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ABSTRACT

The tritium pathways and handling systems in twenty different conceptual magnetic and inertial confinement fusion reactor designs have been examined and compared. The primary objectives of this investigation have been: (1) to determine the effects, if any, of the plasma confinement scheme, reactor fueling method, and first wall protection scheme on the design and relative complexity of the tritium handling systems, and (2) to quantify the advantages and disadvantages of removing the tritium breeding function from the reactor.

It is concluded that, from a tritium handling viewpoint, inertial confinement reactors with either gas-protected or magnetically-protected first walls, pellet-fueled tandem mirrors, and reversed field pinch reactors are preferred. On the other hand, the tritium handling problem is at a maximum in laser-driven reactors with either a wetted wall or lithium fall protection, tokamaks, standard mirrors, and fast-liner reactors. Theta pinches and neutral beam-fueled tandem mirrors belong to an intermediate category.

It is also concluded that transfer of the tritium breeding function from the reactor blanket to an external source does not result in significant benefits.

I. INTRODUCTION

In fusion reactors, only a small fraction of the DT fuel supplied to the reactor chamber is actually consumed. The fractional burnup depends on the reactor type and confinement scheme and ranges from $\leq$ 1.5% in tokamaks to as much as 40% in laser and particle beam fusion reactors. Economic, safety, and environmental considerations make it necessary to recover and recycle the unburned fuel. Numerous conceptual reactor designs have been reported in the literature (1-20). Based on these designs it is clear that the fuel reprocessing system will represent a major component of the fusion reactor and that, from a safety viewpoint, it is one of the most important due to the mobility and radioactivity of tritium.

Substantial differences exist among conceptual reactor designs in the design details and level of technological complexity of the fuel reprocessing system. Some of these differences may be "generic" inasmuch as they may be directly related to the plasma confinement scheme, reactor fueling method, or first wall protection approach. One of the primary objectives of this investigation has been to identify these generic differences and to assess the relative complexity of the tritium handling systems in different reactor designs. Such assessment should aid in identifying the most critical problems. Also, when coupled with studies of other reactor subsystems, the most attractive reactor design concept can be selected.

In addition to the fuel recycling system, a tritium-breeding blanket and a tritium extraction system are usually included in the reactor design to make it self-sufficient. It has been suggested that for fusion-fission hybrids where tritium fuel requirements are relatively modest, the tritium breeding function may be removed from the reactor. The tritium would be bred in dedicated facilities such as Savannah-river-type reactors or in the fission reactors to be supported by the hybrids. The aim is to simplify the reactor design in order to reduce the development cost and allow it to be deployed at an earlier date. As a part of this investigation, the tritium handling systems for different reactors have been examined in order to determine whether the removal of the tritium breeding function from the reactor would result in significant benefits.

The remainder of this paper is divided into two main parts. In the first part the tritium fueling and exhaust systems in different reactor designs are compared. The second part deals with the issue of tritium breeding within or without the reactor.

II. FUELING AND EXHAUST SYSTEMS

The fueling and exhaust system characteristics for twenty different conceptual fusion reactor designs have been examined. Of these designs, three are for fusion-fission hybrids (7,12,18) while the others are fusion-electric. These designs represent different plasma confinement schemes, fueling methods, and wall protection concepts (Table I). The aim is to compare the tritium handling systems in these different designs to identify the generic differences among them. In addition, the effects of the fueling and exhaust systems on the overall steady-state tritium burdens in the different reactor components and the relationship between the fueling and exhaust system tritium inventory and the blanket inventory have been examined. The reactor designs listed in Table I do not include all the confinement schemes proposed so far; however, sufficiently detailed designs for other concepts do not exist at this time.

The main characteristics of the fueling, exhaust, and breeding systems of the different reactors are listed in Tables II-VI. These values have been normalized to a reactor capacity of 1 GWe in order to allow meaningful comparison among them.

II.1. Fractional Burnup

An important parameter characterizing the fueling and exhaust systems is the fractional burnup f_b. Values of f_b for the different reactors examined in this study are given in Table II. Here, f_b is defined as: $f_b \equiv T_b/(T_p+T_b)$ where T_b is the amount of tritium burned per unit time while T_p is the total amount of tritium pumped from the chamber per unit time. This definition is most suitable from a tritium handling viewpoint and may be different from the plasma physics definition of burnup. For example, in the laser fusion reactor SOLASE (17,21,22) the burnup for a successfully imploded target is 45%; however, when 10% misfirings are accounted for, the effective burnup is lowered to 41%. Similarly, for the reference theta pinch reactor RTPR (8), the burnup at the end of the quench stage is 4.8%; however, when the layer of neutral DT gas injected between the hot central plasma and the first wall is included, the effective fractional burnup is lowered to about 1%. This layer is injected for the purpose of cooling, neutralizing, and purging the partially burned DT plasma.

The relationship between the unburned tritium flow rate T_p and the fractional burnup is shown in Fig. 1 for 1 GWe. This relation clearly illustrates that burnups in excess of 5% are highly desirable since lower burnups can result in excessively high tritium flow rates in the fueling cycle.

Examination of Table II shows that the fractional burnup in recent tokamak designs is ~ 1% while earlier designs had f_b values $\geq$ 5%. Presumably, this is a result of our increased knowledge in the plasma physics area. However, this trend must be reversed if tokamaks are to be credible from a tritium handling viewpoint. Table II also shows that reversed-field pinches have "acceptable" burnup fractions. Tandem mirrors have a definite advantage over standard mirrors and other magnetic confinement devices because of their high burnup fractions. Inertial confinement reactors have much higher burnup fractions, and are therefore quite attractive from a tritium-recycle standpoint. As we shall see later, however, this is only one aspect of the tritium handling problem on which to decide the relative attractiveness of these different systems.

II.2. Fueling Method

If neutral beam injectors are used to either drive or fuel a fusion device, as opposed to only igniting it, the amount of tritium circulated around the beam lines may be as much as ten times larger than that actually injected into the chamber (Table III). The deuterium and tritium not injected become isotopically contaminated and must be reprocessed. This additional tritium flow is not accounted for in computing the fractional burnup. This will have a significant impact on the tritium handling system as illustrated by the tandem mirror reactor (13) in which an 18% burnup results in a tritium exhaust flow rate of less than 2 kg/day (Table IV). However, the neutral beam injectors result in the recycle of an additional 12 kg/day which overshadows the advantages gained by the high burnup fraction. Hence, there is an incentive to investigate other means for fueling the central cell. Pellet fueling has been proposed in another tandem mirror design underway at the University of Wisconsin (23); this lowers the recycled tritium flow rate significantly. The standard mirror is most undesirable from a tritium flow rate standpoint as it is not only fueled by neutral beams but also has a low fractional burnup so that the total flow rates are in excess of 100 kg/d (Tables II, III).

II.3. Pumping Speed and Exhaust Gas Composition

The exhaust systems in fusion devices with magnetically-protected first walls are fundamentally different from those utilizing gas protection. The chamber exhaust gas in the first type consists primarily of low purity hydrogen isotopes (78-99%) while in the latter the exhaust gas contains only traces of hydrogen isotopes (Table V). This has a significant impact on the design of the gas handling systems. In magnetic protection, the deuterium and tritium must be purified from contaminants while in gas protection they are regarded as contaminants for the protective gas which must be recovered, processed and reused. In either case, considerable industrial experience exists in the handling of large amounts of these gases.

Several variations of liquid lithium protection exist (1,3,14,15,19,20). These appear difficult inasmuch as they combine the problems of exhaust gas processing and blanket tritium breeding. Some of the unburned fuel is chemically gettered by the flowing lithium while the remainder is conventionally pumped out of the cavity as lithium vapor contaminants (14,15,20) where less than 0.1% of the exhaust vapor are hydrogen isotopes (Table V). These systems differ from magnetic and gas protection as the fuel recycle is no longer solely a gas handling problem.

The reactor exhaust pumping speed (torr•ℓ/s) in magnetically-protected systems is directly related to the fractional burnup while in gas protection the pumping speed is dictated by the protective gas pressure and impurity level (17,18). For liquid lithium protection, the pumping speed is dictated by the amount of lithium evaporated during each shot rather than the fractional burnup (14,15,20). The total moles of gas handled per unit time is higher in gas and liquid lithium protection than in magnetic protection, although only a small fraction of the gas is tritium. However, the gas throughput (ℓ/s) in magnetic protection devices may be considerably higher than liquid lithium or gas protection devices since the chamber pressure in the former is several orders of magnitude lower than that in the latter.

The type of exhaust pumps to be used is dictated by the chamber pressure (Table V). At low pressures ($< 10^{-3}$ torr) cryoabsorption pumps are used while at higher pressures ($> 10^{-2}$ torr) mechanical pumps are feasible. Cryopumps, used in tokamaks and mirrors, operate on a batch basis with on-line times of 2-5 hours so that the tritium inventory associated with pumping alone may be as high as several kilograms in low fractional burnup systems. Mechanical pumps, used in pinches and ICF systems, are considerably better in this regard since only a minute amount of tritium is held up in the pumps. Cryopump technology is less established than mechanical pumps. In addition, they require mechanical pumps to remove tritium from their surfaces after each cycle.

In designs utilizing liquid lithium protection, the liquid lithium is used as a chamber pump (1,3,14,15,19,20). Except for the HYLIFE laser fusion reactor (19), additional pumping means are provided. The ability to pump the chamber using liquid lithium alone is highly questionable since lithium has no chemical affinity for helium. **In addition, the time required** for lithium vapor condensation after each shot will be relatively long so that a means for removing the persistent spray-like medium from the chamber before the next shot will be required (24).

II.4. Nonvolatiles in Chamber Exhaust

Nonvolatile materials will be present in all fusion reactor cavities. They result from sputtering and blistering of the first wall and other reactor components (Tables IV,VI). They may also be injected into the reactor chamber as parts of the targets or liners in inertial confinement systems (Table II). The amount of these materials and their impact on the design and handling of the exhaust systems have not been adequately examined in most reactor designs; hence, the values given in Tables II, IV, and VI are not indicative of the total problem. For example, the amount given in Table VI for RTPR (8) is the result of neutron sputtering only and does not include charged particle sputtering. Similarly for the SMFR (II) the amount given is for direct converter grid sputtering and does not include first wall sputtering.

Despite the incompleteness of Tables II, IV and VI, it appears that inertial confinement systems have a potentially more severe problem with nonvolatiles than magnetic confinement systems. The amount of nonvolatile materials in ICF targets will be 100-1000 times that of the fuel (22,25,26). This means that several hundred to several thousand kgs per day of these materials will be injected in the cavity for 1 GW of fusion power. Clearly, pellet designs using volatile high-Z materials such as xenon will be much preferred. The fast-liner approach appears to have insurmountable problems with respect to nonvolatiles in that several thousand tonnes of these materials must be removed from the chamber per day.

II.5. Tritium Inventory

Tritium inventories gleaned from 11 reactor designs are given in Table VII. These values show that for most reactors the tritium inventory in the blanket system is much smaller than that in the fueling system and storage. This is clearly illustrated in Fig. 2 where the inventory fractions in fueling, storage, and blanket are given.

Onsite tritium storage is required to maintain reactor operation in the event of a temporary, minor malfunction in any of the tritium handling equipment. The storage values used in different reactor designs vary widely (Table VII). They are usually estimated on the basis of either the tritium burning rate or injection rate. For example, the amounts of tritium stored in RTPR (8) and in the mirror hybrid (12) are equivalent to those burned in 1 day and half year of reactor operation, respectively. On the other hand, the storage inventories in the Princeton hybrid (7) and NUWMAK (6) are equal to the amounts injected in 4 hours and one day of reactor operation, respectively. Clearly, if tritium reserves were to be consistently based on the amount of tritium burned, they would be equal for all pure fusion reactors and would be somewhat lower for hybrids because of their higher blanket energy multiplication. However, if tritium storage is to be based on the tritium injection rate, the quantities would vary dramatically among the different designs. While no consistent method for estimating the needed tritium reserves exists, it is clear that storage will represent a significant fraction of the total plant inventory.

Normalized values of the tritium inventories in the 6 pure fusion tokamaks examined are listed in Table VIII. The cryopumps, and getter beds and molecular sieves are assumed to be on-line for two and six hours, respectively. Storage is assumed equal to 12 hours of fueling. Table VIII clearly shows that an inverse relation exists between the inventory and fractional burnup (Fig. 3). This observation is contrasted with laser fusion reactors where the inventory is largely controlled by the fueling and pellet manufacturing system (17,18,19). Since up to 10^6 pellets per day may be imploded, the pellet filling operation will necessarily be a batch process. In SOLASE (17), polyvinylalcohol (PVA) pellets with a fill-time of 1 day give a plant inventory of 11.2 kg while glass pellets with a 5 day fill-time result in a 25.7 kg inventory. Therefore, unless pellets with short fill-times are designed, laser fusion devices may have plant inventories equaling or exceeding those of tokamaks, thereby negating some of the benefits of the laser devices' high fractional burnups.

Pinches have the potential for lower tritium inventories than tokamaks since their exhaust requires mechanical pumps rather than cryopumps. However, the plant inventory for RTPR (8) appears to be very optimistic because of the low storage assumed. At a flow rate of 35 kg of tritium per day into the reactor chamber, the assumed storage represents just 14 minutes of fueling if any exhaust tritium handling systems go down.

Mirror reactors suffer from a tritium inventory problem in the cryopumps associated with the neutral beam injectors in addition to those which pump the tritium from the direct converters. Also, the tritium inventory in the direct converters themselves as a result of bombardment by high energy tritons may significantly increase the overall inventory.

The conclusions to be drawn from the data in Table VII can be summarized as follows. In general the tritium inventory in the fueling and storage systems far exceeds the inventory in the breeding system. Neglecting storage, as it is an unresolved question as to what constitutes an acceptable quantity, the major tritium inventory in the fueling cycle for tokamaks appears in the reactor exhaust cryopumps, for mirrors in both the reactor exhaust and neutral beam cryopumps, and for laser fusion devices in pellet makers.

II.6. Comparison Between Different Reactor Concepts

The preceding discussion is now used to determine which reactor concepts are most desirable from a tritium handling viewpoint. To do this, eight criteria have been used to compare the fueling and exhaust systems in the different reactors listed in Table II. Each criterion has been assigned a score ranging from 1 to 5 with 1 being most desirable. The scores are then combined to obtain a figure of merit for comparing the different reactor concepts (Table IX). For completeness, the HYLIFE laser fusion reactor and the fast liner reactor are included in these comparisons even though there is no clear separation between the exhaust and blanket systems.

The eight categories used in this rating process are:

(1) The total tritium flow rate: A score was assigned based on the sum of the tritium injection rate into the chamber and the recycle rate in the neutral beam injectors (Tables II and III).

(2) The exhaust gas flow rate: A score was assigned based on the number of moles or (torr•liters) of hydrogen isotopes, inert gas, lithium vapor or any other gaseous species pumped out of the reactor chamber per day.

(3) The pumping throughput: A score was assigned based on the volumetric flow rate (ℓ/s) out of the chamber plus the pumping load from the neutral beam lines.

(4) The exhaust composition: A score was assigned based on the relative complexity of separating (or purifying) the hydrogen isotopes from the chamber exhaust.

(5) Pump type: A score was assigned based on state-of-art for the required pumping system.

(6) Nonvolatiles in exhaust: A score was assigned based on the expected amount of nonvolatile materials to be removed per day; this problem may deem fast liners totally unfeasible.

(7) Fueling tritium inventory: A score was assigned based on the inventory values given in Table VII.

(8) Storage tritium inventory: This is assumed to be proportional to the tritium flow rate through the fueling and exhaust systems (Tables II and IV).

The conclusions to be drawn from the scores in Table IX can be summarized as follows. Reversed field pinches, pellet-fueled tandem mirrors and laser-driven reactors with magnetically-protected or gas-protected first walls are most attractive from a tritium-handling viewpoint. The opposite is true for tokamaks, standard mirrors, and laser driven reactors with wetted wall or lithium jet protection. It is clear the wall protection method and plasma confinement scheme will equally affect the relative attractiveness of the tritium handling systems.

The above discussion also shows that for the same electrical output the tritium handling problems in fusion-fission hybrids will be substantially reduced compared to pure fusion devices because of the high blanket energy multiplication.

III. REMOVAL OF TRITIUM BREEDING

It has been suggested that for fusion-fission hybrids where tritium fuel requirements are relatively modest, the tritium breeding function may be removed from the reactor. The tritium would be bred in dedicated facilities outside the hybrid. The aim is to simplify the reactor design in order to reduce the development cost and allow it to be deployed at an earlier date. Here, we examine the extent to which the tritium handling problem would be simplified if the tritium breeding function were to be removed from the reactor.

Examination of Tables II - IV shows the tritium breeding rate is significantly smaller than the tritium flow rate out of the reactor cavity except for devices with high burnup fractions (20-40%) where they are only a factor of 1.5-4.0 smaller. When all the tritium flow rates are considered, however, it appears that little reduction would be achieved by removing the tritium breeding function from the reactor. In addition, while it may appear that the handling of exhaust gas represents a more near-term technology than tritium recovery from the breeding material, the need to remove kilogram quantities of radioactive non-volatiles per day (Table IV) from the exhaust may result in a different conclusion.

With regard to the steady-state tritium inventory in various reactor components, Figure 2 clearly shows that most of the tritium will reside in the fueling and storage systems. Hence, removal of the tritium breeding component would slightly affect the plant inventory. It may in fact have an adverse effect since a larger storage inventory may be required if tritium breeding is to be done off-site. Current designs with on-site breeders allow for tritium storage inventory equal to the amount consumed in a few days. If tritium is to be purchased from an external supplier, the storage inventory would have to increase to ensure continuous operation in case of extended outages of the supplier, transportation problems, or other unforeseen problems unrelated to plant operation.

Another item to be considered in this comparison is the amount of tritium contained in the structure (Table VII). The magnitudes of these values, rather than being closely correlated with the presence or absence of the tritium breeding function, depend on the type of structural material used as the following example illustrates. Two reactors with high structural inventories, NUWMAK (6) and SOLASE-H (18), utilize metals with high hydrogen solubilities, titanium and zirconium, respectively. Although the tritium in the breeder is the cause of 100% of the structural inventory in NUWMAK, only 12% of the structural inventory in SOLASE-H is due to the breeder. The remainder results from tritium permeation through the first wall to the sodium coolant and subsequent absorption by the Zircaloy structure.

Elimination of the tritium breeding function does not automatically eliminate the need for tritium extraction systems for the coolant. Tritium can permeate divertors, neutral beam injectors and direct converters as well as the reactor first wall (Table X). The coolants associated with these components in most cases require a tritium extraction unit. The technology needed to extract tritium to very low concentrations from these coolants may in some cases closely approximate the technology needed to extract tritium from a lithium bearing material. Thus, technological simplifications resulting from removal of the tritium breeding function may be minimal.

In the following, four reactor designs, assumed to be typical of fusion reactors as a whole, are analyzed individually with respect to tritium handling in the blanket cycle and tritium handling in the fueling cycle. The aim is to determine the extent to which the tritium handling problems may be simplified if the tritium breeding function were to be removed from these reactor designs.

III.1. UWMAK-III (4)

The salient features of the tritium handling systems in UWMAK-III are shown in Fig. 4. If tritium is not bred in the blanket, then the unproven technology of a niobium window for tritium extraction from liquid lithium is no longer necessary. However, tritium must still be extracted from the sodium divertor coolant with an yttrium bed - also an unproven technology. In addition, cryopumps, molecular sieves, cryogenic distillation columns and pellet makers are necessary to handle the reactor exhaust regardless of whether tritium is bred.

III.2. LLL Standard Mirror Hybrid (12)

The salient features of the tritium handling systems in this reactor are shown in Fig. 5. The flow rates to the cryogenic distillation columns are only 3 g T + 370 g D per hour from Li + LiD pins; there are 1260 g T + 2810 g D per hour from plasma related sources. It is evident from Figure 5 that the complexity of the tritium pathways in the reactor would be only slightly reduced by eliminating the Li + LiD breeder.

III.3. The SOLASE Laser Fusion Reactor (17)

The tritium handling systems in SOLASE are shown schematically in Fig. 6. Detailed design of the tritium recovery system from the lithium oxide breeding material has not been worked out. However, it is based on a simple concept, the dehydration of solid lithium oxide, and should not present major obstacles. Even if the separator is no longer required, Roots blowers, a scrubber, an oxidizer, molecular sieves, soda lime beds, an electrolyzer, cryogenic distillation columns, cold traps and pellet makers are required. However, the electrolyzer and distillation columns would be substantially decreased in size by removing the breeding function from SOLASE. This is because the flow of hydrogen isotopes into the electrolyzer and distillation columns is composed largely (99%) of protium rather than tritium, from the breeder. (This protium is used as a carrier for the tritium.)

III.4. The HYLIFE Laser Fusion Reactor (19)

Removal of the tritium breeding from this reactor by using a fluid other than lithium for the liquid wall would have little or no effect on the tritium handling system.

III.5. Safety and Economic Issues

Fusion reactors generally contain $\sim 10^6$ kg of lithium breeding material. Removal of the breeding function from a reactor would require replacing the lithium heat transfer agent with another material, which may involve complications and expense equal to that encountered with lithium materials. In addition, an intermediate heat exchanger will probably be required regardless of whether tritium is bred due to buildup of radioactive species in the primary coolant and the possibility of tritium buildup in the primary coolant from first wall permeation (Table X).

A cursory examination of the safety issues involved is given in Table XI. In essence, the benefits gained from removing tritium from the breeder seem to be more than counteracted by the disadvantages associated with transporting tritium between supplier and user on a periodic basis. The concept of an external supplier also requires that there be an increased number of reactors that handle tritium with a corresponding added risk of an accidental tritium release.

The points raised in considering the consequences of removing the tritium breeding function from fusion or hybrid reactors are summarized in Table XII. The conclusion of this analysis is that from a tritium handling standpoint no significant advantage accrues from removing the breeding funciton. In fact, on the basis of the analysis performed in this study, it may even constitute a disadvantage.

IV. CONCLUSIONS

The tritium pathways and handling systems in twenty different conceptual magnetic and inertial confinement fusion reactor designs have been examined and compared. Based on this comparison it is concluded that, from a tritium handling viewpoint, inertial confinement reactors with either gas-protected or magnetically-protected first walls, pellet-fueled tandem mirrors, and reversed field pinch reactors are preferred. On the other hand, the tritium handling problem is at a maximum in laser-driven reactors with either a wetted wall or lithium fall protection, tokamaks, standard mirrors, and fast-liner reactors. Theta pinches and neutral beam-fueled tandem mirrors belong to an intermediate category.

It is also concluded that transfer of the tritium breeding function from the reactor blanket to an external source does not result in significant benefits.

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26. R.O. Bangerter, "Fusion Target Design," UCRL-82026, Lawrence Livermore Lab. (Dec. 5, 1978).

Table I Reactor Designs Examined in this Study

REACTOR	DESIGN GROUP	DATE	FUSION CONCEPT	FIRST WALL PROTECTION SCHEME	CAPACITY (MWe)
UWMAK-I	UW (1)	3/74	Tokamak	Magnetic (Lithium divertor)	1474
PRD	PPPL(2)	8/74	Tokamak	Magnetic (PE-16 divertor)	2030
UWMAK-II	UW (3)	10/75	Tokamak	Magnetic(Lithium divertor+C curtain)	1716
UWMAK-III	UW (4)	7/76	Tokamak	Magnetic(TZM divertor + C curtain + ISSEC)	1985
Doublet	GA (5)	11/76	Tokamak	Magnetic(DT flowing plasma boundary system)	611
NUWMAK	UW (6)	6/79	Tokamak	Magnetic (DT gas blanket)	660
Tokamak Hybrid*	PPPL(7)	11/78	Tokamak	Magnetic (Divertor)	2419
RTPR	LASL & ANL (8)	3/74	Theta Pinch	Magnetic (DT gas layer)	4100
RFPR-I	Culham(9)	10/77	Reversed-Field Pinch	Magnetic (DT gas layer)	600
RFPR-II	LASL(10)	8/79	Reversed-Field Pinch	Magnetic (DT gas layer)	750
SMFR	LLL(11)	1/78	Standard Mirror	Magnetic	447
Mirror Hybrid*	LLL(12)	5/78	Standard Mirror	Magnetic	603
TMR	LLL(13)	7/77	Tandem Mirror	Magnetic	1000
Wetted-Wall	LASL(14)	4/74	Laser	Lithium film	1000
Suppressed Ablation	LLL(15)	4/74	Laser	Lithium film	265
MPLCTR	LASL(16)	4/74	Laser	Magnetic	1500
SOLASE	UW(17)	12/77	Laser	Ne Gas	1000
SOLASE-H*	UW(18)	5/79	Laser	Xe Gas	800
HYLIFE	LLL(19)	3/79	Laser	Lithium Jets	1060
FLR	LASL(20)	2/79	Fast-Liner	Lithium Spray	129

*Fusion-Fission Hybrids.

Table II

Fueling System Characteristics and Flow Rates of Incoming Materials Into the Cavity Normalized to 1 GWe

Type	Reactor	Frac. Burn-up f_b (%)	Incoming Materials - Flow Rates (kg/d)					
			Fuel		Non-Fuel			
			T	D	H	Inert Gas	Non-volatiles	Wall Protection Material
Tokamaks	UWMAK-I	7.2	5.7	3.8				2.8×10^7 (liq. Li)
	PRD	8.7	3.0	2.0		3.8 (Ar)		- (solid divertor)
	UWMAK-II	4.85	7.5	5.0		1.2 (He)		6.9×10^7 (liq. Li)
	UWMAK-III	0.83	37.9	25.3	1.0	4.6 (He)		- (solid divertor)
	Doublet	1.35[a]	30.3	20.2	0.08			DT Fuel[f]
	NUWMAK	0.77[a]	53.7	35.8	0.36			DT Fuel[f]
	Tokamak Hybrid	0.92	4.1	2.7				- (solid divertor)
Pinches	RTPR	0.97[b]	34.8	23.2		0.48 (He)		DT Fuel[g]
	RFPR-I	3.8[b]	15.0	10.0				DT Fuel[g]
	RFPR-II	5.0[b]	9.6	6.4				DT Fuel[g]
Mirrors	SMFR	3.0	14.1	21.1				? (D_2 or DT)
	Mirror Hybrid	1.6	6.3	8.1	0.02			42.3 (D_2)
	TMR	18	2.1	2.3				-
Laser Devices	Wetted-Wall	22	2.0	1.3				1.1×10^7 (liq. Li)
	Suppressed Ablation	21	2.0	1.3		0.65 (He)		~3×10^6 (liq. Li)
	MPLCTR	22	1.8	1.2				-
	SOLASE	41	1.1	0.8	0.05-0.06[c]	190[e] (Xe)	6.3-3.8[c] (Si,C)	4,400-5,800[c] (Ne)
	SOLASE-H (Hybrid)	27	0.9	0.6	2.3 (D) (d)	150[e] (Xe)	2.5 (C)	3.8×10^5 (Xe)
	HYLIFE	30	1.3	0.9		0.90 (He)	>100 (W,C)	3.7×10^9 (liq. Li)
Liner	FLR	11	3.4	2.2			3.3×10^7 (Cu liner)	1.2×10^9 (liq. Li)

Footnotes for Table II

(a) The burnup may range from 0.6-6% depending on fueling mode; the selected final design parameters yield a value of 0.77% (6).

(b) The burnup fractions at the end of the quench stage are 4.8, 30.0, and 50.0% for RTPR, RFPR-I, and RFPR-II, respectively. These values drop to those given in the table when the neutral DT gas layer injected between the hot central plasma and the first wall is taken into account.

(c) The first value is for a glass container; the other value is for a polyvinylalcohol container. Both targets have a hydrocarbon ablator.

(d) 2 kg/d of target gases, including protium, are injected.

(e) Xe is the high-Z material in the target; its mass is assumed to be 100 times that of fuel.

(f) A DT blanket protects the first wall and limiter and acts as a source of fuel for the plasma. 67% of the fuel is fed to the reactor by this means in the case of the Doublet reactor and 18% in the case of NUWMAK.

(g) A layer of neutral DT gas is injected between the hot central plasma and the first wall. In addition to fueling the reactor, it serves as a means of first wall protection by alleviating sputtering problems caused by energetic ions, now replaced by low energy neutrals.

Table III

Neutral Beams and Breeding Blanket Characteristics
Normalized to 1 GWe

Type	Reactor	Recirc. Flow Through Beam Lines (kg/d)		Breeding Rate (kg/d)
		T	D	
TOKAMAKS	UWMAK-I	0.004[a]	0.002[a]	0.70
	PRD	small	small	0.28
	UWMAK-II	0.003[a]	0.002[a]	0.38
	UWMAK-III			0.34
	Doublet		0.2[a]	0.50
	NUWMAK			0.68
	Tokamak Hybrid	4.4	2.9	0.05
PINCHES	RTPR			0.35
	RFPR-I			0.66
	RFPR-II			0.53
MIRRORS	SMFR	102	152	0.51
	Mirror Hybrid	40.2	52.8	0.14
	TMR	11.7[b]	12.7[b]	0.43
LASER DEVICES	Wetted-Wall			0.51
	Suppressed Ablation			0.59
	MPLCTR			
	SOLASE			0.63
	SOLASE-H (Hybrid)			0.25
	HYLIFE			0.68
LINER	FLR			0.44

(a) Computed assuming the amount of gas recycled to be 7 times that injected.

(b) A deuterium fraction of 0.85 is assumed for both the high energy lines driving the end plugs and the low energy lines fueling the central cell.

Table IV

Flow Rates of Exhaustive Materials From The Chamber Normalized To 1 GWe

Type	Reactor	Flow Rates (kg/d) T	D	H	Inert Gas	Li Vapor	$C_2(H,D,T)_2$	CO	Non-volatiles
TOKAMAKS	UWMAK-I	5.2	3.5		0.61	some			9.3
	PRD	2.7	1.8	0.001	4.1				4.6
	UWMAK-II	7.1	4.8		1.7	some			0.90
	UWMAK-III	37.6	25.1	1.0	5.0				19.5
	Doublet	29.9	19.9	0.082	0.55		2.2		4.7
	NUWMAK	53.3	35.5	0.36	0.55				14.7
	Tokamak Hybrid	4.0	2.7	$3X10^{-5}$	0.06				
PINCHES	RTPR	34.4	23.0	<0.23	0.94				0.44
	RFPR-I	14.4	9.6		0.75				
	RFPR-II	9.1	6.1		0.64				
MIRRORS	SMFR	13.7	20.8		0.58				1.6
	Mirror Hybrid	6.2	8.1	0.02	0.14				
	TMR	1.7	2.0		0.52				
LASER DEVICES	Wetted-Wall	1.6	1.0		0.57	$3.1X10^6$			
	Suppressed Ablation	1.6	1.0		1.2	$1.1X10^4$			
	MPLCTR	1.4	0.9		0.51				200
	SOLASE	0.4	0.3		4,400-5,800(b)		5.8-5.6(b)	4.3-1.1(b)	6.3-3.8(b)
	SOLASE-H (Hybrid)	0.6	2.8		$3.8X10^5$			0.84	2.5
	HYLIFE	0.9	0.6	(a)	1.42	$56\text{-}10^6$(c)			>100
LINER	FLR	3.0	2.0		0.50	$1.7X10^4$			$3.3X10^7$

(a) 2 kg/d of target gases, including protium, are pumped

(b) First value is for a glass shell; second value is for polyvinylalcohol

(c) 56 kg/d is the quantity pumped due to the equilibrium vapor pressure of lithium at 500°C. Millions of kg/d is the quantity pumped if no recondensation occurs.

Table V

Pumping Rates and Exhaust Gas Characteristics Normalized to 1 GWe

Type	Reactor	Exhaust Condition Press. (Pa)	Exhaust Condition Temp. (K)	Pump Type	Pumping Speed Pa•m^3/s (at 300 K)	mol% Hydrogen in Exhaust
TOKAMAKS	UWMAK-I	0.0013	773	Li divertor + Hg diffusion	55[a]	(a)
	PRD	0.060	600	diffusion or turbomolecular	31	83.2
	UWMAK-II	0.011	600	Li divertor + Cryo	80	(b)
	UWMAK-III	0.040	588	Cryo	410	91.3
	Doublet	0.13	1700	Cryo	290	97.9
	NUWMAK	0.0013	573	Cryo	520	99.2
	Tokamak Hybrid			Cryo	39	99.0
PINCHES	RTPR	6.1	810	Roots blowers	350	98.0
	RFPR-I				150	96.2
	RFPR-II	0.31		Roots blowers or Cryo	92	95.0
MIRRORS	SMFR	0.00053	300-1000	Cryo	>230	>98.1[c]
	Mirror Hybrid	0.00013 -0.013		Cryo	400	99.7
	TMR			Cryo	27	86.0
LASER DEVICES	Wetted-Wall	<130	673	Supersonic spray condenser	13,000,000	0.00012
	Suppressed Ablation	13	773	"State-of-the-art"	47,000	0.032
	MPLCTR	13		Vapor booster	17	78.5
	SOLASE	67	2023	Roots blowers	6,400-8,400[d]	0.12
	SOLASE-H (Hybrid)	370	773	Roots blowers	83,000	0.028
	HYLIFE	13	773	Li waterfall	(e)	(e)
LINER	FLR	130	773	Roots blowers	72,000	0.04

Footnotes for Table V

(a) 96% of the D and T and 50% of the He is pumped by the Li divertor with the remainder handled by Hg diffusion pumps. Thus, the composition of the gas exiting these two routes is 95.6 and 47.7% H isotopes, respectively.

(b) 90% of the D and T and none of the He is pumped by the Li divertor with the remainder handled by the cryopumps. Thus, the composition of the gas exiting these two routes is 100 and 66.4% H isotopes, respectively.

(c) The unknown quantity of cold plasma introduced to assure plasma stabilization will cause these values to be higher than given.

(d) The first value is for a glass fuel container; the second is for a polyvinylalcohol container.

(e) 31 Pa·m^3/s of unburned fuel, ash and target gases must be pumped along with an unknown quantity (between 1700 and 10^7-10^8 Pa·m^3/s) of vaporized lithium. Thus, the composition of the exhaust gas is between 7% and 10^{-4}% hydrogen isotopes.

Table VI

Fusion Ash and Eroded Material Flows Normalized to 1 GWe

TYPE	REACTOR	Fusion Ash (kg/d) H	Fusion Ash (kg/d) He	Eroded Material (kg/d) Lithium Vapor	Eroded Material (kg/d) Nonvolatiles
TOKAMAKS	UWMAK-I		0.61	some	9.3[c] (316 SS 1st wall)
	PRD	0.001	0.35		2.2[d] + 2.4[c] (PE-16 divertor + PE-16 1st wall)
	UWMAK-II		0.48	some	0.24[c,e] + 0.66[c,e] (316 SS 1st wall + C curtain)
	UWMAK-III	0.001	0.42		18[d] + 1.5[f] (TZM collector + C curtain & ISSEC)
	Doublet	0.002	0.55		4.7[g] (Si from SiC 1st wall)
	NUWMAK		0.55		0.7 + 14 (Ti-64 1st wall + Cu limiter)
	Tokamak Hybrid	$3X10^{-5}$	0.06		
PINCHES	RTPR		0.46		0.44[h] (Al_2O_3 1st wall coating)
	RFPR-I		0.75		
	RFPR-II		0.64		
MIRRORS	SMFR		0.58		1.6[c] (C direct converter)
	Mirror Hybrid		0.14		
	TMR		0.52		
LASER DEVICES	Wetted-Wall		0.57	$3.1X10^6$	
	Suppressed Ablation		0.54	$1.1X10^4$	
	MPLCTR		0.51		200[c] (Nb energy sink)
	SOLASE		0.62		
	SOLASE-H (Hybrid)		0.32		
	HYLIFE	0.007	0.52	$56-10^6$[a]	
LINER	FLR		0.50	$1.7X10^4$[ ]	

Footnotes for Table VI

(a) Millions of kg/d of lithium is vaporized. If 100% of this lithium recondenses, then only 56 kg/d is lost to the pumps.

(b) Only the capacity ($Pa \cdot m^3/s$) of the pumps which will have to remove the vaporized Li from the chamber is given. This value is calculated assuming: (1) the $Pa \cdot m^3/s$ refers to 300 K, and (2) the pumps are working at full capacity.

(c) This erosion rate is due to consideration of ion blistering and sputtering and neutron sputtering.

(d) This erosion rate is due to consideration of ion sputtering.

(e) These values represent geometric means between optimistic (0.019+0.096) and pessimistic (2.9+4.4) predictions of the erosion rate of the 1st wall + curtain.

(f) The C erosion rate is due to consideration of vaporization and ion and neutron sputtering.

(g) SiC erosion is due to α sputtering and chemical reaction with atomic D and T.

(h) This erosion rate considers neutron sputtering only and represents the geometric mean between optimistic (0.14) and pessimistic (1.4) predictions.

Table VII

Tritium Inventory For Different Reactor Designs Normalized to 1 GWe

Type	Reactor	Fueling System (kg)				Blanket System(kg)		Storage (kg)	Total Inventory (kg)	Structural Inventory (kg)
		Pumps	H-isotope Extraction	Liquefaction and isotope fractionation	Fueling mechanism	Breeding material	Breeder reprocessing			
TOKAMAKS	UWMAK I (corr.)	0.21	2.37			1.90[c]	0.71	5.70	10.89	
	PRD		0.25			0.005		1.00	1.26[e]	0.01
	UWMAK II	0.08	2.04			0.42	0.24	7.49	10.27	
	UWMAK III	3.90	3.90			0.50	0.34	9.37	18.02	
	Doublet	2.52	1.01		1.64	0.20	3.76	5.07	14.20	
	NUWMAK	4.44[a]		0.99[a]		0.13	0.02	53.72[a]	59.30[a]	6.00
	Tokamak Hybrid	0.33	0.34		0.38	0.004	0.01	1.41	2.47	0.01
PINCH	RTPR	0.001	0.07	0.03	0.37	0.08	0.03	0.35	0.93[f]	0.001
MIRROR	Mirror Hybrid	0.33	0.01	2.39	0.46	6.63[d]		13.44	23.26	
LASERS	SOLASE	small	0.72	0.03	11.96-2.51[b]	0.98	0.07	12.06-6.84[b]	25.82-11.15[b]	
	SOLASE-H (Hybrid)	small	0.66	0.01	2.09	0.25	0.03	5.26	8.30	1.53

(a) Consistent with values in Tables II-VI.
(b) First value for glass container; second for polyvinylalcohol.
(c) Corrected using recent experimental data for Sieverts Constant=1.08 $(\text{torr } T_2)^{1/2}$/ (atom T/atom Li)
(d) See p. 339 of ref. (12)
(e) Includes 0.003 kg entrained in He coolant streams
(f) Includes 0.002 kg in secondary coolants

Table VIII Normalized Tritium Inventories for Tokamaks

REACTOR	FUELING SYSTEM (kg)				BLANKET SYSTEM (kg)		STORAGE (kg)	TOTAL INVENTORY (kg)	FRACTIONAL BURNUP (%)
	Pumps	H Isotope Extraction	Liquefaction and Isotope Fractionation	Fueling Mechanism	Breeding Material	Breeder Reprocessing			
UWMAK-I (corr.)	0.02	1.26			1.90	0.17	2.85	6.20	7.2
PRD		0.25			0.005		1.49	1.75	8.7
UWMAK-II	0.03	1.78			0.43	0.12	3.75	6.11	4.85
UWMAK-III	1.56	1.56			0.50	0.09	18.99	22.7	0.83
Doublet	2.52	1.01		1.64	0.20	1.23	15.14	21.7	1.35
NUWMAK	4.44		0.99		0.13	0.02	26.86	32.4	0.77

Normalization Procedure: Power is 1000 MWe; pumps on-line 2 hr; getter beds and molecular sieves on-line 6 hr; storage equals 12 hr fueling.

Table IX

Relative Ratings Of The Fueling And Exhaust Systems In Different Reactor Types [(a)]

REACTOR TYPE	Tritium Flow Rate (kg/d)	Exhaust Gas Flow (mol/d)	Pumping Through-put (m^3/s)	Exhaust Composition	Pump Type	Nonvolatiles in Exhaust	Fueling T Inventory	Storage T Inventory	TOTAL SCORE
Tokamaks (4-7) (recent designs)	4	3	4	2	3	1	4	4	25
Theta Pinch (8)	4	3	3	2	1	1	1	4	19
Reversed Field Pinches (9-10)	3	2	3	2	1	1	1	3	16
Standard Mirrors (11,12)	5	3	5	2	3	1	5	5	29
Tandem Mirrors (13,23)	1-3	1	3-4 [(c)]	2	3	1	3-4 [(c)]	1-3 [(c)]	15-21 [(c)]
ICF-Wetted Wall (14,15)	1	5	4	5	1-5 [(d)]	3	3	1	23-27 [(d)]
ICF-Magnetic Protection (16)	1	1	1	2	1	3+	3	1	13
ICF-Gas Protection (17,18)	1	4	3	1	1	3	3	1	17
ICF-Li Jets (19)	1	? [(b)]	? [(b)]	5	5	3	3	1	16-24 [(b)]
Fast Liner (20)	2	5	4	5	1	5	2	2	26

(a) **Low scores imply simple, desirable technology; high scores imply difficult, undesirable technology.**

(b) Value depends on whether the lithium "fog" is completely removed by completely condensing on the flowing lithium jets between shots.

(c) Lower value refers to pellet fueling; higher value refers to neutral beam fueling.

(d) Lower value refers to Roots blowers; higher value refers to supersonic spray condenser.

Table X

Tritium Migration to Coolant Materials From Plasma Related Sources

REACTOR DESIGN	LOCATION	COOLANT	g T/d
UWMAK-II (3)	First Wall	He	∿0.6
SOLASE-H (18)	First Wall	Na	∿0.1
UWMAK-III (4)	Divertor	Na	14.65
PRD (2)	Divertor	He	12
Mirror Hybrid (12)	Neutral Beams	He	7.3
Mirror Hybrid (12)	Direct Convertor	He	1.6

Table XI

Safety Issues Related to Obtaining Tritium From an External Supplier

Pro	Con
T no longer circulated throughout plant in breeder material	T must be transported from supplier to user
No breeder T inventory	Storage inventory increase offsets no breeder inventory thus effecting a net plant T inventory increase
	T handled by a greater number of reactors (suppliers + users > users)

Table XII

Consequences of Removing Tritium Breeding Function From a Reactor

Positive	Neutral	Negative
Lower T flow rates for systems with high burnup fractions	T flow rates for systems with low or intermediate burnup fractions remain nearly unchanged	
		Possibility of increasing plant T inventory (Fig. 2 and Table XI)
No T extraction from Li breeder	T extraction from coolants (Table X)	
	Complexity and size of plant tritium handling equipment (Figs. 4-6)	
	Some heat transfer agent must replace Li material and IHX still required	
		Safety issues (Table XI)
		Higher cost for fuel

Figure Captions

Fig. 1 Variation of the tritium pumping rate with fractional burnup for 1 GWe of fusion power.

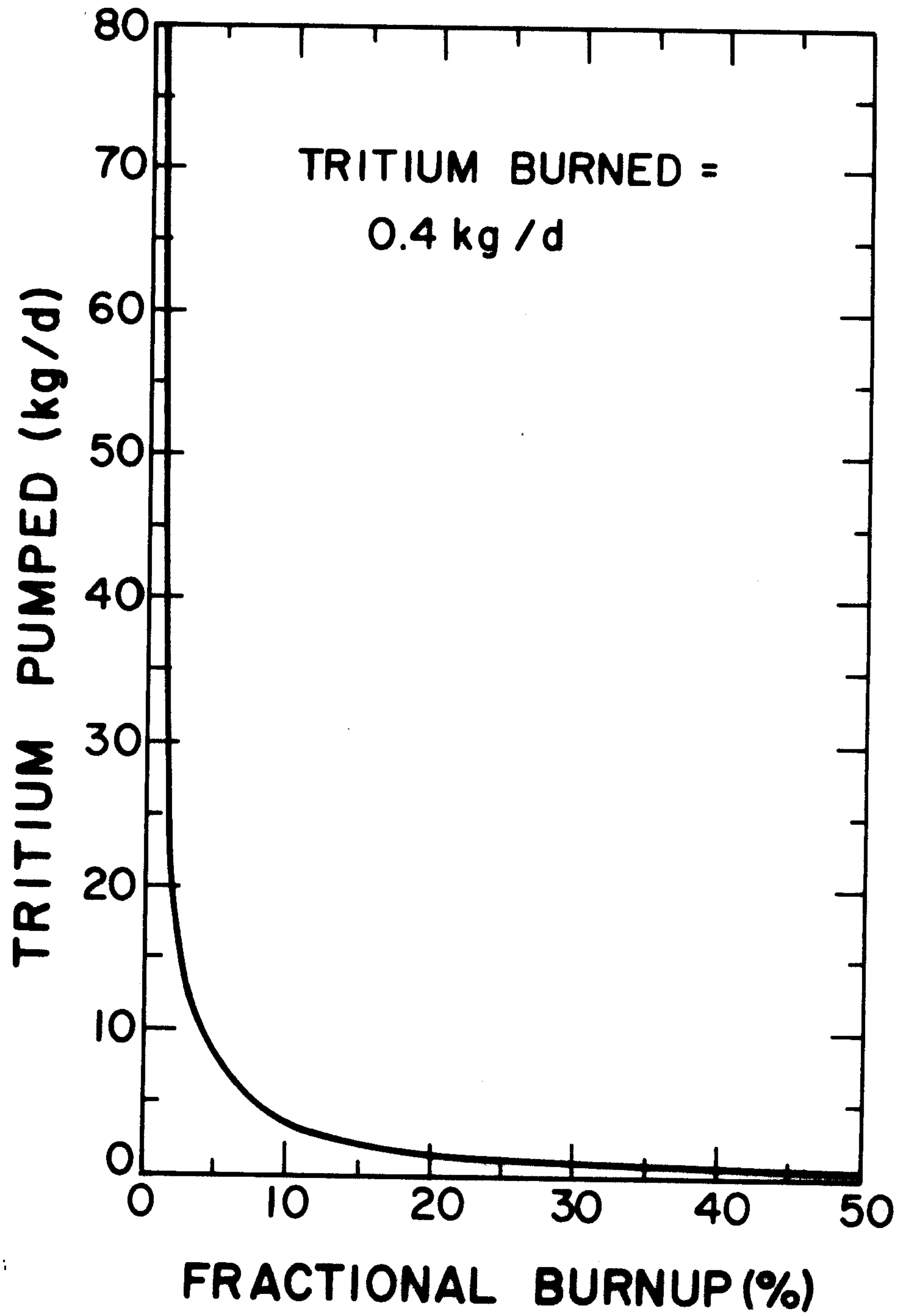
Fig. 2 Distribution of tritium in various reactor systems.

Fig. 3 Normalized tritium inventories of tokamaks vs. fractional burnup.

Fig. 4 Tritium handling in fueling and exhaust cycle and blanket system of UWMAK-III.

Fig. 5 Tritium handling in fueling and exhaust cycle and blanket system of the Standard Mirror Hybrid.

Fig. 6 Tritium handling in fueling and exhaust cycle and blanket system of SOLASE.



Variation of the tritium pumping rate with fractional burnup for 1 GW of fusion power.

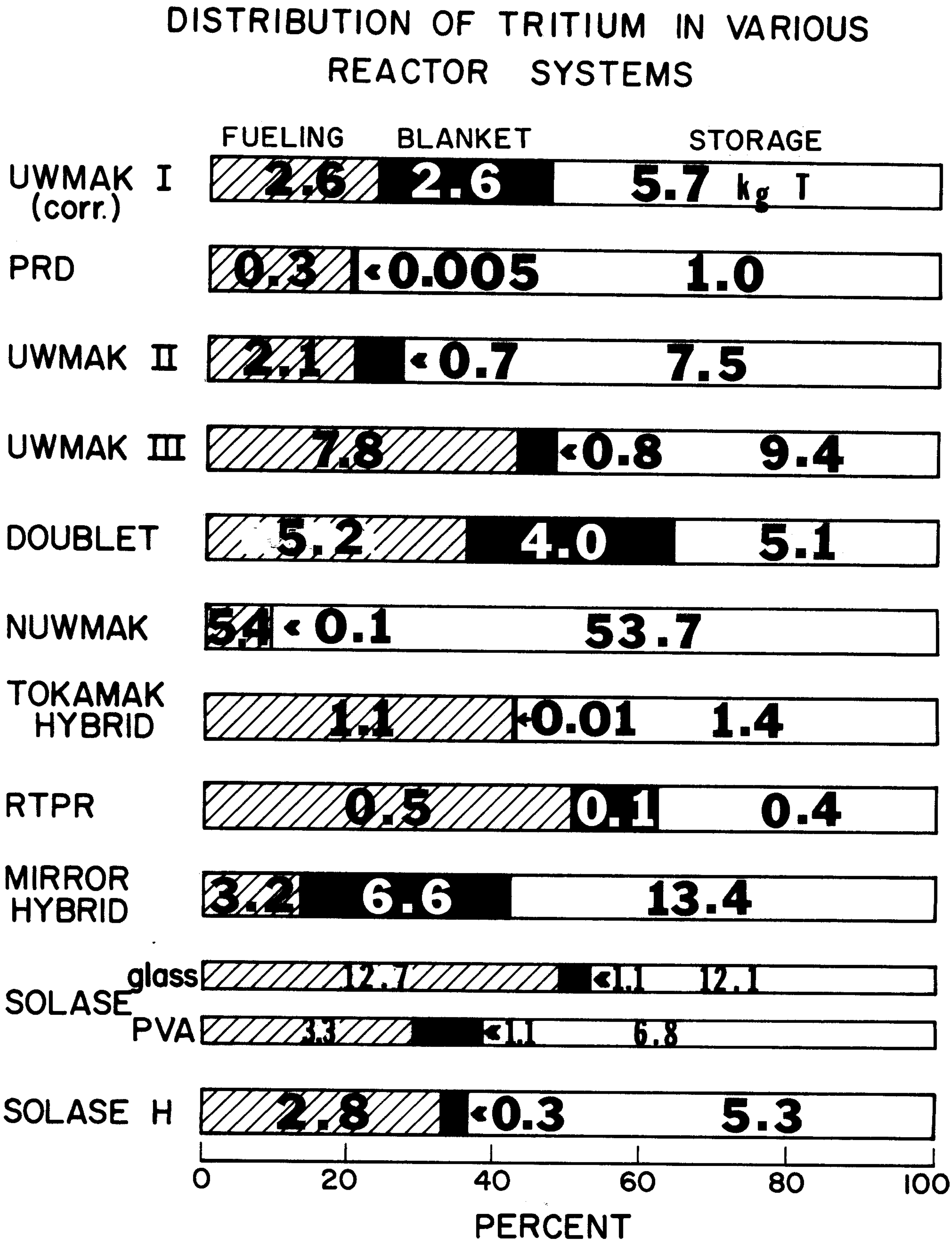

DISTRIBUTION OF TRITIUM IN VARIOUS REACTOR SYSTEMS
FUELING
BLANKET
STORAGE
UWMAK I (corr.)
2.6
2.6
5.7 kg T
PRD
0.3
<0.005
1.0
UWMAK II
2.1
<0.7
7.5
UWMAK III
7.8
<0.8
9.4
DOUBLET
5.2
4.0
5.1
NUWMAK
5.4
<0.1
53.7
TOKAMAK HYBRID
1.1
<0.01
1.4
RTPR
0.5
0.1
0.4
MIRROR HYBRID
3.2
6.6
13.4
SOLASE glass
12.7
<1.1
12.1
SOLASE PVA
3.3
<1.1
6.8
SOLASE H
2.8
<0.3
5.3
0
20
40
60
80
100
PERCENT

FIGURE 3

NORMALIZED TRITIUM INVENTORIES OF TOKAMAKS vs. FRACTIONAL BURNUP

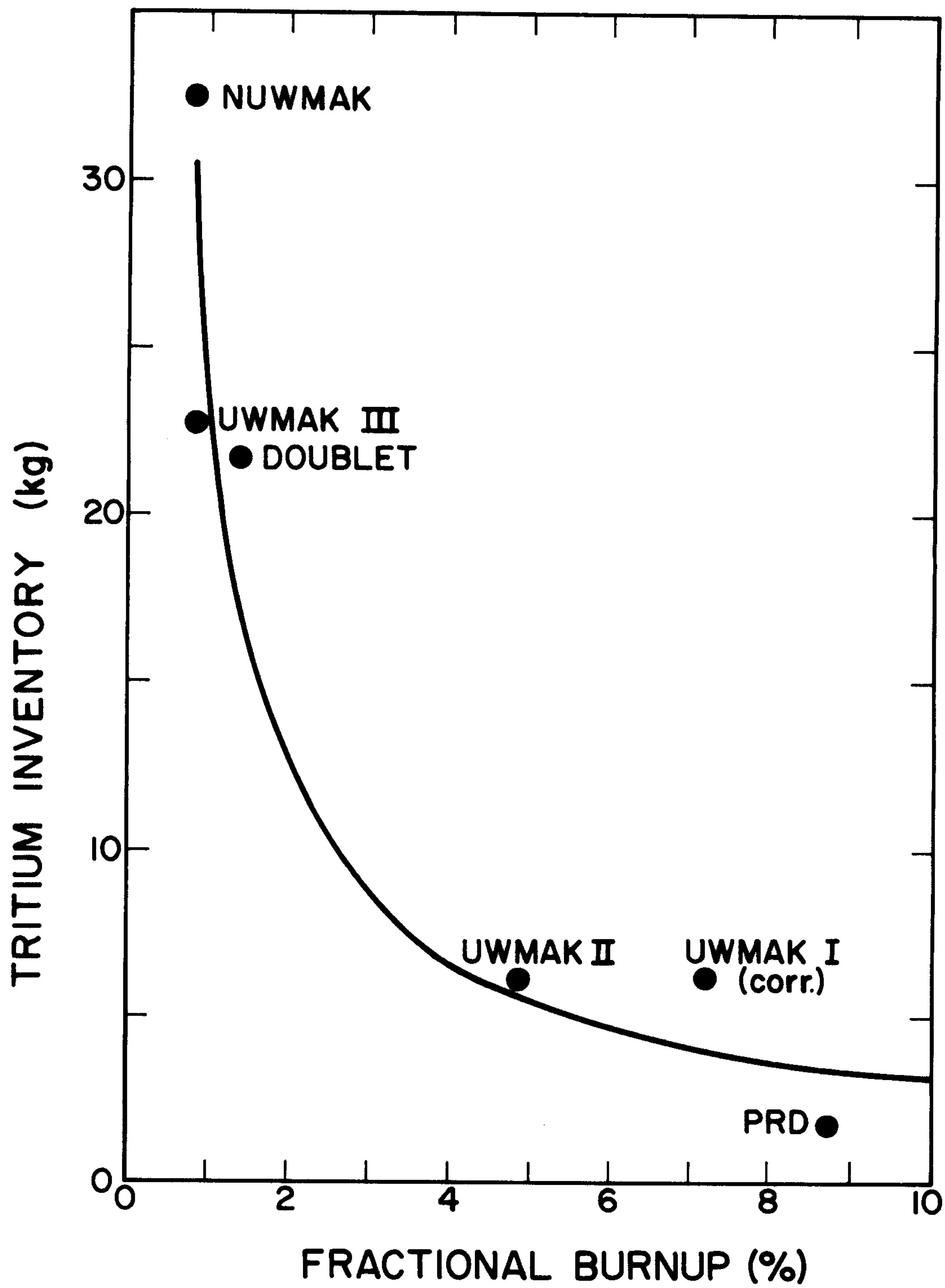
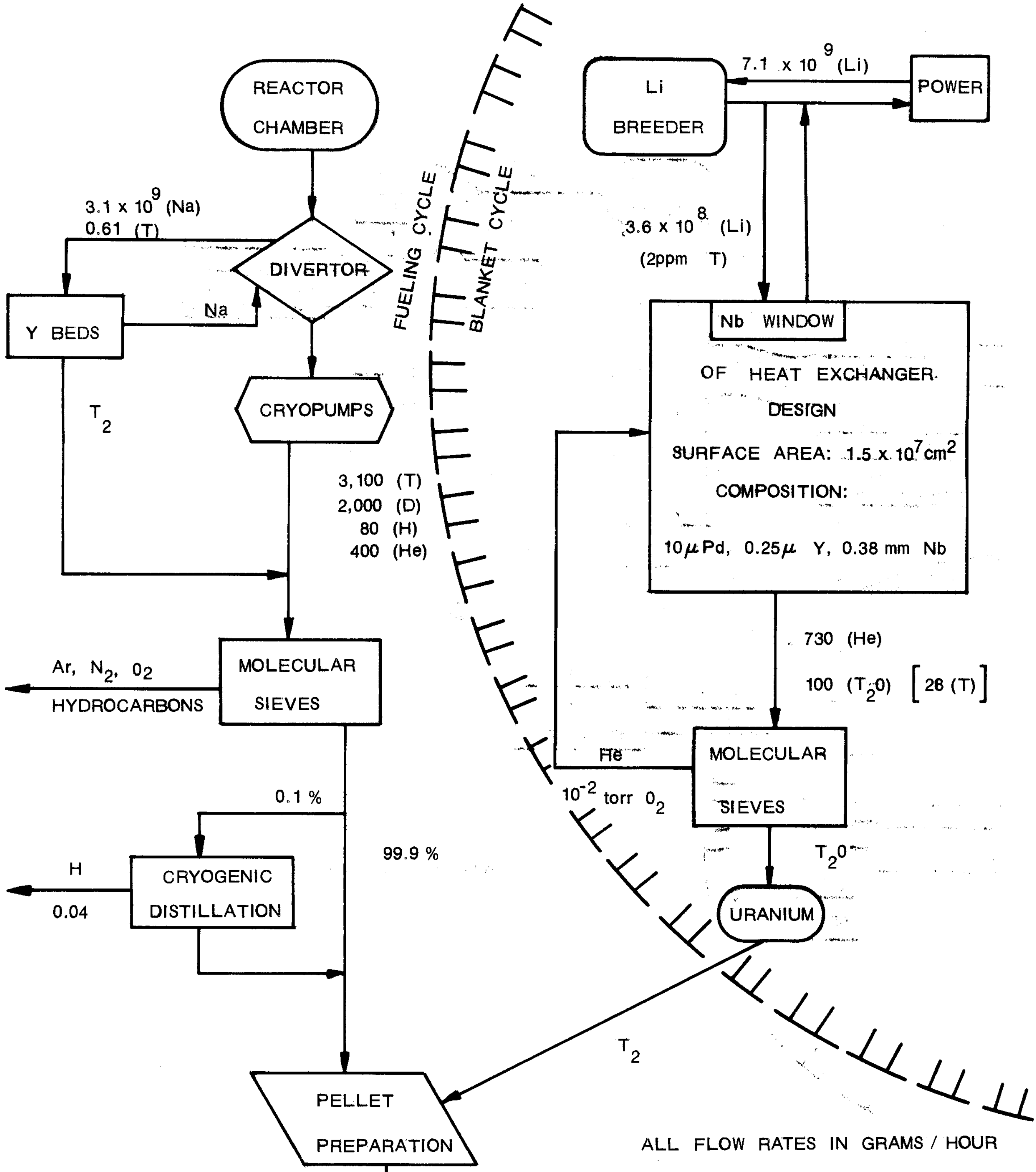


FIGURE 4

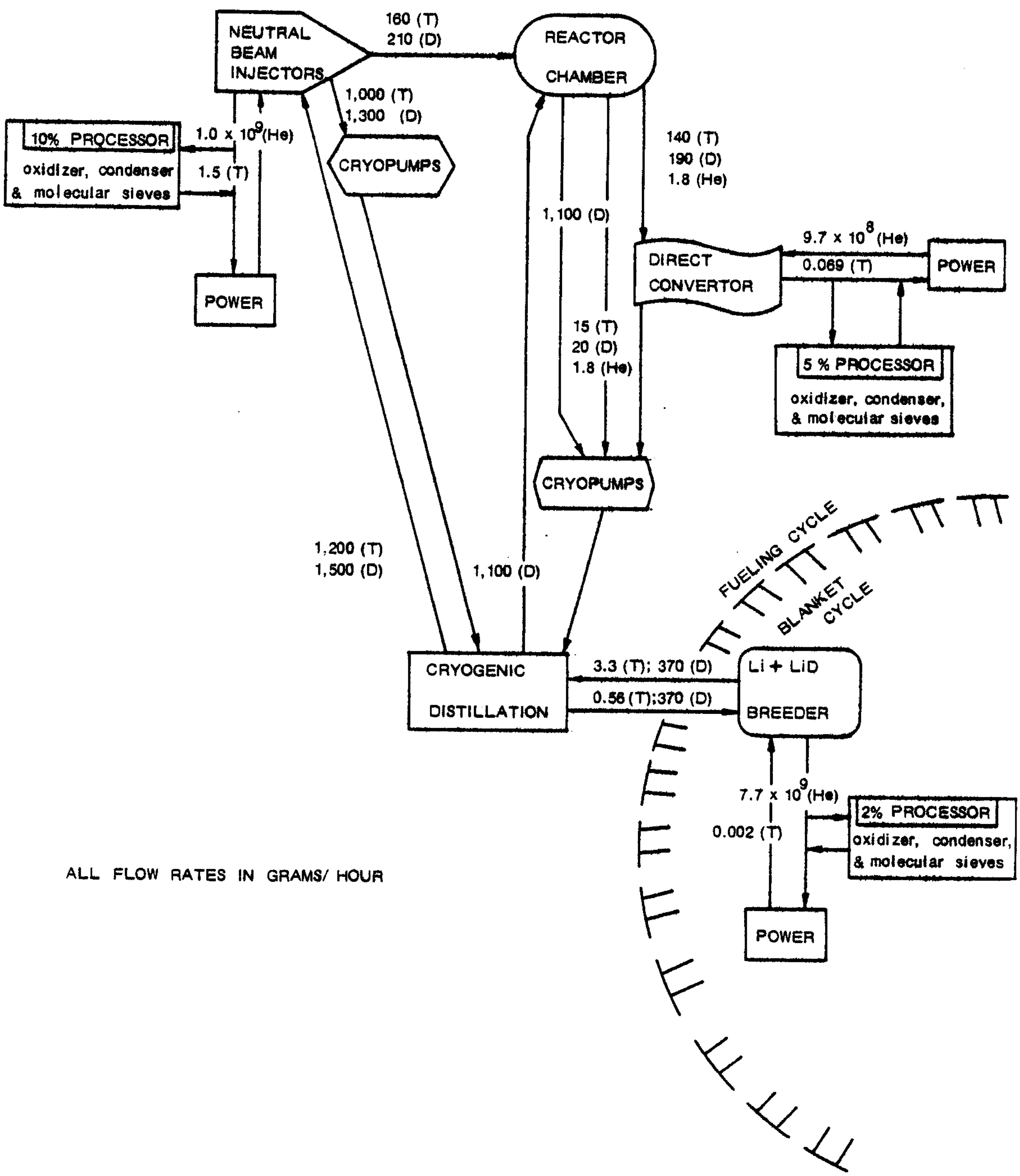
UWMAK III



ALL FLOW RATES IN GRAMS / HOUR

FIGURE 5

STANDARD MIRROR HYBRID



ALL FLOW RATES IN GRAMS/ HOUR

FIGURE 6

SOLASE – GLASS PELLET