacuum Systems

The torus vacuum system is assumed to use compound cryopumping. The unburned DT fuel is pumped by cryocondensation, followed by cryosorption pumping for He.

A cryosorption pump has a unit cost of \$750 per m^3/s pump speed for helium. The cryocondensation pump is estimated to have a unit cost of \$300 per m^3/s. It is assumed that there are two sets of pumps operated in tandem for regeneration purposes. Conventional regeneration pumps (roots blowers, e.g.) will cost about \$300 per m^3/s of total vacuum pumping speed. Large hard-seal metal gate valves are a development item. Available cost figures for valves up to 80 cm in diameter scale as the diameter to the 1.6 power. The derived cost algorithms area:

$$\text{He cryosorption pumping} = \$750 \cdot S_{He} \cdot 2\ N$$

$$\text{DT cryocondensation pumping} = \$300 \cdot S_{DT} \cdot 2\ N$$

$$\text{Regeneration pumping} = \$300 \cdot S \cdot N$$

$$\text{Hard seal metal valves} = \$78{,}500 \cdot D^{1.6} \cdot 2\ N$$

3.5.2 Neutral Beam Vacuum System

The neutral beam vacuum system is assumed to use Zr-Al getter panels having a unit speed of 4.6 ℓ/s/cm^2 with a unit pumping cost of \$750/m^3/s. There is assumed to be a twofold excess of area in order to allow for panel regeneration. The cost of regeneration is estimated to be 20% of the getter costs. The overall cost C_N of the neutral beam vacuum system is:

$$C_N = 1.4 \cdot 750 \cdot S_{NB} \cdot Z_i \cdot 2 \ .$$

where S_{NB} = required pumping speed for neutral beams (m^3/s) and Z_i = number of neutral beam injectors.

3.5.3 Tritium Processing

The total cost of the fuel processing system including auxiliary equipment in the tritium facility building is dominated by a few items. These include the isotope separation unit, the EDS, the pellet fueling system, gloveboxes, and piping. The costs are based upon TNS and EPR design studies, the MLM/ANL TSTF proposal, the TSTA, and cost analyses performed at ANL. The costs in the tritium processing facility should scale as the square root of the flow rate. Further, there are practical minimal sizes for these items, once the decision is made to have a complete fuel cycle. The costs, C_i, therefore, of fuel processing and tritium facility items are expressed as:

$$C_i = C_i^o + C_i' \ (R_T)^{1/2}$$

where C_i^o = fixed costs, C_i' = scaling factor, and R_T = tritium throughput rate (g/day). The derived constants C_i^o and C_i' are listed in Table 1 below.

The capital cost of tritium recovery from the blanket C_{TREC} is represented by:

$$C_{TREC} = \$5000. \cdot \dot{T}/[T]^{1/2}$$

where $\dot{T}$ = tritium production rate (g/day), and [T] = tritium concentration in the breeder blanket, wppm.

Table 1. Capital Costs Scaling Factors for Fuel Processing

Item	C_o (\$K)	C_o' (\$K/$R_T^{1/2}$)
Double-walled transfer piping and valves	520	20.
Gloveboxes, purifiers, inst., auxiliary equipment	1700	70.
Cryogenic distillation cascade	540	22.
Misc. items - storage, waste processing, analysis, etc.	1100	16.
TOTAL FUEL PROCESSING	3860	128.

3.5.4 Emergency Air Detritiation System

The EDS system is an item of significant cost. Comparisons of capital costs of existing systems showed that the average unit cost for $\sim 10^4$ cfm systems was \$500/cfm (\$1.06 x $10^6/m^3/s$). Further, there is some economy of scale. However, in practice there will be a number of smaller units (about ten) rather than one large one to provide redundancy and to provide the capability of processing tritium releases in small contained volumes as well as the reactor room. There is a minimum cost of such systems of about \$1.0 M. The cost of the EDS, C_{EDS} is therefore expressed as

$$C_{EDS} = R_{EDS} \cdot 1.06 \times 10^6 + 1.0 \times 10^6$$

4. Results and Discussion

TCODE can be used for either near-term experimental reactors or for commercial reactors. The code provides options for items that may be included in a commercial reactor such as a divertor, neutral beam heating, and a breeding blanket. The code was used to calculate tritium and vacuum system parameters for the near term reactors ITR[3,4], TNS-UP[3,4] and EPR[2] as well as for some commercial reactor designs, the UWMAK series.[8,10-12] A selected sample of the tritium and vacuum parameters for these reactor designs is shown in Table 2. Also shown in the table are parameters for a hypothetical reactor UWMAK-III M having similar characteristics to UWMAK-III[12] but with a higher fractional burnup (5.0% cf. 0.83%). The impact of the reactor design scenario upon major tritium and vacuum systems as illustrated in Table 2 is discussed below.

4.1 Torus Evacuation System

For reactor designs without a divertor, it is assumed that the torus is evacuated between burns. For those designs with a divertor, it is assumed that the divertor is similar to that in UWMAK-III,[12] with a collection plate to absorb the thermal energy and a vacuum pumping system. In either case, the vacuum pumps are assumed to be compound cryopumps, i.e., having cryocondensation pumping of hydrogenic species (DT) and cryosorption pumping of helium. The code separately calculates required pumping speeds for the two types of species. For reactors having no divertor, the duct conductances for helium pumping were assumed to be reduced by a factor of one-third because of the presence of the cryocondensation surface ahead of the cryosorption panels. It was a significant finding that, for a near-term reactor without a divertor and with large fractional burnup (> 10%), the required speed for helium pumping (Table 2) is very high, being from one to six times the required DT pumping speed This implies severe constraints upon the design of the compound pumps because it is necessary to achieve very high helium pumping speeds and minimize conductance losses by the presence of the condensation surfaces, while preventing accumulation of hydrogenic species on the cryopanels.

Table 2. Selected TCODE Parameters for Tokamak Reactors

TCODE-Version III Selected Parameter List.	GA/ANL ITR	GA/ANL INS-EP	ANL EPR	UWMAK I	UWMAK II	UWMAK III	UWMAK III M
*Burn Time (s)	30.	90.	64.	5400.	5400.	1800.	1800.
*Dwell Time (s)	270.	30.	16.	390.	330.	100.	100.
*Thermal Power (MW)	390.	465.	325.	5000.	5000.	5000.	5000.
*Ion Density (Ions/m^3)/10^{20}	1.48	1.40	1.30	0.75	0.75	0.79	0.79
*Particle Confinement Time (s)	1.63	1.54	5.00	8.28	8.28	0.55	(2.5)
*Divertor	no	no	no	yes	yes	yes	yes
*Fractional Burnup, FB	0.124	0.187	0.161	0.050	0.0485	0.0083	(0.050)
*Evacuation Volume (m^3)	314.	443.	450.	7000.	7000.	2600.	2600.
*Number of Vacuum Pumps (Operating/Total)	3/6	12/24	12/24	(Divertor)	(Divertor)	(Divertor)	(Divertor)
Required Pump Capacity (kPa-m^3)	2.77	4.11	7.36	1.48 x 10^4	1.48 x 10^4	1.87 x 10^4	3.61 x 10^3
Required DT Pump Speed (m^3/s)	2.37	16.62	37.06	8.11 x 10^4	8.12 x 10^4	1.07 x 10^4	1.98 x 10^4
Required He Pump Speed (m^3/s)	2.67	90.96	232.	8.53 x 10^3	8.28 x 10^3	1.79 x 10^3	2.08 x 10^3
Cryopanel Surface Area (m^2)	0.053	1.82	4.64	171.	166.	35.9	41.6
Cost-He Sorption Pumping ($M)	0.012	1.6	4.2	12.8	12.6	2.7	3.1
Cost-DT Condensation Pumping ($M)	0.01	0.1	0.1	48.6	48.7	64.3	11.9
Cost-Cryopump Regeneration ($M)	0.01	0.03	0.1	25.6	25.6	32.4	6.2
Cost-Hard Seal Metal Valves ($M)	0.27	1.1	1.3	9.6	9.4	2.8	3.1
Tritium Input (gas), (g/day)	27.2	84.4	126.	18.0	18.2	21.3	21.3
Tritium Pellet Fueling (g/day)	20.9	201.	121.	1.25 x 10^4	1.21 x 10^4	7.07 x 10^4	1.17 x 10^4
Tritium Burnup (g/day)	6.0	53.3	39.8	624.	587.	587.	587.
Total Tritium Inventory (kg)	0.26	1.81	1.36	38.9	28.8	82.1	28.9
Annual Tritium Consumption (kg)	0.45	14.7	9.15	-92.8	-9.32	-43.7	-44.0
Deuterium Injected (g/day)	12.0	29.9	51.1	1.36	0.88	0.0	0.0
Deuterium Pumped in Injectors (g/day)	77.6	394.1	81.0	4.21	2.71	0.0	0.0
Tritium Backstream to Beam Pumps (g/day)	0.42	1.04	2.60	0.19	0.19	0.0	0.0
*Number of Injectors	6	6	12	16	16	0	0
Beam Pump Speed (m^3/s)	3360.	3360.	820.	1600.	1600.	0.0	0.0
Beam Getter-Pump Surface Area (m^2)	146.	146.	35.6	69.6	69.6	0.0	0.0
Maximum Conceivable Release, MCR (g)	67.5	189.0	144.8	8730.	8325.	47500.	8140.
Building Volume (m^3)/10^5	0.6	0.6	0.6	13.6	5.0	1.0	1.0
*E.D.S. Cleanup Time (hr.)	48.0	48.0	48.0	48.0	48.0	48.0	48.0
E.D.S. Flow rate (m^3/s)	4.31	4.67	4.58	124.3	46.5	10.7	9.68
Tritium Stacked to Environment (Ci/MCR)	3.00	3.00	3.00	13.6	10.0	5.00	5.00
Tritium Vented to Environment (Ci/MCR)	0.15	0.39	0.30	15.3	14.3	70.9	13.5
Cost-Tritium Recovery ($M)	0.0	0.0	0.0	2.1	5.7	3.7	3.7
Cost-Fuel Processing ($M)	4.9	7.3	6.8	35.3	38.5	78.9	36.0
Cost-E.D.S. ($M)	5.6	6.0	5.8	133.	50.2	12.4	11.3
Cost-Torus Evacuation ($M)	0.3	2.8	5.7	96.6	96.1	102.	24.3
Cost-Neutral Beam Vacuum System ($M)	42.3	42.3	20.7	53.8	53.8	0.0	0.0
Total Cost: Tritium and Vacuum Systems ($M)	53.0	58.4	39.0	320.	244.	197.	75.2

*Input Parameters

The required helium pumping speeds for commercial reactors with divertors are very high, but rather insensitive to fractional burnup. By contrast, the required DT speeds are very sensitive to fractional burnup with UWMAK-III having a required DT pumping speed in excess of $10^5 m^3/s$. This speed is reduced by a factor of five in UWMAK-III M when the fractional burnup is increased to 5%.

4.2 Deuterium and Neutral Beam Vacuum Systems

For near-term reactors the neutral beam vacuum system requirements are relatively insensitive to overall reactor design. The design of the neutral beam injectors for EPR had a higher gas efficiency than that for TNS and ITR and, as a result, the pumping speeds and costs were lower. The results than represent the uncertainty in performance of injectors of this size (60 MW, 150 keV). The characteristics of larger (200 MW, 500 keV) neutral beams are even more uncertain at present. It is clear that pump speeds and costs are sensitive to the gas loads and therefore, gas efficiencies. Also, the costs of the neutral beam vacuum systems are very high, ∿ \$20 M – \$50 M.

A significant point is that the deuterium recycle (in the neutral beams) for near-term reactors ranges from 80 to 200 g/day (Table 2). This amount is as large or larger than the amount of deuterium in the main fuel stream recycle. Since the neutral beams require very high isotopic purity feed (D_2 > 99% ^2D), a significant constraint is placed upon the isotope separation unit in the tritium facility. The unit must process large amounts of deuterium recycle from the neutral beam. By contrast, the neutral beam feed for commercial reactors with divertors and long burn times is only a few (< 10) grams per day. Since commercial reactors burn about 400 g of D_2 per day, the high purity feed for the neutral beams can be supplied from an external source and the recycle is simply added to the reactor fuel. Therefore, the fuel processing system for a commercial plant could be simpler than that for a near-term experimental reactor.

4.3 Emergency Air Detritiation System

An item of considerable significance both from the standpoints of safety and costs is the emergency air detritiation system (EDS). The costs of such systems are primarily due to the reactor building volume and the permissible cleanup time. Our earlier studies[17] showed that the cleanup time should be no longer than about 48 hours. The required speed to attain this is about 0.5% of the reactor b ling volume per minute. Further, since the unit costs are about $20,000 per m^3/min, the cost of the EDS is about $100 per m^3 of reactor building. Since this is about half the cost of the reactor building itself, the EDS is a significant cost driver.

4.4 Tritium Mass Flow Rates and Inventories

The tritium throughput rates scale linearly with the power and inversely with the fractional burnup. Since tritium inventories are determined by the throughput rates, the fractional burnup can have a substantial impact upon all tritium systems. A comparison of UWMAK-III and UWMAK-III M (Table 2) shows that there are considerable economic and safety incentives for trying to increase the fractional burnup. Increasing the fractional burnup from 0.83% to 5% dramatically lowers tritium inventories, potential tritium releases, and overall costs.

There is a further implication to this result. If tritium inventories become very high, the decay losses may become unacceptably high.[13] The doubling time is defined as the time necessary to breed enough tritium to equal the operating inventory of the plant, plus enough tritium to begin operation of a second plant. The effect of fractional burnup upon the required breeding ratio for a number of different doubling times is shown in Figure 2. If the fractional burnup is greater than 2%, a breeding ratio of 1.10 will result in a doubling time of less than 5 years. However, if the fractional burnup is less than 1%, it will be difficult to breed enough tritium to supply future reactors. These results show that there are strong incentives to have a fractional burnup of at least 2%.

The presence of a divertor will adversely affect the achievable fractional burnup. Further, the divertor slots are not available for breeding and it is difficult to provide breeding in the zone between the divertor slots. These results show that a form of impurity control other than a divertor is desirable.

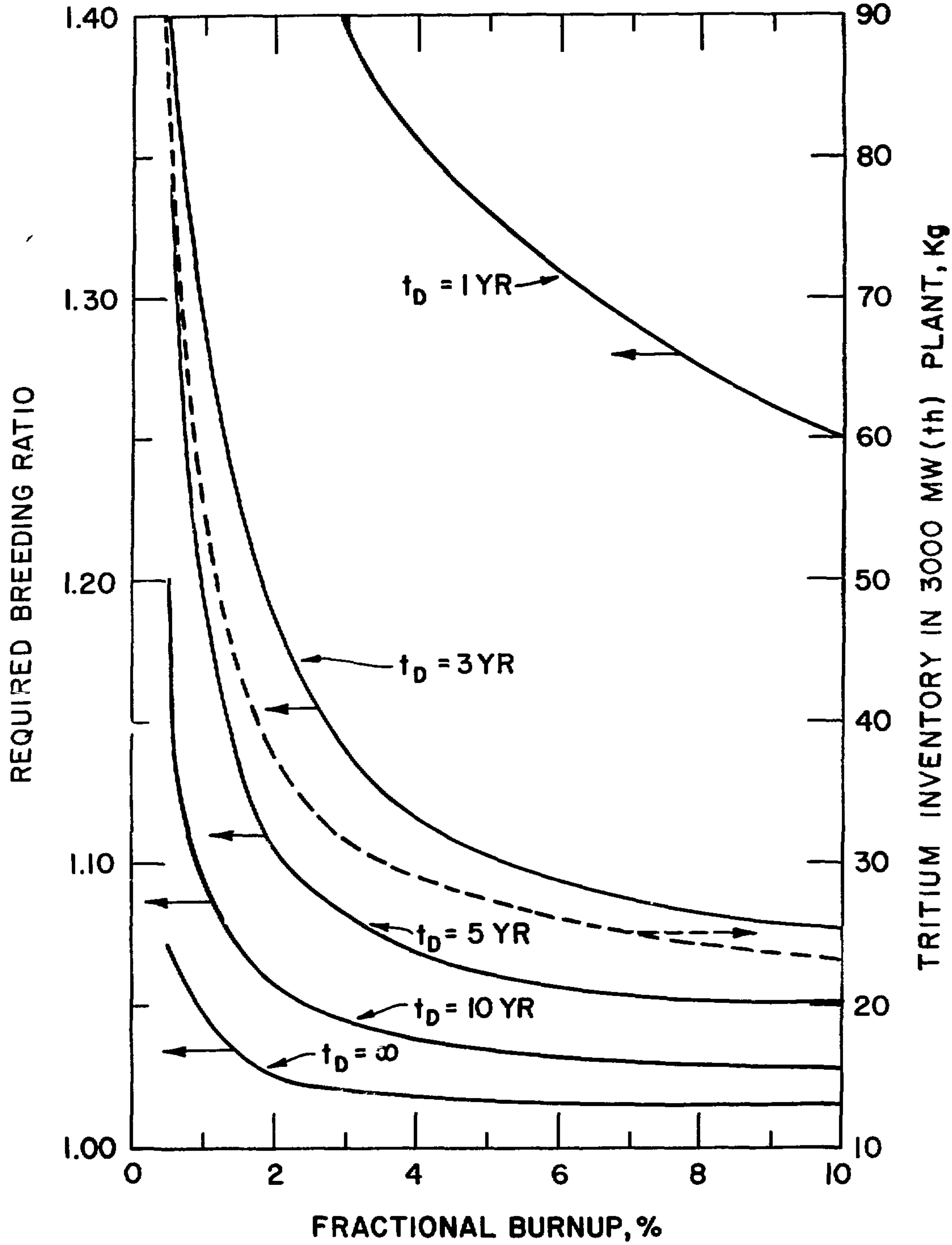


Figure 2. Effect of fractional burnup and doubling time upon required breeding ratio.

5. Conclusions

1. TCODE is a powerful tool for parametric analysis for tritium and vacuum systems of both near-term experimental and commercial tokamak fusion reactors.

2. There are strong incentives for trying to increase the fractional burnup.

3. A divertor adversely affects both achievable breeding ratio and fractional burnup.

4. For compound torus vacuum pumps, the required pumping speeds for helium may be higher than those required for DT. The ability to pump helium in a mixture of gases is a critical R&D issue.

5. A longer burn time will lessen the impact of the deuterium in the neutral beam recycle upon the fuel processing system.

6. The neutral beam vacuum system is a high-cost item. Further, there are considerable uncertainties in the characteristics of large neutral beams. This is an area requiring further study.

7. The emergency air detritiation system (EDS) was identified as a significant cost driver.

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APPENDIX A

Description of the Code

The TCODE requires as inputs approximately 50 input parameters which include plasma performance characteristics, operating conditions, component sizes and unit costs. A description of these variables and some representative values is given in the next section. As a part of the ANL systems code, the TCODE is a subroutine and many of the inputs may be calculated from other routines in the systems code. However, the TCODE is designed so that it can be used independently.

The code then uses the inputs to calculate a plasma mass balance, from which the deuterium, tritium and helium flow rates are calculated. These mass flow rates are used to calculate tritium inventories and processing unit sizes and requirements. Vacuum pumping requirements are calculated using the mass flow rates and the set of design conditions input to the program. The EDS system requirements are calculated from potential release levels and the volume of the reactor building. The determined characteristics of each unit are then used to calculate costs for each items.

Glossary of Variables

Input Parameters

Variable Name in TCODE	Symbol Used in this Report	Description
BBLM		Mass of breeding material, kg
BDTEM		Temperature in neutral beam pumping zones, K
BIGLA		Gas load in neutral beam pumping zone 1, Pa-m^3/s
BIGLB		Gas load in neutral beam pumping zone 2, Pa-m^3/s
BIPPA		Pressure maintained by neutral beam pumps, zone 1, Pa
BIPPB		Pressure maintained by neutral beam pumps, zone 2, Pa
BRNTIM	t_B	Burn time, s
CUEFF	ε	Efficiency of emergency air detritiation system (EDS)
CUTIM	t_{EDS}	Allowable time for EDS operation, hr
DEFF		Divertor efficiency
DGL		Gas load to divertor pumps, Pa-m^3/s
DIAM	D	Diameter of torus vacuum ducts, m
DION	n_i	Ion density in plasma, ions/m^3
DLEN	L	Length of torus vacuum ducts, m
DNUM	N	Number of torus vacuum ducts = number of pumps on line
DPP		Pressure maintained by divertor vacuum pumps, Pa
DWELL	t_D	Dwell time, s
EFUS	E_F	Energy/fusion, pj (= MeV x 0.16)
EINJ	U_B	Neutral beam energy, keV
FB	F_b	Fractional burnup
LAG	t_L	Lag time, s (= portion of t_o not available for pumping)
IDIV		Divertor option: IDIV = 0 (no); IDIV = 1 (yes)
PAF		Plant availability (capacity) factor
PBGT	T_G	Postburn gas temperature, K
PCAP		Torus vacuum pump capacity, Pa-m^3
PINJ	P_B	Neutral beam power, MW
PITEM		Torus vacuum pump inlet temperature, K
PPP	P_{th}	Total thermal power during burn, MW
PREP	P_o	Preburn gas pressure, Pa
PSP		Rated speed per torus vacuum pump, m^3/s
REFLT	R_{DT}	Reflectance (particle recycle) coefficient
REGEN		Allowable time for regeneration of cryopumps, hr
SA	A_T	Surface area of first wall, m^2
SABD	A_{BD}	Surface area of neutral beam port at first wall, m^2
STACK	T°	Tritium level stacked after major release, μCi/m^3
TAUP	τ_{p_o}	Particle confinement time, s
TAUPS	τ_p	Particle confinement time at startup, s
TBCON		Tritium concentration in blanket, wppm
TBREAD	BR	Breeding ratio
TINJ	t_{NB}	Neutral beam duration, s
UCEDS		Unit cost for EDS, \$/m^3/s
UCTRIT		Unit cost of tritium, \$/C_i
VBLDG	V_{Bldg}	Volume of reactor building, m^3
VPLAS	V_p	Plasma volume, m^3
VTOT	V_T	Volume of torus plus ducts, m^3
ZNINJ	Z_i	Number of neutral beam injectors

Representative Values for Input Parameters

Variable Name in TCODE	GA/ANL TNS	ANL FY 1977 EPR	UWMAK I	UWMAK II	UWMAK III
BBLM/10^6	0.0	0.0	1.4	0.44	0.48
BDTEM	298.	298.	298.	298.	--
BIGLA	16.80	4.10	8.0	8.0	--
BIGLB	16.80	4.10	8.0	8.0	--
BIPPA	0.010	0.010	0.010	0.010	--
BIPPB	0.010	0.010	0.010	0.010	--
BRNTIM	30.	64.	5400	5400	1800
CUEFF	0.99	0.99	0.99	0.99	0.99
CUTIM	48.0	48.0	48.0	48.0	48.0
DEFF	0.00	0.00	0.99	0.99	0.99
DCL	0.0	0.0	853.	853.	1080.
DIAM	0.70	0.80	0.	0.	0.
DION/10^{20}	1.48	1.30	0.75	0.75	0.79
DLEN	8.00	6.00	0.	0.	0.
DNUM	3.	12.	0.0	0.0	0.
DPP	0.0	0.0	0.010	0.010	0.010
DWELL	270.	16.	390.	330.	100.
EFUS	2.82	2.82	3.22	3.46	3.48
EINJ	150.	150.	500.	500.	--
FB	0.124	0.161	0.050	0.0485	0.0083
LAG	2.	2.	200.	100.	10.
IDIV	0	0	1	1	1
PAF	0.20	0.625	0.85	0.85	0.90
PBGT	373.2	773.2	800.	800.	900.
PCAP/10^4	0.40	1.07	1500.	1500.	2000.
PINJ	60.	60.	200.	200.	--
PITEM	273.2	273.2	273.2	273.2	273.2
PPP	390.	325.	5000.	5000.	5000.
PREP/10^{-3}	4.00	4.00	0.0010	0.0010	0.0010
PSP	30.	80.	85,000	85,000	110,000
REFLT	0.98	0.95	0.001	0.001	0.001
REGEN	4.00	4.00	4.00	4.00	4.00
SA	350.	430.	6600.	6600.	2400.
SABD	1.0	1.0	1.0	1.0	0.0
STACK	50.	50.0	10.	20.0	50.0
TAUP	1.63	5.00	8.28	8.28	0.55
TAUPS	3.3	10.0	10.0	10.0	1.0
TBCON	0.00	0.00	6.2	0.29	2.08
TBREAD	0.00	0.00	1.49	1.10	1.25
TINJ	5.00	5.70	11.00	7.00	0.0
UCEDS/10^6	1.06	1.06	1.06	1.06	1.06
UCTRIT	0.70	0.70	0.70	0.70	0.70
VBLDG/10^5	0.60	0.60	13.6	5.0	1.0
VPLAS	255.	360.	6415.	6415.	2370.
VTOT	314.	450.	7000.	7000.	2600.
ZNINJ	6.	12.	16.	16.	0.

Output Parameters

Variable Name in TCODE	Symbol Used in this Report	Description
ADT		Average temperature of torus vacuum duct, K
AMW	$\bar{A}$	Average molecular weight of species evacuated from torus, g/mole
ANTC	T_{AN}	Annual net tritium consumption, kg (if < 0, net production)
AREXD		Argon exhausted to fuel cycle, g/day
BPC	B_c	Tritium burned per cycle, g
BPDAY	N_B	Number of burn cycles per day
CANTC		Annual cost of tritium consumed, $
CBREC		Capital cost of tritium recovery system, $
CCDIST		Capital cost of isotopic separation unit (cryogenic distillation cascade), $
CCPHE		Capital cost of cryosorption pumping of He, $
CCSPDT		Capital cost of cryocondensation pumping of DT, $
CEDS	C_{EDS}	Capital cost of EDS, $
CEXD		Carbon exhausted to fuel cycle, g/day
CGBOX		Capital cost of gloveboxes in tritium facility, including purifiers, $
CMISCT		Total capital cost of miscellaneous tritium facility items, $
CNBPR		Capital cost for neutral beam pump regeneration system, $
COND	C_d	Conductance of torus vacuum duct, m^3/s
CONEF	C_{ef}	Effective conductance of torus vacuum duct, m^3/s
CONEN	C_{en}	Conductance of entrance to duct, m^3/s
CPBZA		Capital cost of getter pumps per neutral beam injector - zone 1, $
CPBZB		Capital cost of getter pumps per neutral beam injector - zone 2, $
CPFLS		Capital cost of pellet fueling system, $
CPIP		Capital cost of tritium puping and valves, $
CPSA		Cryosorption panel surface area, m^2
CRPS		Capacity required equivalent cryosorption pump size, m^3/s
CTIME		Allowable time for EDS operation, min
CTRECB	C_{TREC}	Capital cost of tritium recovery system, $
CUFR	R_{EDS}	EDS flow rate, m^3/s
DBINV		Amount of tritium needed to start a second plant, doubling inventory, kg
DBPD		Deuterium burnup per day, g
DBPDA		Deuterium pumped per day - neutral beams, zone 1, g
DBPDB		Deuterium pumped per day - neutral beams, zone 2, g
DECF		EDS decontamination factor (= 1.0×10^{-6})
DF		Plasma duty factor
DFULD		Deuterium fueling rate, g/day
DGLPD		Total deuterium feed as preburn gas charge for startup, g/day

Variable Name in TCODE	Symbol Used in this Report	Description
DIA	D	Torus vacuum duct diameter, m
DIAMIN		Minimum torus vacuum duct diameter, m
DINJD	$\dot{D}$	Total deuterium injected by neutral beams, g/day
DL	ΔD	Perturbation on duct diameter
DPIND		Deuterium pumped in neutral beams, g/day
DPREG		Capital cost of divertor pump regeneration, $
DPSDT		Divertor cryocondensation pump speed for DT, m^3/s
DPSHE		Divertor cryosorption speed for He, m^3/s
DPSP		Divertor pump speed, m^3/s
DTIME		Doubling time, years
EPP		Energy per burn pulse, MJ
EPS		Effective torus vacuum pump speed, m^3/s
FIC	F_c	Total tritium input per cycle, g
FIFPD		Total tritium input per day, g
FIFPH		Total tritium input per hour, g
HEEXD		Helium exhausted to fuel cycle, g/day
HSMV		Capital cost of hard seal metal valves for torus vacuum pumps, $
MPR		Maximum credible tritium release, g
NEXD		Nitrogen in fuel cycle, g/day
OEXD		Oxygen in fuel cycle, g/day
PBGP	P	Postburn gas pressure, Pa
PBHEP		Postburn He pressure, Pa
PEXD		^1H exhausted to fuel cycle, g/day
PF		Plant Factor = DF x PAF
PFAC		Allowable fraction of pump capacity (set at 0.83)
PRHEP		Preburn He pressure, Pa
PSBZA		Neutral beam pumping speed - zone 1, m^3/s
PSBZB		Neutral beam pumping speed - zone 2, m^3s
QPGP		Postburn gas load, $Pa\text{-}m^3$
REPS	S_{tot}	Required torus vacuum pumping speed, m^3/s
REPSHE		Required torus vacuum pumping speed for He, m^3/s
RETIM		Cryopump regeneration time, hr
RPCAP		Required cryopump capacity, $Pa\text{-}m^3$
SAPZA		Neutral beam getter pump surface area, m^2
SAPZB		Neutral beam getter pump surface area - zone 2, m^2
SF		Cost scaling factor
SPD	S	Required effective speed per torus vacuum pump, m^3/s
SPDHE		Required He pump speed (at the pump), m^3/s
SPDP	Sp	Required DT pump speed (at the pump), m^3/s
TBPD		Tritium burnup per day, g
TBPH		Tritium burnup per hour, g
TBRPY		Tritium bred per year, kg
TCDVS		Total capital cost of divertor vacuum system, $
TCNBP		Total capital cost of neutral beam vacuum pumps, $

Variable Name in TCODE	Symbol Used in this Report	Description
TCNBVS	C_N	Total capital cost of neutral beam vacuum system, $
TCON	T'	Maximum tritium concentration after MPR, $\mu Ci/m^3$
TCTHS		Total capital cost of tritium handling systems, $
TCTVS		Total capital cost of tritium and vacuum systems, $
TDPY		Tritium decay losses, g/year
TEXC	T_{exc}	Tritium exhaust per cycle, g
TEXD	R_T	Tritium exhaust per day, g
TEXH		Tritium exhaust per hour, g
TFLBD		Tritium backstreaming flux to neutral beams, g/m^2-s
TFULC	T_{Fc}	Tritium pellet fueling per cycle, g
TFULD		Tritium pellet fueling per day, g
TFULH		Tritium pellet fueling per hour, g
TGLPD		Total tritium feed as preburn gas charge for startup, g/day
TGLPH		Total tritium preburn gas charge, g/hr
TINBL		Tritium inventory in blanket, g
TINFP		Tritium inventory - fuel preparation, g
TINIS		Tritium inventory - isotopic separation unit, g
TINPL		Tritium inventory - liquefaction unit, g
TINPS		Tritium inventory-- surge tank, g
TINVP		Tritium inventory - torus vacuum pump, g
TINVS		Tritium inventory - storage for 30 days burnup, g
TPIND	T_B	Tritium backstreaming to neutral beams, g/day
TPPD		Tritium production rate, g/day
TPMW		Cycle average thermal power, MW
TREL		Tritium stacked to environment at end of EDS operation, Ci
TRINV		Tritium inventory - tritium recovery system, g
TSTART	T_i	Initial tritium in preburn gas charge for startup, g
TTINV		Total tritium inventory, g
TVENT		Tritium vented to environment during EDS operation after MPR, Ci
VCCPHE		Capital cost of He cryosorption pumping, $
VCPDT		Capital cost of DT cryocondensation pumping, $
VCPSA		He cryosorption pump surface area, m^2
VCREG		Capital cost - torus vacuum pump regeneration, $
VENT		Vent rate to maintain reactor building at negative pressure, m^3/min
VFR		EDS volumetric flowrate, % bldg. volume/min
VHSMV		Capital cost of hard seal metal valves for torus vacuum system, $
Y	Y	A constant for duct conductance calculations (= 0.86 for cylindrical duct).

LISTING OF CODE

```
LEVEL 21.7 ( JAN 73 )                                   OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=57,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
                C       TCODE-VERSION III 1/13/77
                C       CALCULATES TRITIUM FACILITY AND VACUUM SYSTEMS PARAMETERS
                C       FOR TOKAMAK-TYPE FUSION REACTORS
                C
                C       INPUTS TO TCODE
 ISN 0002               DIMENSION TITLE1(20),TITLE2(20)
 ISN 0003               REAL*4 LAG,NEXD,MPR
 ISN 0004             1 READ(5,10,END=999) TITLE1,TITLE2
 ISN 0005            10 FORMAT(20A4/20A4)
 ISN 0006               READ(5,20) BRNTIM,DWELL,LAG,PAF
                C       BRNTIM=BURN TIME(S),DWELL=DWELL TIME(S),LAG=LAG TIME(S),
                C       PAF=PLANT AVAILABILITY FACTOR (FRACTION),
 ISN 0007               READ(5,21) IDIV
 ISN 0008            21 FORMAT(I2)
                C       DIVERTOR?  IDIV=0 (NO),IDIV=1 (YES)
 ISN 0009               READ(5,20) VTOT,SA,VPLAS,PSP,PCAP
                C       VTOT=VOLUME OF TORUS(M**3), SA=SURFACE AREA OF TORUS(M**2),
                C       VPLAS= PLASMA VOLUME(M**3),PSP=RATED SPEED PER PUMP(M**3/S),
                C       PCAP=PUMP CAPACITY(PA-M**3)
 ISN 0010               READ(5,20) DION,TAUP,PPP,EFUS,REFLT
                C       DION=ION DENSITY(IONS/M**3),TAUP=PARTICLE CONFINEMENT TIME(S),
                C       PPP=POWER(TH) PER BURN PULSE(MW),EFUS=ENERGY PER FUSION(PJ),
                C       REFLT=REFLECTANCE COEFFICIENT
 ISN 0011               READ(5,20) DEFF,FB,DGL,DPP
                C       DEFF=DIVERTOR EFFICIENCY(FRACTION), FB=FRACTIONAL BURNUP,
                C       DGL=DIVERTOR GAS LOAD(PA-M**3/S), DPP=DIVERTOR PUMP PRESSURE(PA)
 ISN 0012               READ(5,20) PBGT,PBGP,PREP
                C       PBGT=POSTBURN GAS TEMPERATURE(K),PBGP=POSTBURN GAS PRESSURE(PA),
                C       PREP=PREBURN GAS PRESSURE(PA)
 ISN 0013               READ(5,20) DIAM,DLEN,DNUM,PITEM,REGEN
                C       DIAM=VACUUM DUCT DIAMETER(M), DLEN=DUCT LENGTH(M),
                C       DNUM=NUMBER OF VACUUM DUCTS=NUMBER OF VACUUM PUMPS ON LINE,
                C       PITEM=PUMP INLET TEMPERATURE(K), REGEN =REGENERATION PERIOD(HRS)
 ISN 0014               READ(5,20) ZNINJ,EINJ,PINJ,BDTEM,TINJ,SABD
                C       ZNINJ=NUMBER OF NEUTRAL BEAM INJECTORS,
                C       EINJ=NEUTRAL BEAM ENERGY(KEV),PINJ=NEUTRAL BEAM POWER(MW),
                C       BDTEM=TEMPERATURE OF NEUTRAL BEAM DUCT(K),
                C       TINJ=NEUTRAL BEAM DURATION(S),SABD=SURFACE AREA OF BEAM DUCT(M**2)
 ISN 0015               READ(5,20) TAUPS,BIGLA,BIPPA,BIGLB,BIPPB
                C       TAUPS=PARTICLE CONFINEMENT TIME AT STARTUP
                C       BIGLA=GAS LOAD PER INJECTOR-CHAMBER1 (PA-M**3/S),
                C       BIPPA=PRESSURE(PA) AT BEAM PUMPS - CHAMBER 1 ,
                C       BIGLB=GAS LOAD PER INJECTOR - CHAMBER2 (PA-M**3/S),
                C       BIPPB=PRESSURE(PA) AT BEAM PUMPS - CHAMBER 2
 ISN 0016               READ(5,20) CTRIT,BR,TBCON,BBLM
                C       BBLM=MASS OF BREEDER BLANKET(KG)
                C       CTRIT=COST OF TRITIUM($/CURIE), BR=BREEDING RATIO,
                C       TBCON=CONCENTRATION OF TRITIUM IN BREEDER BLANKET(PPM)
 ISN 0017               READ(5,20) UCEDS,VBLDG,CUTIM,STACK,CUEFF
                C       UCEDS=UNIT COST FOR EMERGENCY AIR DETRITIATION SYSTEM($/M**3/S),
                C       VBLDG=VOLUME OF REACTOR BUILDING(M**3),
                C       CUTIM=ALLOWABLE TIME FOR CLEANUP OF MAJOR SPILL(HRS),
                C       STACK=TRITIUM LEVEL AT WHICH BUILDING AIR IS EXHAUSTED(UCI/M**3),
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                  C      CUEFF=E.D.S. REMOVAL EFFICIENCY(FRACTION)
 ISN 0018            20 FORMAT(6E12.0)
                  C      MASS FLOW RATES - FUEL CYCLE
 ISN 0019                EPP=PPP*BRNTIM
 ISN 0020                TPMW=EPP/(BRNTIM+DWELL)
 ISN 0021                DF=BRNTIM/(BRNTIM+DWELL)
 ISN 0022                PF=PAF*DF
 ISN 0023                TSTART=DION*VPLAS*2.5E-24
 ISN 0024                BPC=BRNTIM*PPP*4.99E-06/EFUS
 ISN 0025                TEXC=(BPC/FB)-BPC
 ISN 0026                BPDAY=24.*3600./(BRNTIM+DWELL)
 ISN 0027                TEXD=TEXC*BPDAY
 ISN 0028                TFULC=TEXC-TSTART+BPC
 ISN 0029                TFULD=BPDAY*TFULC
 ISN 0030                TGLPD=BPDAY*TSTART
 ISN 0031                TGLPH=TGLPD/24.
 ISN 0032                TEXH=TEXD/24.
 ISN 0033                TFULH=TFULD/24.
 ISN 0034                TBPD=BPC*BPDAY
 ISN 0035                TBPH=TBPD/24.0
 ISN 0036                FIC=TEXC+BPC
 ISN 0037                FIFPH=TEXH+TBPH
 ISN 0038                FIFPD=TEXD+TBPD
 ISN 0039                TPPD=TBPD*BP
 ISN 0040                HEEXD=TBPD*1.33
 ISN 0041                PEXD=0.031*HEEXD
 ISN 0042                CEXD=0.186*HEEXD
 ISN 0043                OEXD=0.015*HEEXD
 ISN 0044                NEXD=0.013*HEEXD
 ISN 0045                AREXD=(40./3.)*TSTART*BPDAY*0.050
 ISN 0046                AREXD=0.124*HEEXD
                  C      TRITIUM INVENTORIES
 ISN 0047                TINVP=TEXD*REGEN/24.
 ISN 0048                TINVS=30.0*TBPD
 ISN 0049                TINPS=TINVP*1.2/(DNUM+1.0)
 ISN 0050                TINPL=5.0+0.01*TEXD
 ISN 0051                TINIS=5.0+0.025*TEXD
 ISN 0052                TINBL=BBLM*TBCON*0.001
 ISN 0053                TRINV=BR*TBPD*0.5
 ISN 0054                TINFP=50.0+0.50*TFULD
 ISN 0055                TTINV=TINVP+TINVS+TINPS+TINPL+TINIS+TINFP+TINBL+TRINV
 ISN 0056                TDPY=0.056*TTINV
 ISN 0057                ANTC=365.24*TBPD*(1.0-BR)*PAF+TDPY
 ISN 0058                CANTC=ANTC*CTRIT*9700.
 ISN 0059                DTIME=0.0
 ISN 0060                DBINV=0.0
 ISN 0061                IF(BR.LT.1.0) GO TO 777
 ISN 0063           776 TBRPY=365.24*TBPD*(BR-1.0)
 ISN 0064                DBINV=2.0*TTINV-TINVS-TINBL
 ISN 0065                DTIME=(-1./0.056)*ALOG((TBRPY-0.056*DBINV)/TBRPY)
 ISN 0066           777 CONTINUE
                  C      NEUTRAL BEAM AND DEUTERIUM CYCLE
 ISN 0067                DBPD=0.67*TBPD
 ISN 0068                DINJD=1793.*PINJ*TINJ/(EINJ*(BRNTIM+DWELL)+1.0E-06)
                  C      PUMPING SPEEDS,COSTS,SAES GETTER  SURFACE AREA
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```
      PSBZA=BIGLA/(BIPPA+1.0E-06)
      PSBZB=BIGLB/(BIPPB+1.0E-06)
      CPBZA=750.*PSBZA*2.0
      CPBZB=750.*PSBZB*2.0
      SAPZA=(PSBZA/46.0)*2.0
      SAPZB=(PSBZB/46.0)*2.0
      TCNBP=(CPBZA+CPBZB)*ZNINJ
      CNBPR=0.20*TCNBP
      CBREC=0.20*TCNBP
      TCNBVS=TCNBP+CNBPR+CBREC
      DBPDA=BIGLA*TINJ*BPDAY
      DBPDB=BIGLB*TINJ*BPDAY
      DPIND=(DBPDA+DBPDB)*4.0/(8.31*BDTEM+1.0E-06)
      TFLBD=(2.5E-24)*DION*VPLAS*TINJ/(SA*TAUPS+1.0E-08)
      TPIND=TFLBD*SABD*ZNINJ*BPDAY
      DFULD=0.67*TFULD-DINJD*(TFULD/(TFULD+TGLPD))
      DGLPD=0.67*TGLPD-DINJD*(TGLPD/(TFULD+TGLPD))
C     PUMPING-DIVERTOR OPTION
      DPSP=0.0
      CCPHE=0.0
      CCSPDT=0.0
      DPSDT=0.0
      DPSHE=0.0
      CPSA=0.0
      DPREG=0.0
      HSMV=0.0
      TCDVS=0.0
      Y=0.86
      PFAC=0.83
      PBGP=4.15*DION*PBGT*(1.0+FB)*VPLAS/(VTOT*6.023E+23)
      IF(IDIV.EQ.0) GO TO 111
      REGTIM=PCAP*PFAC/(DGL*3600.)
      RPCAP=DGL*REGEN*3600./PFAC
      QPGP=0.0
      REPS=0.0
      SPD=0.0
      CONEN=0.0
      COND=0.0
      CONTF=0.0
      SPDP=0.0
      EPS=0.0
      DIAMIN=0.0
      CRPS=RPCAP/133.32
      PBHEP=0.0
      PRHEP=0.0
      REPSHE=0.0
      PSPDHE=0.0
      SPDHE=0.0
      VCPSA=0.0
      VCCPHE=0.0
      VCPDT=0.0
      VCREG=0.0
      VHSMV=0.0
      TCVS=0.0
  110 DPSP=DGL/DPP
```

```
ISN 0124          DPSDT=(1.0-FB)*DPSP
ISN 0125          DPSHE=FB*DPSP*2.0
ISN 0126          CPSA=DPSHE/50.
ISN 0127          CCPHE=750.*DPSHE*2.0
ISN 0128          CCSPDT=300.*DPSDT*2.0
ISN 0129          DPREG=300.*DPSP
ISN 0130          HSMV=((CPSA)**0.8)*(7.85E+0.)*2.0
ISN 0131          TCDVS=CCPHE+CCSPDT+DPREG+HSMV
ISN 0132          GO TO 400
            C     TORUS EVACUATION SYSTEM-BETWEEN BURNS
ISN 0133      111 CONTINUE
            C     PFAC=ALLOWABLE FRACTION OF PUMP CAPACITY
ISN 0134          QPGP=PBGP*VTOT
ISN 0135          REPS=(VTOT*ALOG(PBGP/PREP))/(DWELL-LAG)
ISN 0136          SPD=REPS/DNUM
ISN 0137          DL=DLEN*39.37
ISN 0138          DIA=DIAM*39.37
ISN 0139          AMW=5.0-FB
ISN 0140          CONEN=0.059*(DIA**2.0)*Y*0.31*((PBGT/AMW)**0.5)
ISN 0141          ADT=(PBGT+PITEM)/2.0
ISN 0142          COND=0.079*(DIA**3.0)*(Y/DL)*0.31*((ADT/AMW)**0.5)
ISN 0143          CONEF=1.0/((1.0/CONEN)+(1.0/COND))
ISN 0144          SPDP=1.0/((1.0/SPD)-(1.0/CONEF))
ISN 0145          EPS=1.0/((1.0/PSP)+(1.0/CONEF))
ISN 0146          RETIM=PCAP*PFAC*(BRNTIM+DWELL)*DNUM/(QPGP*3600.)
ISN 0147          RPCAP=(REGEN*PCAP*PFAC)/RETIM
ISN 0148          CRPS=RPCAP/133.32
ISN 0149          IF (SPD.GT.PSP) GO TO 50
ISN 0151          CST1=CONEN/(DIA**2.0)
ISN 0152          CST2=COND/(DIA**3.0)
ISN 0153          DINC=0.1
ISN 0154          DTEST=DIA
ISN 0155       41 BTEST=1.0/((1.0/(CST1*(DTEST**2.0)))+(1.0/(CST2*(DTEST**3.0))))
ISN 0156          CTEST=1.0/((1.0/BTEST)+(1.0/PSP))
ISN 0157          IF (SPD-CTEST) 43,49,42
ISN 0158       42 DTEST=DTEST*2.0
ISN 0159          GO TO 41
ISN 0160       43 BTEST=1.0/((1.0/(CST1*(DTEST**2.0)))+(1.0/(CST2*(DTEST**3.0))))
ISN 0161          CTEST=1.0/((1.0/BTEST)+(1.0/PSP))
ISN 0162          IF (SPD-CTEST) 46,49,44
ISN 0163       44 DTEST=DTEST+(DINC*DTEST)
ISN 0164          DINC=0.1*DINC
ISN 0165          GO TO 43
ISN 0166       46 TOLER=SPD-CTEST
ISN 0167          IF (0.1+TOLER) 48,49,49
ISN 0168       48 DTEST=DTEST-(DINC*DTEST)
ISN 0169          GO TO 43
ISN 0170       49 DIAMIN=DTEST/39.37
ISN 0171          GO TO 52
ISN 0172       50 WRITE(6,51)
ISN 0173       51 FORMAT(8X,'*****DMIN DID NOT CONVERGE************')
ISN 0174       52 CONTINUE
ISN 0175          PBHEP=FB*PBGP*2.0
ISN 0176          PRHEP=0.25*PREP
ISN 0177          REPSHE=VTOT*(ALOG(PBHEP/PRHEP))/(DWELL-LAG)
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ISN 0178          PSPDHE=REPSHE/DNUM
ISN 0179          SPDHE=1.0/((1.0/PSPDHE)-(1.5/CONEF))
ISN 0180          VCPSA=SPDHE/50.
ISN 0181          VCCPHE=750.0*SPDHE*2.0*DNUM
ISN 0182          VCPDT=300.*SPD*DNUM*2.0
ISN 0183          VCREG=300.*SPD*DNUM
ISN 0184          VHSMV=(DIAM**1.6)*(7.85E+04)*2.0*DNUM
ISN 0185          TCVS=VCCPHE+VCPDT+VCREG+VHSMV
ISN 0186      400 CONTINUE
            C     EMERGENCY AIR DETRITIATION SYSTEM (E.D.S)
ISN 0187          MPR=TINEP+TRINV+TINVP
ISN 0188          TCON=9.6E+09*MPR/VBLDG
ISN 0189          CTIME=60.0*CUTIM
ISN 0190          VFR=(100.0/(CUEFF*CTIME))*ALOG(TCON/STACK)
ISN 0191          CUFR=VFR*VBLDG*0.01/60.0
ISN 0192          DECF=1.0E-06
ISN 0193          VENT=0.0010*VBLDG/60.0
ISN 0194          TVENT=MPR*(1.0-STACK/TCON)*DECF*(VENT/CUFR)*9600.
ISN 0195          TREL=1.0E-06*VBLDG*STACK
ISN 0196          CEDS=CUFR*UCEDS+1.0E+06
            C     $$$$$COSTS$$$$$
ISN 0197          CTRECB=5000.*TPPD/((TBCON**0.5)+.0001)
ISN 0198          SF=(TEXD/1500.0)**0.5
ISN 0199          CPIP=0.8E+06*SF+5.2E+05
ISN 0200          CCDIST=8.5E+05*SF+5.4E+05
ISN 0201          CGBOX=SF*(2.7E+06)+1.7E+06
ISN 0202          CMISCT=1.1E+06*SF+6.0E+05
ISN 0203          CPFLS=(TFULD**0.5)*1.3E+05
ISN 0204          TCTHS=CTRECB+CPIP+CCDIST+CMISCT+CPFLS+CGBOX
ISN 0205          TCTVS=TCTHS+CEDS+TCVS+TCDVS+TCNBVS+CTRECB
            C
            C      *****OUTPUTS**************
ISN 0206          WRITE(6,60) TITLE1,TITLE2
ISN 0207       60 FORMAT(1H1//20A4/20A4//)
ISN 0208          WRITE(6,61)
ISN 0209       61 FORMAT(8X,'PLASMA AND BURN CYCLE',/)
ISN 0210          WRITE(6,62) BRNTIM,DWELL,LAG,DF,PAF,PF,EPP,PPP,TPMW,DION
ISN 0211       62 FORMAT(9X,'*BURN TIME (S)                        =',F8.1,/,
                1 9X,'*DWELL TIME (S)                  =',F8.1,/,
                2 9X,'*LAG TIME (S)                    =',F8.1,/,
                3 10X,'DUTY FACTOR                     =',F8.3,/,
                4 9X,'*PLANT AVAILIBILITY FACTOR       =',F8.3,/,
                5 10X,'PLANT FACTOR                    =',F8.3,/,
                6 10X,'ENERGY PER BURN PULSE (MJ)      =',1PE12.2,/,
                7 9X,'*POWER PER BURN PULSE(MW)        =',0PF8.1,/,
                8 10X,'CYCLE AVERAGE POWER (MW)        =',F8.1,/,
                9 9X,'*ION DENSITY (IONS/M**3)         =',1PE12.2)
ISN 0212          WRITE(6,63) VPLAS,TAUP,REFLT,EFUS,FB
ISN 0213       63 FORMAT(9X,'*PLASMA VOLUME(M**3)                  =',F8.1,/,
                1 9X,'*PARTICLE CONFINEMENT TIME(S)    =',F8.2,/,
                2 9X,'*REFLECTION COEFFICIENT          =',F8.3,/,
                3 9X,'*ENERGY PER FUSION (PJ)          =',F8.2,/,
                4 9X,'*FRACTIONAL BURNUP               =',F8.4)
ISN 0214          WRITE(6,998)
ISN 0215      998 FORMAT(///,9X,'*INPUT PARAMETERS')
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ISN 0216          WRITE(6,60) TITLE1,TITLE2
ISN 0217          WRITE(6,71)
ISN 0218       71 FORMAT(8X,'TORUS EVACUATION SYSTEM PARAMETERS'/)
ISN 0219          WRITE(6,72)DGL,DPP,DPSP,DPSDT,DPSHE,CPSA,CCPHE,CCSPDT,DPREG,
                 XHSMV,TCDVS
ISN 0220       72 FORMAT(9X,'*GAS LOAD-DIVERTOR (PA-M**3/S)   ='1PE12.2,/,
                1 9X,'*DIVERTOR PUMP PRESSURE (PA)       =',E12.2,/,
                2 9X,'DIVERTOR PUMP SPEED (M**3/S)       =',E12.2,/,
                3 9X,'DIVERTOR PUMP SPEED-DT (M**3/S) =',E12.2,/,
                4 9X,'DIVERTOR PUMP SPEED-HE (M**3/S) =',E12.2,/,
                5 9X,'CRYOPANEL SURFACE-DIV. (M**2)     =',E12.2,/,
                6 9X,'COST - HE PUMPING DIV. ($)        =',E12.2,/,
                7 9X,'COST - DT PUMPING DIV. ($)        =',E12.2,/,
                8 9X,'COST- DIV. PUMP REGENERATION ($)=',E12.2,/,
                9 9X,'COST-DIV. HARD SEAL METAL VALVE =',E12.2,/,
                1 9X,'TOTAL COST DIV. VACUUM SYSTEM($)=',E12.2)
ISN 0221          WRITE(6,80) VTOT,SA,DNUM,DIAM,DLEN,PSP,PCAP,PFAC
ISN 0222       80 FORMAT(9X,'*EVACUATION VOLUME(M**3)            =',F8.1,/,
                1 9X,'*SURFACE AREA (M**2)                =',F8.1,/,
                2 9X,'*NUMBER OF DUCTS                    =',F8.0,/,
                3 9X,'*DUCT DIAMETER(M)                   =',F8.2,/,
                4 9X,'*DUCT LENGTH(M)                     =',F8.2,/,
                5 9X,'*RATED SPEED/PUMP(M**3/S)           =',F8.1,/,
                7 9X,'*PUMP CAPACITY (PA-M**3)            =',1PE12.2,/,
                8 9X,'*PUMP LOADING FACTOR                =',0PF8.2)
ISN 0223          WRITE(6,100) PBGT,PBGP,PREP,QPGP,REPS,PBHEP,PRHEP,REPSHE
ISN 0224      100 FORMAT(9X,'*POST BURN GAS TEMP(K)                    =',F8.1,/,
                1 10X,'POST BURN GAS PRESSURE (PA)     =',1PE12.2,/,
                2 9X,'*PREBURN PRESSURE (PA)           =',E12.2,/,
                3 10X,'POST BURN GAS LOAD(PA-M**3)     =',E12.2,/,
                4 10X,'REQUIRED DT SPEED (M**3/S)      =',E12.2,/,
                5 10X,'POST BURN HE PRESSURE (PA)      =',E12.2,/,
                6 10X,'PREBURN HE PRESSURE (PA)        =',E12.2,/,
                7 10X,'REQUIRED HE SPEED (M**3/S)      =',E12.2)
ISN 0225          WRITE(6,101) PITEM,SPD,CONEF,EPS,RETIM,DIAMIN,REGEN,RPCAP,
                 XCRPS,SPDP,SPDHE,VCPSA,VCCPHE,VCPDT,VCREG,VHSMV,TCVS
ISN 0226      101 FORMAT(9X,'*PUMP INLET TEMP (K)                  =',F8.1,/,
                1 10X,'REQUIRED DUCT SPEED (M**3/S)    =',F8.2,/,
                2 10X,'DUCT CONDUCTANCE (M**3/S)       =',F8.2,/,
                3 10X,'EFFECTIVE DUCT SPEED (M**3/S)   =',F8.2,/,
                4 10X,'REGENERATION PERIOD (HOURS)     =',F8.3,/,
                5 10X,'MINIMUM DUCT DIAMETER (M)       =',F8.4,/,
                6 10X,'FIXED REGENERATION TIME (HOURS)=',F8.2,/,
                7 10X,'REQD. PUMP CAPACITY (PA-M**3)   =',1PE12.2,/,
                8 10X,'CAPACITY EQ. PUMP SIZE (M**3/S)=',E12.2,/,
                9 10X,'REQUIRED PUMP SPEED (M**3/S)   )=',0PF8.2,/,
                1 10X,'REQD. HE PUMP SPEED (M**3/S)    =',F8.2,/,
                2 10X,'CRYOPANEL SURFACE AREA (M**2)   =',F8.4,/,
                3 10X,'COST-HE SORPTION PUMPING ($)    =',1PE12.2,/,
                4 10X,'COST-DT CONDENS. PUMPING ($)    =',E12.2,/,
                5 10X,'COST-PUMP REGENERATION ($)      =',E12.2,/,
                6 10X,'COST-HARD SEAL METAL VALVES ($)=',E12.2,/,
                7 10X,'TOTAL VACUUM SYSTEM COST ($)    =',E12.2)
ISN 0227          WRITE(6,998)
ISN 0228          WRITE(6,60) TITLE1,TITLE2
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ISN 0229          WRITE(6,103)
ISN 0230      103 FORMAT(8X,'TRITIUM AND FUEL PROCESSING PARAMETERS',/)
ISN 0231          WRITE(6,104) TSTART,BPDAY,TGLPH,TGLPD,BPC,TBPH,TBPD,TEXC,TEXH,TEX
                 XD,TFULC,TFULH,TFULD,FIC,FIFPH,FIFPD
ISN 0232      104 FORMAT(10X,'TRITIUM INITIAL LOAD/BURN (G)  =',F8.4,/,
                 A10X,'NUMBER OF BURN CYCLES/DAY       =',F8.1,/,
                 110X,'TRITIUM GAS LOAD/HOUR (G)       =',F8.4,/,
                 210X,'TRITIUM GAS LOADING/DAY (G)     =',F8.3,/,
                 310X,'TRITIUM BURNUP PER CYCLE (G)    =',F8.4,/,
                 610X,'TRITIUM BURNUP PER HOUR(G)      =',F8.3,/,
                 510X,'TRITIUM BURNUP PER DAY (G)      =',F8.2,/,
                 710X,'TRITIUM EXHAUST PER CYCLE (G)  =',1PE12.2,/,
                 810X,'TRITIUM EXHAUST PER HOUR (G)    =',E12.2,/,
                 910X,'TRITIUM EXHAUST PER DAY (G)     =',E12.2,/,
                 110X,'TRITIUM FUELING PER CYCLE (G)   =',E12.2,/,
                 210X,'TRITIUM FUELING PER HOUR (G)    =',E12.2,/,
                 310X,'TRITIUM FUELING PER DAY(G)      =',E12.2,/,
                 410X,'TRITIUM INPUT PER CYCLE (G)     =',E12.2,/,
                 610X,'TRITIUM INPUT PER HOUR (G)      =',E12.2,/,
                 710X,'TRITIUM INPUT PER DAY (G)       =',E12.2)
ISN 0233          WRITE(6,106) HEEXD,PEXD,CEXD,OEXD,NEXD,AREXD
ISN 0234      106 FORMAT(10X,'HELIUM EXHAUST PER DAY (G)      =',F8.3,/,
                 910X,'PROTIUM EXHAUST PER DAY (G)     =',F8.3,/,
                 110X,'CARBON EXHAUST PER DAY (G)      =',F8.3,/,
                 210X,'OXYGEN EXHAUST PER DAY (G)      =',F8.3,/,
                 310X,'NITROGEN EXHAUST PER DAY (G)    =',F8.3,/,
                 410X,'ARGON EXHAUST PER DAY(G)        =',F8.3)
ISN 0235          WRITE(6,105) BR,TINVP,TINVS,TINPS,TINPL,TINIS,TINFP,TINBL,TRINV,
                 XTTINV,TPPD,TDPY,DBINV,DTIME,ANTC,CANTC
ISN 0236      105 FORMAT(9X,'*BREEDING RATIO                  =',F8.2,/,
                 19X,'TRITIUM INVENTORIES (G)************************',/,
                 210X,'VACUUM PUMPS                    =',F8.1,/,
                 310X,'STORAGE                         =',F8.1,/,
                 410X,'SURGE TANK                      =',F8.1,/,
                 510X,'LIQUEFACTION UNIT               =',F8.1,/,
                 610X,'CRYOGENIC DISTILLATION CASCADE =',F8.1,/,
                 710X,'FUEL PREPARATION                =',F8.1,/,
                 810X,'BREEDER BLANKET                 =',F8.1,/,
                 910X,'TRITIUM RECOVERY SYSTEM         =',F8.1,/,
                 110X,'TOTAL TRITIUM INVENTORY         =',F8.1,/,
                 210X,'TRITIUM BRED PER DAY (G)        =',F8.2,/,
                 310X,'TRITIUM DECAY PER YEAR (G)      =',F8.2,/,
                 C10X,'DOUBLING INVENTORY(G)           =',1PE12.2,/,
                 C10X,'DOUBLING TIME(YEARS)            =',0PF8.2,/,
                 410X,'ANNUAL TRITIUM CONSUMPTION (G) =',1PE12.2,/,
                 510X,'ANNUAL COST OF TRITIUM ($)      =',E12.2)
ISN 0237          WRITE(6,998)
ISN 0238          WRITE(6,60) TITLE1,TITLE2
ISN 0239          WRITE(6,200)
ISN 0240      200 FORMAT(8X,'DEUTERIUM AND NEUTRAL BEAM SYSTEM',/)
ISN 0241          WRITE(6,201) BIGLA,BIPPA,BIGLB,BIPPB,PINJ,EINJ,TINJ,ZNINJ,TFLBD,
                 XPSBZA,PSBZB,CPBZA,CPBZB,SAPZA,SAPZB,TCNBVS
ISN 0242      201 FORMAT(9X,'*GAS LOAD/INJ.-ZONE1 (PA-M**3/S)=',1PE12.2,/,
                 19X,'*BEAM PUMP PRESSURE-ZONE 1 (PA) =',E12.3,/,
                 29X,'*GAS LOAD/INJ.-ZONE2 (PA-M**3/S)=',E12.3,/,
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              39X,'*BEAM PUMP PRESSURE-ZONE 2 (PA) =',E12.3,/,
              49X,'*NEUTRAL BEAM POWER (MW)        =',0PF8.2,/,
              59X,'*NEUTRAL BEAM ENERGY (KEV)      =',F8.2,/,
              69X,'*NEUTRAL BEAM DURATION (S)      =',F8.2,/,
              79X,'*NUMBER OF INJECTORS            =',F8.0,/,
              810X,'T UP BEAM DUCTS (G/(M**2-BURN))=',1PE12.2,/,
              910X,'PUMP SPEED-ZONE 1 (M**3/S)     =',E12.2,/,
              110X,'PUMP SPEED-ZONE 2 (M**3/S)     =',E12.2,/,
              210X,'PUMP COST-ZONE 1 ($)           =',E12.2,/,
              310X,'PUMP COST-ZONE 2 ($)           =',E12.2,/,
              410X,'PUMP SURFACE AREA-ZONE 1 (M**2)=',E12.2,/,
              510X,'PUMP SURFACE AREA-ZONE 2 (M**2)=',E12.2,/,
              610X,'TOTAL COST BEAM VACUUM SYS. ($)=',E12.2)
ISN 0243       WRITE(6,107) DBPD,DINJD,DPIND,TPIND,DFULD,DGLPD
ISN 0244   107 FORMAT(10X,'D BURNED PER DAY(G)            =',F8.2,/,
              810X,'D INJECTED PER DAY (G)         =',F8.2,/,
              910X,'D PUMPED/DAY-BEAMS    (G)      =',F8.2,/,
              110X,'T PUMPED/DAY-BEAMS    (G)      =',F8.4,/,
              210X,'D FUELING/DAY (G)              =',F8.2,/,
              310X,'D COLD GAS FILL/DAY (G)        =',F8.2)
ISN 0245       WRITE(6,998)
ISN 0246       WRITE(6,60) TITLE1,TITLE2
ISN 0247       WRITE(6,202)
ISN 0248   202 FORMAT(8X,'EMERGENCY AIR DETRITIATION SYSTEM (E.D.S.)',/)
ISN 0249       WRITE(6,203) MPR,TCON,CUTIM,VBLDG,DECF,CUEFF,CUFR,VFR,STACK,TREL,
              XVENT,TVENT,CEDS
ISN 0250   203 FORMAT(10X,'MAXIMUM CONCEIVABLE RELEASE (G)=',F8.2,/,
              110X,'INITIAL T CONC. (UCI/M**3)     =',1PE12.2,/,
              29X,'*CLEANUP TIME (HOURS)           =',0PF8.2,/,
              39X,'*VOLUME OF REACTOR BLDG. (M**3) =',1PE12.2,/,
              X9X,'*DECONTAMINATION FACTOR         =',E12.2,/,
              49X,'*CLEANUP EFFICIENCY             =',0PF8.3,/,
              510X,'E.D.S. FLOW RATE (M**3/S)      =',F8.3,/,
              A10X,'E.D.S. FLOW RATE (%VBLDG/MIN)  =',F8.3,/,
              69X,'*T LEVEL STACKED (UCI/M**3)     =',F8.3,/,
              710X,'TRITIUM RELEASE (CI)           =',F8.3,/,
              810X,'VENT RATE(M**3/S)              =',1PE12.2,/,
              910X,'TRITIUM VENTED TO ENV.(CI)     =',E12.2,/,
              110X,'E.D.S. CAPITAL COST ($)        =',E12.2)
ISN 0251       WRITE(6,998)
ISN 0252       WRITE(6,60) TITLE1,TITLE2
ISN 0253       WRITE(6,204)
ISN 0254   204 FORMAT(8X,'TRITIUM AND VACUUM SYSTEMS COSTS',/)
ISN 0255       WRITE(6,205) CTRECB,CPIP,CCDIST,CGBOX,CMISCT,CPFLS,TCTHS,CEDS,
              XTCVS,TCDVS,TCNBVS,TCTVS
ISN 0256   205 FORMAT(10X,'TRITIUM RECOVERY ($)           =',1PE12.2,/,
              110X,'PIPING ($)                     =',E12.2,/,
              210X,'ISOTOPIC SEPARATION UNIT       =',E12.2,/,
              310X,'GLOVEBOXES AND PURIFIERS($)    =',E12.2,/,
              410X,'MISC. T. FACILITY COSTS ($)    =',E12.2,/,
              510X,'PELLET FUELING ($)             =',E12.2,/,
              610X,'TOTAL-FUEL PROCESSING ($)      =',E12.2,/,
              710X,'COST - E.D.S. ($)              =',E12.2,/,
              810X,'COST-VAC+ROUGHING SYSTEM ($)   =',E12.2,/,
              910X,'COST-DIVERTOR VACUUM SYSTEM ($)=',E12.2,/,
              110X,'COST-N. BEAM VACUUM SYSTEM ($) =',E12.2,/,
              210X,'TOTAL-TRITIUM+VACUUM SYSTEMS($)=',E12.2)
ISN 0257       GO TO 1
ISN 0258   999 STOP
ISN 0259       END
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SAMPLE RESULTS

TRITIUM FACILITY AND VACUUM SYSTEM
PARAMETERS FOR THE ANL EPR-FY1977

PLASMA AND BURN CYCLE

*BURN TIME (S)	=	64.0
*DWELL TIME (S)	=	16.0
*LAG TIME (S)	=	2.0
DUTY FACTOR	=	0.800
*PLANT AVAILIBILITY FACTOR	=	0.625
PLANT FACTOR	=	0.500
ENERGY PER BURN PULSE (MJ)	=	2.08E 04
*POWER PER BURN PULSE(MW)	=	325.0
CYCLE AVERAGE POWER (MW)	=	260.0
*ION DENSITY (IONS/M**3)	=	1.30E 20
*PLASMA VOLUME(M**3)	=	360.0
*PARTICLE CONFINEMENT TIME(S)	=	5.00
*REFLECTION COEFFICIENT	=	0.950
*ENERGY PER FUSION (PJ)	=	2.82
*FRACTIONAL BURNUP	=	0.1610

*INPUT PARAMETERS

SAMPLE RESULTS (Cont'd)

TRITIUM FACILITY AND VACUUM SYSTEM
PARAMETERS FOR THE ANL EPR-FY1977

TORUS EVACUATION SYSTEM PARAMETERS

*GAS LOAD-DIVERTOR (PA-M**3/S)	=	0.0
*DIVERTOR PUMP PRESSURE (PA)	=	0.0
DIVERTOR PUMP SPEED (M**3/S)	=	0.0
DIVERTOR PUMP SPEED-DT (M**3/S)	=	0.0
DIVERTOR PUMP SPEED-HE (M**3/S)	=	0.0
CRYOPANEL SURFACE-DIV. (M**2)	=	0.0
COST - HE PUMPING DIV. ($)	=	0.0
COST - DT PUMPING DIV. ($)	=	0.0
COST- DIV. PUMP REGENERATION ($)	=	0.0
COST-DIV. HARD SEAL METAL VALVE	=	0.0
TOTAL COST DIV. VACUUM SYSTEM($)	=	0.0
*EVACUATION VOLUME(M**3)	=	450.0
*SURFACE AREA (M**2)	=	430.0
*NUMBER OF DUCTS	=	12.
*DUCT DIAMETER(M)	=	0.80
*DUCT LENGTH(M)	=	6.00
*RATED SPEED/PUMP(M**3/S)	=	80.0
*PUMP CAPACITY (PA-M**3)	=	1.07E 04
*PUMP LOADING FACTOR	=	0.83
*POST BURN GAS TEMP(K)	=	773.2
POST BURN GAS PRESSURE (PA)	=	6.43E-01
*PREBURN PRESSURE (PA)	=	4.00E-03
POST BURN GAS LOAD(PA-M**3)	=	2.89E 02
REQUIRED DT SPEED (M**3/S)	=	1.63E 02
POST BURN HE PRESSURE (PA)	=	2.07E-01
PREBURN HE PRESSURE (PA)	=	1.00E-03
REQUIRED HE SPEED (M**3/S)	=	1.71E 02
*PUMP INLET TEMP (K)	=	273.2
REQUIRED DUCT SPEED (M**3/S)	=	13.61
DUCT CONDUCTANCE (M**3/S)	=	25.26
EFFECTIVE DUCT SPEED (M**3/S)	=	19.20
REGENERATION PERIOD (HOURS)	=	8.155
MINIMUM DUCT DIAMETER (M)	=	0.6902
FIXED REGENERATION TIME (HOURS)	=	4.00
REQD. PUMP CAPACITY (PA-M**3)	=	4.34E 03
CAPACITY EQ. PUMP SIZE (M**3/S)	=	3.26E 01
REQUIRED PUMP SPEED (M**3/S))	=	29.50
REQD. HE PUMP SPEED (M**3/S)	=	94.25
CRYOPANEL SURFACE AREA (M**2)	=	1.8850
COST-HE SORPTION PUMPING ($)	=	1.70E 06
COST-DT CONDENS. PUMPING ($)	=	9.80E 04
COST-PUMP REGENERATION ($)	=	4.90E 04
COST-HARD SEAL METAL VALVES ($)	=	1.32E 06
TOTAL VACUUM SYSTEM COST ($)	=	3.16E 06

*INPUT PARAMETERS

TRITIUM FACILITY AND VACUUM SYSTEM
PARAMETERS FOR THE ANL EPR-FY1977

TRITIUM AND FUEL PROCESSING PARAMETERS

TRITIUM INITIAL LOAD/BURN (G)	=	0.1170
NUMBER OF BURN CYCLES/DAY	=	1080.0
TRITIUM GAS LOAD/HOUR (G)	=	5.2650
TRITIUM GAS LOADING/DAY (G)	=	126.360
TRITIUM BURNUP PER CYCLE (G)	=	0.0368
TRITIUM BURNUP PER HOUR(G)	=	1.656
TRITIUM BURNUP PER DAY (G)	=	39.75
TRITIUM EXHAUST PER CYCLE (G)	=	1.92E-01
TRITIUM EXHAUST PER HOUR (G)	=	8.63E 00
TRITIUM EXHAUST PER DAY (G)	=	2.07E 02
TRITIUM FUELING PER CYCLE (G)	=	1.12E-01
TRITIUM FUELING PER HOUR (G)	=	5.02E 00
TRITIUM FUELING PER DAY(G)	=	1.21E 02
TRITIUM INPUT PER CYCLE (G)	=	2.29E-01
TRITIUM INPUT PER HOUR (G)	=	1.03E 01
TRITIUM INPUT PER DAY (G)	=	2.47E 02
HELIUM EXHAUST PER DAY (G)	=	52.868
PROTIUM EXHAUST PER DAY (G)	=	1.639
CARBON EXHAUST PER DAY (G)	=	9.833
OXYGEN EXHAUST PER DAY (G)	=	0.793
NITROGEN EXHAUST PER DAY (G)	=	0.687
ARGON EXHAUST PER DAY(G)	=	6.556
*BREEDING RATIO	=	0.0
TRITIUM INVENTORIES (G)************************		
VACUUM PUMPS	=	34.5
STORAGE	=	1192.5
SURGE TANK	=	3.2
LIQUEFACTION UNIT	=	7.1
CRYOGENIC DISTILLATION CASCADE	=	10.2
FUEL PREPARATION	=	110.3
BREEDER BLANKET	=	0.0
TRITIUM RECOVERY SYSTEM	=	0.0
TOTAL TRITIUM INVENTORY	=	1357.7
TRITIUM BRED PER DAY (G)	=	0.0
TRITIUM DECAY PER YEAR (G)	=	76.03
DOUBLING INVENTORY(G)	=	0.0
DOUBLING TIME(YEARS)	=	0.0
ANNUAL TRITIUM CONSUMPTION (G)	=	9.15E 03
ANNUAL COST OF TRITIUM ($)	=	6.21E 07

*INPUT PARAMETERS

SAMPLE RESULTS (Cont'd)

TRITIUM FACILITY AND VACUUM SYSTEM PARAMETERS FOR THE ANL EPR-FY1977

DEUTERIUM AND NEUTRAL BEAM SYSTEM

*GAS LOAD/INJ.-ZONE1 (PA-M**3/S)	=	4.10E 00
*BEAM PUMP PRESSURE-ZONE 1 (PA)	=	1.000E-02
*GAS LOAD/INJ.-ZONE2 (PA-M**3/S)	=	4.100E 00
*BEAM PUMP PRESSURE-ZONE 2 (PA)	=	1.000E-02
*NEUTRAL BEAM POWER (MW)	=	60.00
*NEUTRAL BEAM ENERGY (KEV)	=	150.00
*NEUTRAL BEAM DURATION (S)	=	5.70
*NUMBER OF INJECTORS	=	12.
T UP BEAM DUCTS (G/(M**2-BURN))	=	1.55E-04
PUMP SPEED-ZONE 1 (M**3/S)	=	4.10E 02
PUMP SPEED-ZONE 2 (M**3/S)	=	4.10E 02
PUMP COST-ZONE 1 ($)	=	6.15E 05
PUMP COST-ZONE 2 ($)	=	6.15E 05
PUMP SURFACE AREA-ZONE 1 (M**2)	=	1.78E 01
PUMP SURFACE AREA-ZONE 2 (M**2)	=	1.78E 01
TOTAL COST BEAM VACUUM SYS. ($)	=	2.07E 07
D BURNED PER DAY(G)	=	26.63
D INJECTED PER DAY (G)	=	51.10
D PUMPED/DAY-BEAMS (G)	=	80.99
T PUMPED/DAY-BEAMS (G)	=	2.0100
D FUELING/DAY (G)	=	55.81
D COLD GAS FILL/DAY (G)	=	58.51

*INPUT PARAMETERS

SAMPLE RESULTS (Cont'd)

TRITIUM FACILITY AND VACUUM SYSTEM
PARAMETERS FOR THE ANL EPR-FY1977

EMERGENCY AIR DETRITIATION SYSTEM (E.D.S.)

MAXIMUM CONCEIVABLE RELEASE (G)	=	144.79
INITIAL T CONC. (UCI/M**3)	=	2.32E 07
*CLEANUP TIME (HOURS)	=	48.00
*VOLUME OF REACTOR BLDG. (M**3)	=	6.00E 04
*DECONTAMINATION FACTOR	=	1.00E-06
*CLEANUP EFFICIENCY	=	0.990
E.D.S. FLOW RATE (M**3/S)	=	4.576
E.D.S. FLOW RATE (%VBLDG/MIN)	=	0.458
*T LEVEL STACKED (UCI/M**3)	=	50.000
TRITIUM RELEASE (CI)	=	3.000
VENT RATE(M**3/S)	=	1.00E 00
TRITIUM VENTED TO ENV.(CI)	=	3.04E-01
E.D.S. CAPITAL COST ($)	=	5.85E 06

*INPUT PARAMETERS

TRITIUM FACILITY AND VACUUM SYSTEM
PARAMETERS FOR THE ANL EPR-FY1977

TRITIUM AND VACUUM SYSTEMS COSTS

TRITIUM RECOVERY ($)	=	0.0
PIPING ($)	=	8.17E 05
ISOTOPIC SEPARATION UNIT	=	8.56E 05
GLOVEBOXES AND PURIFIERS($)	=	2.70E 06
MISC. T. FACILITY COSTS ($)	=	1.01E 06
PELLET FUELING ($)	=	1.43E 06
TOTAL-FUEL PROCESSING ($)	=	6.81E 06
COST - E.D.S. ($)	=	5.85E 06
COST-VAC+ROUGHING SYSTEM ($)	=	3.16E 06
COST-DIVERTOR VACUUM SYSTEM ($)	=	0.0
COST-N. BEAM VACUUM SYSTEM ($)	=	2.07E 07
TOTAL-TRITIUM+VACUUM SYSTEMS($)	=	3.65E 07

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