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EVALUATION OF ORGANIC MODERATOR/COOLANTS FOR FUSION BREEDER BLANKETS

by

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ABSTRACT

Organic coolants have several attractive features for fusion breeder blanket design. Their apparent compatibility with lithium and their ideal physical and nuclear properties allows straightforward, high performance designs. Radiolytic damage can be reduced to about the same order as comparable fission systems by using multiplier/stripper blanket designs. Tritium recovery from the organic should be straightforward, but additional data is needed to make a better assessment of the economics of the process.

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BACKGROUND

Proposed fusion breeder blanket design concepts are at present constrained by compatibility, thermal/hydraulic, neutronic, and tritium-recovery problems. Organic hydrocarbon coolants have some attractive features by which it might be possible to relieve these constraints if their undesirable nuclear characteristics (e.g. radiolytic damage) can be held to tolerable levels. It is the purpose of this report to evaluate organic coolants for fusion blanket applications.

Fusion tritium breeder research has generally concentrated on blankets using flowing liquid lithium, stagnant pools or beds of liquid lithium, or lithium compounds, or lithium/salt systems. The coolants proposed are liquid lithium, water, helium, or molten salts [1,2]. The primary problem in using liquid-lithium metal is one of safety; the incompatibility of this element with water, and its reactivity with many materials of construction. Less well-known is its interaction with the large magnetic fields used in fusion devices necessitating large pumping powers. Using inert gaseous coolants such as helium to cool liquid lithium pools or solid-lithium compounds sacrifices good heat transfer since gases have poor thermal/hydraulics characteristics. The use of molten salt systems is potentially a viable approach, though some concern has been raised about the chemical stability of the salts.

Organic compounds have been studied intensively for use in fission reactors, and at least three reactors have been operated that use these coolants [3-6]. The most appropriate compounds found are the polyphenyl hydrocarbons whose properties are particularly ideal for these applications: low volatility, compatibility with common materials of construction, good thermal/hydraulic properties, good neutronic properties, and reasonable resistance to radiolytic damage.

These compounds decompose and polymerize to some extent in the radiation environment of a nuclear reactor. Presumably this drawback has precluded their consideration for fusion reactor applications where at least in the initial concepts a high radiation environment is also present. However, because there is considerable flexibility in the design of fusion blanket systems, there are options available to reduce radiation damage. Indeed, by rather straightforward design alterations the radiolytic effects can be considerably mitigated. These and other considerations are believed to make organic coolant/moderators attractive for fusion applications.

ORGANIC COOLANT COMPATIBILITY AND SAFETY

Research with the use of organic coolants in reactor systems was originally instigated by the excellent physical and neutronic properties that some organic compounds have. An extensive research effort was conducted in the 1950's and early 1960's and a number of organic compounds having desirable properties for reactor applications were found. Table I, taken from Ref. 4, lists the physical properties of four unirradiated polyphenyl compounds which have been found to have good radiation stability in addition to excellent thermophysical properties. The polyphenyls are organic structures comprised of benzene rings that possess low-melting points, high-boiling points, low-vapor pressures, and other properties desirable of coolants.

It has been found that mixtures of the polyphenyls have even better properties than the pure compounds and are also cheaper [4]. Several of these mixtures

Table I

Properties of Unirradiated Polyphenyls

Property	Diphenyl	α-terphenyl	m-terphenyl	p-terphenyl
Melting point, °C	69.4	57.2	87.2	213.3
Boiling point, °C	255.6	332.2	365.0	376.1
Density, gm/cm^3:				
200°F (993°C)	1.01	1.05	1.03	
600°F (315.6°C)	0.83	0.90	0.93	0.96
800°F (426.7°C)	0.66	0.77	0.83	0.86
Viscosity, centipoises				
200°F (93.3°C)	1.02	2.38	3.34	
600°F (315.6°C)	0.12	0.22	0.30	0.17
800°F (426.7°C)	0.07	0.14	0.16	0.08
Vapor pressure, pa × 10^{-4}				
200°F (93.3°C)	0.0427	0.0276	0.0138	
500°F (260.0°C)	11.0	2.1	0.69	0.69
600°F (315.6°C)	32.4	11.0	6.9	5.2
800°F (426.7°C)	75.8	18.6	11.0	8.3
900°F (482.2°C)	275.8	91.0	53.1	41.4
Molecular mass	154.20	230.29	230.29	230.29
Critical temperature, °C	495.6	559.4	602.8	621.1
Critical pressure, pa × 10^{-4}	322.2	241.1	241.1	241.1

are produced commercially and sold under the trade names of Santowaxes O-M and R, HR-40, and OS-84 (mixtures of di- and terphenyls sold by Monsanto Chemical Company) and Dow Therm A (mixture of diphenyl and diphenyl oxide sold by Dow Chemical Company). HB-40 and OS-84 are hydrogenated forms of the Santowax mixtures, which are liquid at room temperature. The cost of the hydrogenated mixtures is about $2.50/kg [7].

Because the polyphenyls are hydrocarbons, they have excellent neutronic properties. The low mass of its constituent atoms, hydrogen and carbon, endows these compounds with excellent neutron moderating properties, and the low neutron absorption cross section of these atoms results in reduced activation of the coolant. In fission reactors, the induced radioactivity is low enough that the coolant loop is accessible even during reactor operation. Most of the induced radioactivity results from inorganic impurities in the coolant, such as ^{24}Na, ^{34}Cl, and ^{64}Cu, so that there is potential for even further reduction of radioactivity by purification of the coolant.

Organic coolant compatibility with lithium is a compelling factor in considering the safety of fusion reactor systems. Although work in this area is just now in progress, preliminary results are encouraging. Tests done at HEDL in support of the FMIT program indicate little reactivity between lithium metal and polyphenol coolants [8]. Tests have been run up to a lithium temperature of 427°C (800°F). In one series of tests, lithium at 260°C (500°F) was added to HB-40 and OS-84 liquids also at 260°C in an inert argon atmosphere. Post-examination showed somewhat of a crust formed over the lithium surface, but no exothermic reaction occurred. In other tests lithium was immersed in organic coolant in air with the organic heated to 232°C (450°F) and the lithium to 260°C and 427°C. A white fog formed but no exothermic reaction on fire occurred, even though the organic was above the flash point. The results so far indicate that these materials as a mixture are reasonably benign and that probably a greater concern is a conventional fire. The program now in progress at HEDL should yield sufficient information in the near future to allow design of organic fusion blankets with a high degree of safety assurance.

Radiolytic damage to the organic molecules is, no doubt, a major concern of organic-cooled concepts. In fission systems, organic coolant damage necessitates reprocessing to remove degraded material; this adds cost to the operation. A large amount of research has been done on this problem, and fortunately there is already operational data available from the organic-moderated research reactor (OMRE), the organic power plant (PIQUA), and the Canadian White Shell Nuclear Research Station.

Analytical methods are available in the literature for estimating both pyrolytic and radiolytic damage [4,7,9-11]. Pyrolytic damage is correlated simply with coolant temperature. Tolerable decompositions are possible up to a temperature of about 427°C (800°F), but decomposition increases rapidly above this temperature.

Radiation damage changes the properties of the coolant mainly by a polymerization process (i.e., the coolant molecules become heavier and heavier). Effects of radiation on such properties as specific heat, viscosity, density, and heat transfer are well documented and may be found in Refs. 4 and 9. Radiation is partially self-nullifying; that is, the coolant becomes more resistant to radiation as it is further irradiated. At 30% high-boiler (high boiler refers to the material in the coolant less volatile than p-terphenyl), it is about twice as resistant. Since the thermal/hydraulic properties of the material are still good at the high-boiler ratio, it is common practice to run a reactor near this ratio. The coolant is allowed to polymerize to this level and processing is used to maintain the coolant composition roughly constant. Some degradation of the coolant also occurs although this is much less than polymerization. In the unhydrogenated coolants about 2% gases, predominantly hydrogen, are formed and typically have the composition 63% H_2, 10% CH_4, 18% ethane and ethylene, 6% propane and propene, and 2% butane and butene, and the rest impurities [12].

Perhaps the most outstanding example of the performance of organic coolants has come from the Canadian experience with their White Shell Nuclear Research Station [7]. This reactor is now in operation, and their data on organic coolant behavior under operating conditions is the most recent. This reactor is organically cooled but not organically moderated and has a tight core (low moderator/fuel ratio); thus it may be more representative of "protected" fusion blankets. Using one of the hydrogenated forms of terphenyls, OS-84, this system has achieved a coolant temperature of 400°C with tolerable radiolytic damage. Based on their experience they estimate that the cost of reprocessing the coolant in a commercial fission power plant of this type would be less than 0.1 mill/kW-h (this was a 1973 estimate and is probably higher now). Other advantages that they have noted are: no reaction of coolant with materials of construction (in fact, the coolant has inhibited reactions), very little activation (on-line inspection possible), easy to maintain (e.g., leaks are easily detectable), and low cost. They remove the low boilers from the coolant on a continuous basis and process the high boilers by distillation, and the desired coolant composition can be easily maintained.

There is some disagreement in the literature on the nature of radiolytic damage to the polyphenyl organic materials. British work has generally shown a dependence of damage on the type of radiation, with fast neutron radiation being the most damaging [11]. In contrast, American work has found a dependence only on total energy absorbed regardless of the particle causing the radiation [12]. Figure 1 is a plot summarizing damage data obtained by various workers [13]. It is interesting to note that at concentrations of about 25-30% high boiler, the damage is roughly equivalent for all studies. Since this is the concentration at which reactors are usually run, from an engineering point of view, the difference is somewhat academic.

Nonetheless, these results raise the possibility that damage may be neutron-spectrum dependent. Since fusion systems have a harder virgin neutron spectrum than fission systems, some consideration must be given to this phenomenon in the design of the blanket.

ORGANIC BREEDER BLANKET PERFORMANCE

Preliminary calculations indicated that conventional blanket designs (i.e., those in which the blanket is directly wrapped around the plasma shell) are impractical because of the severe radiation field present and the resulting intolerably large coolant loss from radiolytic damage. Therefore, the study focused on schemes by which the radiation damage could be mitigated. Figures 2 and 3 show two concepts by which this is achieved.

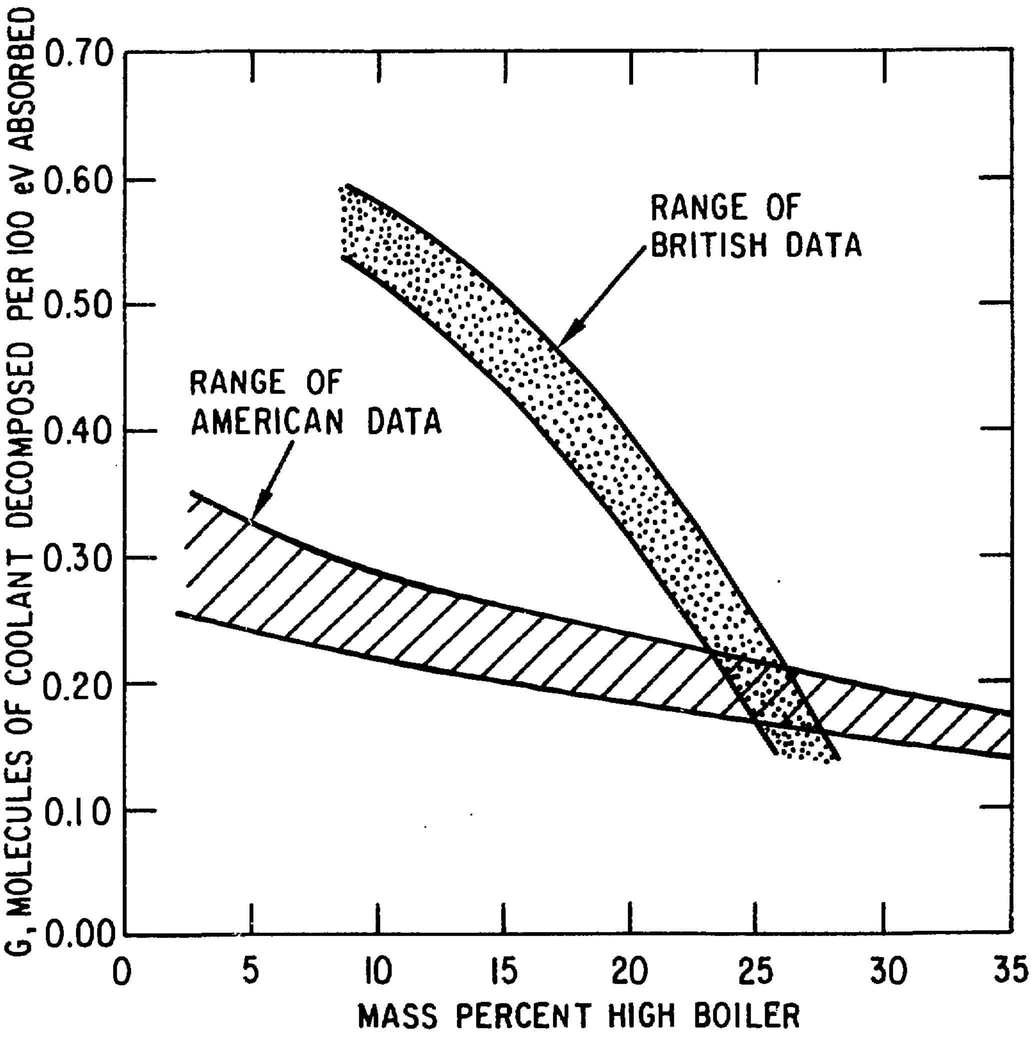

Fig. 1. Summary of coolant damage data.

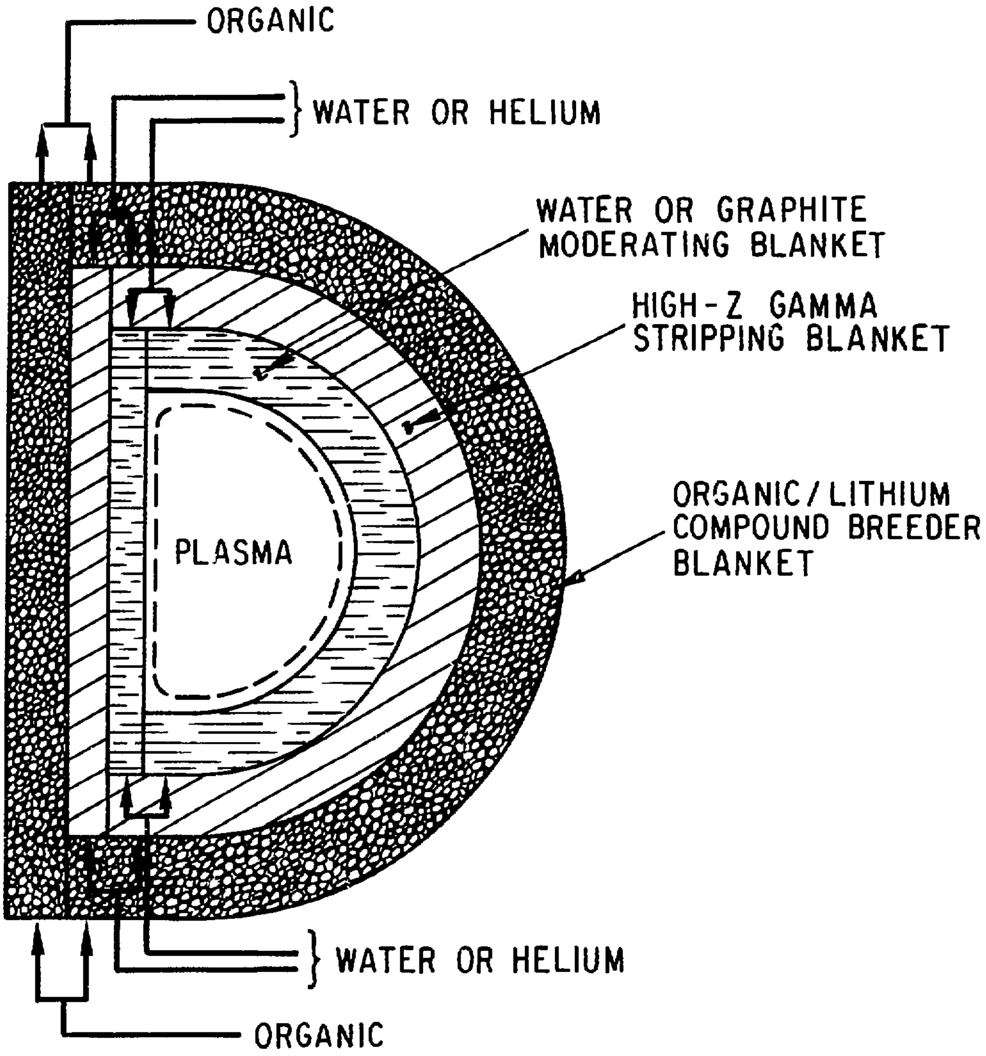

Fig. 2. Energy stripping organic breeding blanket concept.

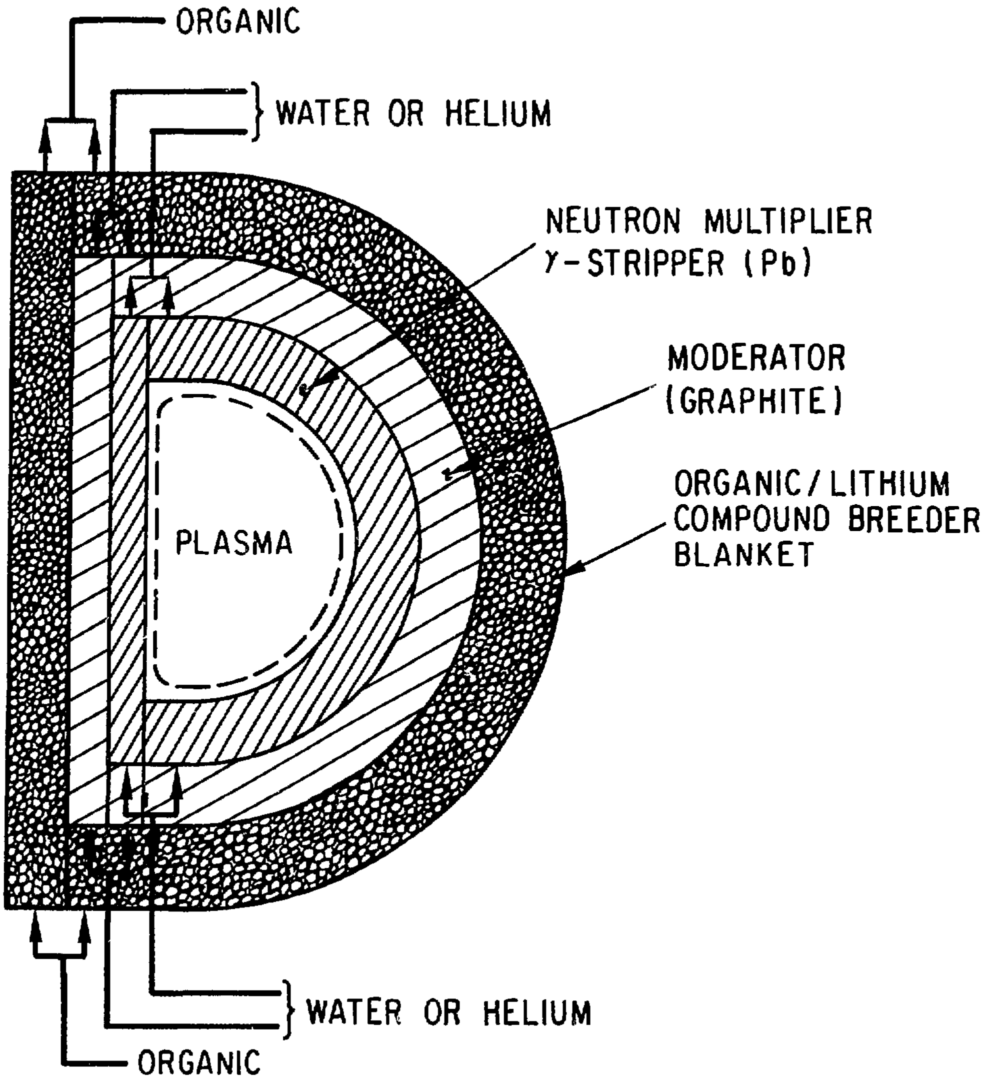

Fig. 3. Neutron multiplier/energy stripping organic breeding blanket concept.

The concept in Fig. 2 uses a neutron prethermalizer in combination with a gamma-stripper to reduce the radiation to the coolant. Neutrons are prethermalized in the first blanket, which may consist of a low-Z material such as water or graphite. The gamma-stripping second blanket attenuates a large fraction of the gamma radiation produced, thereby also reducing the radiation load to the coolant. This blanket is made of a high-Z material such as lead or tungsten. These blankets could be cooled with gaseous helium in a design approximating the NERVA nuclear propulsion reactor (except that the NERVA reactor used H_2 as a coolant and was operated at very high temperatures). The third blanket is the organic breeder blanket consisting of lithium or lithium compound through which the organic flows and serves as a coolant and moderator.

Another attractive concept is obtained by reversing the positions of the stripper and moderator and making the stripper also a neutron multiplier as shown in Fig. 3. This concept has the potential of greatly increasing the breeding performance, while at the same time softening the neutron spectrum and absorbing a portion of the radiation energy. As in the previous concept, the outer blanket is organically cooled and breeds the tritium.

Neutronic parametric analysis of organic fusion blanket concepts focused on breeding performance and coolant radiolytic damage. The existing ANISN one-dimensional neutron transport code was used for the analysis, and a baseline tokamak fusion reactor having a major radius of 5 m and a minor radius of 1.3 m was used for parametric studies. Preliminary runs were done on a conventional blanket design having a blanket thickness of 1 m to obtain an indication of system sensitivities. This thickness was reduced to 0.8 m for the energy-stripping concept analyses. The organic material for neutronic analysis was assumed to have the properties of m-terphenyl. Figure 4 summarizes some of the results obtained.

The conventional blanket concept is capable of high tritum breeding performance but as expected the nuclear heating of the coolant is high. Breeding ratios above 1.5 are achieved over a large range of coolant/Li_7Pb_2 ratios. More than 90% of the breeding occurred in the first 0.6 m of blanket, indicating that the 1-m blanket used was overdesigned. Thus, in the stripper concepts this was reduced to 0.8 m. The insensitivity of breeding ratios to the organic ratio in the blanket over the range typical of packed beds, fluidized beds, or packed-tube bundles suggests that there is a wide latitude of design with these coolants. In combination with the low-pressures obtained with organic coolants, simple packed-bed or fluidized-bed shell structures appear possible.

The results for a system using an energy stripper made of tungsten are shown in the lower curve of Fig. 4. Even though the nuclear heating can be greatly reduced, the breeding ratio is very sensitive to the water pre-thermalizer blanket thicknesses and drops rapidly with increasing thickness. Interestingly enough, breeding ratios greater than one are only obtained when a negligible amount of pre-thermalizer blanket is used and when the lithium is enriched (50% enrichment in this case). The heavy energy stripping blanket by itself provides some thermalization of the neutrons and some gamma attenuations, but not enough to obtain a substantial reduction of coolant damage. Considering that they also require lithium enrichment, it is doubtful that they would be competitive with multiplier concepts.

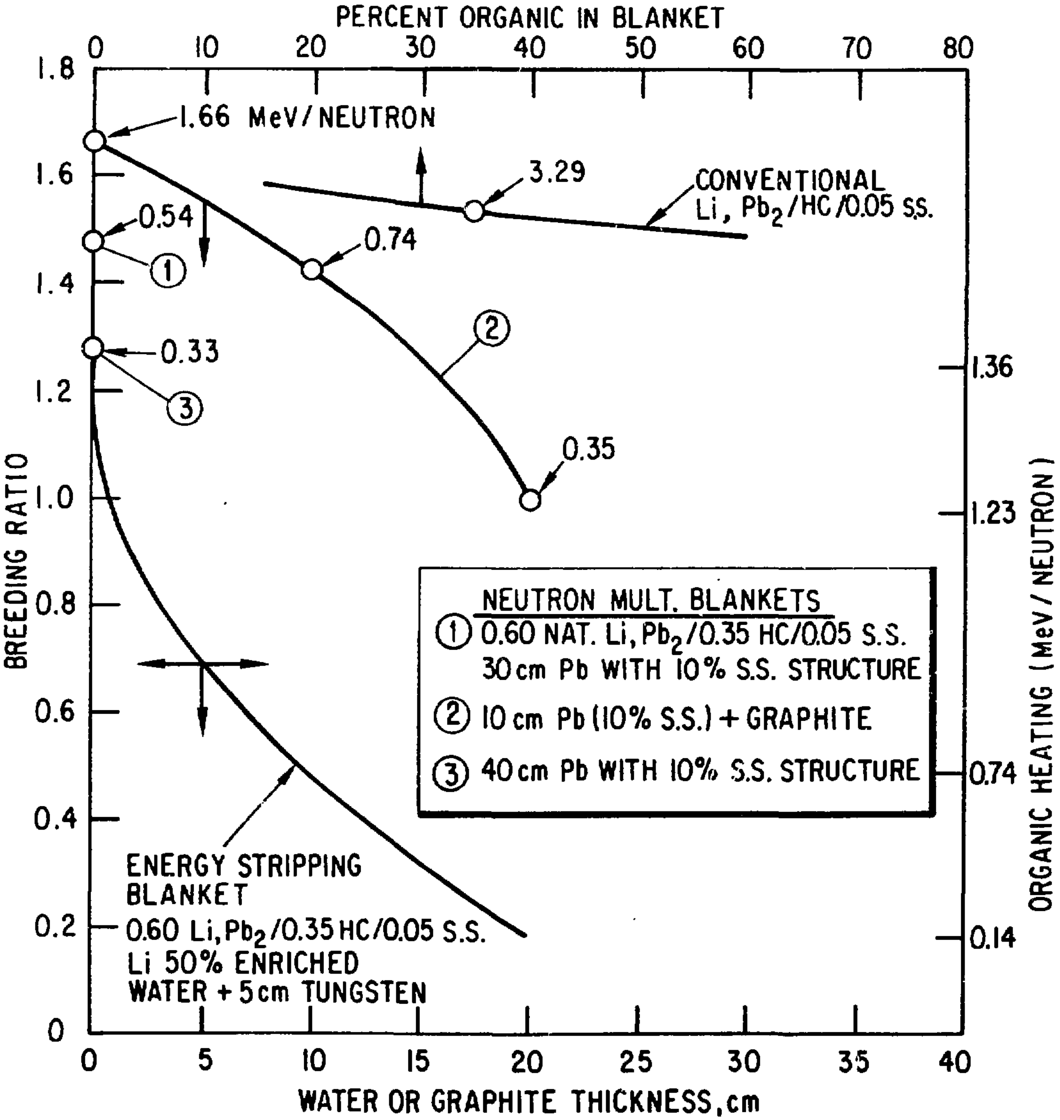

Fig. 4. Breeding performance of organic blankets.

If a neutron multiplier is used, greatly improved breeder performance results. As shown in Fig. 4 by using a lead multiplier first blanket, 10-cm thick, it is possible to obtain a breeding ratio above 1.6 and reduced heating loads. Using only lead with no graphite, for example, 40 cm of lead further reduces the heating load and gives good breeding ratios. Combined with a follow-on prethermalizer still gives good breeding ratios at greatly reduced coolant radiation loads. For example, using a follow-on 10-cm thick graphite prethermalizer leads to a breeding ratio of 1.4 at a heating load about four times less than with conventional blankets.

A disadvantage of stripper concepts is that a two-fluid coolant process is necessary, the breeder blanket being cooled by the organic liquid while the inner blanket(s) by helium or water. Typically, of the total reactor power about 60% is deposited in the inner blanket(s) and 40% in the breeder blanket. From a power production point of view this is is a disadvantage because it complicates the cycle. On the other hand, a two-fluid system offers the advantage that the breeder blanket could be run somewhat cooler than usual further reducing damage to the organic coolant. There is tradeoff here, which future work should address in more detail.

COOLANT RADIOLYTIC DAMAGE

An estimate of the decomposition rates of organic coolants in fusion systems was made from the nuclear heating results obtained from the ANISN computer program and from available data from fission reactor studies. As seen in Fig. 4, the typical organic/coolant heating for the conventional blanket concept is about 3.3 MeV per source neutron. The heating for the multiplier blanket concept depends on the blanket composites used, but reductions in organic coolant heating by several factors can be obtained. Using existing fission reactor data, these results can be translated into amounts of coolant decomposed. It has been estimated that in an organically cooled fission reactor about 4% of the thermal energy will deposit in the coolant. Table II compares the fission systems with the various fusion blanket concepts and gives estimates of coolant damage rates assuming that radiolytic damage is proportional to the energy deposited. The decomposition rates for the conventional blanket concept are several times fission reactor systems but in mutiplying/stripping blankets the rates are reduced to values comparable or below fission systems.

As mentioned above, radiolytic damage may depend on the nature of the radiation, and, in particular fast neutron radiation may be more damaging [7,11]. Fusion and fission systems are substantially different in both the spectrum of neutrons and the gamma-neutron composition of the radiation. Existing data could be used with more confidence, if the neutron spectra of these systems were comparable. It turns out that by properly designing the energy multiplier/stripper, the neutron spectrum of fusion systems can be tailored to approach that of fission systems. Figure 5, which compares the neutron spectra for various stripper designs with the typical fission spectrum from the ANL low-temperature facility shows this effect. For example, by using a lead/carbon composite, the high-energy portion can be reduced substantially. No attempt was made to optimize these results, but it is evident that there is potential here to appropriately tailor the spectra in fusion systems if this turns out to be necessary.

Table II

Estimate of Organic Coolant Damage in Fusion Power Systems

	Estimated % of Thermal Energy Deposited	Estimated Coolant Damage (kg/MWt-day)
Fission systems	4	14
Fusion systems		
Conventional blanket	20	70
Stripping blanket	8	30
Multiplying/stripping blankets	2-4	7-15

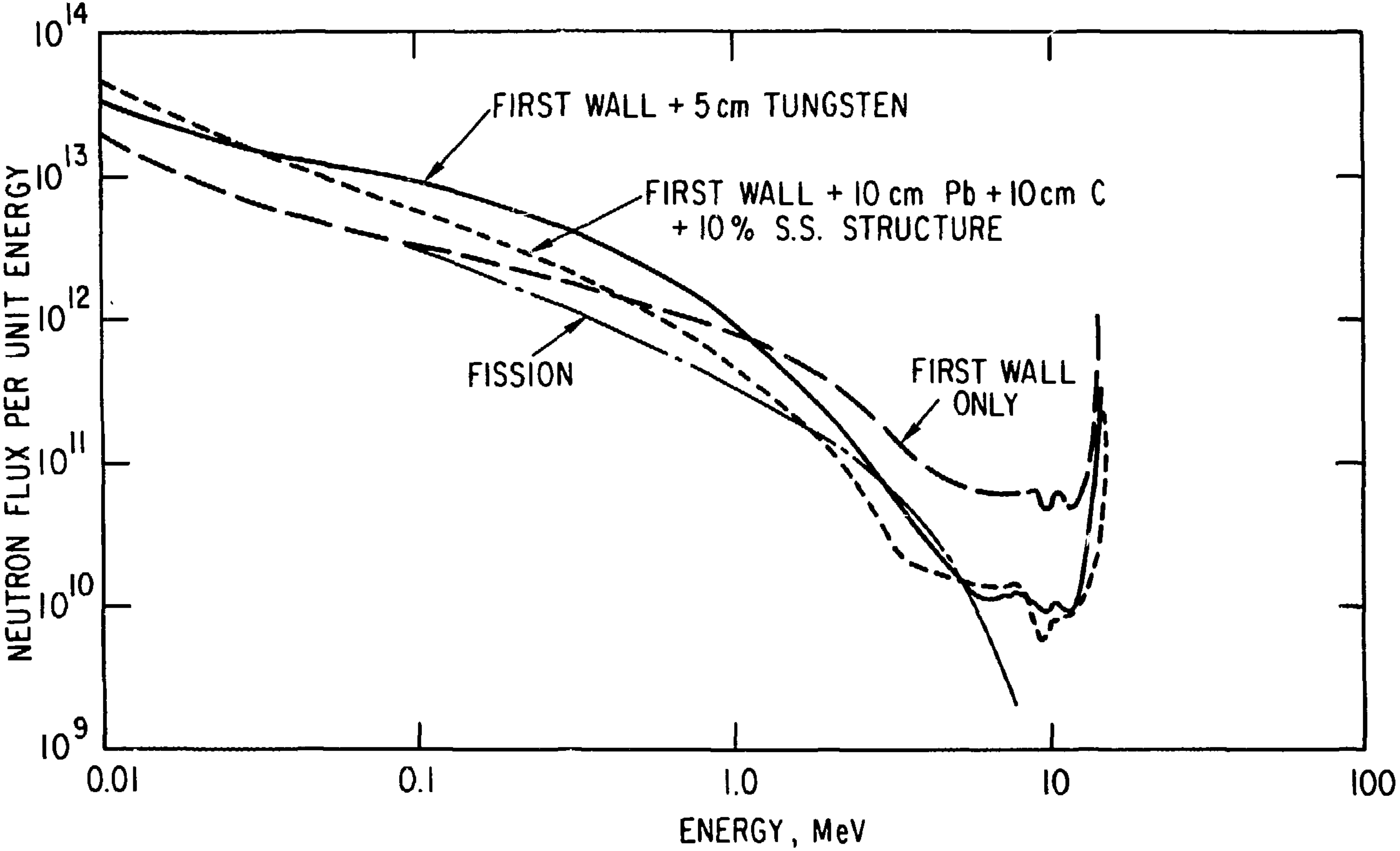

Fig. 5. Neutron spectrum tailoring in fusion breeder blanket.

Coolant damage is obviously not small; for example, for a 3000-MWt fusion reactor the damage is about 45,000 lbm per day. By optimizing the blanket this value can probably be reduced to about 30,000 lbm/day. About 50% of this can be recycled by the purification process. Thus the replacement loss will be of the order of 15,000 lbm per day. Schemes have been developed for cracking this material and making it useful again as a coolant. However, the attitude so far has been that this is not cost effective because of the low cost of the coolant. If this same attitude were followed in commercial fusion systems, a substantial effort in coolant purification is required. Even so, results for fission systems show that this process is economically very reasonable because of its simplicity and the low cost of the coolant.

Costs for coolant reprocessing in fusion systems should be comparable to fission systems as this technology should be basically identical. Estimated coolant reprocessing costs in fissison systems vary; earlier estimates (∿1960) quote a cost for fission power plants of roughly 1 mill/kWe-h. More recent Canadian estimates, which are probably more representative of fusion systems, quote a much lower figure than this, roughly 0.1 mill/kWe-h (1973 estimate) [14]. These costs may be reduced for fusion systems if tritium processing can be interfaced advantageously with the processing of the coolant. In any case, since the cost of generating electricity by fusion power is estimated to be around 30-40 mill/kWe-h, the cost of coolant reprocessing is a small fraction of the total cost [15].

THERMAL/HYDRAULICS

Thermal/hydraulics of particle, fluidized, and packed-tube beds have been studied extensively in the past and are well-known to the state of the art [16]. Heat transfer from solid particles to a flowing fluid is very high because of the large surface areas available and the favorable thermal resistances. This property of packed and fluidized beds has motivated many applications in the chemical and nuclear industries.

Fusion packed-bed blankets have much latitude in design and a practical design will probably be a compromise between good heat transfer and reasonable pressure loss. These factors can be tailored by such options as direction of flow, particle size, cross-sectional area, etc. Figure 6 shows heat transfer and pressure-drop characteristics for a particular packed bed which used Santowax-R organic constants flowing through Li_7Pb_2 particles 1 mm in diameter. The pressure drop has been calculated using the Ergun-Orning equation and heat transfer using the Colburn analogy.

Estimates made for a typical 3000-MWt nuclear fusion power plant are indicative of the thermal/hydraulic characteristics of the size packed bed expected in fusion power plants. It is assumed that the organic liquid flows toroidally in parallel through 50 modules spaced around the torus, each 0.6 m (∿2 ft) wide. The coolant temperature rise is 52°C (125°F) at a total flow rate of 0.665×10^8 kg/hr (1.47×10^8 lbm/hr). The calculation shows that the total thermal power can be easily removed by the coolant with only about a 1°C temperature driving force between particles and coolant. The power required to pump the liquid through the bed is about 4000 hp. Losses through pipes, valves, and other obstructions have not been included as the detailed layout is not known; nonetheless, this sample calculation indicates that packed-bed blankets using organic coolant will have excellent thermal/hydraulic characteristics.

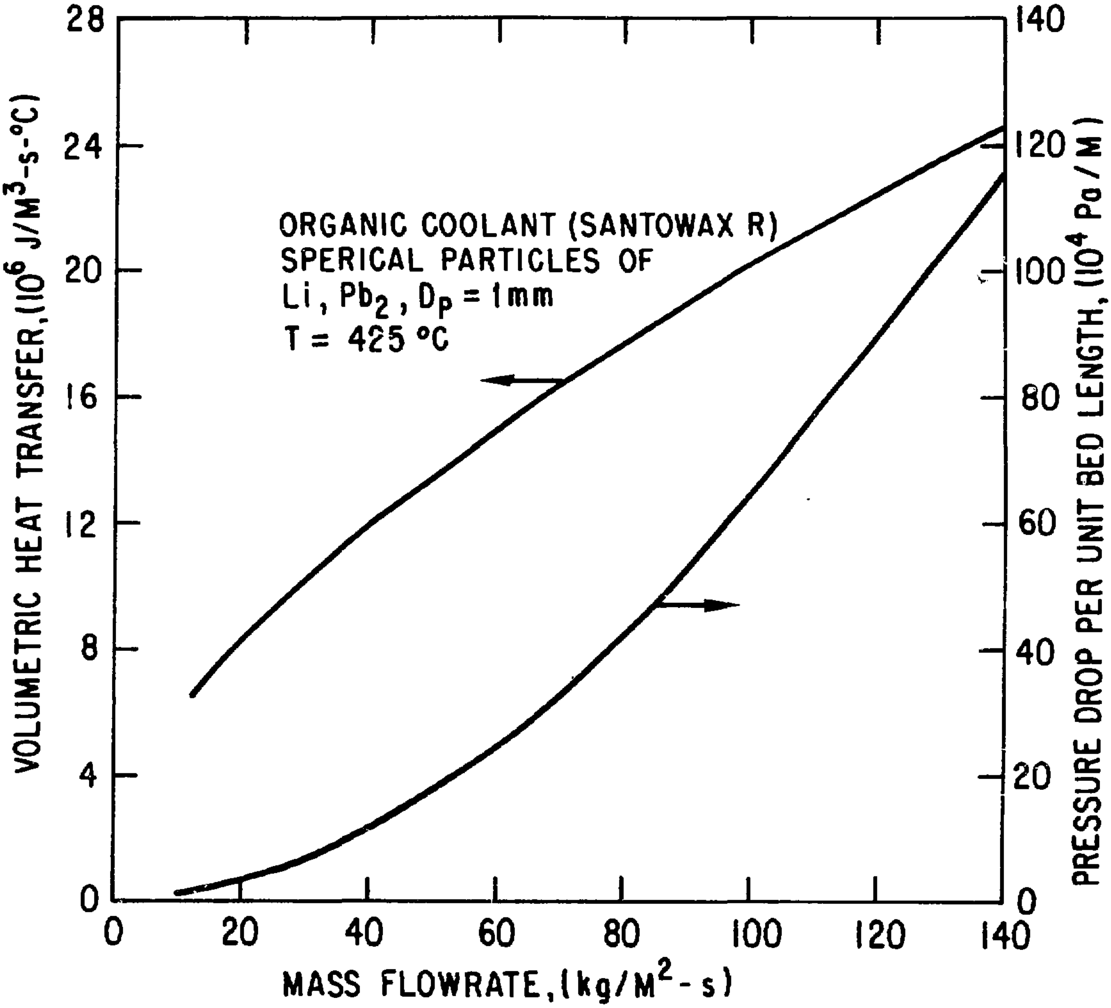

Fig. 6. Thermo/hydraulics of Li_7Pb_2 packed beds, Santowax-R cooled spherical particles, D_p = 1 mm, T = 427°C (800°F).

A more critical problem might be the elimination of stagnant regions in the flow. In the past, this has been shown to cause coolant coking and fouling and special precautions need be taken to assure adequate fluid velocities. It is believed that fusion blanket designs are flexible enough to accommodate design changes that may be imposed by these requirements.

TRITIUM RECOVERY AND COOLANT PROCESSING

Organic blankets are adaptable to either a lithium diffusion or a lithium containment process for tritium recovery. The compatibility and neutronic characteristics of organic coolant blankets offers great latitude in design changes to assure success of the recovery process. As an example, if tritium requires large particle porosity for diffusion, this can be built into the system without significantly altering its safety or performance. Organic coolants are relatively insensitive to the chemical form of tritium. Tritium in water form mixed in the organic behaves essentially as superheated steam and tritium in gaseous form is also compatible (hydrogen gas is present in the coolant).

Conceptually, organic blankets offer the potential of existing technology for recovery of tritium from the coolant. The form of tritium in the coolant does not impact the recovery process; that is, viable processes for recovery are possible whether the tritium ends up as free gas or as a hydrogenate organic product. The recovery in either or both forms can be interfaced with the processing of damaged coolant. In fact, having the tritium in the "hydrogenate" form may be advantageous as this will tie up the tritium in a heavy material and ameliorate the tritium diffusion and contamination problem. If this is advantageous, a catalyst may be added to the system to accelerate the hydrogenation reaction of tritium.

How tritium may be recovered from the organic coolant is shown schematically in Fig. 7. A portion of this diagram shows one of the proposed coolant purification processes for fission reactors [4]. This process uses a vacuum still to remove gases, recycle volatiles, and separate heavy waste residue; and a burner to dispose of the organic waste as gases and waste ash. In fusion systems burning of the waste would release the tritium tied up in the organic molecules as tritiated water. This "super heavy" water can be separated in a distillation (catalytic) or diffusion column by a process similar to that for heavy-water technology. Any tritium occurring as a gas could be separated by a diffusion process or converted to a water product and separated from the lighter water. The above process marries the purification of the coolant to the recovery of the tritium and disposal of the water is interfaced with the tritium recovery.

Environmental contamination from by-product, activated, exhaust gases in fusion systems should be extremely small and comparable to fission systems. In organic coolants this comes mostly from inorganic impurities and a slight amount from ^{14}C production. Activation in fission systems is so low as to be barely detectable [14]. The waste from these systems can be burned and the gases exhausted without undue environmental hazard. There is, of course, the possibility that the slightly harder neutron spectrum of the fusion system would enhance the production of ^{14}C by the $^{13}C(n,\gamma)^{14}C$ reaction. However, the radiative capture cross sections for both ^{12}C and ^{13}C, which would lead to production of ^{14}C, are reported in the literature to be very small [17]. Thus, the possibility of anamolous production of ^{14}C in fusion systems is extremely

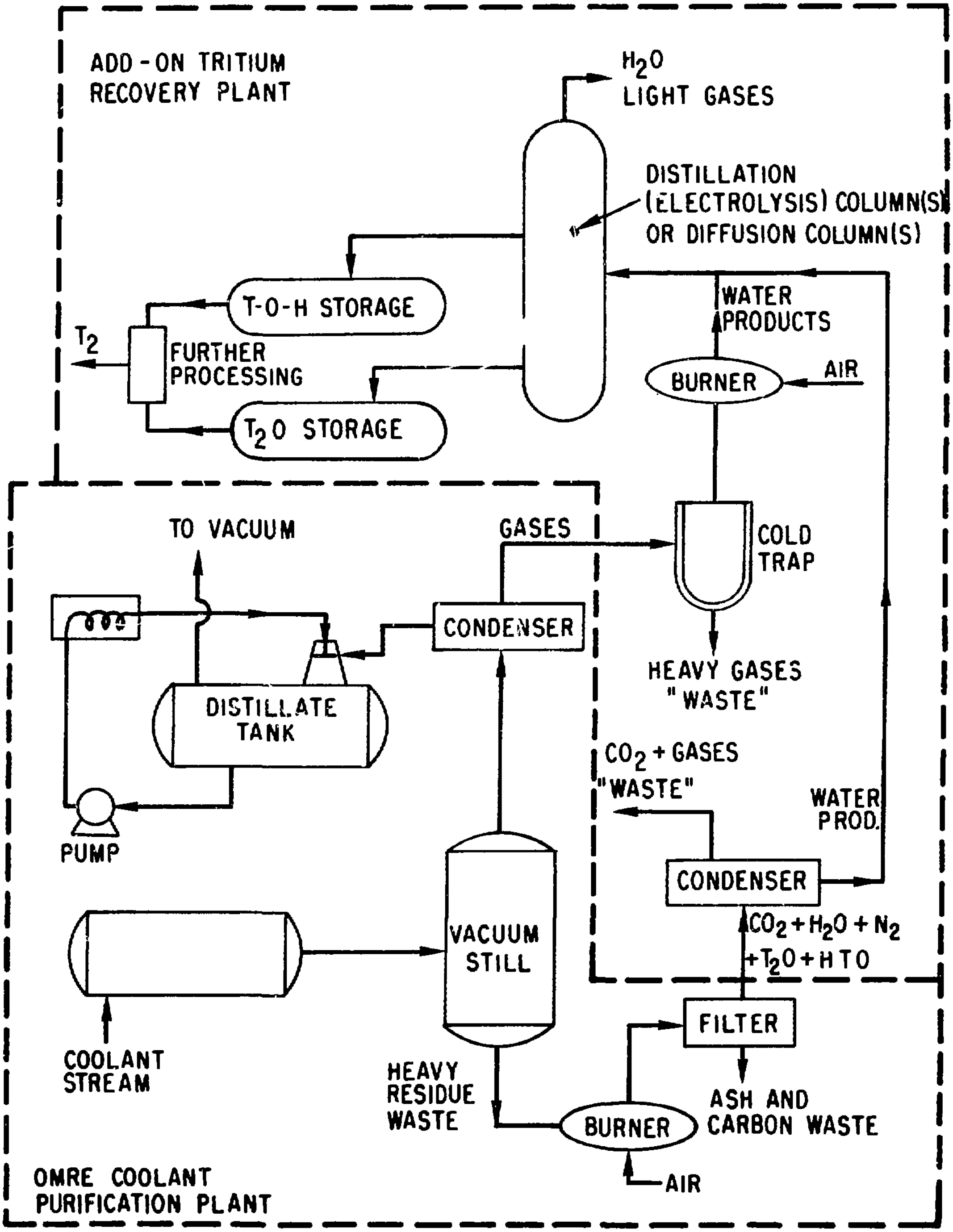

Fig. 7. Interface of tritium recovery process with coolant purification process

remote. Much of the radioactivity in the organic coolant is carried by impurities such as ^{64}Cu, ^{24}Na, and ^{34}Cl, and the Canadian work has shown that these impurities are the main cause of fouling and should be removed anyway as much as possible. This, in turn, assures lower coolant environmental contamination. With care, the amount of radioactivity released to the environment by the burning process is well within allowable limits. Contamination from tritium (if carried in the coolant) may be a more serious problem, but it appears that this can be held to very low levels in a water distillation process such as shown in Fig. 7 where very effective cold traps using helium could be employed.

Recovery of tritium by the process just described is complicated and reported to be very expensive [18]. A preferable process is one in which the tritium is totally contained and kept separate from the organic coolant. Packed-bed systems are also readily adaptable to this containment process. In this approach lithium or Li_7Pb_2 particles are clad with a metal, ceramic, or a glassy material through which tritium does not diffuse, or are contained in tubes. In a packed-bed concept, it is possible to use low-strength materials for clad as there are minimal stresses on the particles, and even should a few rupture and release tritium to the coolant there is no danger of catastrophic events. The slight contamination to the organic coolant that would result can be easily detected by monitoring the tritium contamination in the coolant.

Containing the tritium appears to be a better strategy in the long run and the packed-bed concept opens up interesting possibilities for reactor on-line refueling and off-site tritium recovery as illustrated in Fig. 8. Here irradiated lithium particles are removed by gravity flow out of the blanket into a container below. Refueling is done by similarly introducing particles at the top of the blanket. It is believed that this concept would allow refueling without interrupting the reactor operation, while also decoupling the reactor operation, from the tritium recovery. The constraint of having a large tritium inventory spread out around the fusion reactor is eliminated, and the possibility of tritium contamination relieved. This concept is especially attractive with organic coolant because the activation of the organic material is low and handling and transferring irradiated material is easier with the existing low pressures.

Organic coolants have some characteristics which makes them attractive for fusion breeder blanket design. Compared to other coolants, tests indicate that they are benign with lithium and lithium compounds and more adaptable to a variety of designs. In addition, their excellent nucleonic properties give good tritium breeding performance in fusion blankets. These characteristics, in combination with other well-known ones (low volatility, compatibility with most materials of construction, nonreactivity, and low cost) allow for simplicity and safety in fusion breeder blanket design. A large backlog of information on organic coolant technology developed in past studies on fission reactors can be exploited in fusion applications.

The major disadvantage of organic blankets results because of radiolytic damage to the coolant. Some protection of the organic material is necessary to reduce radiolytic damage to tolerable levels. This can be done by using multiplier/stripping designs, but the penalty paid is the necessity to use a two-coolant system. The comptetiveness of the concept, thus depends on whether the concept offers other advantages to fusion breeder applications.

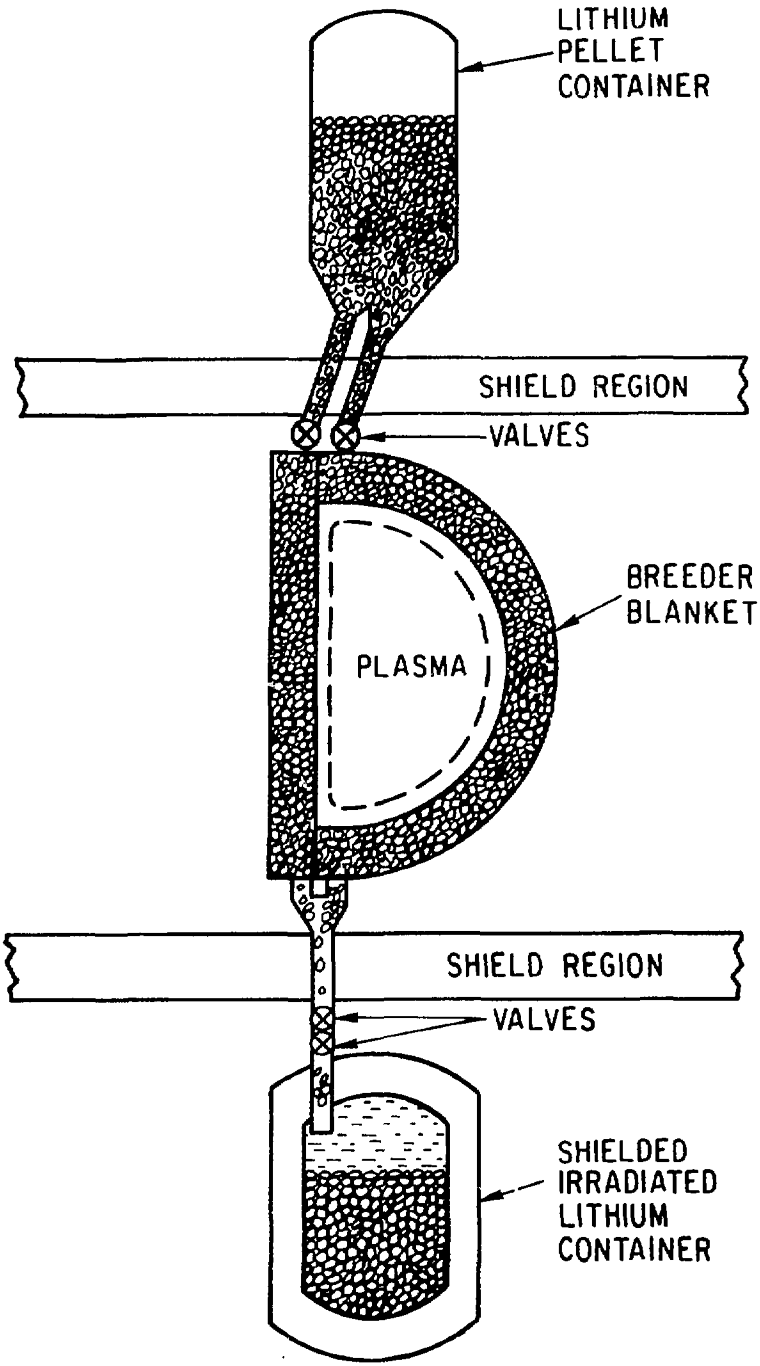

Fig. 8. In-situ fusion reactor refueling concept

Recovery of tritium from organic liquids appears to be easily interfaced with coolant purification process. Basically, the organic waste can be burned and the tritium can be recovered as water by well-established technology. A better alternative is to attempt to fully contain the tritium; organic-cooled blankets are also adaptable to this concept.

Contamination from the processing of the coolant itself should be comparable to fission reactors and thus minimal. The contamination that would result from the adjoint tritium is unknown at this time but it seems likely that this can be reduced to tolerable levels.

The results of this study show that organic coolants are sufficiently interesting for fusion applications to warrant work at a more detailed level. It is recommended that future work address the following areas on which additional information would be very useful:

- Compatibility tests of organic compounds with lithium and lithium compounds at reactor conditions especially for long-term effects.
- Radiolytic damage to organic coolants at fusion reactor conditions.
- Neutronic properties of organic breeding blankets.
- Energy distribution in organic blankets especially composite blankets.
- Optimization of organic blanket designs.
- Flow of organic fluids through packed beds especially flow of damaged coolant.
- Low-cost structural materials for use with organic coolants.

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